Whole Building Diagnostics

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Introduction

Whole building diagnostics may be considered a “top-down” approach to diagnostics. The performance of the whole building is examined to determine whether there are indications of problems in the way the building or its systems are operating. Data on whole building heating, cooling, or electricity consumption, return air temperature, etc. may be examined in an attempt to identify failures in the equipment or the systems in the building, or the data may be examined for signs of sub-optimal operation. This approach can be expected to spot large problems, e.g. problems which typically lead to increases of 5% or more in energy use. It can not be expected to locate an office where the occupants never turn off the lights! However, many, many buildings have problems which are amenable to whole building diagnostics - and we argue that the first stage of any diagnostic program should install the equipment needed to identify major problems. Then refinements may be added as needed to operate a building or buildings in the most economically efficient and effective way.

This discussion of whole-building diagnostics will emphasize applications of the technique which have proven to be practical for identifying and improving operation of over 100 buildings. This approach is in large measure shaped by our experience with these techniques and includes two early case studies and two which illustrate major differences in the type of problems which may be diagnosed with whole building data. A summary of the costs of implementing whole building diagnostics as practiced by the Continuous Commissioning Group at the Energy Systems Laboratory, and the resulting savings is presented. The paper concludes with the introduction of a formalism which may be used to categorize these diagnostic approaches and a discussion of the capabilities and limitations of whole building diagnostics.

Early Work Related to Whole-Building Diagnostics

It may be noted that the cases cited here are not intended to provide a comprehensive coverage of early work related to or dealing with whole-building diagnostics. Rather, these incidents and references have been influential in whole-building diagnostics developments at Texas A&M.

One of the earliest techniques used to forecast energy use was the work by the natural gas industry which lead to introduction of the degree-day method for estimating the gas usage of buildings. Gas companies were interested in ways to forecast demand for gas, and noted that there was a correlation between gas usage and temperature as might be intuitively expected. This correlation was not purely linear - rather it contained two linear segments. Gas use decreased approximately linearly with temperature, as long as the ambient temperature in the service territory was below 65°F. Then the gas use became approximately constant as a function of temperature. Later investigation developed physical models which showed that heating use of most simple buildings is approximately linear with temperature below a temperature at which heating is no longer needed (the balance temperature) - typically about 65°F when the original gas industry observations were made. Above this temperature, the primary gas consumption was for cooking and water heating - applications which show no significant temperature dependence. The original application of the degree-day model was for prediction - not diagnostics, but this early model, with its roots in physical explanation and empirical data, is representative of the modeling and data measurement needed for effective diagnostics in general, and whole building diagnostics in particular.

An early recommendation related to whole building diagnostic efforts is contained in a classic commercial building energy audit case study (Dubin and Long, 1978). This study examined a 139,400 ft^2 chemistry laboratory. Several of the measures identified were projected to have a payback period of less than one year such as lowering winter thermostat settings to 68°F, chiller adjustment and installation of new humidistats to lower steam consumption for humidification in the winter. Other measures included a range of typical capital-intensive retrofits. However, the installation of metering for purposes of tracking and lowering energy use was also recommended. Unfortunately, there is no evidence that this recommendation was taken seriously in this building, and little evidence that it was applied elsewhere.

A few years later, a major study (SERI, 1982), which examined the potential for savings in the U.S. economy from implementation of energy efficiency and renewable energy measures, searched for measured evidence of efficiency savings in the commercial buildings sector and found only anecdotes which included year-to-year comparisons of utility bills. There was no data on sub-metering of the type advocated by Dubin and Long. Kennedy and Turner (1984) discuss the importance of energy submetering in large installations for purposes of energy accounting and control of energy use and cite two unpublished corporate reports as the primary background for their discussion. They also note that metering systems often fail because the information collected is not actually used.

Whole-Building Diagnostic Experiences at a Student Recreation Center

Our experience with whole building diagnostics began about this time with a study of the University of Colorado Student Recreation Center (Claridge, et al., 1984) – though it wasn't called whole building diagnostics then! The description which follows is largely taken from Claridge et al., 1994.

This Student Recreation Center is a multipurpose university recreation facility which occupies approximately 150,000 ft^2 (13,935 m^2) on two main levels. The facilities include a full-size indoor ice rink, indoor swimming and diving pools, a multipurpose gymnasium, handball courts, systems exercise rooms, and locker rooms. Two audits made numerous recommendations for both O&M measures and capital intensive retrofit measures which were based on the traditional engineering practice of estimating a measure's effectiveness with little measured data (Dow 1981; Haberl and Claridge, 1985). Eight of the measures recommended in these studies were implemented and resulted in a 30 percent ($60,000/year) energy consumption reduction.

However, this work also lead to the conclusion that there was a need for continuous inspection of all the energy using systems – or an application of whole-building diagnostics. This was implemented through the development of a prototype expert system to institutionalize building operating efficiency and predict future utility bills for budgeting purposes (Haberl and Claridge, 1987); development of the knowledge base for this expert system relied on 18 months of manual daily readings from seven meters in the building. Examination and analysis of these data identified additional measures (see Table 1) which further improved energy efficiency. Abnormal energy use was detected by comparing daily energy use to that predicted by a multiple linear regression model developed by combining the measured daily data with physical principles.

The fundamental concept, continually monitoring and analyzing a building's energy consumption, was not new by itself. In the 1970s, Socolow et al. (1978) showed that this kind of feedback could produce energy savings all by itself. However, the application to a large recreation complex was a radical departure from the original experiment that was applied to townhouses at the Twin Rivers complex in New Jersey. The first three measures in Table 1 can be viewed as traditional "turn it off when it isn't needed" measures which were discovered from the careful examination of the consumption data and system operations. In the first measure, the sloping driveway leading to the garbage containers for the building was being heated whenever outside temperatures were below 35°F to prevent icing from snowstorms. This wasted energy since the ramp only needed to be heated when temperatures were below 35°F and when it was snowing (a visual observation). Likewise, heat tapes in the rain gutters were turned on in September and off in May when experience showed they were only needed when large ice dams formed. The lights in the men's locker room were cross wired with the emergency lighting and could not be switched off. This was corrected so all the lights except the emergency lights could be turned off at night.

