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IMPLEMENTATION OF INTEGRATED COMMISSIONING, RETROFITS, AND CONTROL OPTIMIZATION PROCESS IN A SMALL COMMERCIAL BUILDING

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IMPLEMENTATION OF INTEGRATED COMMISSIONING, RETROFITS, AND CONTROL OPTIMIZATION PROCESS IN A SMALL COMMERCIAL BUILDING

By

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A THESIS

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Implementation of Integrated Commissioning, Retrofits, and the Control Optimization Process in a Small Commercial Building

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A large amount of the primary energy consumed in the US is derived from the built environment followed by energy consumed in the transportation and industrial sectors. Consequently, improving the energy efficiency of buildings is an important part of ensuring a more sustainable world for future generations. Of the various techniques employed to improve the energy efficiency of buildings, commissioning and retrofits continue to be the most widely applied solutions. Control optimization, mainly imbedded with continuous commissioning so far, is not applied as widely. Even though there are currently a few applications that integrate all three techniques, no comparison has been made between the integrated process and conventional process. The objective of this research is thus to conduct such a comparison.

This thesis begins with a review of the applications for commissioning, retrofits, and control optimization of existing buildings. Then, to compare the conventional commissioning and retrofit process with integrated process, a case demonstration is applied to an existing small commercial building.

Study results indicate that in this existing commercial building, conventional retrofits should not be implemented without commissioning because of long simple payback period. The integrated process is more cost effective than conventional process. It can achieve Net Present Value (NPV) of 251,390$ during a 20-years span, which is 2.82 times of commissioning-only process and 1.62 times of combined commissioning and retrofits process.

Acknowledgment

I am full of deep gratitude to Professor Mingsheng Liu for his guidance in my research, professional life and personal development. Dr. Liu is not only a strict scholar, but also a experienced engineer.

I also would like to express my thankfulness to my committee members, Dr. Lily Wang and Dr. Siu Kit Lau, for your helpful recommendations and precious time. Also, I want thank the whole project team, including ESL, OPPD, Bestech, and Grubb&Ellis Pacific Realty. Without their help, I would not have finished this project.

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Chapter 1 Introduction

1.1 Background

The 99.5 Quads (1 Quad=10^{15}BTU) of energy the U.S. consumed in 2008 represents 20% of the total energy consumed world-wide—the largest share from any single country. In the United States, energy consumed by the building sector accounts for almost 40% of the total primary energy consumed, followed by transportation and industrial sectors. 54% of the building sector consumption is derived from the residential sector, while 46% is derived from commercial. Given such a high consumption rate, it is clear that improving the energy efficiency of buildings may have a positive and lasting implication on the built environment.

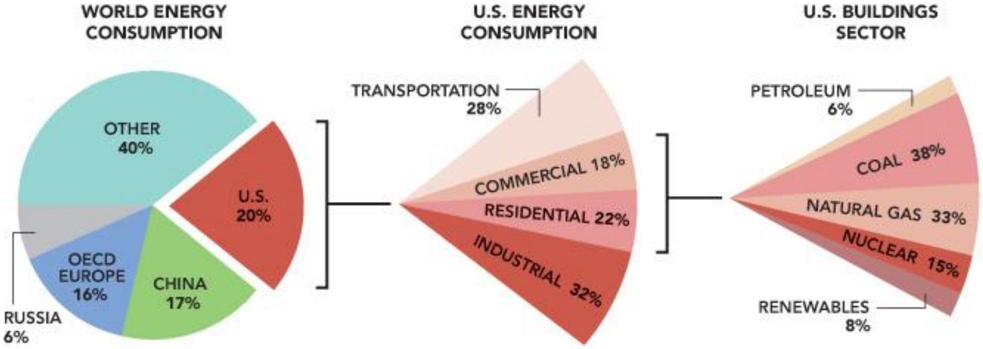


Figure 1-1: Energy chart (Buildings energy data book, U.S. Department of Energy, 2008)

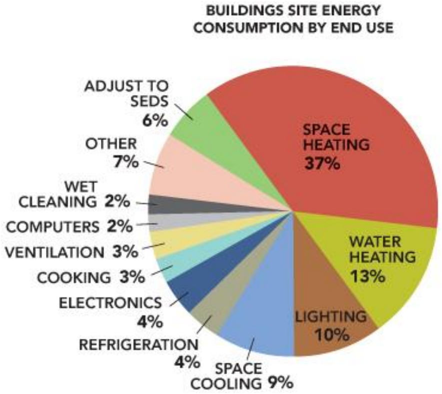


Figure 1-2: Building energy consumption by end uses in the U.S. (Buildings energy data book, U.S. Department of Energy, 2008)

1.1.1 Three Measures for Improving the Energy Performance of Existing Buildings

A large number of case studies in the previous literature conclude that further research is needed to improve the energy efficiency of most existing buildings. Typically, building energy waste is caused by outdated, inefficient, or malfunctioning equipment. It may also occur as a result of problems with the operation of HVAC systems. Commissioning, retrofits, and control optimization are often employed as techniques to both improve the energy performance of buildings and address energy related issues in existing buildings.

