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MODEL-BASED CHILLER ENERGY TRACKING FOR PERFORMANCE ASSURANCE AT A UNIVERSITY BUILDING

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ABSTRACT

Buildings and their various subsystems often do not perform as well as intended at the design stage. Building energy performance suffers from insufficient documentation of design intent, inadequate building commissioning, and a lack of robust methods for short-term and continuous performance tracking. This paper discusses how calibrated models can be used to track building systems and component performance from design, through commissioning, and into operations. Models of the chillers energy use and efficiency were developed and used to evaluate energy performance and control changes to minimize energy use. The example discussed is based on an actual University building. A detailed discussion of the extrapolation and associated uncertainty of using six months of data to develop annual energy use scenarios from various chiller models is included. An important lesson concerning the design is that there was significant oversizing of the chillers resulting in poor part-load performance and over $3000/year of annual energy cost increases. The oversizing is related to extremely high estimates of office equipment loads. The oversizing also causes frequent cycling of chillers, which shortens chiller life. Due to the lack of careful start-up procedures, it appears construction debris fouled one of the new chillers, resulting in about $5200/year in energy increases. Additional comments on design and commissioning issues are included. The monitoring, modeling, and software development efforts were developed to demonstrate the value of collecting and organizing information regarding design, commissioning, and ongoing performance. This case study is part of a larger effort to examine methods and technologies to improve buildings performance and develop interoperable Building Life-Cycle Information Systems (BLISS).

INTRODUCTION

Buildings and their various subsystems often do not perform as well as intended at the design stage. There are many reasons for this, including changes in building loads and schedules from early design assumptions, equipment failing to meet performance specifications, and improper installation, operations or control sequences. A related problem is that many building operators do not understand important performance characteristics of building equipment. Critical information is lost as the building passes from the design stage into construction and operations. Building energy performance suffers from insufficient documentation of design intent, inadequate building commissioning, and a lack of robust methods for short-term and continuous performance tracking.

The LBNL Building Performance Assurance Project was initiated to address problems related to poor information transfer through the building life cycle. The goal of this effort is to improve building performance by working with public and private industry to create life-cycle information systems. The project has had several subprojects. One subproject deals with the conceptual design of interoperable, Building Life-Cycle Information Systems (BLISS, see Selkowitz, 1996).[1] Another subproject is the development of prototypical computer-based commissioning tools (Piette, 1996). The subproject discussed in this paper deals with model-based performance tracking tools and techniques. Much of the effort to date has focused on working with cooling plants and chiller performance.

This paper discusses the analysis of chiller energy use at a new Computer Science building at U.C. Berkeley to examine problems associated with information transfer and the benefits of prototypical information systems for performance tracking. The discussion below begins with an overview of the commissioning and monitoring activities at the case study building. Next we discuss the development of the calibrated models and the technique to extrapolate from six months of monitoring to annual results. This is an important part of the evaluation methodology since there is a need for monitoring and verification methods based on short-term data. The results of a scenarios analysis are then presented. The final section is a summary and discussion of related work.

PROJECT OVERVIEW

Soda Hall, a 109,000 ft^2 Computer Science building was selected as our case-study site for several reasons. First, it is a new building, and our monitoring and commissioning tests were scheduled during the first year of occupancy. Second, the building was equipped with an Energy Management Control System that the research team had worked with before, which was used as the platform for continuous monitoring. Third, the building was located near LBNL, permitting easy access. Finally, the building has two, 220 ton screw chillers, for a total of 440 tons of cooling plant capacity. Early in the building performance assurance project we decided to focus on chillers, which are the largest single energy-using component in buildings with central cooling plants. The commissioning and performance tracking consisted of the following eight activities:

- Compiled HVAC specifications, control sequences, and as-built documents.
- Conducted short-term measurements to characterize flows, temperatures, and pressures.

[1] See also http://eande.lbl.gov/CBS/BPA/BPA.html

- Conducted additional power measurements on cooling towers for use in estimating energy savings from set-point optimization.
- Installed long-term, permanent metering equipment for as-operated model calibration and diagnostics using the EMCS as the data acquisition system.
- Conducted false load tests of chillers to evaluate kW/ton at partial and full loads.
- Evaluated model calibration methodologies and developed calibrated models of the chillers and cooling towers.
- Identified and implemented improved control sequences.
- Extrapolated from six months of measurements and modeling analysis to evaluate annual energy impacts of various operating strategies and retrofit scenarios.

