Case Study in Building Commissioning and Savings Verification Applied to a 311,000 ft²Office Tower Retrofit

Howard S. Reichmuth, Lambert Engineering Kevin C. Fish, Microgrid, Inc.

The subject of this case study is a 311,000 ft² office building that was comprehensively retrofit to achieve a verified savings of 33%. An electric utility sponsored the project and it was financed as an "energy service charge (ESC) project" with the building owner repaying the utility over 15 years on the basis of verified savings. A principal feature of the retrofit is a digitally based control system employing more than 3,500 sensor and control points.

The installation of such a complex system required a structured inspection/quality control system that included extensive "just in time" calibrations and inspections. Because of the extensive and continued systems checkout procedure, this retrofit could be done on a fully occupied building without major disruptions to its occupancy. Monitoring, auxiliary to the retrofit, and a weather-normalized presentation of the DOE2 post-retrofit performance model, allowed a confident estimate of the savings with less than one year of post-retrofit billing history.

Introduction

The subject of this case study is a $311,000 \text{ ft}^216$ -story, Class A office tower built in the early 1970's. The retrofit was comprehensive and included the following major features:

- 1. 34,000 ft² single glazing to low E double glazing,
- 2. 500 kW variable speed fan control on supply, return, and cooling tower fans,
- 3. 3,000 office lighting fixtures replaced with parabolic fixtures containing T-8 lamps, magnetic ballast and lighting sweep control, and
- 4. Full direct digital control (DDC) of all building HVAC and lighting systems, about 3,500 points altogether with more than 400 air mixing boxes under Terminal Regulated Air Volume (TRAV) control.

The retrofit controls strategy of this building was designed to run the central systems based on actual zone requirements, using variable speed fan controls and full DDC of the terminal units. This is commonly called TRAV, for Terminal Regulated Air Volume (Hartman 1988). This type of control system has broad software capabilities and enough system measurement points that most of the system testing can be done through software.

Cost and Financing

The full project cost was \$2,100,000 and the project duration was seven months. The sponsoring utility financed the project, with the building owner paying an "Energy Service Charge" to the utility over 15 years. This ESC was designed to be about 80% of the project savings.

The service charge is initially determined from the savings projected by DOE2 estimates of the before and after electric energy consumption of the building. If the actual savings are less than 90% of expectations, then the ESC is adjusted by re-running the model in the first year after the retrofit to reflect actual savings.

The project commissioning and associated monitoring play a key role in assuring that the immediate post-retrofit building performance meets modeling expectations. Monitoring was also done as needed to identify and quantify differences between the actual building performance and modeling assumptions.

Project Execution

The execution of a project of this type calls for a very rigorous quality management approach that is seamless from project design and controls engineering through to the final inspections. The controls of a building of this type, with more than 1,500 sensors and 1,500 computer controlled points, are roughly comparable to those of a jet airliner.

A building retrofit of this level of complexity will only function up to its full potential when the project design, installation, inspection, and commissioning are wellcoordinated.

We have found that it is vital to manage quality at every step of the process rather than only in the final formal checkout of the project. This quality management approach allows the building functions and comfort conditions to run uninterrupted throughout project construction, permitting comprehensive retrofits on fully occupied buildings.

Retrofit Does Not Disrupt Occupancy. A key distinguishing feature of this project is that it was to be done with the building fully occupied. The ability to execute a comprehensive retrofit on a fully occupied building is important from the perspective of the technical potential of savings from large building retrofits. ¹

The inventory of occupied retrofit candidates is much larger than the inventory of unoccupied retrofit candidates. Also, sufficiently comprehensive retrofits reduce lost opportunities.

The need to work around an occupied building had a major influence on the structure of the project. Special care kept building occupants aware of project activities. Material deliveries and disposal were done on a "just in time" basis because of very limited storage space. In some cases, special security was necessary to ensure the complete privacy of occupant records. **Project Work Schedule.** Project execution proceeded as shown in Figure 1 with a basic control "spinal cord" and primary electrical rewiring established first. Lighting and HVAC distribution were done on a floor-by-floor basis in one week per floor with the work done at night.

Glazing was done one exposure (that is, N, S, E, W) at a time in 4 weeks per exposure working at night.

Switch of Controls Functions with Full Occu-

pancy. Cutover from the old controls to the new controls was a key issue. The lighting and HVAC distribution for each floor remained on the old local control until completion of the HVAC distribution retrofit for that floor. Then the new controls took over the energy management of that floor. Building operations staff trained on the new controls early in the process.