Commissioning

Commissioning is a word that was originally a form of military jargon. The purpose of commissioning was to ensure that navy battleships and submarines functioned properly prior to their deployment on a mission. Nowadays, however, the term is more widely used to refer to a common process in the building construction industry. Total building commissioning is applied to all systems and components within a building to include the envelope, life safety systems, lighting systems, and the HVAC system. In this thesis, commissioning will be more narrowly defined in terms of its use in building HVAC systems.

As defined by ASHRAE Guideline 1-1996 (ASHRAE, 1996, p. 23), “Commissioning is the process of ensuring that systems are designed, installed, functionally tested, and operated in conformance with the design intent.”

Over time, building HVAC systems become outdated and hard to realize the functions as intended in the original design phase. Buildings change in terms of how they are used and occupied, and the new demands may not necessarily be satisfied by the existing conditions. Problems with sensor drifts, malfunctions of the actuator, damper/valve leakage, and other conditions often go unnoticed by building operators unless they lead to comfort complaints. Examples include buildings that have higher air-side and water-side pressures than needed, inefficient hot-deck and cold-deck set-points, reset ranges, etc. Some of these problems may be known by the operators but are not taken seriously given their limited knowledge. Above all, commissioning is necessary as an effective tool for identifying a deficiency in order to satisfy the design intent.

The commissioning of existing buildings has been called retro-commissioning (commissioning of an existing building that has never before been commissioned) and re-commissioning (commissioning an existing building subsequent to one or more previous commissioning processes).

The specific benefits of commissioning existing buildings have been enumerated by Haasl and Sharp (1999) who state that commissioning:

1. Identifies system operating, control, and maintenance problems
2. Aids in long-term planning and major maintenance budgeting
3. Helps ensure a healthy, comfortable, and productive working environment for occupants
4. Reduces energy waste and ensures that energy-using equipment operates efficiently
5. Provides energy cost savings that often pay back the investment.
6. Reduces maintenance costs and premature equipment failure
7. Provides complete and accurate building documentation and expedites troubleshooting
8. Provides appropriate training to operating staff to increase their skill levels and effectively serve their customers or tenants
9. Reduces risk and increases the asset value of the building

Building Retrofits

As equipment ages it has a tendency to break down more frequently. The age at which breakdowns occur will vary according to the type of equipment. Increased maintenance costs and/or the frequency of the breakdowns are major clues that the equipment should be modernized.

In a building retrofit project the building owner makes an initial investment and takes energy conservation measures into the existing building. Due to the high efficiency of the new equipment the building is able to perform at a lower cost. The utility cost savings accumulate and eventually make up for the initial project costs.

Opportunities for mechanical system retrofits in buildings are numerous and vary due to the wide variety of heating and cooling systems and supporting equipment. Common retrofits for maximizing mechanical system efficiencies include 1) installing the VFD on the pumps and fans; 2) converting the constant air volumetric system (CAV) to a variable air volumetric system (VAV); 3) lighting retrofits; 4) chiller upgrade or replacement; 5) boiler upgrade or replacement; and 6) Energy Management & Control System (E.M.C.S) upgrades. A number of studies have shown that most retrofitted HVAC systems are able to improve system reliability, reduce energy consumption, and satisfy new environmental standards.

Control Optimization

It is generally believed that a well-designed new building with state-of-the-art technologies has little or no potential to reduce energy by control optimization. However, in a study by Song (2003), optimizing the existing control sequence in state-of-the-art buildings is an effective way to improve building comfort and reduce HVAC related energy costs.

Building control optimization is a method to implement advanced electronic building control strategies using the Energy Management and Control System (EMCS). In this approach, the components of the HVAC system work more efficiently to meet the current condition and requirements. Most current control optimization measures focus on optimizing operating schedules such as those for maximum airflow, minimum airflow, supply air temperature and static pressure, supply water temperature and differential pressure, primary/secondary loop pump control, and parallel pump control (Liu, 2002).

1.1.2 Case Studies

The followings are two case studies. The first one is about separate implementations of retrofits and control optimization. The second one is about the integrated approach.

Case Study 1- Three Buildings in the LoanSTAR Program, Texas

In a case study of the LoanSTAR program by Texas A&M University, control optimization was implemented in three buildings that were already considered "completely" retrofitted. The energy savings that result from retrofits and control optimization are compared in Figures 1-3. Surprisingly, control optimization lead to remarkable savings, surpassing the savings from retrofits in two of the tested facilities and saving only slightly less than the retrofits in a third facility.