Table 1. Efficiency Measures Diagnosed from Measured Data at the Student Recreation Center

Efficiency Measure
Modify snow melt - outdoor loading ramp
Gutter heat tape usage reduced
Cross wiring problem with men's locker room corrected
Brine circulation problem corrected
Raise ice rink brine temperature
Shower heat reclaim from ice rink reactivated and fine tuned by adjusting temperature
Use cold water for ice resurfacing
Pool leak discovered in surge tank
Disconnect steam condensate patch from adjacent buildings

The next four items involved modification of system operations. In the ice rink refrigeration system, a service valve in the brine loop which freezes the ice rink was partially closed, lowering the flow rate. When this was fully opened, it was possible to raise the brine temperature from 10°F to 17°F, thereby increasing the refrigeration system efficiency. It was also discovered that the shower water heat reclaim from the steam condenser had been disabled. This was reactivated and the shower water temperature was reduced from 140°F to 115°F. The ice resurfacing machine which was routinely using hot water was switched to cold water for all resurfacings except those before figure skating and competitive events. Use of cold water for other resurfacings reduced hot water consumption by 2000 gallons per day.

The last two items don't fall in either of the above categories. Daily monitoring of pool water consumption lead to discovery of a 20,000 gallon/day water leak within days of occurrence. The water and chemical expense involved were appreciable, $10-$20 per day, but the significance was much greater, because the building is perched on expansive soils on a bluff above a nearby river and this leakage would have caused massive structural damage had it gone undetected and uncorrected. Observation of steam condensate consumption lead to the discovery that condensate lines from some adjacent smaller buildings had been patched into the Recreation Center's return line and the Recreation Center was being charged for their steam as well. Gas meter recalibration was initiated when it was observed that the measured consumption was 3-5 times the rated consumption of the gas clothes dryer which was the only gas use in the building (except for an emergency generator which was started once every two weeks). The meter was recalibrated when it was verified that the dryer was operating as rated. The puzzle wasn't solved until it was finally learned that the person in charge of the meter reading had been incorrectly scaling the readings by a factor of 10, so the Recreation Center was paying $20,000 per year for gas instead of $2,000!

Thus the use of daily meter readings for diagnostic purposes resulted in another 15% ($30,000/year) reduction in the consumption through implementation of the O&M measures listed in Table 1. It also resulted in identification of an $18,000/year billing error, and prevented major structural damage to the building -- after typical O&M measures and capital-intensive retrofit measures had cut consumption by 30%. It should be noted that while anomalies in the daily energy-use data suggested that problems were present, additional investigation was necessary to pin-point the actual cause of these anomalies.

Whole-Building Diagnostics at the Forrestal Building

In the Fall of 1986, based in part on the success at the Student Recreation Center, the USDOE initiated a continuous metering project at the Forrestal headquarters facility located in Washington, D.C. This 1.3 million ft^2 complex consists of interconnected north, south and west wings with a large portion of the building (668,000 ft^2) below grade. Additional information concerning the building and details about the program can be found in Haberl and Vajda (1988); a summary of the results and approach follows.

Originally, DOE's facility administrator was interested in the continuous metering concept because it could provide him with a means of forecasting his energy bills. This was particularly interesting because he had just been notified that his office would receive full responsibility for the $4 million annual utility bill.

Complicating the administrator's task was the fact that no one had kept accurate monthly records of the utility bills since DOE only required quarterly utility reports. There were also problems with a questionable whole-building steam meter and pro-rated chilled water use.

Within several months, a $250,000 per year steam leak was discovered and immediately fixed. It had gone unnoticed for years because the Forrestal staff never read their own meters or knew how much steam the building was using since the utility expenses were hidden as a prorated portion of DOE's rental fee to GSA. Although the staff had some idea that steam was always being consumed, prior to the continuous metering program, no motivation had existed for finding and fixing the leaks. During the first heating season following its discovery, fixing the leak involved simply turning off the building's main steam valve Friday evening and turning it back on early Monday morning whenever ambient temperatures were above 35°F. Eventually, a major steam trap replacement and steam converter retubing patched many of the leaks. As of 1994, this single O&M measure had resulted in over $2 million in total steam savings.

Whole-Building Diagnostics in the LoanSTAR Program

The Texas LoanSTAR (Loans to Save Taxes And Resources) program is a $98.6 million revolving loan program, administered by what is now called the Texas State Energy Conservation Office, which retrofits state, local government, and school district buildings within Texas (Turner, 1990). The buildings retrofit under this program have savings reported for at least one year based on hourly monitoring of energy consumption. Many have had follow-up assistance which fine tuned building operation after using the whole-building metered data for diagnostic purposes.

A major factor in the decision of the predecessor organization to the State Energy Conservation Office to implement the LoanSTAR metering program to measure savings in the LoanSTAR Program was the evidence from the University of Colorado Student Recreation Center and the DOE Forrestal Building that the metered data could be successfully used to identify and subsequently implement additional cost-saving measures following the LoanSTAR retrofits. This diagnostic function lead the metering program to be regarded as an insurance program to help ensure the success of the LoanSTAR program. Subsequent experience showed this to be true well beyond the initial expectations.

Diagnostics in Texas State Buildings

During the Fall of 1992 a comprehensive survey was conducted on eight state government buildings in Austin, Texas to identify opportunities for operating savings. None of the buildings had been retrofitted with energy conservation reduction measures, but over $3,000,000 in LoanSTAR retrofits were scheduled for these buildings. Hence, the operating measures investigated for these buildings were primarily shut-off opportunities. The data shown is taken from Claridge, et al. (1994), as is most of the description.

Shut-down Opportunities Identified. The buildings range in size from 80,000 to 491,000 ft^2 with a total area of approximately 2.2 million ft^2. The annual energy costs vary from $129,736 to $1,117,585, totaling more than $4.2 million for the eight buildings, based on utility billing data from September 1, 1990 through August 31, 1991. Examination of the daily whole-building electricity use data showed that night usage of electricity was unusually high and that the HVAC systems were operated continuously. Detailed investigation of shut-off opportunities in these eight buildings diagnosed potential annual savings of $486,300 (11.5% of current total energy cost) as shown in Table 2. The savings due to air handler and exhaust fan shutdown (including reduced heating and cooling expense) account for 69% of the total savings. Savings from turning off lights and office machines account for the remaining 31% of the savings.

