Cutting heating and cooling use almost in half without capital expenditure in a previously retrofit building

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1. SYNOPSIS

The Continuous Commissioning process is presented and its application to a previously retrofit 30,000 m^2 building which further reduced cooling by 49%, heating by 33% and fan power by 27% is described.

2. ABSTRACT

The Continuous Commissioning (CC^{SM} - a table of acronyms used is provided following the references) process identifies and implements optimal operating strategies for buildings as they are currently being used rather than implementing design intent as is customary with most commissioning processes. It emerged at the Energy Systems Laboratory from a program of implementing operation and maintenance improvements following retrofits in buildings. The normal steps in the CC process are delineated followed by a description of its application to a large building (30,000 m^2) housing classrooms, laboratories and offices on the Texas A&M University campus that was successfully retrofit earlier. This retrofit reduced cooling consumption by 23%, heating consumption by 84% and the air handling unit (AHU) power consumption by 44% in 1994, a year typical of those following the retrofit.
The continuous commissioning process was applied to the building in 1996 and this systematic examination and optimisation of the heating, ventilating and air conditioning (HVAC) systems identified and implemented numerous changes in AHU operational parameters, water loop operation, and terminal box operation, as well as identifying and correcting a number of items needing repair in individual AHU systems. This optimisation process cut combined heating and cooling energy use by another 49% without further capital investment. Individually, cooling use dropped by almost half to 36% of its original value, heating was cut by another third to 10% of its original value, and AHU use was cut from 56% to 41% of its original value in 1997.
Application of the CC process has produced energy savings averaging 20% with payback from energy savings routinely under three years and sometimes under one year.

3. INTRODUCTION TO CONTINUOUS COMMISSIONING^{SM} AND ITS APPLICATION TO A PREVIOUSLY RETROFIT BUILDING

Continuous Commissioning began at the Energy Systems Laboratory (ESL) of Texas A&M University as an attempt to achieve energy and cost savings with operations and maintenance (O&M) procedures. It evolved into a commissioning process that is a way of problem solving in buildings, which helps problems stay fixed longer than conventional problem solving procedures and simultaneously helps reduce energy expenses. It requires knowledge of the fundamentals of humidity, airflow, water flow, and heat flow. This knowledge must be combined with a practical and fundamental knowledge of building systems and building operation. These elements must then be combined to solve problems and educate the operator's intuition. Use of this approach typically not only makes problems stay fixed longer; it makes a building operate more efficiently, and hence at lower cost. To date it has been applied to over a hundred buildings with a total floor area of over 1 million square meters and has reduced energy costs by an average of 20% without capital investment.

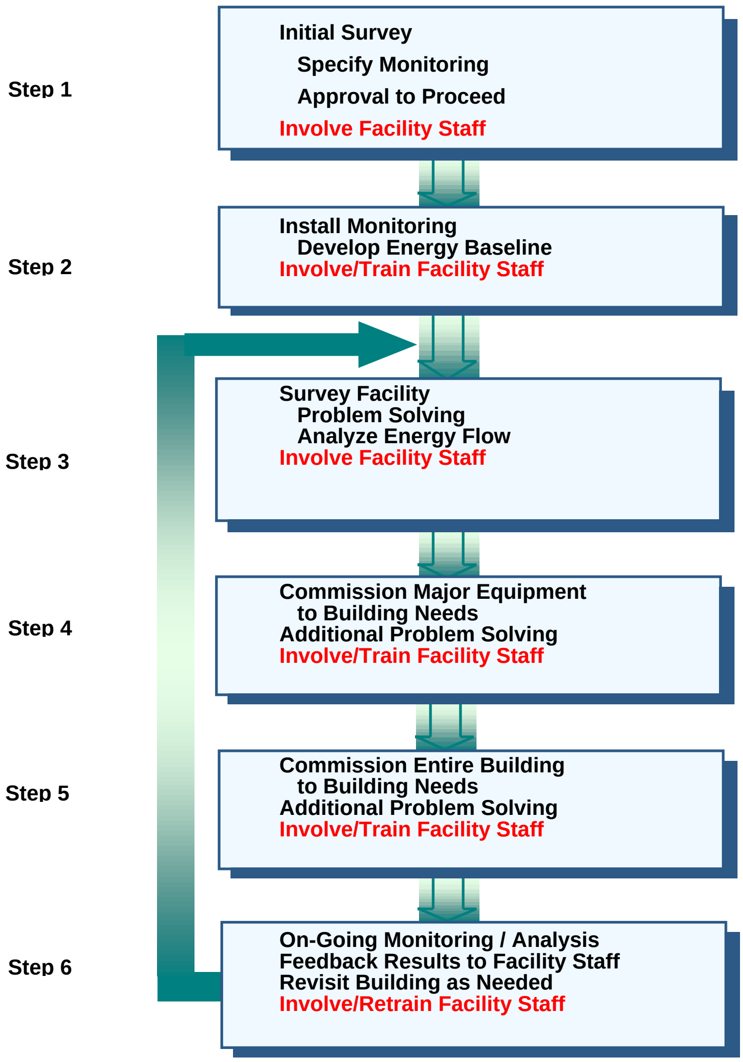
This process attempts to optimise building operation rather than commission to design intent. Gregerson (1997) investigated existing building commissioning in 1997 and reported average savings of 11.8% for 13 buildings which had undergone conventional commissioning. The average savings noted for the 21 buildings which had undergone CC was 23.8%.