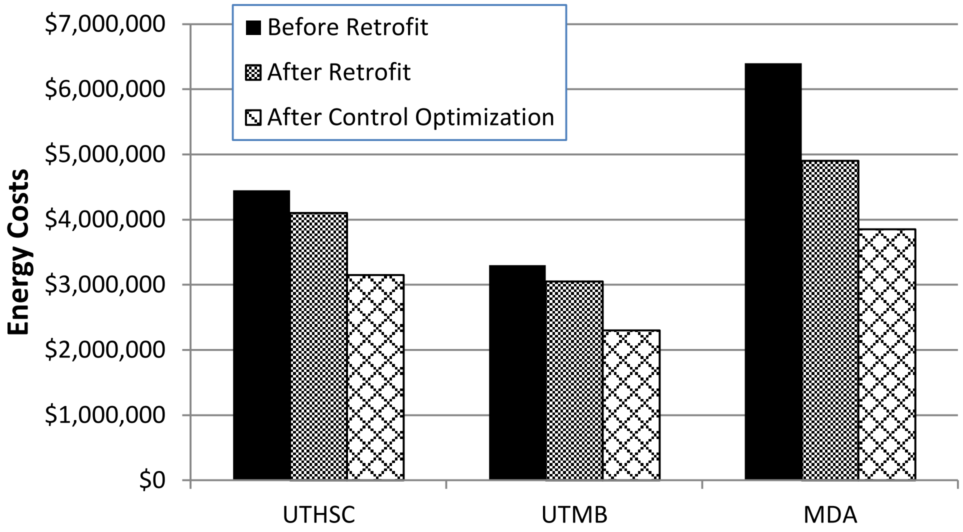


Figure 1-3: Energy costs comparison from retrofits and control optimization in three buildings in the LoanSTAR Program. (Graph modified from a chart appearing in the Continuous Commissioning Guidebook for Federal Managers by Liu, 2002)

This case study supports the idea that simply doing retrofits is not enough to achieve high energy savings. If control optimization had been integrated with retrofits on those three buildings the whole project would be much more cost effective.

Case Study 2 – Terrace Plaza, Omaha, Nebraska

This is an example of building energy project integrating commissioning, retrofits and control optimization. Terrace plaza is a 3-story rental office building with conditioned area of 49,436 ft^2. This building shows a large amount of energy saving potential. Some major findings include: 1) 30 year-old chiller is running at very low efficiency and limited capacity; 2) outside air damper and cooling valves are modulated manually; 3) unnecessary simultaneous cooling and heating; 4) old pneumatic control systems.

Based on the findings, an integrated process plan is developed to improve the building energy performance. Detailed measures are shown in table 1-1.

Table 1-1: Some measures taken at Terrace Plaza

Retrofit	Chiller Replacement Lighting modification New DDC controller installation
Commissioning	Reset supply air based on outside air Optimize economizer and minimum outside air intake Schedule optimization for chiller and boiler Check the air distribution system for thermal comfort
Control optimizations	Volumetric return fan control technology Static pressure reset based on airflow Minimum OA damper position reset based on supply airflow ratio

As results of the integrated process, annual electricity consumption is reduced by 49.3% and gas consumption by 40.6%.

Though integrated process has been implemented in a number of projects, there is no comparison so far to determine if the integrated process is better than conventional process.

1.2 Objective and Scope

The objective of this thesis is to compare the integrated process with conventional process and to demonstrate its advantages through a case study.

To achieve these objectives, the following tasks were accomplished:

1. A literature review on commissioning, retrofits, and control optimization.
2. An introduction to the integrated process
3. A case demonstration of the integrated process in a real commercial building.

4. A costs and benefits analysis that compares the integrated process and conventional process.
5. Recommendations for future research.

Chapter 2 Literature Review

2.1 Commissioning on Commercial Buildings

The concept of commissioning emerged into the building industry in the late 1970's, a time with energy crisis and development of technology. At that time, many designers began utilizing sophisticated equipment that requires continuous maintenance.

The first case of using commissioning happened in 1977, when Public Works Canada used building commissioning in their project delivery system. Then in 1981, Disney used building commissioning for the design, construction, and start-up of Expo center. In 1984, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) formed the Commissioning Guideline Committee. The guideline is intended to define a process which guarantees that only fully functional buildings would be turned over to owners. Three versions of commissioning guideline have been released by ASHRAE so far, which are ASHRAE guideline 1-1989, 1-1996 and 0-2005 respectively.

The first National Conference on Building Commissioning (NCBC) was held in 1993. In 1996, the Building Commissioning Association was established to help regulate and connect the commissioning industry (Turkaslan-Bulbul 2006). Finally, in 2000, the United States Green Building Council (USGBC) mandated commissioning as part of its Leadership in Energy and Environmental Design (LEED) requirements. In 2001, the Energy Conservation in Buildings and Community System (ECBCS) of the International Energy Agency (IEA) launched "Annex 40"- a four year project on the "Commissioning of Building HVAC Systems for Improved Energy Performances". The objective of the Annex is to develop, validate and document tools for the commissioning of buildings and building services.

Nowadays, a variety of commissioning guidelines and toolkits has been developed by such organizations as the California Commissioning Collaborative (CCC), the Building Commissioning Association (BCA), and the Environmental Protection Agency (EPA).