Value of Occupied Retrofit. The ability to execute an energy retrofit of a continuously occupied building has significant monetary value from a building owner's and tenants' perspective. There are cases where a comprehensive retrofit required the temporary moving of the occupants to other floors or buildings while the work was underway. For a rough financial evaluation of occupancy cost assume that, if displaced, the occupants are forgiven two months lease payments for their trouble. For the subject building with lease rates of \$15.00/ft2/yr, the occupancy cost would be more than \$1,500,000. The project would have almost doubled in cost and not been cost-effective.

The Context of Commissioning in the Project

We focus here on the following three aspects of the commissioning of this building:

- 1. "Just in Time" calibration,
- 2. functional performance testing, and
- 3. monitoring.

Tim	neline								
	Note	May 1994	Jun 1994	Jul 1994	Aug 1994	Sep 1994	Oct 1994	Nov 1994	Dec 1994
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	Variable Frequency Drives		a	2.601			1		

The work on each floor was checked and calibrated "Just in Time" as the work ended. The building as a whole was commissioned after the project by a formal functional performance test of all systems.

In addition to the commissioning inspections and performance tests, pre- and post-retrofit monitoring was done on many variables. This provided a check on pre- and postretrofit comfort conditions, on DOE2 modeling assumptions, and an additional consistency test on the EMCS sensors.

Methodology

Commissioning played a key role in this project because the building owner's 15-year ESC is calculated on the predicted first year's post-retrofit performance. If the actual performance was more than 10% short of expectations, then the ESC is adjusted through further modeling.

Although there is an elaborate remodeling procedure, the program has no provision for correcting billing data for weather differences. We recommend a billing analysis technique described in the section, Billing Data Analysis. It provides a basis for deciding whether the building performance is inefficient enough to warrant a costly model tuning exercise.

Commissioning Procedures

In principle, the commissioning was to be done using an extensive set of commissioning procedures (Pacific Power & Light, 1992). However, this building was the largest, and most complicated in control systems, so far commissioned.

Therefore, it became a test of how to commission such a building. The functional test plan that finally evolved was included in a revision to the utility's commissioning procedures as an example of how to do a functional test on an extensive direct digital control (DDC) system (Pacific Power & Light, 1993).

"Just in Time" Tests

During construction, the commissioning became a 100% calibration checkout of the contractors work on all terminal HVAC boxes, sensors, controls, and the electronic board at the HVAC box at the time of installation. This immediate check was vital in assuring uninterrupted comfort conditions for the occupants and in making the whole building functional tests more reliable.

These calibration checks had added value because about 40% of the terminal HVAC boxes were deficient in some

way. If these deficiencies had passed this stage, they would have seriously complicated the checkout of the building as a whole.

Functional Performance Tests

The component functional performance tests focussed on the systems and functions shown in Table 1.

These functional performance tests examined the installed DDC system. They consisted principally of exercising the control loops and verifying the signs of correct responses. Note that these functional performance tests included yet another check of three terminal HVAC boxes randomly chosen on each floor.

The structure of each functional performance test was similar. It consisted of a trend log of 4 to 8 significant variables showing the response of the system to a varying control variable, usually a temperature set point.

Variable Air Volume (VAV) Terminal Box Testing and Verification. Three VAV terminal boxes were chosen at random on each floor for testing from the main control center. This was done by altering the temperature set points and examining the response of each box. The box tests were in two modes: the TRAV control mode, and the default (local control) mode.

The aims of these tests were:

- 1. to verify that the box would properly switch to the hot or cold air supply, and
- 2. to verify proper operation of the flow modulating damper.

The testing was done in a window of time between 5 PM and 6 PM to reduce occupant discomfort while maintaining "business hour" central plant function. Each test took about an hour as the space temperature set point was stepped through 2-degree Fahrenheit increments, each lasting 5 minutes. The test usually covered six floors, or 18 boxes, each day, requiring intensive computer keyboard operations for more than 3 hours.

Central Plant Component Testing. Central plant components consisted of two chillers, 2 boilers, 1 cooling tower and 3 sets of supply and return fans. The building operator's concerns about testing resulted in the main equipment often being "locked out" during testing, thereby limiting a significant part of the testing to an exercise of the control logic.