Buildings that have had retrofits and buildings that have not had recent upgrades to the HVAC equipment comprise two significantly different categories. The average savings due to the CC process in buildings that had already been retrofit were about 20% beyond the retrofit savings (Claridge *et al*. 1996). A more recent paper (Claridge *et al.* 2000) reported that application of the CC process to buildings that had not generally been retrofit produced savings averaging 28% for cooling, 54% for heating, and savings of 2 to 20% for other electrical uses.

4. CONTINUOUS COMMISSIONING PROCESS

The first step is to perform an initial survey of the building and discover the comfort and operational problems which are present. During this survey, an initial estimate of the potential CC savings and the monitoring requirements is made. One of the fundamental requirements for CC to be effective is to involve the facility staff in each of the steps so that they will understand and support the planned enhancements for the facility. Training in Step 1 is usually informal and generally involves discussions as the CC engineer surveys the facility. Figure 1 describes the steps in the Continuous Commissioning process.

Figure 1. The continuous commissioning process



A method for measuring and modelling the baseline performance of the facility must be established to determine the impact of the CC process. Equipment is normally installed to separately monitor at least heating, cooling, and other electric consumption on at least an hourly basis and a baseline started in Step 2. An operations staff person needs to be involved and should be given installation responsibility if possible. This creates ownership and will allow a much faster repair of sensors when needed. The training in Step 2 is informal and should involve hands-on participation in the installation process.

The CC engineer next performs a detailed facility survey in Step 3. This survey utilises data from the energy monitoring equipment, the control system, and numerous one-time measurements of temperatures, pressures, and flows made throughout the building. Any dysfunctional items or any causes of discomfort are identified and fixed. Also, a team must be formed between the CC engineers and the facility staff. Getting the building back up to proper function is very important as this provides an immediate benefit to the occupants. Having the facility person involved with this step helps to minimise actions by operators to "undo" changes implemented as part of the repair process if complaints occur. Before proceeding, the facility environment should be comfortable and the equipment should be operating acceptably. For example, if the airflow through air handler 5 is increased to improve the temperature in the Dean’s Office, discomfort may be created in the EE Department Head’s office, two doors down. The CC team identifies these problems, develops a plan for solving them and then solves them. The CC engineers work with the facility staff until solutions are identified and in place. The CC engineer must have an excellent fundamental understanding of the systems in the building combined with substantial practical experience with these systems.

Commissioning the equipment to the facility needs and then commissioning the entire facility to the facility needs are completed in Steps 4 and 5. Commissioning to facility needs involves problem analysis and solution. When equipment is oversized, a typical finding, the operation is usually non-optimal. The CC engineer must understand the operation of the equipment in the equipment room and also how energy is transported in the facility.

Monitoring, in Step 6, is key to measuring the changes and being able to report the savings obtained. Monitoring also serves as an early warning if changes were made in the facility which degrade the operation or savings. A CC engineer needs to visit to facility to review the operation whenever the building consumption increases significantly. Often facility staff change and retraining is important. Also, facility use often changes and these visits will be useful for identifying additional needs at the site. The CC process optimises the building as it was being operated. For example, if one-half of a floor of offices was converted to labs, it is very likely the energy use of the space will have changed and will need to be optimised. Additional information on the CC process is provided in Liu *et al.* (1997) and in Claridge and Liu (2000).

5. CASES WHERE CONTINUOUS COMMISSIONING MAY BE USED

The CC process has been applied almost exclusively to buildings with a floor area of at least 5,000 m^2. About 90% of the buildings to which the process has been applied are in cooling dominated climates where typical cooling consumption in large buildings is at least two times the heating consumption. However, it has also been successfully applied to buildings in the coldest parts of the continental United States. It is a relatively labor intense process at this time, making it generally more applicable to buildings with large air handlers and large total energy use. Automated control systems tend to simplify implementation of CC and it and has been particularly effective in buildings that exhibit significant simultaneous heating and cooling. If the CC process were to be implemented in all in the commercial buildings larger than 5,000 m^2 in the United States, and achieve comparable savings, it would have the potential to reduce consumption in the commercial buildings sector by 8%. Of course, if it were successfully implemented on that scale, it can be anticipated that a variety of automated techniques would make it applicable to smaller buildings and expand the potential impact.