Table 2. Summary of the O&M Savings Opportunities in Eight State Government Buildings

Building ID Code	Air Handling Units	Exhaust Fans	PCs and Office Machines	Lights	Savings $/year
SFA	$138,500	$1,500	$15,500	$6,900	$162,400
LBJ	94,800	1,300	28,300	10,900	135,300
WBT	69,700	3,800	17,900	10,900	102,300
JER	24,900	-0-	2,900	3,500	31,300
JHR	-0-	-0-	6,100	8,200	26,000
INS	-0-	-0-	3,700	4,300	14,300
ARC	-0-	-0-	4,300	2,400	8,000
JHW	-0-	-0-	18,100	7,900	6,700
Savings $/year	$327,900	$6,600	$96,800	$55,000	$486,300

These findings were presented to the facilities personnel at a briefing in October 1992 and copies of overheads which summarized the findings and recommendations were provided to the facilities managers. Since three buildings (SFA, LBJ, and WBT) account for 83% of the potential savings shown, it was suggested that the highest priority be given to implementation of the systems shut-off opportunities in these three buildings. This was followed by a complete written report in January, 1993 (Houcek, et al., 1993).

Short-Term Shut-down Test. Monitored data and calls to the facilities manager revealed that no shut-downs had been implemented by March, 1993, despite clear directives from the agency director that energy efficiency was a priority. Several barriers which delayed implementation of the shut-down measures were encountered. First, it was learned that the agency had operated on a "zero complaints" priority for many years and the facilities manager was afraid that temperature swings would generate complaints. Consequently, a field test was scheduled where staff from the Energy Systems Laboratory worked with facilities personnel to conduct a one-time shut-down test in the SFA, LBJ and WBT buildings. The object of the field test was to turn off as many AHUs, exhaust fans, lights, PCs and office machines as possible in each building, and consequently establish the minimum base load and confirm the impact of shut-offs which could be implemented.

Before beginning the test, a meeting was held with facilities personnel to finalize the test procedure, and identify areas where the shut-down was not to be performed. The original report estimated nighttime AHU power savings of 405 kW. However, because of special agency requests to leave certain equipment and AHUs running, the staff was only able to turn off 386 kW of AHUs (95%).

In the other two buildings, more AHUs were left on by request, so only 677 kW of the 819 kW AHU load was turned off during the trial shutdown. This reduced the potential AHU savings from $303,000/yr to $247,944/yr in the three buildings. The data loggers were switched to record at five-minute intervals during this test so the sequential effect of turning off AHUs and lighting could be clearly seen. Counts of PCs and peripherals indicated that 27% of the PCs, 56% of the printers and 75% of the copiers were left on overnight. Since the potential savings due to exhaust fan, PC and lighting shutdown was not changed as a result of the test, the originally reported potential shut-down savings of $486,300/yr for all eight buildings was revised to $400,000/yr based on the test results.

Figure 1 displays the results of the AHU shut-down and lighting turn-off test that was performed on April 17. The shut-down reduced the cooling consumption by 3 MMBtu/hr and electricity use by 600 kW at the SFA building.

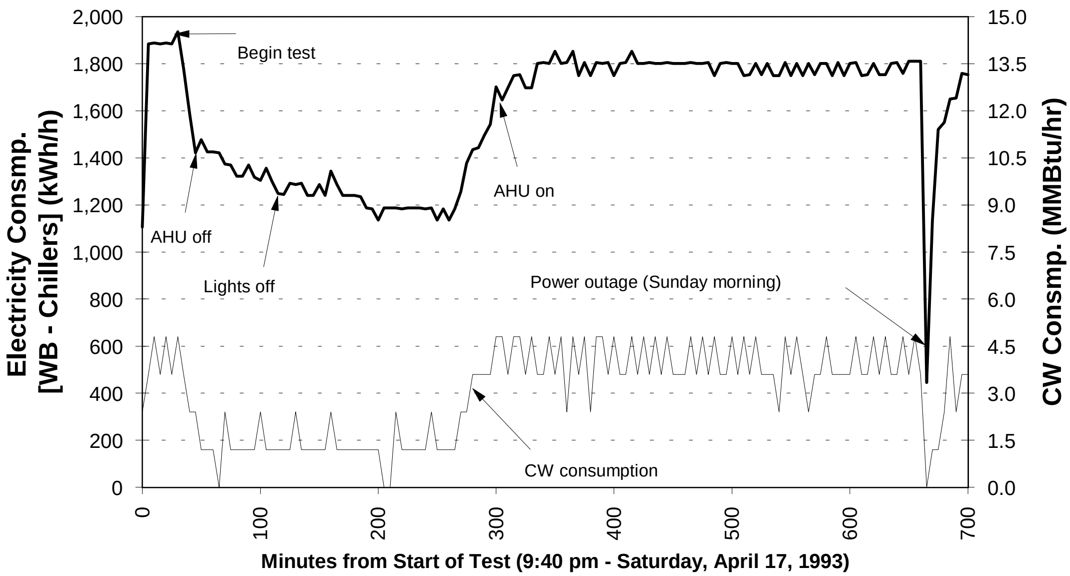


Figure 1. Data from Short Term Test at the SFA Building

Implementation. Following additional meetings with both administrative and building operations personnel, a decision was made to begin an AHU shutdown at the SFA building. Phase 1 of the shutdown began on the evening of Friday, September 3, 1993, with five air handlers for a duration of four hours each night. Recording thermometers were located in areas affected by the shutdown to determine to what extent the temperature changed, if at all. Weekly graphs of building energy consumption were faxed to the building operators to provide positive feedback on the results of their actions.

During the first week of October, 1993, Phase 2 began when an additional five air handlers were turned off each night followed by six more air handlers each night during the second week of October. By mid-October, 16 out of a total of 25 air handlers were being turned off each night for a period of four hours.

Figure 2 displays the results of the progressive AHU shutdown at the SFA building in terms of the lights, receptacles and AHU load. The figure shows that prior to the initial shut-down, average nighttime consumption was approximately 1250 kW. After Phase 1 implementation, average nighttime consumption dropped to approximately 1100 kW. After Phase 2 implementation, the average nighttime consumption dropped to approximately 900 kW. Three months after implementing the shut-off of 16 AHUs for four hours per night, the shut-off was extended to six hours per night.