The BCA defines Existing Building Commissioning (EBCx) as: "…a systematic process for investigating, analyzing, and optimizing the performance of building systems through the identification and implementation of low/no cost and capital intensive Facility Improvement Measures and ensuring their continued performance. The goal of EBCx is to make building systems perform interactively to meet the Current Facility Requirements and provide the tools to support the continuous improvement of system performance over time. The term EBCx is intended to be a comprehensive term defining a process that encompasses the more narrowly focused process variations such as retro-commissioning, re-commissioning and ongoing commissioning that are commonly used in the industry."

According to the guidebook entitled "A Practical Guide for Commissioning Existing Buildings" prepared by the Portland Energy Conservation, Inc. (PECI) and Oak Ridge National Laboratory (1999), the retrocommissioning process consists of four phases: Planning, investigation, implementation and hand-off phase (Figure 2-1). During the planning phase, project objectives are firstly developed and team members chosen. Engineers collect the updated building documentation and plan the work scope. Then, in the investigation phase, they perform a site assessment. A list of deficiencies and potential improvements are identified. After diagnostic monitoring and tests are developed and implemented, they then give recommendations on those opportunities that are most cost-effective. Measures taken in the implementation phase to improve the building performance are followed by re-testing and re-monitoring. In the project hand-off phase, a final report documents the benefits of investment.

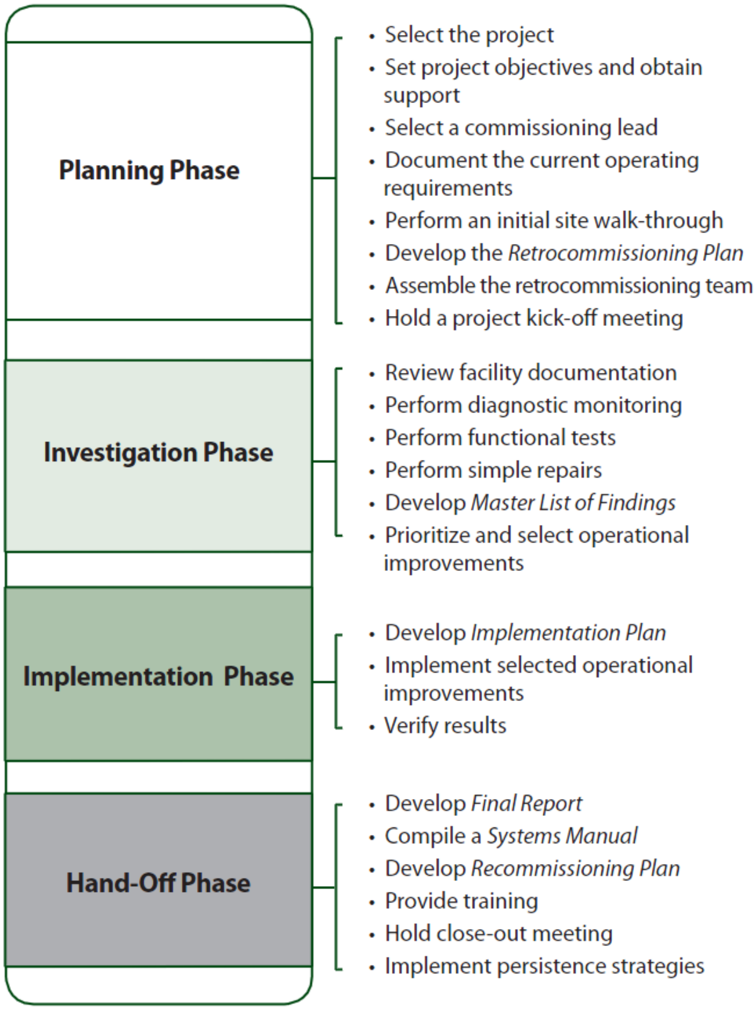


Figure 2-1: Retrocommissioning process overview (California Commissioning Guide: Existing buildings, California Commissioning Collaborative, 2006)

According to the "California Commissioning Guide", retrocommissioning not only results in cost saving benefits but also improvements to almost every aspect of building operations and maintenance. A detailed analysis of several of the most obvious benefits is listed below:

1. Energy Savings

Retrocommissioning analyzes a building's performance. The analysis includes not only recommendations on how to reduce the building's energy consumption but also guidance on how to implement the most cost-effective improvements. Early in the project, commissioning engineers perform a utility bill analysis to better understand how the building consumes energy. In the investigation phase, commissioning engineers look for typical operating issues like simultaneous heating and cooling, poorly operating economizers, and excessive air and water flows - all of which lead to energy waste. Throughout the entire project, the team takes a comprehensive view of the building operations and looks for ways to improve how equipment functions together as an integrated system. Energy savings from retrocommissioning can be significant.

2. Improve System Operation: Beyond Preventive Maintenance

Compared with preventive maintenance focusing on reliability and capacity of individual equipment, retrocommissioning takes a holistic view. On the one hand, the retrocommissioning process is a conditions assessment that looks at maintenance issues and practices; on the other hand, it is an operations assessment that looks at control strategies and how well the mechanical equipment, lighting, building envelope and related controls perform together.