6. CASE STUDY BUILDING DESCRIPTION

The building studied in this paper is the 30,000 gross m^2 (23,000 m^2 net) Zachry Engineering Center (ZEC), located on the Texas A&M University campus (30°N, 96°W) where the average January temperature is 10°C and average July temperature is 29°C, and pictured in Figure 2. The building has four-floors plus an unconditioned basement parking level. It was constructed in the early 1970s and is a heavy structure with 0.15-m concrete floors and insulated exterior walls made of precast concrete and porcelain-plated steel panels. About 12% of the exterior wall area is covered with single-pane, bronze-tinted glazing. The windows are recessed approximately 0.6 m from the exterior walls, which provides some shading. Approximately 288 m^2 of northeast-facing clerestory windows admit daylight into the core of the building.

Figure 2. The Zachry Engineering Center on the Texas A&M campus

The ZEC includes offices, classrooms, laboratories and computer rooms and is open 24 hours per day, 365 days per year with heaviest occupancy during normal working hours between 8 a.m. and 6 p.m. on weekdays. Occupancy, electrical consumption and chilled water consumption show marked weekday/weekend differences with peak weekend electrical consumption less than 10% above the nightly minimum; weekday holiday occupancy is similar to weekend usage with intermediate usage on weekdays between semesters when class rooms are not in use, but laboratories and offices are occupied.

Original HVAC Systems

Twelve identical dual-duct constant volume systems with 29.8 kW fans rated at 16.5 m^3/s and eight smaller air handlers (2 kW average) supply air to the zones in the building. Supply and return air ducts are located around the perimeter of the building. These were operated with a constant outdoor air intake at a nominal value of 10% of design flow. Additional information about the building can be found in Katipamula and Claridge (1992a, 1992b), Bronson (1992), Bronson *et al.* (1992), and Haberl *et al.* (1993, 1995).

Monitoring of energy use

In the engineering center about 50 channels of hourly data have been recorded and collected each week since May 1989. The sensors are scanned every 4 seconds and the values are integrated to give hourly totals or averages as appropriate. The important channels for savings measurement are those for air handler electricity consumption and whole-building heating and cooling energy use. Air handler electricity consumption is measured at the building's motor control center (MCC) and represents all of the air-handling units and most of the heating, ventilating, and air-conditioning (HVAC)-related pumps in the building. Cooling and heating energy use are determined by a Btu meter which integrates the monitored fluid flow rate and temperature difference across the supply and return lines of the chilled- and hot-water supply to the building. The majority of the 50 channels of monitored information come from one air handler that was highly instrumented (Katipamula and Claridge 1992a).