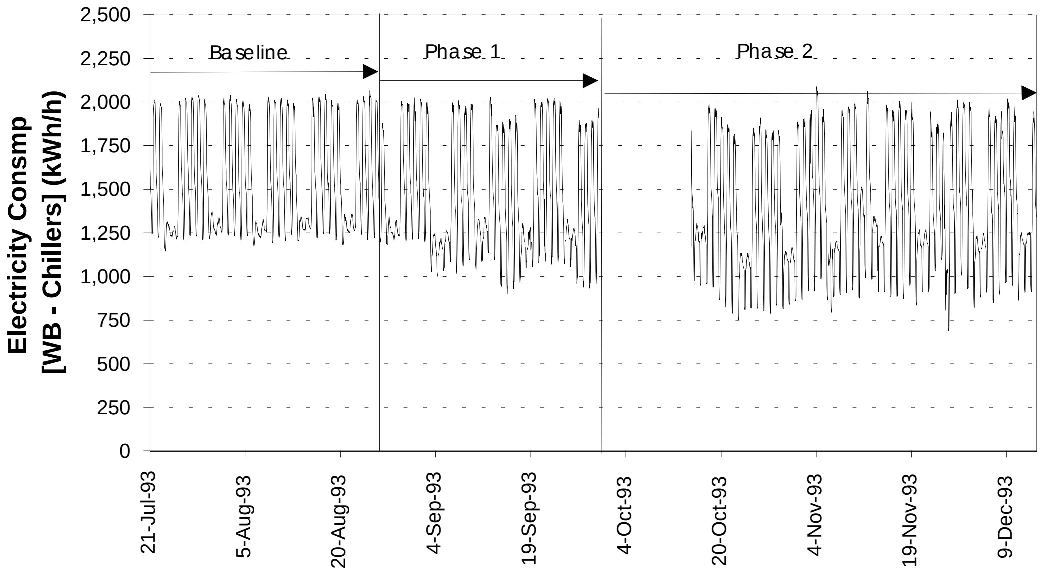


Figure 2. Whole Building Lights, Receptacles and Air Handler Electricity Use at the SFA Building During Implementation of AHU Night Shutdown

The savings of electricity, gas and chilled water consumption were approximately $300/night. Building operator feedback indicated no comfort complaints as a result of the shutdown. Interior temperature recordings also confirmed that comfort did not decrease during working hours.

System Optimization Opportunities Diagnosed in a Medical School Research Center

Five buildings with a total floor area of 779,000 ft^2 at a large medical school research center in Southeast Texas received retrofits under the LoanSTAR program. These buildings had a total annual energy bill of $2,709,000 following the retrofits for an average cost of $3.48/$ft^2$ as shown in Table 3. Two of the buildings are hospitals, two are laboratory/classroom buildings and one is a research library. The major retrofit implemented in all five buildings was installation of energy management and control systems (EMCS) which provide monitoring, temperature control, start/stop control of major AHUs and pumps, and control of some lighting. The data shown and descriptions provided have largely been taken from Claridge et al. (1994, 1996) and Liu et al. (1993, 1994).

Table 3. Energy Use Characteristics of Five Medical Center Buildings

	JSN	CSB	BSB	MLB	JSS	Total
Building Type	Hospital In-patient	Lab & Class	Lab & Class	Library	Hospital	
Floor Area (ft^2)	75,700*	124,900	137,900	67,400	373,000	778,800
Thermal Energy ($/yr)	$405,300	$235,300	$573,900	$153,200	$759,000	$2,126,600
Electricity ($/yr)	$96,800	$115,200	$97,000	$41,800	$231,600	$582,400
Total Energy ($/yr)	$502,100	$350,500	$670,900	$194,900	$990,600	$2,709,000
Total Energy ($/$ft^2$yr)	$6.64	$2.81	$4.87	$2.89	$2.65	$3.48

*Including a kitchen area (18,000 ft^2)

All of the buildings at the Medical Center are operated continuously and the library has critical temperature/humidity requirements since it contains a major rare books collection. Examination of these buildings found that the limited opportunities for start/stop control had been implemented and that lighting levels were generally appropriate, although hallway lighting levels in one building (JSS) substantially exceeded IES standard levels and delamping in this building offered the potential for annual savings of $45,900.

The HVAC systems in three of these buildings (CSB, JSS and JSN) are dual duct constant volume systems. They use 50% - 100% outside air because of medical requirements, and humidity levels are high at this Gulf of Mexico location, so the systems also utilize a "precooling" coil, primarily to reduce humidity levels. This permits the main cooling coil to primarily provide sensible cooling. A portion of one building (JSN) has a single duct constant volume system using 100% outside air and the other two buildings use a hybrid system which is basically a constant volume reheat system, except it uses a single heating coil to provide reheat to all zones.

The requirements for continuous operation and for very high outside air fractions severely limit the effectiveness of most traditional shut-off measures. However, these factors lead to the relatively high operating costs shown in Table 3 and combine to create greater opportunities for optimization of the air handling systems.

Optimization of the AHU schedules was performed in these buildings (Liu et al., 1993, 1994). The results from the BSB building are shown as an example here. This building is a 137,856 ft^2, free-standing, seven-story building which consists primarily of offices, classrooms, labs and storage space. The building is provided with 75% outside air by two 150-hp constant-volume, dual-duct AHUs, each capable of moving 110,000 cfm which corresponds to 1.24 cfm/ft^2 of conditioned area. Chilled water and steam are supplied by the main chiller plant. The building HVAC system is operated continuously.