3. Improve Equipment Performance

One of the main objectives of the retrocommissioning process is to assess whether each piece of the system is functioning properly. If not, the commissioning team will investigate the cause of the problem and recommend a solution. As a result, equipment not only lasts longer, but works more reliably, needs fewer repairs, and uses less energy.

4. Increase O&M Staff Capabilities and Expertise

An essential duty of the retrocommissioning process is to provide training to the facility management staff. Normally after training the staff members can better understand the performance of the building equipment, know how to troubleshoot, and learn how to operate and maintain the equipment.

A wide range of HVAC deficiencies are usually found during the commissioning process in both existing and newly constructed buildings. Only a slight difference between them exists in terms of distribution issues. Most deficiencies in existing buildings occur as a result of inappropriate operation and control. As a result, the advanced reset schedule is the most commonly applied corrective measure. Due to poor maintenance, outdated or malfunctioning equipment is the second most common problem in existing buildings. A mechanical fix is another measure frequently taken in existing buildings to get better performance results. Calibrating sensors and actuators is another effective strategy for dealing with poor maintenance in most existing buildings. Among all the commissioned spots, air handling and distribution systems are the location of most problems followed by cooling plant, heating plant, terminal units and lighting fixtures.

New constructions show different issue distribution than existing buildings. While operations and control improvement potential is little, more measures are taken in terms of maintenance and equipment installation modification. Among all the commissioned spots, air handling and distribution system are still where most problems take place, but then goes lighting, whose energy waste surpasses cooling plant and heating plant.

While there is abundant research on the cost effectiveness of building commissioning process, Joan Effinger and Hannah Friedman (2010) instead focused their study on specific measures in commissioning and their cost effectiveness. They summarized some of the most frequently used but not necessarily most efficient measures, such as optimizing the airside economizer, reducing equipment runtime, reducing / resetting discharging static pressure setpoint, revising control sequence, adding / optimizing SAT reset, reducing lighting schedule, and replacing/repairing/calibrating sensors. On the other hand, the most energy saving measures involve: Tuning / Upgrading Controls, adding / optimizing HWST reset, relocating / shielding temp sensor, adding /optimizing boiler lockout, adding small A/C unit, adding / optimizing chiller staging, lowering / reset VAV box flow, optimizing waterside economizer.

As a matter of fact, the findings from the of commissioning process vary depending on the particularamong different projects. There is not a standard list of commissioning defined findings by any of the mainstream organizations , including ASHRAE, the California Commissioning Collaborative (CCC), the Building Commissioning Associate (BCA), or the EPA., The author developed a master list of traditional commissioning findings from more than thirty sample reports and guidelines. The list is shown in table 2-1.

Table 2-1: Master list of findings in conventional commissioning process

Issue sources		Major commissioning findings
Design/Installation		Design detail inadequate
		Equipment selection inappropriate
		Lighting - spaces over-lit
		O&M access insufficient
		Over pumping or throttled discharge valve
		System selection inappropriate
		Equipment not based on design
		Equipment not properly installed
Maintenance		Ductwork leaky
		Filtration requires modification
		Flow obstructions
		Poor actuator operation
		Valves leaky
Operation	Scheduling	Equipment scheduling sub-optimal
		Equipment staging sub-optimal
		Equipment start/stop sub-optimal
		Lighting scheduling sub-optimal
	Controls	Control loop needs tuning
		Manual changes or overrides causing problems
		Sensor problem
		Sequence of operations inadequate
		Simultaneous heating and cooling
	Outside air	Economizer sub-optimal
		Ventilation issues
	Setpoints/reset	Temperature/pressure setpoints sub-optimal
		VAV box minimums high
	Variable flow	Pump speed/flow high or constant when it should vary
		Fan speed/flow high or constant when it should vary

Benefits and cost

Evan Mills from Lawrence Berkeley National Laboratory has done detailed research on the cost and effectiveness of building commissioning (2009). It was found that commissioning is arguably the single-most cost-effective strategy to reduce energy, costs, and greenhouse gas emissions in buildings today. The median normalized cost to deliver commissioning is \$0.30/ft^2 for existing buildings and \$1.16/ft^2 for new construction (or 0.4% of the overall construction cost). In his study, more than 10,000 specific deficiencies were identified across the half of the sample for which data were available. Fixing these problems leads to 16% median whole-building energy savings in existing buildings and 13% in new construction, with payback times of 1.1 years and 4.2 years respectively. Figure 2-2 shows the U.S. mid-range CO^2 abatement potential by 2030, where a range of CO^2 reduction opportunities are compared in terms of cost-effectiveness. Abatement can be achieved through building commissioning at negative cost, which are -\$110 per ton for existing buildings and -\$25/ton for new construction. This compares quite well with market prices for carbon trading and offsets in the +\$10 to +\$30/ton range.