In this paper we discuss the analysis of measurements taken from September 1995 through February, 1996. One-minute data covering various temperatures, flows, power, and equipment status were archived and evaluated for over forty channels that cover the chillers, pumps, cooling tower, plus whole-building electricity use. We also describe the development of a PC-based Performance Evaluation and Tracking Tools.

MODELING AND ANNUAL EXTRAPOLATION METHODOLOGY

A major component of the effort to date has been the development, calibration, and testing of equation-based chiller models. The HVAC industry needs chiller models that accurately describe energy requirements for chillers over a variety of operating conditions. Physical models are useful because model coefficients take on valuable diagnostic information. One such state-of-the-art model is Gordon's model, which could not be used with the chillers at Soda Hall because it assumes compressor irreversibility varies as linear functions of temperature (Gordon and Ng, 1995). This assumption does not describe a screw chiller for which the irreversibility varies as a function of load as well.

Modeling was done using components available in the Simulation Problem Analysis and Research Kernel (SPARK), which is under development at LBNL in partnership with California State University at Fullerton (Sowell et al., 1993). The two models are based on DOE-2 chiller models and a statistically derived 10-parameter regression model, both described in Meyers (1996). The evaporator load (tons), chilled water supply temperature, and condenser water supply temperature are predictor variables. The chiller's electric power is the predicted variable.

The DOE-2 model has the following form:

Tevap:	chilled water supply temperature
Tcond:	condenser inlet temperature
Load:	load on the chiller
Capacity:	available capacity
PLR:	part load ratio
f1:	capacity correction factor for off-design temperatures
f2:	power correction factor for off-design temperatures
f3:	power correction factor for part load performance

$$f1(Tevap, Tcond) = a1 + b1\ Tevap + c1\ Tevap^2 + d1\ Tcond + e1\ Tcond^2 + f1\ Tevap\ Tcond$$

$$f2(Tevap, Tcond) = a2 + b2\ Tevap + c2\ Tevap^2 + d2\ Tcond + e2\ Tcond^2 + f2\ Tevap\ Tcond$$

Capacity	= f1(Tevap, Tcond) * Rated Capacity
PLR	= Load / Capacity
f3(PLR)	= $a3 + b3\ PLR + c3\ PLR^2$
Power	= Rated Power * f1 * f2* f3

The 10-parameter statistical fit has the following form:

Power = f (Tevap, $Tevap^2$, 1/Tevap, Tcond, $Tcond^2$, 1/Tcond, Tevap*Tcond, 1/(Tevap*Tcond), Load)

The chiller models and calibration techniques were evaluated to determine the importance of calibration data sets and goodness of fit. Measured power agreed with modeled power within a few percent RMS for the models discussed in the scenarios presented below. The models are highly sensitive to the operating temperatures around which they are calibrated. Therefore, the more complete the data set is in covering the entire range of operating conditions, the better for calibration. While this is a somewhat obvious finding, a detailed paper discusses the variations in "goodness of fit" with changes to the calibration data set (Meyers, 1996). These sensitivity analyses are useful for cases where modelers may have more limited data sets than those available for this research project.

Part of the analysis included compiling a series of part-load and full-load data from the chiller manufacturer to obtain a model of the chiller based on the performance specifications. Neither of the two chillers met these specifications, as discussed below. Such comparisons are difficult because of measurement issues and the fact that the manufacturer's rating is based on steady state points while only a subset of the data from actual chillers are steady state points. Further comments on this comparison are found in Meyers (1996). Although the chillers are identical, Chiller One is more efficient (lower kW/ton) than Chiller Two, also further discussed below. This paper reports on the following four scenarios:

- comparison of existing chillers to each other
- comparison of existing chillers to manufacturer's data
- setpoint changes (two chilled water and condenser water temperature set point changes)
- retrofit options (three options presented)

To estimate the annual energy use and savings associated with a change in control of the chillers or retrofit of the chillers, the modeled data were extrapolated to a typical weather year using weather regressions. The method used to annualize the electrical energy use for the different scenarios is described below.