Identification of Optimization Potential at BSB. Figure 3 shows measured average daily chilled water and steam energy consumption versus the ambient temperature for July 1, 1992 through June 30, 1993. Substantial steam consumption occurred during the hot summer days, increasing only slightly when an

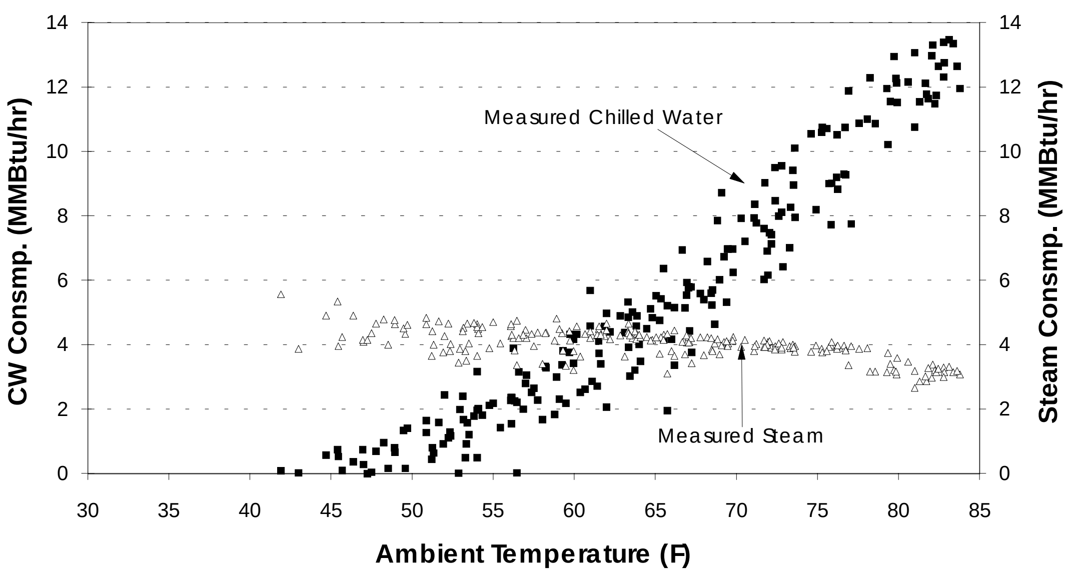


Figure 3. Measured Chilled Water and Steam Energy Consumption vs. Average Daily Ambient Temperature in the BSB Building in Galveston for July 1, 1992 through June 30, 1993

ambient temperature dropped, a symptom of substantial reheat. This suggested that large amounts of chilled water and steam could be saved by optimizing the operating schedules and minimizing the reheat.

Specialized Model and Calibration. A specialized engineering model was developed to model the building's HVAC system (Liu et al. 1993). This model was calibrated against the measured chilled water and steam consumption. Figure 4 compares the measured data with the model's predicted chilled water and steam consumption from December 1992 through June 1993.

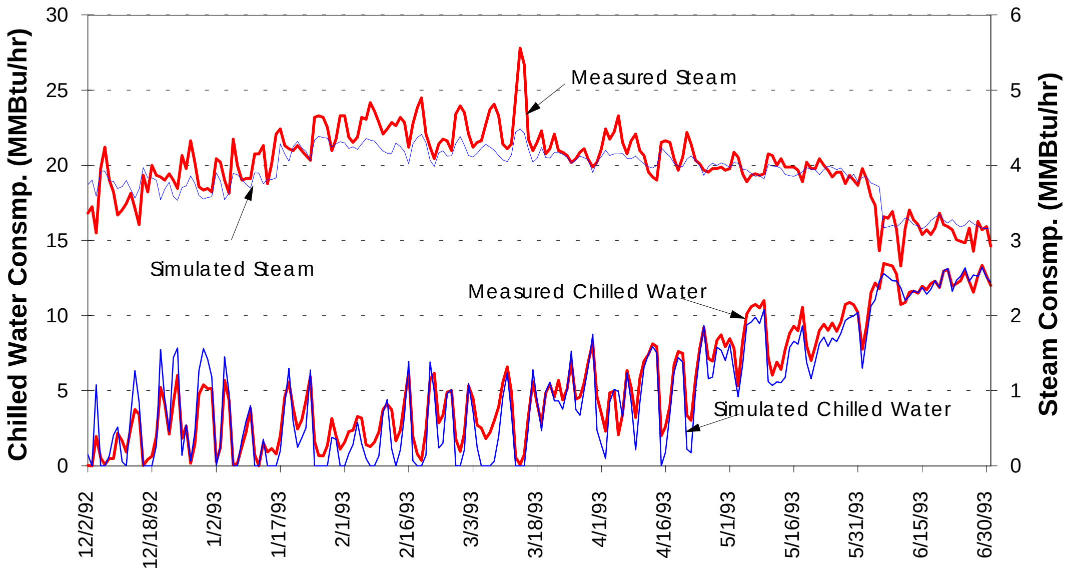


Figure 4. Comparison of Simulated & Measured Daily Average Steam and Chilled Water Energy Consumption in the BSB Building in Galveston (December 1992 - June 1993)

Optimized Schedule. Optimized operating schedules were determined by trial and error using the calibrated model. The baseline and optimized schedules are shown in Figure 5. The cold deck temperature is increased under the optimized schedule. This cold deck temperature increase can reduce chilled water and steam consumption substantially as discussed below.