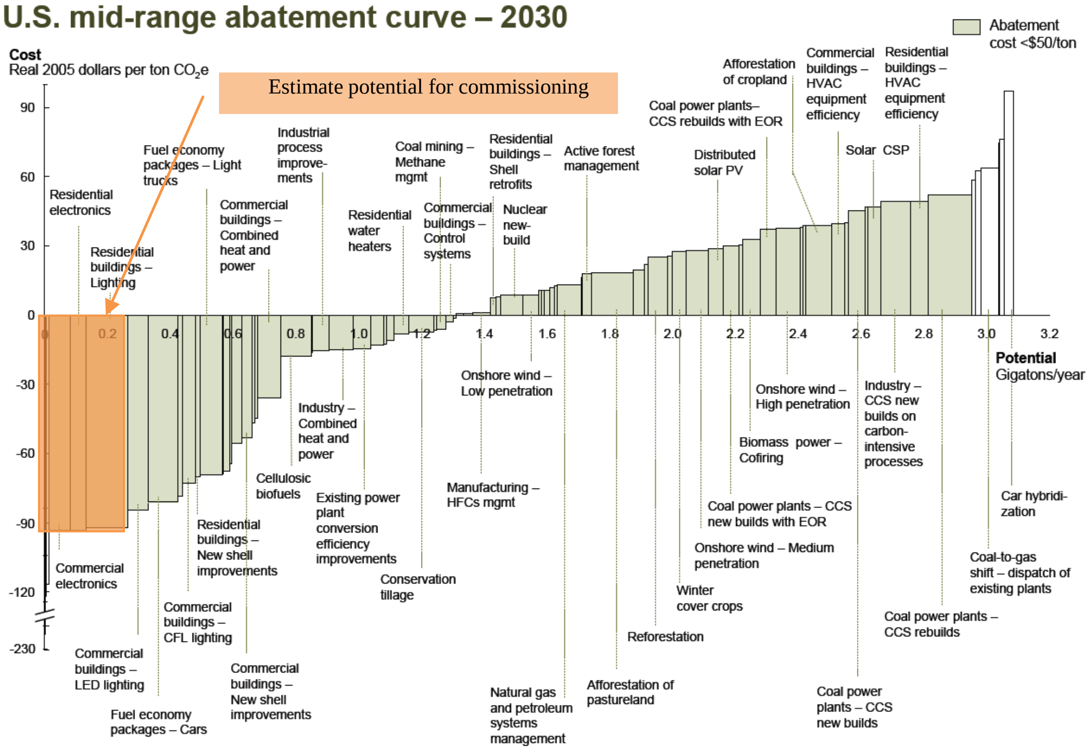


Figure 2-2: The comparison of cost-effectiveness of different measures in reducing CO^2 (Reducing U.S. Greenhouse Gas Emissions: How Much at What Cost? Executive Report, McKinsey & Company, 2007)

Figure 2-3 shows the general payback time for different types of buildings. It is found that those high-tech buildings with bigger energy intensity (such as healthcare centers and laboratories) have shorter payback periods. Buildings with low energy intensity usually take longer to pay back.

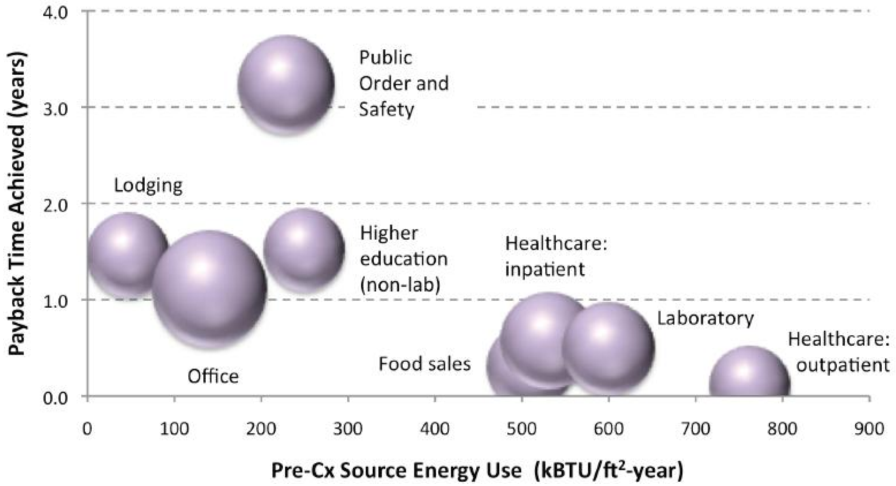


Figure 2-3: Commissioning payback time comparison among different types of buildings (Building Commissioning: A Golden Opportunity for Reducing Energy Costs and Greenhouse-gas Emissions, Evan Mills. 2009.)