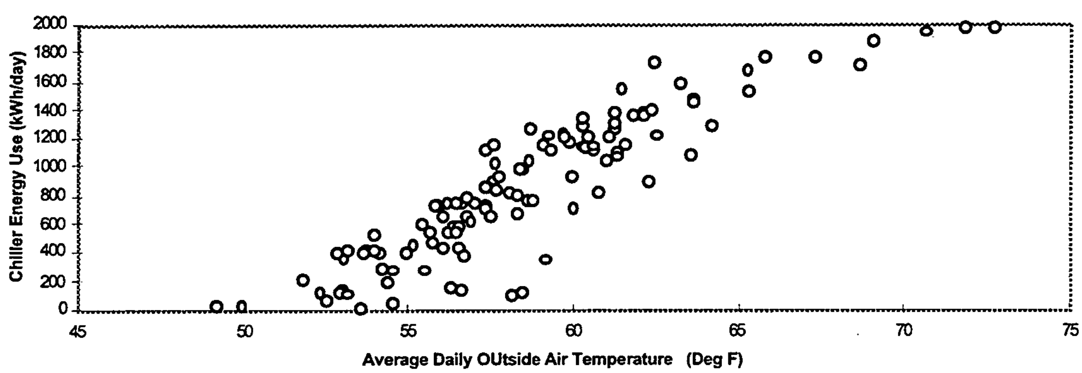
Normalized Annual Consumption (NAC)

It is generally accepted that monitored energy data for weather sensitive end uses (cooling and heating) in buildings can be normalized to a typical weather year by characterizing the daily energy use as a function of average daily outdoor air temperature or as a function of heating and cooling degree days (Fels, 1986). The resulting regression model can then be used with weather data from a typical meteorological year (TMY, TRY, WYEC2, etc.) to provide the Normalized Annual Consumption (NAC) estimate (Ruch and Claridge 1993). As mentioned above, models to predict steady state chiller kW based on the one-minute monitored data were developed. The one-minute data were aggregated to daily energy use (kWh/day) and the average daily outdoor air temperature was computed to allow the data to be used in EModel (Kissock et al., 1994). EModel is a building energy analysis software tool with a variety of easy to use regression analysis methods.

The models used to predict kW from load, flow rates, and water temperatures are steady state models, thus some of the measured data were not included in the modeled data. The filters to remove dynamic data were set such that approximately seven minutes of low load data at start up and shut down were filtered. Assuming 604 (one start and one stop for 302 days) starts and stops per year, there are approximately 3,500 kWh/yr. that are not accounted for in the models. Thus all NAC estimates in Table 1 have a bias of about 1.5%.

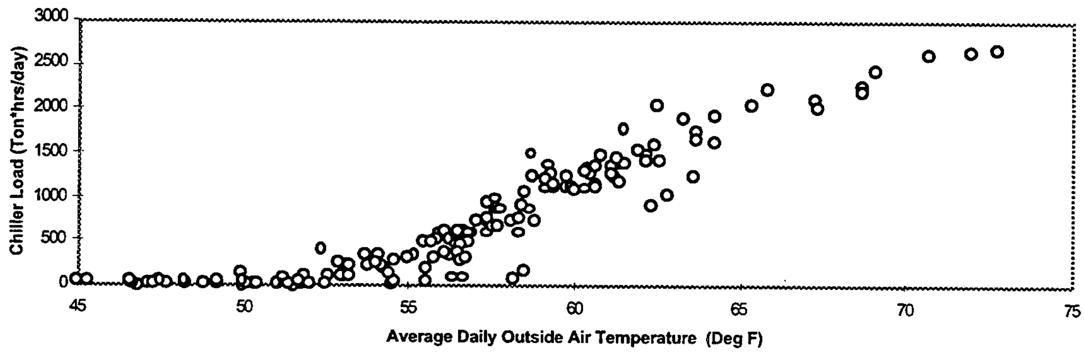
EModel was used to find the best fit four-parameter change point model (4P-CP), which is a piecewise linear model having two intercepts and two slopes. Researchers at Texas A&M's Energy Systems Laboratory have found this type of functional form to have physical significance in characterizing heating and cooling loads in buildings. In Texas A&M's experience the change point has been related to outdoor air dampers being set to minimum or preheat coils being activated as outdoor ambient temperatures drop (Ruch and Claridge, 1992). The chiller energy use in Soda Hall has a very different characteristic as seen in Figure 1 compared to the cooling energy use in buildings studied by Texas A&M. In the case of Soda Hall, the high load region has a lower slope than the low load region. This contrasts with buildings studied by Texas A&M where the high load region has the steeper slope.