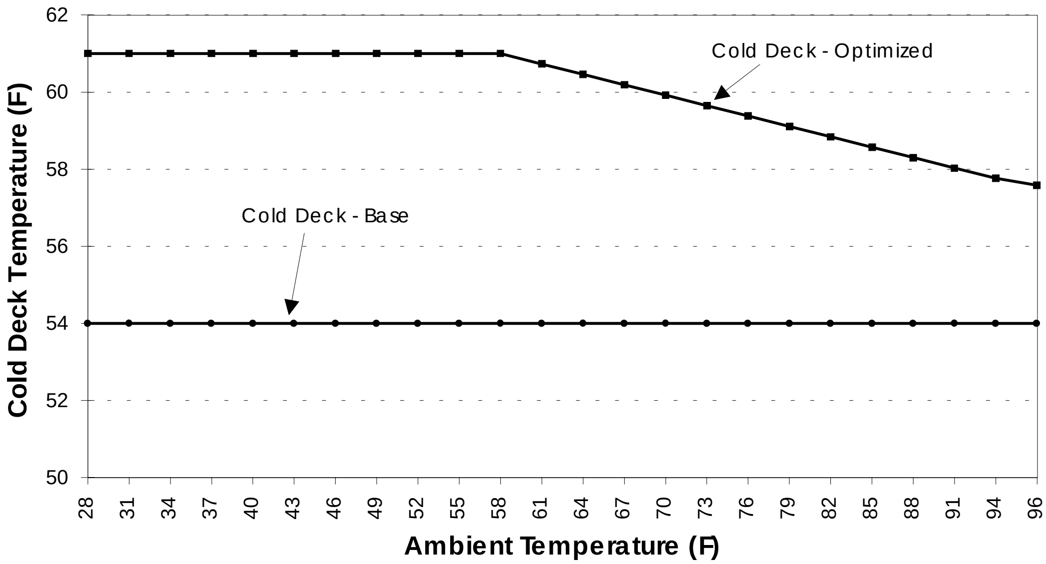


Figure 5. Base and Optimized Cold Deck Schedules for the BSB Building

Comparison of Energy Performance. Figure 6 compares the optimized energy performance with the baseline energy performance. The horizontal axis shows the dry bulb ambient temperature while the vertical axes show the model-predicted chilled water and steam consumption in MMBtu/hr. The predicted values were calculated for each 3°F temperature bin at its mean coincident dew point temperature. Figure 6 shows that the optimized schedule can reduce chilled water consumption by approximately 1.9 MMBtu/hr and steam consumption by approximately 1.2 MMBtu/hr although the

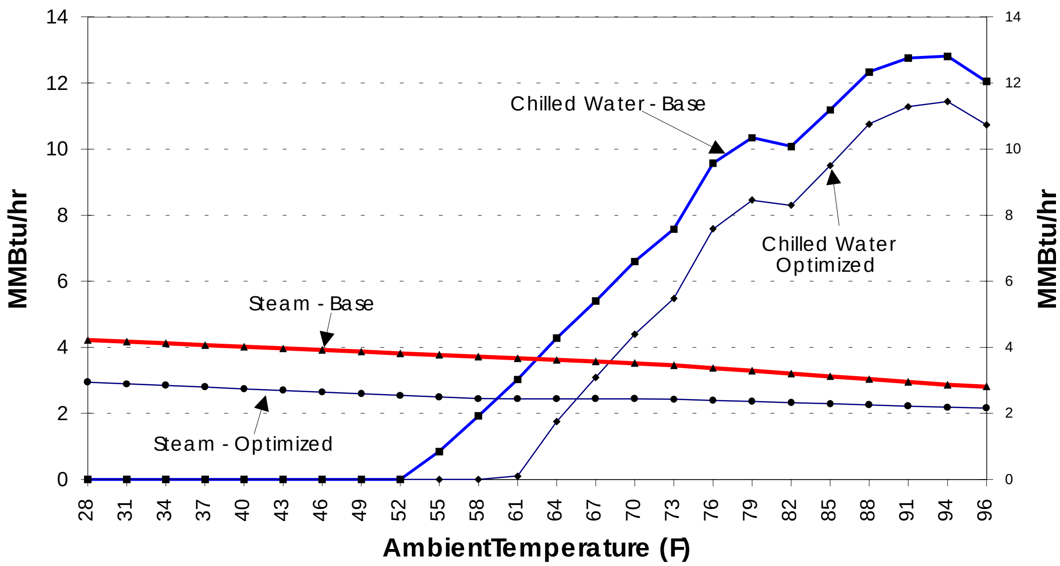


Figure 6. Comparison of the Predicted Chilled Water and Steam Energy Consumption Under Base and the Optimized Operation Schedule in the BSB Building

savings depend slightly on the ambient temperature. The simultaneous reduction of the chilled water and the steam consumption indicates that the major part of the savings is due to elimination of simultaneous heating and cooling.

The optimized schedule was predicted to reduce annual chilled water consumption from 55,500 MMBtu to

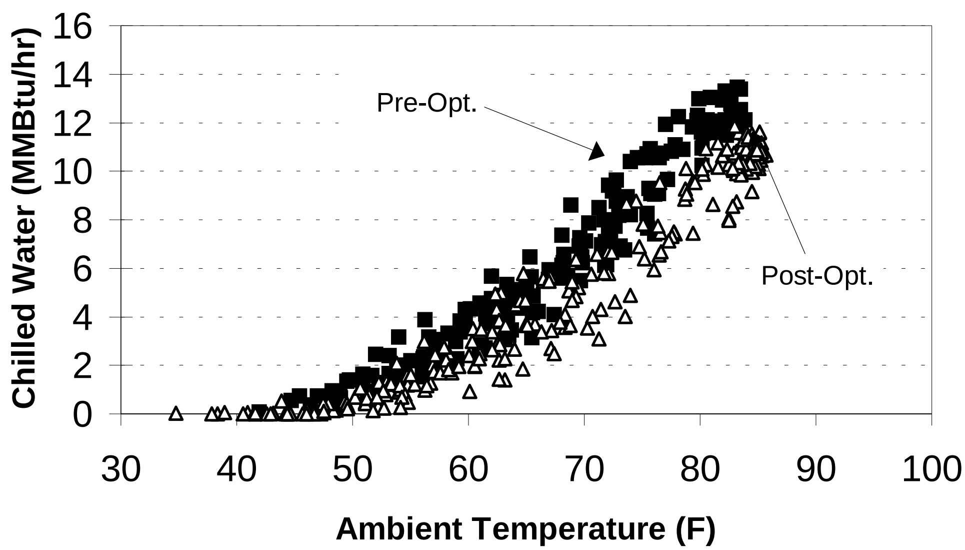


Figure 7. Chilled Water Consumption for the BSB Building at a Medical Research Center. Solid Squares Represent Data Taken Before Optimizing the Cold Deck Temperature while Open Triangles Represent Data Taken After Cold Deck Optimization.

40,600 MMBtu, with a savings of 14,900 MMBtu/yr and also reduce the annual steam energy consumption from 30,600 MMBtu to 21,200 MMBtu for savings of 9,400 MMBtu/yr. These energy savings correspond to cost reductions of $108,700 for chilled water and $47,300 for steam. The total potential savings of $156,000/yr represent a decrease of 23% of the building's annual energy cost, or 27% of the building's thermal energy costs when using the baseline cold-deck schedule.