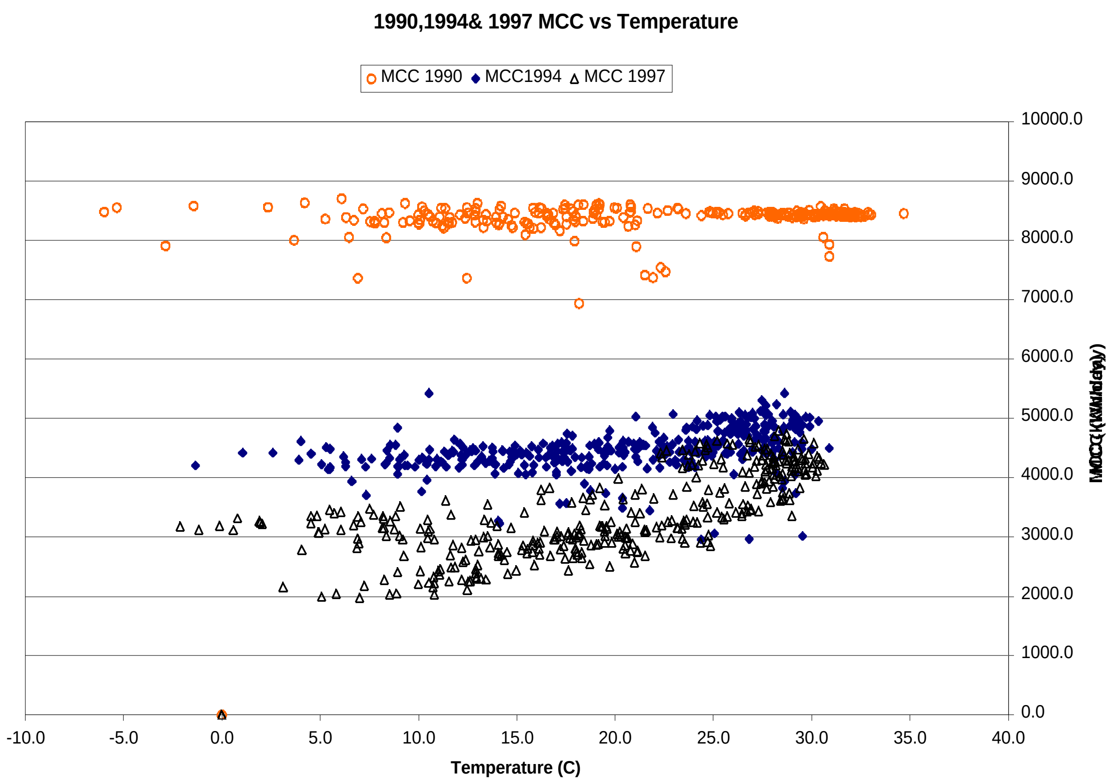
7. HVAC SYSTEM RETROFIT

An energy audit of the Zachry Engineering Center was conducted in 1986 (TECCP, 1986). This audit recommended a lighting retrofit to convert the four-lamp fixtures to 3-lamp fixtures with reflectors and conversion of the large dual-duct constant air volume (DDCAV) systems to dual-duct variable-air volume (DDVAV) systems accompanied by connection to the campus energy management and control system (EMCS). The lighting retrofit was projected to save 975,600 kWh/year of electricity, 732,000 kWh-thermal/year of chilled water and increase hot water use by 244,000 kWh-th with a payback of 4.4 years. The variable air volume (VAV) conversion with controls improvements was projected to save 1,952,7764 kWh/yr on fan power, 121 GJ/yr of hot water and 280 GJ/yr of chilled water at a cost of 1,315,000 Euro for a payback of 3.3 years. The university chose not to implement the lighting retrofit, but had variable speed drives installed on the twelve large AHUs, replaced the constant volume dual-duct terminal boxes with VAV dual-duct terminal boxes, and connected the building to the campus automated control system.

The audit proposed that the DDCV be converted to DDVAV systems installing variable speed drives on 17 fans along with associated static pressure sensors and controls. The existing constant volume terminal boxes which typically operated at static pressures above 130 Pa were to be replaced by DDVAV boxes with independent controls on the hot decks and cold decks to provide constant minimum flow rates of 0.0033 $m^3/s\text{-}m^2$. The new boxes and controls were to be tied to the campus EMCS. This was intended to permit shut down of heating and cooling to non-critical areas such as classrooms during unoccupied hours by closing the dampers in the VAV boxes while the fans continued to supply heating and cooling to laboratory areas. The repair and upgrade of the existing EMCS in the building was intended to control time-of-day settings, DDVAV box load group override, hot and cold deck reset, optimal start-stop of a load group DDVAV box to insure space comfort, and space temperature reset.

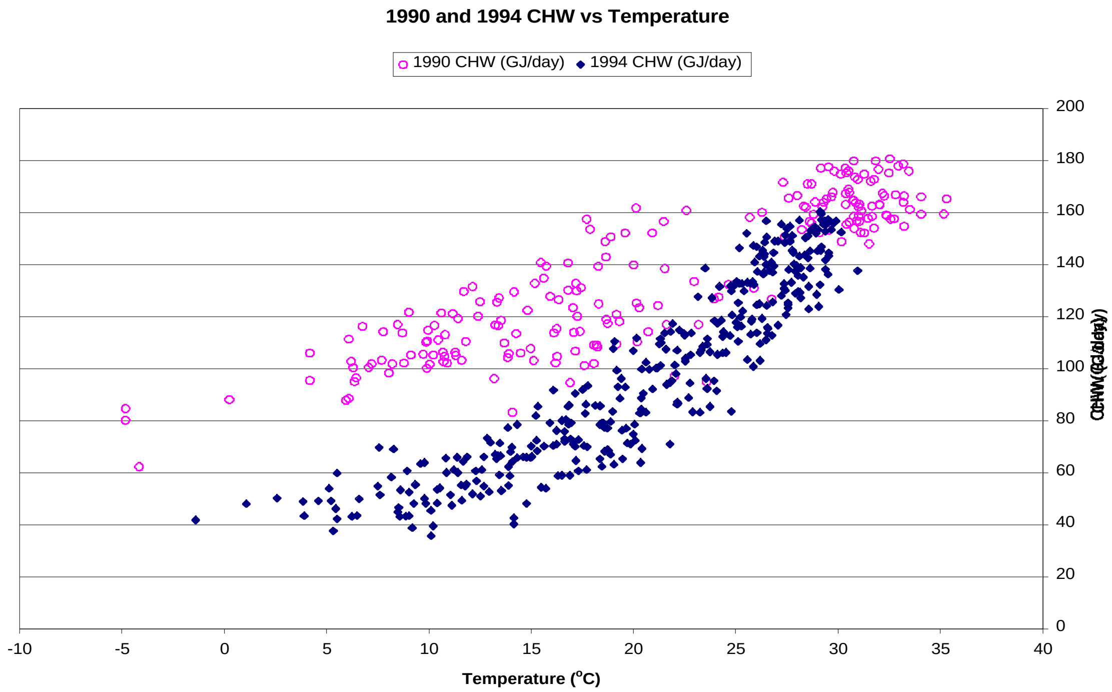
After the retrofit was installed in 1991, fan power, chilled water consumption, and hot water consumption all dropped substantially. The fan power dropped from virtually constant consumption of about 350 kW before the retrofit as shown in Figure 3 to consumption that varied from about 180 kW below 10 °C to about 200 kW between 20°C and 30°C.