The test procedure varied for each component, but usually a test consisted of initializing variables that triggered the

System	Functions To Be Tested				
VFDs	Fan speed modulation in response to input signals Switchover to autocontractor				
Chillers	Start/stop, lead/lag and capacity modulation Chilled water reset Auxiliary interlocks				
Boilers	Start/stop, lead/lag and capacity sequency Hot water reset Auxiliary interlocks				
Cooling tower	Fan speed modulation in response to input signals				
VAV boxes	Hot/cold mode switching damper Modulating damper response				
Air handlers	Start/stop to weekly schedule and manual override Hot/cold deck coil valve control Mixed air control				
Lighting sweeps	Correct response to weekly schedule and override inputs				
Other	Space pressurization control Heat reclaim sequencing				

component into the mode we wanted to test. Then trend logs of variables associated with the mode under test were examined to verify that responses were as expected.

We tested the most common working modes of the component. However, there are many "uncommon modes," the results of various subtle aspects of the control programming. These "uncommon modes" were not explicitly tested. Because of the high reliability exhibited by the programming modes tested, and because the programming software will not allow many types of programming "bugs," testing of these modes was not thought necessary.

In fact, the use of trend logs of the monitored data discussed below was the main strategy for finding the tuning points and other points of adjustment in the building controls.

Variable Speed Drive Commissioning. Testing of the variable speed drives by the vendor before installation provided the rated output kW versus input signal. The contractor then recalibrated the drives after installation on the specific controlled motor. The functional test plan did not specify a test for total harmonic distortion. However, we performed an exploratory test at the end of the project.²

Monitoring and Monitoring Targets

Monitoring was done on several elements of the building operation as a check on assumptions used in the preand post-retrofit building modeling. This monitoring was not done comprehensively. Monitoring targets were chosen based on judgement of past problems, and in an attempt to document improved (or deteriorated) space comfort conditions. The monitoring targets are shown in Table 2.

For central plant variables, the monitoring relied extensively on the EMCS. As is clear from Table 1, data loggers monitored some variables before retrofit because the EMCS capability did not yet exist. All power measurements, whether monitored by EMCS or data logger, were actually current measurements. Each current measurement was corrected by a power factor measured once for that load.

The one exception was the elevator load that we measured using a true power logger that recorded VARS, WATTS and power factor. We measured this load in this manner because it had a very low (.2) and highly varying power factor.

	Instrumentation		
	Pre-Retro	Post-Retro	
System Fan Power (into VFD)	EMCS	ACR current	
System 2 Fan Power (into VFD)	EMCS	ACR current	
System 1 Pressures	EMCS	EMCS	
System 2 Pressures	EMCS	EMCS	
System 1 Temperatures	EMCS	EMCS	
System 2 Temperatures	EMCS	EMCS	
Chiller Current	EMCS	EMCS	
Chiller Water Temperatures	EMCS	EMCS	
Chiller Pump Current	EMCS	EMCS	
Boiler Current	EMCS	EMCS	
Boiler Water temperatures	EMCS	EMCS	
Boiler and Heat Reclaim Pump Current	EMCS	EMCS	
Iumidity	EMCS	EMCS	
Economizer Temperatures	EMCS	EMCS	
rd (Floor) NE (Corner) Space Temperatures	ACR Temp	EMCS	
th (Floor) SW (Corner) Space Temperatures	ACR Temp	EMCS	
Oth (Floor) SE (Corner) Space Temperatures	ACR Temp	EMCS	
Average Space Temperatures	ACR Temp	EMCS	
rd (Floor) NE (Corner) Duct Temperatures	ACR Temp	ACR Temp	
th (Floor) SW (Corner) Duct Temperatures	ACR Temp	ACR Temp	
rd (Floor) NE (Corner) Duct Pressures	ACR Temp	ACR Temp	
th (Floor) SW (Corner) Duct Pressures	ACR Temp	ACR Temp	
2nd - 4th Floor Lighting Current (277 Volt)- nany tenants	ACR Current	ACR Current	
3th Floor Lighting Current (277 Volt)—previous retrofit	ACR Current	ACR Current	
6th Floor Lighting Current (277 Volt)—(single tenant floor)	ACR Current	ACR Current	
Plug load (120 Volt and Elevator Current	ACR Current	ACR Current	

Table 2. Monitored Variables

Results

The results of the entire commissioning process physically make up hundreds of inspection checkout sheets, trend logs, EMCS print outs, and monitoring plots. Of necessity the results can be only briefly and anecdotally summarized here.