Figure 1: Chiller Energy Use Versus Outside Air Temperature for Soda Hall



The difference in slopes is most likely explained by different climates, HVAC systems, and controls. Originally it was thought that lower slope at high loads was due to more efficient chiller operation. Many buildings studied at Texas A&M's Energy Systems Laboratory have had cooling provided by a district chilled water system. The energy consumption data presented for these buildings is determined by measuring water temperatures in and out of the building and water flow. However, at the central plant there are chillers that have inefficiencies, which are not accounted for in the building level energy consumption. In Soda Hall we measure kW into the cooling plant, thus the Soda Hall data contain the inefficiencies. Chillers operate at higher load, where they are more efficient, during hotter days. Therefore, Soda Hall's chiller energy consumption versus outside air temperature (OAT) will have a lower slope in the high load region due to more efficient operation.

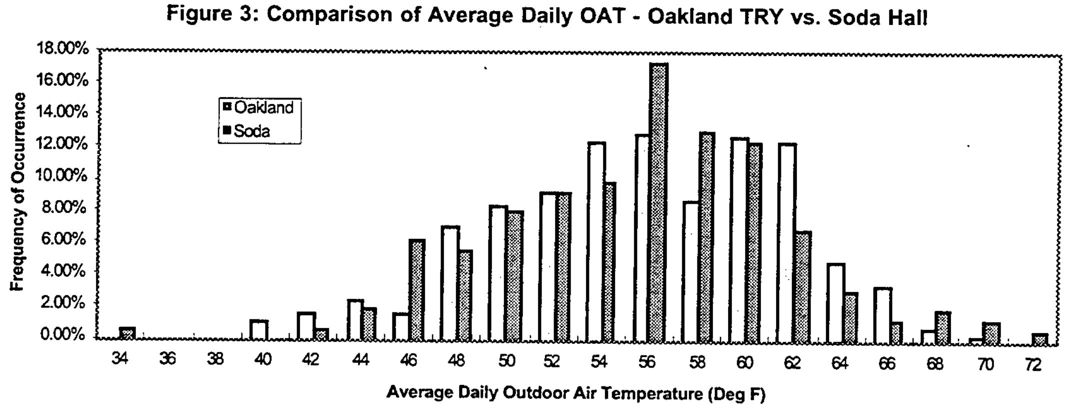
Figure 2: Chiller Load (Tons) Versus OAT for Soda Hall



The four-parameter change point model was used to characterize chiller energy use as a function of average daily OAT. Separating the data into workdays and weekends plus holidays revealed no significant differences in the regression models because the building is heavily used by students and faculty on weekends; thus, one model was sufficient for all day types. Since the R^2 of the 4P-CP models were all greater than 0.81, the effort required to find a more appropriate functional form was not justified.

In characterizing the chiller energy use as a function of OAT, it is critical that the OAT measured is representative of actual conditions (i.e. direct sunlight or exhaust air on the sensor could produce inaccurate results). Care has been taken in placing Soda Hall's OAT sensor so that it is not influenced by building exhaust or solar effects. Figure 3 shows a frequency distribution of average daily OAT for the monitored period compared to the Oakland Typical Reference Year (TRY) weather. The shape of the distributions are similar. The TRY weather tape for Oakland Airport was used to find the average daily OAT for the 365 days of a typical weather year. These were put in 1°F bins and combined in an Excel spreadsheet with the regression models to calculate the NAC estimates.

Figure 3: Comparison of Average Daily OAT - Oakland TRY vs. Soda Hall



Uncertainty Analysis

When using the standard error of the residuals of a model fit to calculate confidence intervals on a prediction, we assume that the residuals are independent of each other. When residuals are not independent of each other they are correlated. In the case of time series data this is called auto-correlation. A significant amount of auto-correlation can cause the standard errors to be underestimated when predicting daily energy use, as was shown by Ruch et al. (1993). Ruch presented adjusted estimates of the standard error for the NAC estimates when using single linear and Four-parameter change point regression models with the presence of auto-correlation in the residuals.

In the current work the first auto-correlation coefficient was found to be 0.16 on average, which indicates minimal autocorrelation. The first auto-correlation coefficient measures the correlation between observations at t and those at t-1. The small degree of auto-correlation combined with the fact that we were interested in annual estimates as opposed to daily estimates, justified the decision to ignore auto-correlation to simplify the uncertainty analysis.

Ruch and Claridge (1993) presented a method to estimate the standard error of the NAC estimate for both a single linear regression model and for a Four-parameter change point model. The uncertainty analysis for a 4P-CP model requires a multi-dimensional search to find the change in the NAC given an error in one of the four parameters. Recognizing that an uncertainty analysis of the single linear regression models would bound the uncertainties on a 4P-CP model and that the uncertainty analysis of a single linear regression model is much simpler, we chose to use the uncertainties of a single linear regression model as an estimate of the uncertainty for the NAC's of the 4P-CP models. Assuming the NAC is normally distributed, a student test statistic was used to calculate the 95% confidence intervals presented below in Table 1.