Commissioning case study 1: Clover Park Elementary Schools, Lakewood, Washington

Due to higher-than-average energy costs, Idlewild and Oakbrook Elementary Schools in the Clover Park School District were selected for retrocommissioning in 2002. Approximately 15% of baseline energy costs were expected to be saved after the commissioning project. At the beginning, the commissioning team designed the work scope in the following systems:

Idlewild Elementary

- Central hot water heating system with two boilers
- 20 unit ventilators, 4 heating and ventilating (H&V) units
- Direct digital control system
- Oakbrook Elementary
- 36 air-to-air heat pumps with electric resistance backup heat
- Direct digital control system

During the commissioning process, several issues on both mechanical system and control operations were identified and improved as follows:

Idlewild Elementary

- Boiler plant: Field inspection identified a problem with pressure relief valves—water was regularly being blown off during startup. To correct over-pressurization, make-up water systems were adjusted. The project also corrected lead/lag boiler sequencing and hot water supply temperature controls.
- After-hours operation: The sequence of operation for unoccupied heating was revised to first use the hydronic baseboard radiator rather than the less efficient unit ventilators.
- Hydronic baseboards: Three uncontrolled radiators in entry vestibules were identified and fitted with a thermostatic control valve.

Oakbrook Elementary

- Electric resistance backup: backup heat was disabled for 9 of the 36 heat pumps when outdoor temperatures are above 45°F (the others are set for 50°F).
- After-hours operation: Override switches used after regular school hours were operating the heating and ventilation longer—and with more outside air—than necessary for the typical 3 or fewer occupants. Thus, the controls were reprogrammed.

Both Schools

- Nearly 80% of the electronic thermostats were out of calibration by 1-3 degrees. In addition to calibrating the thermostats, their setpoints were modified to save energy.
- 27 mixed air damper actuators were observed to either not track or stroke properly, or to be stuck open.

During the 4-month period after retrocommissioning, energy savings were calculated to be \$3,303- approximately 10% well short of the expected 15%. To investigate this shortfall, the commissioning agent surveyed the school principals and district staffs, reviewed control system settings, and installed power logging equipment at Oakbrook. They found several variations from the baseline year contributed to the lower-than-expected savings, e.g.:

- One additional classroom was used at Idlewild, and a new refrigerator was added.
- Occupied heating setpoints had been increased by 1°F at Oakbrook.
- The school district had not yet retrofitted the three vestibule hydronic radiators with control valves.

- The outdoor temperature sensor for the control system failed during the coldest winter months and was over-ridden by district staff, disabling the lockout of electric resistance heating.

By taking steps to follow up on the system's performance, investigate potential opportunities to reduce peak demand at Oakbrook, and work with school district staff, the commissioning agent make sure additional saving strategies will be implemented.

Commissioning case 2: Ronald V. Dellums Federal Building in Oakland, California

During 2001-2004, Ronald V. Dellums Federal Building in Oakland, California undertook a commissioning project. The commissioning provider identified several opportunities for improvements to the air distribution system that may result in significant savings. Those measures include relocating supply and mixing air sensors, optimizing the static pressure setpoint, repairing the economizer dampers and relief dampers. $66,981 is saved annually with payback less than a year (Figure 2-4).

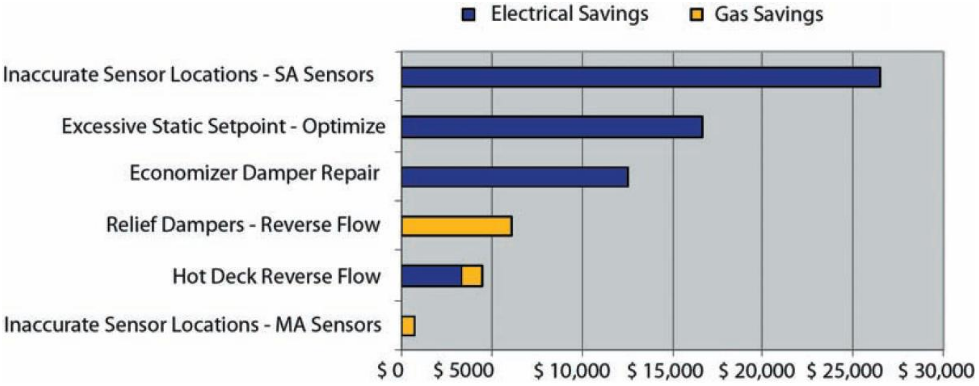


Figure 2-4: Retrocommissioning measures and their associated cost savings

2.2 Building Retrofits

Building retrofits on existing commercial buildings are necessary because most mechanical and lighting systems become inefficient after a period of operation. Approximately 86% of building construction expenditures in the U.S. is related to renovation of existing buildings. It is estimated that about 14 billion m^2 of existing buildings (roughly half of the entire building stock in the United States) will need to be renovated over the next 30 years. Most documented retrofits include replacements and improvements on chillers and boilers, building automation systems, and conversion of constant air volume system to variable air volume system, etc.

Chiller retrofit

Chilled-water systems are usually found in large buildings, featuring separate central chillers and air handlers with a network of pipes and pumps to connect them. Although only 18 percent of all U.S. commercial building floor area cooling load is met by chillers, about 39 percent of all buildings larger than 100,000 ft^2 use chilled-water systems.

When the existing chiller is approaching the near the end of its lifespan or in need of substantial maintenance, replacement with a new high-efficiency model is usually considered. Since the annual energy cost of for operating a chiller is almost one-third of its purchase price, even a modest improvement in the chiller efficiency can yield substantial savings and attractive paybacks.