Figure 3. ZEC daily MCC consumption in 1990 before the retrofit, in 1994 after the retrofit, and in 1997 after CC



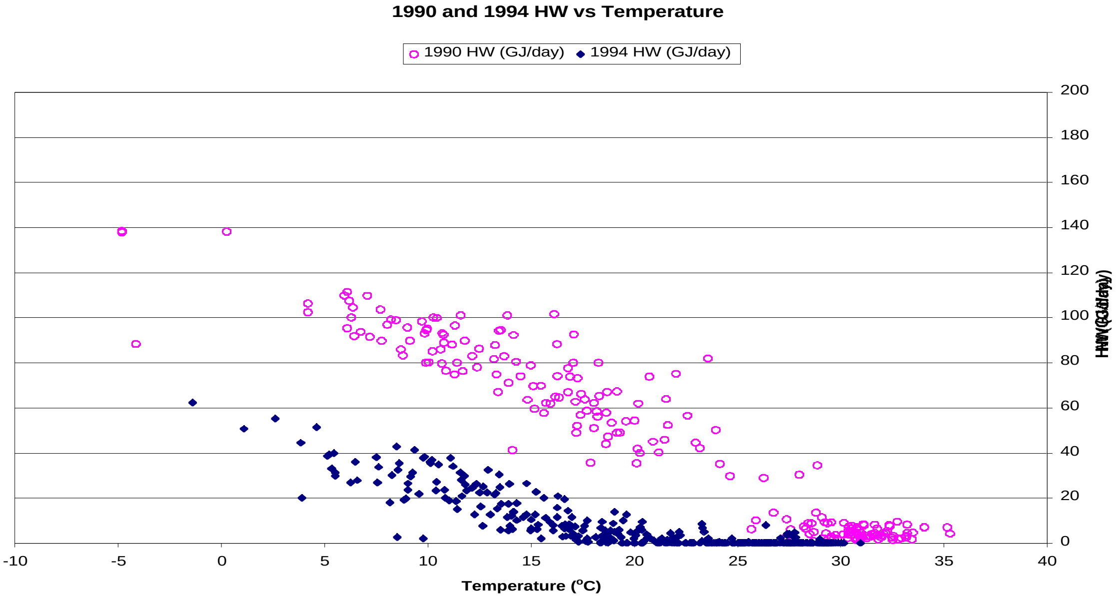
Chilled water use also dropped substantially. Figure 4 shows the daily chilled water consumption (GJ/day) in 1990 and 1994 as a function of daily average ambient temperature. Prior to the retrofit, the consumption depended almost linearly on the ambient temperature, increasing from about 100 GJ/day at 5°C to about 170 GJ/day at 30°C. The consumption following the retrofit was about the same at high temperatures, but dropped quite rapidly to about 90 GJ/day at 20 °C and then dropping more slowly to about 45 GJ/day at 5°C. There is of course considerable scatter due to variation of ambient humidity conditions and some operating practices. The general linear and piece-wise linear behaviour of the chilled water consumption of the DDCV and DDVAV systems (respectively) is consistent with the theoretically expected system behaviour (Kissock *et al.* 1998).

Figure 4. ZEC daily chilled water consumption in 1990 before the retrofit and in 1994 after the retrofit



The measured daily hot water consumption values for 1990 and 1994 are shown in Figure 5. Summer use of hot water was essentially eliminated with peak winter consumption being cut in two.

Figure 5. ZEC daily hot water consumption in 1990 before the retrofit and in 1994 after the retrofit



The annualised savings estimated in the audit and the savings determined from the measured consumption data before and after the retrofit are shown in Table 1. The "measured" savings correspond to those for 1994 which was chosen as a typical year after the retrofit and before the continuous commissioning process was applied to the building. The fan power savings were determined by subtracting 1994 hourly consumption values from the average hourly fan power consumption before the retrofit. The fractional reduction in fan consumption is very close to that projected in the audit, but the consumption reduction is substantially smaller than expected since the audit engineers overestimated the original fan power.

The annual chilled water and hot water savings have been determined using a process that normalises the savings from the retrofit and from the subsequent CC process to the same weather year. The process calibrated a simulation program (AirModel - Liu and Claridge 1998) to the measured consumption for one year prior to the retrofit (1989-90), one year after the retrofit (1994) and one year after the CC process was applied (1997). Each of the three calibrated simulations were then run using 1994 weather data and compared to determine the annualised savings.

Table 1. Retrofit savings for the Zachry Building

	Savings			
	Audit	Estimated	Measured	
Fan Power	40%	1,952,764 kWh/yr	44%	1,300,000 GJ/yr
Chilled Water	37%	28,000 GJ/yr	23%	11,100 GJ/yr
Heating Water	49%	12,100 GJ/yr	84%	16,700 GJ/yr

This process resulted in the weather normalised "measured" chilled water and heating water savings shown in Table 1. It can be seen that both the fractional chilled water savings and the reduction in chilled water consumption were substantially smaller than projected in the audit. The audit engineers again overestimated pre-retrofit consumption - in this case by more than 50%. On the other hand, both the fractional heating water savings and the consumption reduction were larger than expected.