RESULTS

Soda Hall consumes about 34 kWh/sqft-year, of which approximately 13 % is directly used for the chillers (not including the rest of the cooling plant, such as the cooling towers and pumps). The commissioning tests executed to evaluate the chillers and cooling plant were somewhat exploratory in nature. A variety of design and installation problems were identified. Design problems included: oversized pumps, an unneeded isolation valve, an unneeded three-way diverting valve on the cooling tower, unneeded thermometers on the inlet and discharge of each pump, two-way instead of three-way valves on the computer room condenser water, unclear design drawings, and a VAV minimum set point specified at only 50% of the peak. These problems result in energy waste and design cost overruns estimated at over $25,000. Installation problems included: incomplete programming and debugging of the energy management control system (EMCS), oversized control values that cause large pressure drops and unstable operation, a water-logged expansion tank, a mislocated thermostat, poor control strategies, strainers covered with insulation (inhibiting proper maintenance), incorrect piping of the chiller rupture disk, and a high condenser set point. These problems relate to safety issues, energy waste, and maintenance issues.

Scenario Analysis Results

Table 1 below shows the normalized results for eight scenarios studied along with their associated uncertainties of the NACs and difference between NACs. The scenarios presented in Table 1 are based on the same chiller models as those in the Performance Evaluation and Tracking Tools discussed below. A discussion of the results in this table and the particulars of each scenario follows. In most cases Chiller One is used as the base since it is the more efficient of the two existing chillers. All dollar estimates are based on $0.080/kWh which is larger than the University's average cost of electricity ($0.057/kWh), but representative of typical cost of electricity in the US for commercial buildings.

Though the uncertainties for the NAC's are small, the uncertainties associated with the difference between any two NAC's is larger since uncertainties are additive. If more time had been taken to carry out the uncertainty analysis for a 4P-CP model, the resulting uncertainties for the differences could be tightened.

Table 1: Normalized Annual Consumption (NAC) Estimates

Case #	Description	Annual Energy Use: NAC (kWh/yr.)	Annual Energy Use: $/yr.	Difference Relative to Chiller One Actual: (%)	Difference Relative to Chiller One Actual: (kWh/yr.)	Difference Relative to Chiller One Actual: ($/yr.)	Difference Relative to Chiller Two Actual: (%)	Difference Relative to Chiller Two Actual: (kWh/yr.)	Difference Relative to Chiller Two Actual: ($/yr.)
1	Chiller One Actual (Base Case)	237,603 ± 13,250	$ 19,008 ± 1,060	0%	0	$0	-16%	-45,841 ± 29,130	-$3,667 ± 2,330
2	Chiller Two Actual	283,444 ± 15,880	$ 22,676 ± 1,270	19%	45,841 ± 29,130	$3,667 ± 2,330	0%	0	$0
3	Manufacturer's Data	216,685 ± 12280	$ 17,335 ± 982	-9%	-20,918 ± 25,530	-$1,673 ± 2,042	-24%	-66,759 ± 28,150	-$5,341 ± 2,252
4	Chiller Two (CHWST = 44, CWST = 85)	410,377 ± 48,940	$ 32,830 ± 3,915	73%	172,774 ± 62,190	$13,822 ± 4,975	45%	126,933 ± 64,820	$10,155 ± 5,185
5	Chiller Two (CHWST = 47, CWST = 83)	357,899 ± 27,080	$ 28,632 ± 2,166	51%	120,296 ± 40,330	$9,624 ± 3.226	26%	74,455 ± 42,950	$5,956 ± 3,436
6	Retrofit A (100 Ton Screw)	184,057 ± 24,150	$14,725 ± 1,932	-23%	-53,546 ± 37,400	-$4,284 ± 2,992	-35%	-99,387 ± 40,030	-$7,951 ± 3,202
7	Retrofit B (100 Ton Screw + ARI Tol.)	194,969 ± 42,520	$ 15,598 ± 3,401	-18%	-42,634 ± 55,770	-$3,411 ± 4,462	-31%	-88,475 ± 58,390	-$7,078 ± 4,672
8	Retrofit C (100 Ton with DOE-2 curves)	193,285 ± 24,990	$ 15,463 ± 1,999	-19%	-44,318 ± 38,240	-$3,545 ± 3,059	-32%	-90,159 ± 40,870	-$7,213 ± 3,269

Note: Uncertainties shown are based on a 95% confidence interval

Existing Chillers

The first two rows of the table show Chiller One and Chiller Two energy use as they are currently installed. Based on measurements of refrigerant pressures and temperatures and detailed discussions with the manufacturer, the difference between the two is believed to be sludge and construction debris in Chiller Two's condenser and evaporator resulting in less efficient heat exchange. This debris probably accumulated because the chiller inlet headers are low points in the system.