In general the commissioning process proceeded smoothly, without major unexplainable problems, and the building

has performed close to expectations since the conclusion of the project. The summarized results are as follows:

VAV Box Calibration

Calibration and checkout of the VAV boxes, just after completion by the contractor, revealed that about 40% of the boxes had a calibration out of specification. This deficiency was decided to be by and large attributable to poor organization of the calibration process by the contractor. The commissioning calibration check of the contractor's work was done on a box-by-box basis with emphasis on the proper operation of the box as a whole unit.

VAV Box Functional Performance Testing

The functional performance testing of the VAV boxes (3 per floor) by exercising the control system, revealed that the control of the boxes worked as expected, however some boxes showed deficient operation. These failures were all mechanical (i.e., leaks in the ductwork, incomplete hot/cold flapper operation, damper motor falling off shaft). While this exercise did not examine all boxes, it showed the general nature of the problems that arise. Problems were divided into those of contractor responsibility and owner responsibility (pre-existing conditions).

Fans and Central Plant Functional Performance Testing

The only problems met in the commissioning of the central plant components were associated with the air handler control. This control loop modulates the supply fan flow in response to the total airflow required by the operating VAV boxes in the building.

Scrutiny of the programs showed that one floor wasn't included in the needed airflow calculations and that some branches of the control program were inaccessible. We attributed the problem to fragments of outdated programming; a re-initialization of the whole program corrected the problem.

While it may seem remarkable that so few problems were detected in commissioning, remember that this was a continually working building with existing and functional central plant components. This is a reasonable expectation of a process where quality has been carefully managed and controlled as installation proceeds. Problems that arose were immediately addressed.

Monitoring Results Applicable to Commissioning

Monitoring results were extensive and showed several anomalous events during normal operation. These anomalous events were very important indicators of system control deficiencies and could not or did not reveal themselves in the formal functional performance testing.

Others have highlighted the need for extensive review of "As Operated" monitoring data in refining system operation (Herzog and Wajcs 1993). The importance of this trend log capability is such that the data storage capacity of the EMCS should be extensive, at least enough

to trend one-third to one-half of the points (Hartman 1988). Some of the most significant deficiencies revealed were as follows:

- 1. The VFD current sensors that show power to the control system were installed on the load side of the VFD. Under this condition the voltage was not constant and the calculations for power were incorrect.
- 2. Building total power transducer input to the controls gave erratic readings and needed replacement.
- 3. Automatic lighting sweep controls on some floors were bypassed.
- 4. The mixed air dampers cycled inappropriately and needed some changes in the control program.
- 5, There were instances of chiller short cycling that required controls program changes.
- 6. There were instances when fans were off at night and should instead have been run at low speed.
- 7. There was a case where space temperature instabilities occurred due to an electric heater in the space.

Monitoring Results Applicable to Savings Verification

Monitoring was also used to prove basic assumptions that were used in the DOE2 simulations of the building. The most important assumptions have to do with internal gain, building lighting load and plug load. Space temperatures, occupancy duration, and percent of outside air are also significant modeling assumptions.

The monitoring results have been used to explain the differences between the modelled predictions and the billing data. We did not compare all the monitoring data to the DOE2 assumptions. However, we examined the plug loads and the elevator load in some detail.

Plug Loads. The most noteworthy monitoring results that play a role in the savings verification described below relate to the plug load. It was a continuous equivalent of .62 watts/ft² instead of the .347 watts/ft² assumed in DOE2. Ratioed to the size of the building this load translates to an underestimate by DOE2 of about 1100 kWH/day.³

Elevator Loads. Current loggers originally monitored the total power of the vertical transport. The use of current loggers on this type of load is inappropriate because the load has a low and varying load factor.

A recording power meter monitored the load a second time. A sample of these measurements shown in Figure 2 shows how the elevator power and power factor varies with time of day. Figure 3 shows the measured elevator power superimposed on the assumed elevator power used in DOE2. Overall, DOE2 assumed slightly more elevator power than we measured, or about 300 kWH/day.

Billing Data Analysis

The billing data gives the most authoritative estimate of the savings for the building. We evaluated post-retrofit billing data by associating each billing month and average daily temperature over the billing interval.

We reduced the billing data to kWH/day to normalize for billing interval and plotted versus the average monthly temperature as shown in Figure 4 below. Figure 4 is also a convenient format for presenting DOE2 estimated monthly performance. In general, this method of presentation shows the energy use as predicted by DOE2 and the billed energy use both varying in a coherent manner with temperature. An imaginary line connecting the DOE2 predictions becomes a performance threshold;

- Billing points above the line show performance worse than predicted, and
- Points below the line show performance exceeding predictions.