Through the 1990s, energy costs at the university were very low and the retrofit was evaluated using the following energy costs: electricity at 0.031Euro/kWh with no demand charge, chilled water at 4.96Euro/GJ and hot water at 5.04Euro/GJ. Thus the 1994 retrofit savings were 55,000Euro (cooling), 84,000Euro (heating) and 40,600Euro (fan power) for a total of 179,600Euro. This is 69% of the 260,900Euro projected in the audit, with the major reason for the difference being the high estimates of baseline consumption used in the audit. The university Physical Plant department considered the retrofit to be successful.

8. CONTINUOUS COMMISSIONING OF THE ZACHRY ENGINEERING CENTER

The Continuous Commissioning process described earlier was developed subsequent to the retrofit of this building. In 1996 and early 1997, it was applied to the Zachry Engineering Center as part of campus-wide implementation of the process. In this case, the initial survey and specification of monitoring shown in Step 1 of Figure 1 were not performed since the university president had decided to implement the continuous commissioning process on campus based on its success in numerous other locations rather than on the results of individual building surveys. Metering was specified and installed in most campus buildings as described elsewhere (Claridge *et al.* 2000). Metering had been installed much earlier in the Zachry Engineering Center as part of the retrofit process.

9. FACILITY SURVEY

The facility survey found that the building control system set-up was far from optimum found numerous other problems in the building as well. The basic control strategies found in the building are summarised in Table 2. The ranges shown for constant parameters reflect different constant values for different individual air handlers.

Table 2. Major control settings found in the Zachry Engineering Center

Parameter	Control Practice
Pressure in air ducts	Constant at 625-875 Pa
Cold air temperature	Constant at 10_ C - 12.8_ C
Hot air temperature	Constant at 43_ C - 49_ C
Air flow to rooms	Variable - but inefficient
Heating pump control	Operated continuously
Cooling pump control	Variable speed with shut-off

The control practices shown in the table are all widely used in Texas, but none are optimal for this building. The campus control engineer worked closely with the CC engineers during the survey. The items shown in Table 2 could all be determined by examination of the control system in the building, but the facility survey also examines a great deal of the equipment throughout the building and found numerous cases of valves that let too much hot or cold water flow, control settings that caused continuous motion and unnecessary wear on valves, air ducts that had blown off of the terminal boxes, kinks in air ducts that led to rooms that could not be properly heated or cooled, etc.

10. COMMISSION MAJOR EQUIPMENT

Following the survey, the building performance was analysed and optimum control schedules were developed for the building in co-operation with the campus control engineer. The air handlers, pumps and terminal boxes had major control parameters changed to values shown in the "Post-CC" column of Table 3.

Table 3. Major control settings in the Zachry Engineering Center before and after implementation of CC

Parameter	Pre-CC Control Practice	Post-CC Control Practice
Pressure in air ducts	Constant at 625-875 Pa	250-500 Pa as T_{oa} increases
Cold air temperature	Constant at 10_ C - 12.8_ C	15.6_ C - 12.8_ C as T_{oa} increases
Hot air temperature	Constant at 43_ C - 49_ C	32.2_ C - 21.2_ C as T_{oa} increases
Air flow to rooms	Variable - but inefficient	Optimised min/max flow and damper operation
Heating pump control	Operated continuously	On when T_{oa}>12.8C
Cooling pump control	Variable speed with shut-off	Pressure depends on flow

Most of the control parameters were optimised to vary as a function of outside air temperature, T_{oa}, as indicated.

11. COMMISSION ENTIRE BUILDING TO BUILDING NEEDS

In addition to optimising the control settings for the heating and cooling systems in the building, numerous problems specific to individual rooms, ducts, or terminal boxes were diagnosed and resolved. These included items like damper motors that were disconnected, bent air ducts that could not supply enough air to properly control room temperature, leaking air dampers, dampers that indicated open when only partly open, etc.

Problems of this sort often had led to occupant complaints that were partially resolved without fixing the real problem. For example, if a duct was constricted so inadequate flow reached a room, the pressure in the air handler might be increased to get additional flow into the room. "Fixes" like this typically improve room comfort, but sometimes lead to additional heating and cooling consumption in every other room on the same air handler.

12. RESULTS OF CC MEASURES

Implementation of these measures resulted in significant additional savings beyond the original savings from the VAV retrofit and controls upgrade as shown in Figures 3, 6 and 7. Figure 3 shows the motor control center power consumption as a function of ambient temperature for 1990, 1994 and 1997. It is evident that the minimum fan power has been cut in half and there has been some reduction even at summer design conditions. Figure 6 shows the hot water consumption for 1990, 1994 and 1997, again as a function of daily average temperature. The retrofit reduced the annual hot water (HW) consumption for heating to only 16% of the baseline, so there is little room for further reduction. However, it can be seen that the CC measures further reduced HW consumption, particularly at low temperatures. The largest savings from the CC measures are seen in the chilled water consumption as shown in Figure 7. The largest fractional savings occur at low ambient temperatures, but the largest absolute savings occur at the highest ambient temperatures.