Having these comparative results based on measured data, LBNL was able to convince the Department of Facilities Management on campus that running Chiller One instead of Chiller Two could save a significant amount of energy. The change in operations was made in mid-March of 1996 and, with all else equal, is estimated to save the University $3,667/yr. in electricity charges (a 19% savings). We have not yet cleaned Chiller Two to examine whether this would improve the efficiency, but hope to explore this in the future.

Manufacturer's Data

Though Chiller One is more efficient than Chiller Two, both chillers are operating significantly less efficiently than the manufacturer's literature suggests. A closer look at the chiller rating procedure, ARI-550 (1992) shows that according to the standard for rating chiller efficiency, Chiller One is barely operating within specification. It is not uncommon for manufacturers to exploit the ARI tolerances to obtain more favorable efficiency ratings. The tolerance defined in ARI-550 has the following form:

Percent kW/ton = $10.5 - 0.07 \times \%\mathit{full\text{-}load} + \frac{1500}{\Delta T_{design} \times \%\mathit{full\text{-}load}}$ where ΔT is the design ΔT.

The difference in annual operating costs between the chillers meeting the manufacturer's specifications and the measured field performance is $1,673/yr. for Chiller One $5,341/yr for Chiller Two.

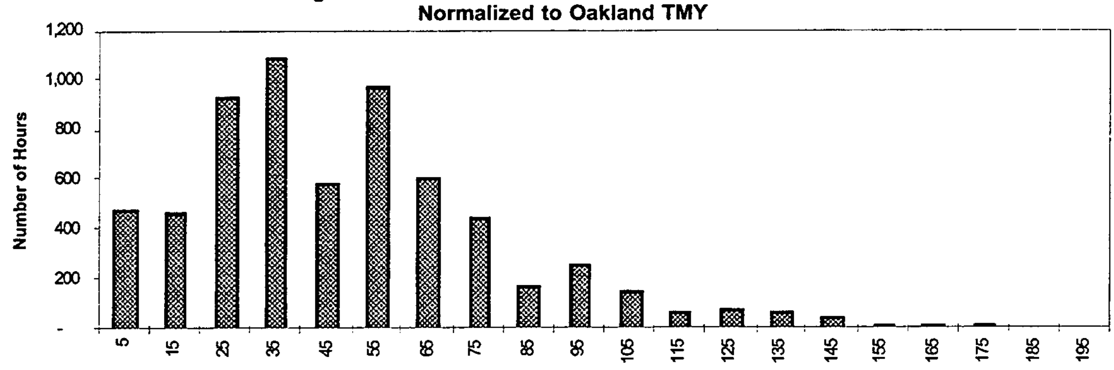
Setpoint Changes

As expected from basic principles of chiller operation, Scenarios 4 and 5 show that the chillers operate much more efficiently with a lower condenser water supply temperature (CWST) and a higher chilled water supply temperature (CHWST). Insufficient data over Chiller One's operating range limited the analysis of different control points to Chiller Two only. From September 1995 through May 1996, Chiller Two was operated as the lead chiller with an average condenser water supply temperature (CWST) of 77°F and a chilled water supply temperature which was reset with load (these are the conditions for scenario 2). The CHWST was reset in the high 50's for much of the time. Compared to the ARI conditions in scenario 4 (CWST = 85°F, CHWST = 44°F), Chiller Two was estimated to save $10,155/yr, a 45% reduction in energy use. Compared to more efficient conditions (CWST = 83°F, CHWST = 47°F), the operating points saved $5,956/yr., a 26% savings. Another factor not considered here is the effect of changing chiller operating points on chilled water pumping and cooling tower fan energy use. Forthcoming work at LBNL will include an evaluation of the trade-offs between more efficient chiller operation with increased tower energy use and increased secondary pumping requirements.