Differences seen between the billing data and the DOE2 monthly estimates are usually consistent. These differences typically reveal potential operational problems or suggest monitoring targets for refining DOE2 input assumptions.

One of the authors did a sensitivity analysis of two DOE2 modeled buildings, changing 17 significant variables one at a time. That analysis shows how variations in DOE2 assumptions will appear in this energy versus temperature format (Reichmuth 1994).



Figure 2. Elevator Load Measurements



Figure 5. Elevator Power vs Assumed DOE2 Elevator Power

In this case, the post-retrofit billing data is close to the DOE2 predictions.

The initial estimates of savings for this building were based on the difference between the DOE2 modeled preand post-retrofit performance. Savings estimated in this manner were 45%. However, the pre-retrofit model does not fit the pre-retrofit billing data very well, as is clear from Figure 5 below.

Because the pre-retrofit model fits the pre-retrofit billing data so poorly, it could not be used confidently as a preretrofit baseline. Therefore, we developed an alternate method of estimating the savings.

The alternate method uses the real pre-retrofit billing data for comparison to both:

- a. the DOE2 post-retrofit estimate and
- b. the actual post-retrofit billing data.

This comparison shows the savings for the building if the post-retrofit weather had been the same as the pre-retrofit weather.

Since these savings will represent the average savings for only two specific pre-retrofit weather years, they may differ from the true long term average savings. However in this case, these specific savings are preferable to using an inaccurate pre-retrofit baseline. This comparison is done by fitting a quadratic equation to the DOE2 post-retrofit and to the billed post-retrofit data. The quadratic fits quite well in both cases, as illustrated in Figure 6.

The use of a quadratic fit in this case is purely empirical. The purpose of this fit is to "interpolate" kWH/day to preretrofit average monthly temperatures. These temperatures may vary by a few degrees from either the TMY monthly average temperatures used in DOE2 or from the temperatures corresponding to the billing data.

Using this method of comparing the monthly pre-retrofit kWH/day figures to the DOE2 and post-retrofit figures at the pre-retrofit average monthly temperatures yields a DOE2 predicted savings of 41% of the pre-retrofit energy use, and an observed savings of 33%.

We must note that in the DOE2 prediction, the assumed plug load and night time fan speed were too low. If we changed both assumptions in a DOE2 rerun, then the DOE2 estimate of the savings will be less than the originally estimated 41% and closer to the observed 33% savings.²

Conclusions

A comprehensive retrofit using a complex digitally based control system can be installed and commissioned without major disruptions to owner or tenants by the application of a carefully structured inspection and quality management system.



Figure 4. Post Retrofit DOE Prediction vs Billing Data



Figure 5. Billing Data vs DOE Pre- and Post-Retrofit



Figure 6. Backcast of Post-Retrofit Models on Pre-Retrofit Data

The structure of the management system used successfully in this case employed 100% calibration and checkout of all distributed control system points (VAV boxes) and extensive testing and refinement of system control programming with trend log analysis.

Trend log analysis will be relied on extensively in the quality management of the system installation. It will require that the memory storage requirements of the control system be enough to maintain trend logs on up to 30% of system points.

True power monitoring external to the EMCS for plug loads, lighting loads, and elevator loads will be an important check on the accuracy and utility of the DOE2 predicted performance. In this case monitoring showed higher internal gains than assumed in the DOE2 model. A rerun of this model with the actual gains would have provided an even closer estimate of the observed billing data.

Savings verification showed actual post-retrofit savings of 33% when compared to the energy use for the two years immediately before the retrofit. The use of an energy versus temperature format for the presentation of DOE2 monthly predictions allows the immediate, month-by-month, weather-normalized comparison of post-retrofit billing data to the engineering expectations of the project.

In this case, we made a reasonable estimate of postretrofit savings with only 7 months of post-retrofit billing and temperature information. This was possible because the observed temperatures spanned the full annual range of temperatures at the site.

Acknowledgments

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Endnotes

- 1. This building won the Energy User News award for 1992 for integrated design recognizing the comprehensiveness of the retrofit.
- 2. The test for total harmonic distortion, THD, was done with a Dranitz meter by exercising the VSD through a range of speeds. On later buildings, the VSD purchase contract now requires that the contractor document THD at five different power levels.
- 3. This assertion is based on analysis of DOE2 "perturbation" runs made by SBW for Pacific Power. In these runs all variables remain constant except one. Where internal gain variables were changed the whole curve of kWH/day versus temperature was displaced vertically.

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