The annualised consumption values for the baseline, post-retrofit and post-CC conditions are shown in Table 4. The MCC consumption for 1997 was 1,209,918 kWh, 74% of the 1994 consumption and only 41% of the 1990 consumption. On an annual basis, the post-CC HW consumption normalised to 1994 weather was 2050 GJ, a reduction to only 10% of baseline consumption and a reduction of 34% from the 1994 consumption. The CC measures reduced the post-CC chilled water (CHW) consumption to 18,400 GJ, a reduction of 18,800 GJ which is noticeably larger than the 14,700 GJ savings produced by the retrofit. The CHW savings accounted for the largest portion of the CC savings in this cooling dominated climate.

Table 4. Consumption at the Zachry Engineering Center before and after retrofit and after implementation of CC measures

	Baseline Consumption	Post-retrofit	Post-Retrofit %	Post-CC	Post-CC
Fan Power	2,950,000 kWh	1,640,000 kWh	56%	1,210,000 kWh	41%
Chilled Water	48,300 GJ	37,200 GJ	77%	18,400GJ	37%
Heating Water	19,800 GJ	3100 GJ	16%	2050 GJ	10%

Figure 6. ZEC daily chilled water consumption for 1990 before the retrofit, 1994 after the retrofit, and 1997 after CC

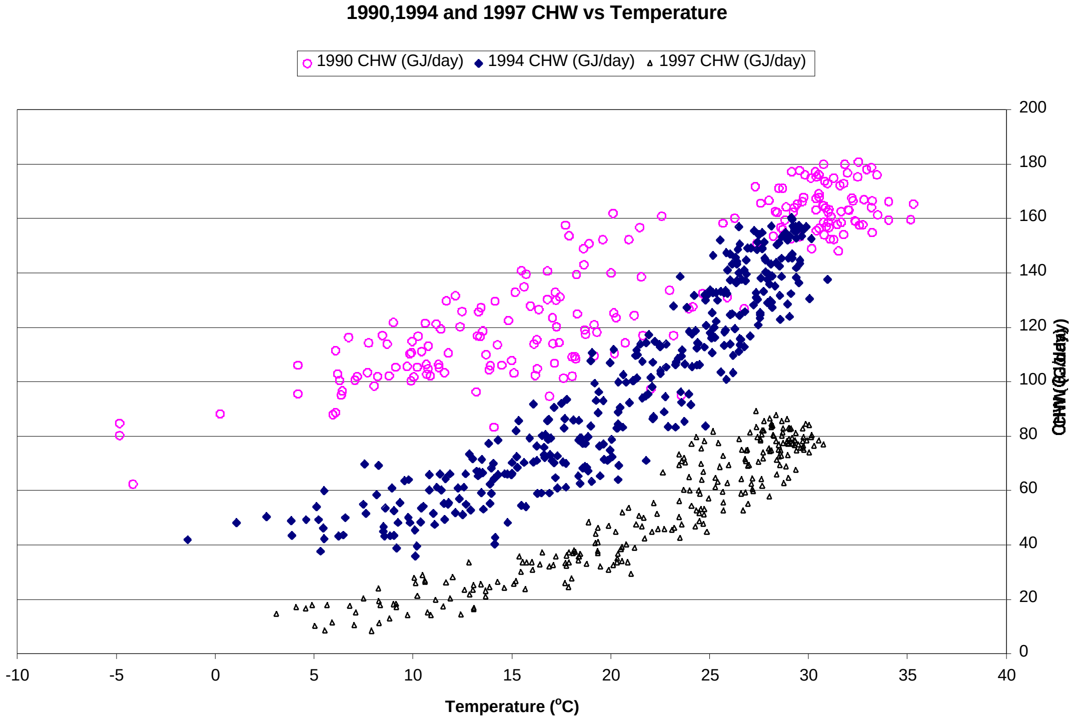
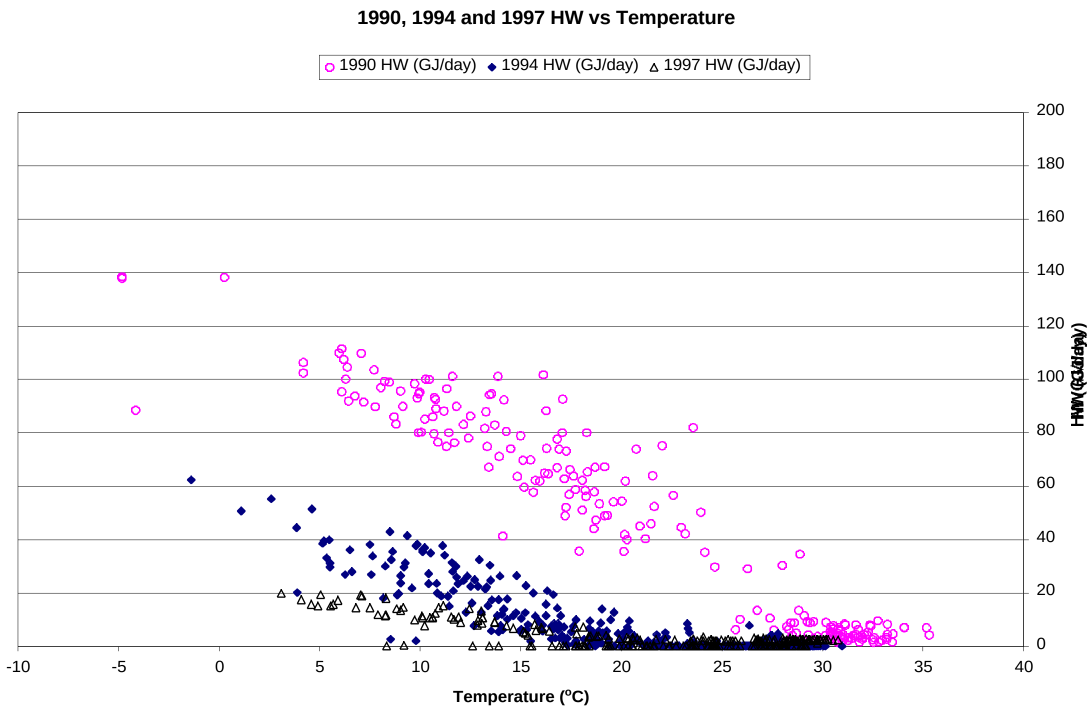