Implementation of Optimized Schedules and Measured Savings. The cold deck temperature for the air handling units was raised from 54°F to 59°F on July 2, 1993 and the optimized schedule was subsequently implemented. A reduction in the chilled water use and steam consumption was noticed immediately. Figure 7 shows daily values of chilled water consumption (as average hourly consumption) for BSB with the baseline data shown as solid squares and the data collected after the cold deck schedule optimization shown as open triangles. The consumption was reduced by $485,000 for the period 7/93 – 12/95 which is even greater than the annual savings of $156,000 predicted for this building.

The measured cost savings in these five buildings due to continuous commissioning measures are summarized in Table 4. The table shows the average annualized optimization or CC savings for each building through December, 1995 for the measures implemented. These results come from measures implemented for as little as three months and as long as 30 months. The average savings due to the CC measures in these five buildings are 22.5% of previous consumption. The annualized measured retrofit savings in these buildings are $213,479, or 79% of the audit estimated savings of $271,328/year for the measures implemented. The combined annual savings of $823,122 are 303% of the audit estimated retrofit savings.

Table 4. Summary of Measured Cost Savings at Five Medical Center Buildings Due to Optimization or CC Measures from Implementation Date Through December, 1995.

Savings	JSN	CSB	BSB	MLB	JSS	Total
Annualized ($/yr)	$164,320	$50,752	$193,900	$34,329	$166,342	$609,643
$/ft^2-yr	2.17	0.41	1.41	0.51	0.445	0.78
Per Cent	33%	14%	29%	18%	17%	22.5%
Months Implemented	27	3	30	13	16	

Savings and Costs

The Continuous Commissioning Group at Texas A&M has commissioned, or improved operating efficiency in over 100 buildings since 1993, with savings of approximately $20 million to date. These savings have typically been achieved while improving building comfort and reducing occupant complaints. The pay-back period for the savings achieved has uniformly been below two years, often well below two years. Whole-building diagnostics represent an important component of the process used in these buildings, but it must be noted that in our experience, diagnosis of problems without follow-up to quantify the importance of the problems identified (i.e. provide dollar-values for the potential savings) and provide direction and assistance in implementing changes recommended has been ineffective in achieving changes in building operation. The process used by Texas A&M to achieve the results noted above is described in some detail in Liu et al. (1997), Claridge et al. (1998), and elsewhere.

Table 5 summarizes the building type, location, floor area, measured annual savings, savings per square foot of floor area, and average commissioning labor required for 28 of the buildings commissioned by the Energy Systems Laboratory at Texas A&M.

Table 5: Summary of Measured Savings and Costs for 28 Buildings Commissioned and "Optimized" by the Energy Systems Laboratory.

Building Type & Number	Area Range (1000-ft^2)	Average Area (ft^2)	Savings Range ($/ft^2-year)	Avg. Savings ($/ft^2-year)	Average Time Spent (hr/ft^2)
Hospitals – 6	37 – 412.9	231,000	$0.18 - $2.68	$0.75	0.0047
Med. Labs.– 8	114.7 –165	137,000	$0.28 - $2.39	$1.26	0.0037
Class-Offc – 5	113.7 –324	182,000	$0.23 - $1.38	$0.43	0.0023
Schools – 2	62.4 – 92.9	77,650	$0.13 - $0.23	$0.17	0.0034
Library – 1	67	67,000	$0.47	$0.47	0.0027
Offices – 7	90- 390	176,800	$0.10 - $0.36	$0.22	0.0033

The measured annual savings varied from $10,000/yr to $395,000/yr with an average of $90,000 or $0.64/ft^2/yr for the 28 buildings. The measured savings per unit of floor area were strongly dependent on the building type. The measured average savings were $1.26/ft^2/yr for seven medical research laboratory buildings, $0.75/ft^2/yr for six hospitals, $0.43/ft^2/yr for five university teaching and office buildings, $0.22/ft^2/yr for seven office buildings, and $0.17/ft^2/yr for two school buildings.

The actual cost of commissioning depends on building size, system type, EMCS system, existing operating conditions, location of building and owner's requirements. The labor required to complete the identification and implementation of the optimization procedures varied from 0.00024 hr/ft^2 to .020 hr/ft^2 with an average of 0.00359 hr/ft^2 for the 28 buildings summarized in Table 5. Thus, if loaded labor rates were $100/hour, the commissioning costs above correspond to a range of $0.024 - $2.00/ft^2 with an average of $0.359/ft^2. It can be seen that with this labor cost, the average payback times for the different building types shown in Table 5 would range from under 4 months ($0.37/ft^2/$1.26$/ft^2-yr = 0.3 yr) for the medical research laboratory buildings shown to 2 years for the two schools shown.

It should be noted that the EMCS system had a significant impact on the commissioning cost. When an advanced EMCS is in a building, the commissioning cost can be significantly lower than when no EMCS is installed or when an old EMCS is in place.

Approaches to Whole-Building Diagnostics

The examples described above, and indeed, most whole-building diagnostic procedures can be split into two major categories – examination of time series data, and use of physical or empirical models in the analysis of whole-building data streams.

<u>Diagnostics with Time Series Data</u>

The simplest for of diagnostics with whole-building data is manual or automated examination of the data to determine whether prescribed operational schedules are followed. The normal minimum set of whole-building data required for diagnostics are separate channels for heating, cooling, and other electrical uses". With these data streams, it is possible to identify probable opportunities for HVAC system shut-offs, excessive lighting operation, etc.

Shut-off Opportunities: this is often the most intuitive of all diagnostic procedures. However, the use of whole-building data, even with heating and cooling removed can cause some confusion, since night-time electric use in many buildings is 30% - 70% of daytime use. If night-time and week-end use seems high, then connected load must be investigated to determine whether observed consumption patterns correspond to reasonable operating practices. Our experience indicates that while many if not most opportunities for equipment shut-off at by an EMCS or other system-level action have been implemented, time series data analysis can still find opportunities in 10-20% of buildings.

While many of these opportunities can be observed using plots which show several days of hourly data, it is often helpful to superimpose several days or weeks of hourly data on a single 24-hour plot to observe typical operating hours and the frequency of variations from the typical schedule. Several helpful ways of constructing such plots have been described by Katipamula and Haberl (1991) and by Haberl and Abbas (1998).