Downsizing Chillers

One of the most striking findings at Soda Hall has been the loading on the chillers. Chillers are ideally sized to have most of their operating hours at about 70 to 80 percent of full load. Chillers are less efficient, consuming more power for each ton delivered (high kW/ton), at low loads. Although 440 tons of cooling capacity are available at Soda Hall, the building requires 35 to 55 tons during most operating hours (Figure 4). These results are for the first year of operation. It is possible that loads will increase as more computer equipment are brought into the building. However, the building was considered fully occupied and it is unlikely that the cooling load will double. Even if it did double to an average of 80 tons, the 220 ton chiller is larger than needed and the 440 ton capacity greatly exceeds the peak loads. Even during the hottest month, only one of the two chillers was required, and the building rarely needed more than 150 tons.

Figure 4: Soda Hall Annual Chiller Load Distribution Normalized to Oakland TMY



We do not have a complete account of the assumptions used in sizing the chillers. It appears that the largest factor that lead to oversizing was an overestimate of computer loads. The tenants were previously housed in a building that was designed during the era of mainframe computers, which suffered from inadequate cooling with the emergence of desktop PCs and workstations. The CS department suggested they might need as much as 1500 W/person for large, high-end graphic workstations. This estimate was scaled back to 600 W/person, which still appears to be far greater than the actual loads.

In evaluating retrofit scenarios, the base case was assumed to be Chiller One, the more efficient chiller, running for all loads. The loads in Soda Hall are not so high that a 220 Ton chiller cannot meet them. A 100 Ton chiller was selected for a hypothetical retrofit. The 100 Ton chiller was run with three different sets of curves: manufacturer's curves (scenario 6); manufacturer's curves with the ARI Tolerances added on (scenario 7); and, the DOE-2 chiller curves. The ASHRAE Standard 90.1 recommended DOE-2.1 curves were fit to manufacturer's data for an actual chiller by changing the rated load and rated power to minimize the squared error between the manufacturer's data set and the model prediction. The 100 Ton chiller was run as the lead chiller for loads less than 100 tons. When load exceeded 100 tons, the 100 Ton chiller would be shut off and Chiller One (the existing 220 Ton chiller) would be used.

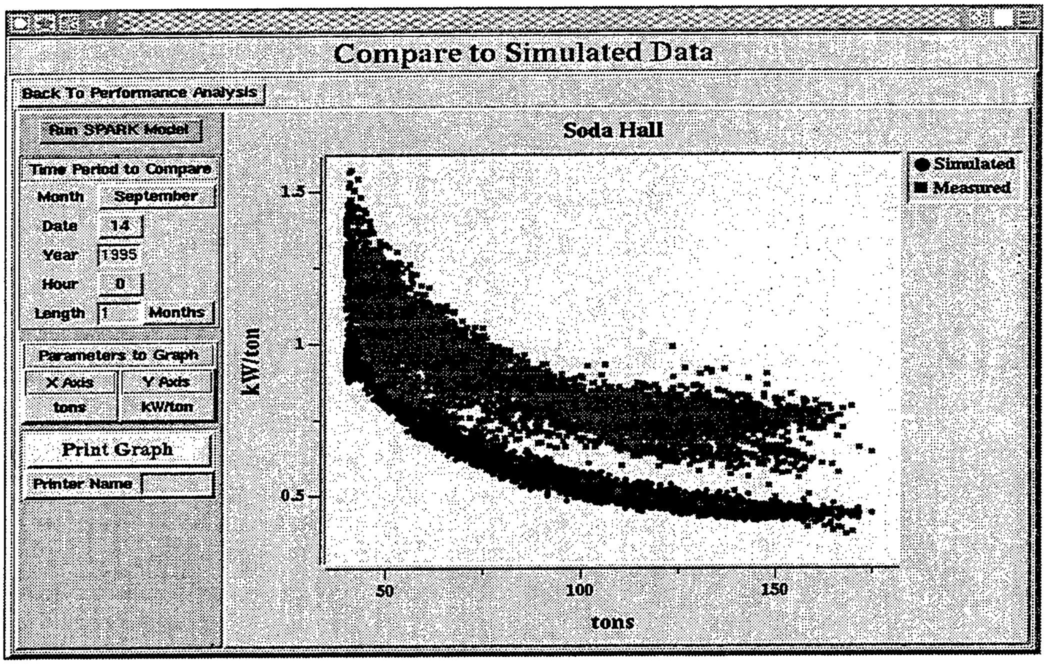
The most realistic comparison is with scenario 7 since this scenario takes into account the likelihood that an installed chiller may not meet manufacturer's curves, but will likely be within ARI tolerances. The results show that the savings associated with retrofit are quite large. Though the annual dollar savings ($3,411/yr.) are significant, they are not sufficient to justify a retrofit (100 tons @ $250/Ton for chiller only = $25,000). However, the first cost for the chillers was far greater than necessary because of the oversizing. Though a retrofit may not be justified at this time, the results show that there are significant inefficiencies associated with oversizing the chillers. In hindsight, a better design would be a 75 Ton and a 200 Ton chiller combination since only 867 of the estimated 6,445 annual run hours occur at loads above 75 tons. This hypothetical design would have provided significant capital and operating cost savings while still providing extra capacity for load growth.