Figure 7. ZEC daily hot water consumption for 1990 before the retrofit, 1994 after the retrofit, and 1997 after CC



13. GENERALISED APPLICATION OF CASE STUDY

The major energy savings from the CC activities in the case study building resulted from five items.

1. Optimisation of duct static pressures at lower levels. This reduces fan power and also reduces damper leakage that increases both heating and cooling consumption.
2. Optimisation of cold air temperatures. Most buildings in our experience use a constant set-point for the cold air temperature which is very inefficient. Even if this set-point is changed, it is seldom optimised.
3. Optimisation of hot air temperatures. We find that most buildings modulate hot air temperature according to outside air temperature, but it is normally significantly higher than necessary.
4. Optimise settings on VAV boxes. Most VAV terminal boxes have minimum flow set-points at night that are too high.
5. Optimise pump control. Static pressure set-points on chilled water and hot water pumps are generally set higher than necessary.

It requires careful engineering to optimise these settings. This is particularly true of air side and water side system balance. There will be zones in most buildings that will not properly heat or cool until the system has been properly balanced as part of the optimisation process. However, just about every building we have examined has benefited from at least one of these items, and most benefit from all five. Typical costs for carrying out the optimisation portion of the CC process are 3-6 Euro/m^2 and the payback from energy savings is almost always less than 3 years. A number of buildings have shown paybacks from energy savings in less than a year.

Normal maintenance practices will almost certainly degrade the optimum settings within a few years. We recommend that heating, cooling and other electric consumption be monitored on a continuous basis as done in the case study building, and when consumption increases by a few percent, the building should be examined again and re-optimised.

14. CONCLUSIONS

The Continuous Commissioning process of optimising building energy use has been applied to over 100 large buildings in the United States where it has achieved average savings of 20% as reported earlier. Most of the buildings in which the CC process has been implemented to date are in hot cooling dominated climates, but limited use of these techniques in northern climates has shown similar reductions, with savings much more heavily concentrated on heating than cooling. The process has been illustrated in this paper by application to a large building which had earlier had a major retrofit performed. The post-CC consumption values represent 41% of the pre-retrofit fan and pump consumption, 10% of the pre-retrofit hot water consumption, and 38% of the pre-retrofit chilled water consumption. Using the baseline energy prices, the post-CC consumption reflects an HVAC energy cost that is only 36% of the baseline HVAC cost and is only 65% of the HVAC cost after the retrofit. The measures implemented in the case study building are quite typical of CC measures implemented in other buildings. These results are better than average for the process, but are not one-of-a-kind.

Continuous Commissioning requires a common sense approach to maintaining building mechanical and control equipment. We have yet to find any building with all of the mechanical systems working optimally. A detailed fundamental understanding of the equipment and functions of the building is used to solve long term problems. Solutions which optimise building performance in the context of current use are implemented rather than solutions which implement design intent. The energy conservation measures are almost entirely operational changes, though minor retrofits to the mechanical systems are sometimes implemented. Monitoring is very useful for identifying problems and for maintaining operational savings once these changes have been implemented. Finally, both informal and formal training of the facility staff is essential to maintain optimal operating practices.

Continuous Commissioning requires on-going monitoring and analysis. At the Energy Systems Laboratory, the monitored data is collected and quality checked weekly. The analysis is performed monthly and put into a Monthly Energy Consumption Report which shows trends and savings Based on these reports the building staff can take appropriate action to correct a degrading situation.

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16. TABLE OF ACRONYMS USED

AHU - air handling unit
CC - continuous commissioning
CHW - chilled water
DDCV - dual-duct constant volume
DDVAV - dual-duct variable air volume
EMCS - energy management and control system
HVAC - heating, ventilating and air conditioning
HW - hot water
VAV - variable air volume