Operating Anomalies: a slightly different category of opportunities can be identified using the same techniques. Mistakes in implementing changes in thermostat set-up/set-back schedules sometimes result in short-time simultaneous heating and cooling which shows up as large spikes in consumption which lsat only an hour or two. Time series plots of motor control centers often show that VAV systems seldom operate above their minimum box settings – and hence are essentially operating CAV systems. Comparisons between typical weather-independent operating profiles from one year to the next will often reveal "creep" in consumption which is often due to addition of new computers or other office equipment.

Blink Tests: a valuable way in which whole-building data can be used to identify the size of various equipment loads such as switchable connected lighting load, AHU consumption, etc. is the use of short-term "blink tests" such as that described in the example of the state office building discussed earlier. More detail on such tests is available in Carlson and Bryant (1999).

<u>Diagnostics with Models and Data</u>

The description of the process used to diagnose opportunities for improved operation at the BSB building made heavy use of a physical simulation model. Calibration of simulation models has generally been regarded as so time consuming that it is appropriate only for research projects. However, this approach has been systematized by the authors using a series of energy "signatures" (Wei et al., 1998a, 1998b) which have enabled the performance of calibrated simulation as a classroom assignment. Figure 8 shows a partial set of these signatures suitable for use with a building which has constant volume dual-duct AHUs. Similar sets of signatures have been developed for dual-duct VAV systems, single-duct CAV systems and single-duct VAV systems.

These model-based approaches can readily be used in conjunction with limited field measurements to diagnose and determine the potential savings from correcting a large variety of systems problems which include:

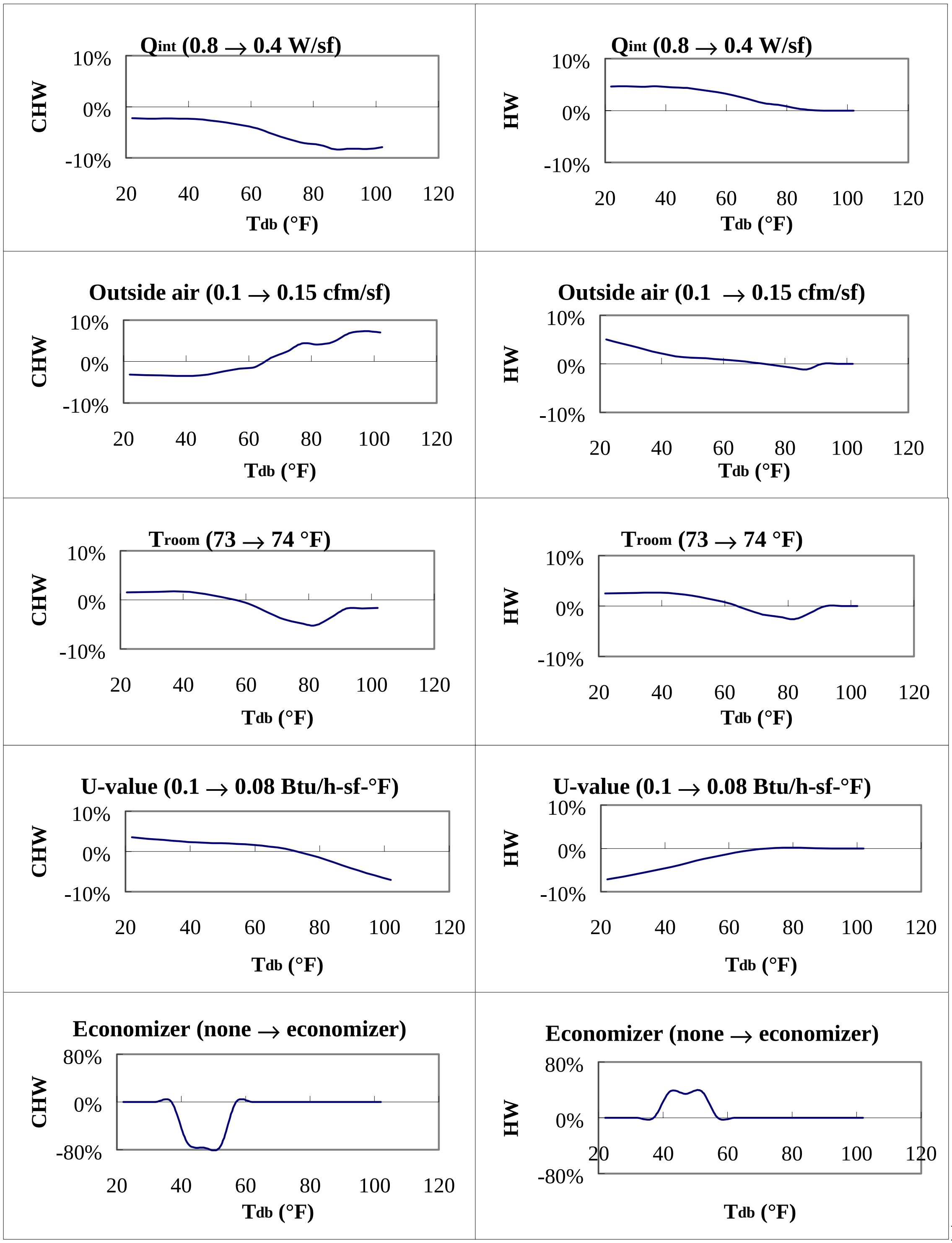
VAV behavior as CAV systems
Simultaneous heating and cooling
Excess supply air
Excess OA
Sub-optimal cold deck schedule
Sub-optimal hot deck schedule
High duct static pressure
Etc.

Conclusions

Whole building data for heating, cooling, and non-weather-dependent electricity consumption can be used to identify a range of shut-off opportunities, scheduling changes, and operating anomalies due to improper control settings and other factors. It can also be used in conjunction with appropriate simulation tools and energy signatures to identify an entire range of non-optimum system operating parameters. It is then very straightforward to reliably predict the energy savings which will be realized from correction of these problems.

It should be recognized that the systems diagnostics available from whole building data and modeling are indications of probable cause. Additional field measurements are generally needed to confirm the probable cause.

Figure 8. Signatures of heating and cooling energy consumption for constant volume dual-duct AHUs



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