Performance Evaluation and Tracking Tool

Figure 5 shows a prototype Performance Evaluation and Tracking Tool (PETT) developed to allow a building operator to compare actual energy use with modeled energy use under a variety of difference operating assumptions. PETT is built on SPARK, providing a graphical user interface or shell for SPARK. The data shown are "minute" data for September, 1996. The "measured" points are based on actual on-site measurements for both chillers, and the "simulated" points are based on a model of the manufacturer's ratings for the chillers. Notice that the measured data show two regimes. The lower kW/ton is Chiller One and the higher is Chiller Two.

PETT can be used for performance tracking, for analysis of different control strategies, and also for the analysis of different options during the retrofit phase. Deviations of the building data from the simulated data may indicate problems in the HVAC system. PETT options related to "control strategy analysis" facilitate changes to the control logic used during the measurement and comparison of the emulated results to the actual measured data. The environmental conditions and the building loads are maintained at the measured levels, but changes are made on the control choices such as temperature set points, or equipment status. At this stage, these control strategy analysis options facilitate "what-if" type of analysis. The model capabilities can be expanded to include optimization. In such an application, the tool would produce an optimal set of choices for all of the control (set-points and configuration) options. Finally, longer term actions can be analyzed using the "retrofit analysis" options of the tool. Here, changes that would require implementation of new equipment and hardware are analyzed. A typical example would be a chiller replacement project. Using the retrofit analysis options of the tool, one can compare the performance of the overall system under different chiller sizing and efficiency choices similar to the scenarios show in Table 1.

Figure 5. Prototype Performance Evaluation and Tracking Tool showing measured versus the manufacturer's-simulated efficiency



SUMMARY AND RELATED WORK

One of the primary motivations for this research is to explore how calibrated models could be used to track building systems and component performance from design, through commissioning, and into operations. Models of the chillers energy use and efficiency can be developed during design, calibrated during commissioning, and used during ongoing performance to identify fouling or other degradation that might occur over time. Such a model can also be used for control optimization to minimize energy use.

The monitoring, modeling, and software development efforts involving Soda Hall demonstrate the value of collecting and organizing information regarding design, commissioning, and ongoing performance. This information has been used to illustrate the benefits of building life-cycle information systems. One important lesson concerning the design is that there was significant oversizing of the chillers. This results in over $3400/year of annual energy cost increases. Frequent cycling of chillers also shortens chiller life. Due to a lack of careful start-procedures it appears that construction debris fouled one of the brand new chillers, resulting in $5200/year in energy increases when compared to manufacturer's efficiency ratings. Finally, in operations, we made recommendations to improve the control strategy by changing the condenser water set point, resulting in actual savings (not shown explicitly in the scenarios presented above).

Soda Hall has been the subject of several other activities that are part of the Building Performance Assurance project. We developed a prototype Chiller Commissioning Toolkit (CCT) with the assistance of Steve Taylor, Wayne Dunn, and Softworks. Soda Hall has also been used in the development of a Design Intent Tool and in the creation of a video of a prototype Building Life-Cycle Information Systems (BLISS). Accurate HVAC component models will support other trends in the industry, such as remote building monitoring and control. As real-time pricing emerges and deregulation of the electricity utility industry proceeds, chiller models may be of greater interest to building owners interested in optimal control and energy use. Owners of multiple buildings will likely want to access these data remotely. A related project underway at Soda Hall is the Remote Building Monitoring and Operations Project (RBMO, Olken, 1996). The RBMO project has created an Internet gateway to the Energy Management Control System (EMCS). The gateway polls the EMCS and the data are archived in a relational database[2]. ASHRAE's BACnet protocol will also help improve linking EMCS within individual buildings and between buildings for remote monitoring.

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