A case retrofit of the chilled water system at Lawrence Street Center was studied. Lawrence Street Center is a Class A, fourteen-story office building built in Denver, Colorado in 1982. It offers with 140,000 square feet of rentable space built in 1982 in Denver, Colorado. The original building chiller was a 400-ton electric centrifugal chiller using R-11 refrigerant. A full-load efficiency of 0.72 kW/ton can be reached. At less than 15 years old, the chiller was still running reliably. However it was only operating at a maximum of 60% of its capacity. The facility manager heard about a local retrofit rebate program from the local utility and decided to convert the chiller to a non-CFC refrigerant..

As a result, a driveline retrofit was conducted on the existing chiller, which involved replacing the chiller's starter, motor, compressor, purge unit and controls. To check the condition of the heat exchanger's shell and tubes, eddy-current testing was carried out and the heat exchanger was deemed to be in acceptable shape. The full-load efficiency of the chiller after the conversion improved to 0.59 kW/ton, while the capacity dropped from the 400 tons to 290 tons.

Since the original chiller was oversized and run mostly at inefficient part-loads of no more than 60%, the reduced capacity could still meet the building's cooling load. Table 2-2 gives the costs, rebate, energy savings, and simple payback period statistics for this work.

Table 2-2: Costs and savings of chiller retrofit at Lawrence Street Center

Retrofit Costs	Rebate	Annual Energy Savings	Payback Period
$94,000	$32,000	$12,500	5 years

Boiler retrofit

Approximately 40 percent of all commercial buildings use boilers for space heating. Of these, roughly 65 percent are gas fired, 28 percent are oil fired, and 7 percent are electric. The combustion efficiency of older boilers varies from 65 percent to 75 percent, although inefficient boilers can have efficiencies between 40 percent and 60 percent. Energy-efficient gas- or oil-fired boiler systems can have efficiencies between 85 and 95 percent.

Table 2-3 presents the installed base of commercial boilers in the US (Science Applications International Corporation, 2009).

Table 2-3: Commercial boilers installed in the U.S.

Building Type	Number of Boilers	Aggregate Boiler Capacity (MMBtu/Hr)	Average Capacity per Facility (MMBtu/hr)
Education	35,895	128,790	3.6
Office	28,030	297,090	10.6
Health	15,190	317,110	20.9
Other	11,900	88,970	7.5
Lodging	10,545	140,830	13.4
Public Assembly	7,280	55,205	7.6
Retail	5,585	47,230	8.5
Warehouse	5,365	72,385	13.5
Total	**119,790**	**1,147,610**	**9.6**

In Cityside Middle School, west of Michigan, a retrofit on the hot water system was done after an energy evaluation. The existing boiler system was replaced with four new high efficiency condensing type boilers. Figure 2-5 shows gas consumption and cost reduction for this retrofit project.

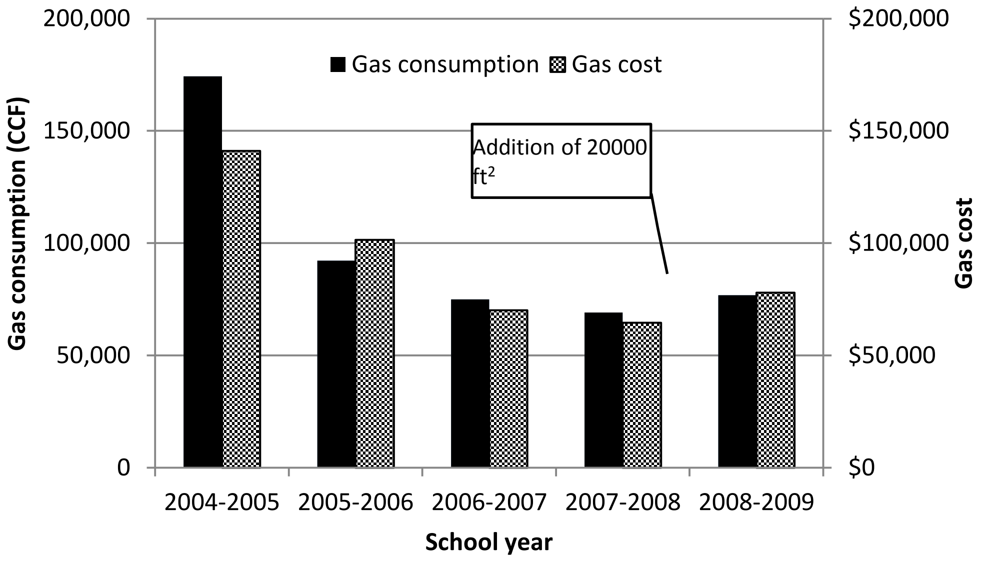


Figure 2-5: Gas consumption after boiler retrofit at Cityside Middle School

Building Automation System

With the development of computers, information technology, and communications protocols, building automation systems (BASs) becomes an effective technology for controlling heating, ventilation, and air conditioning (HVAC) systems in most large buildings. BASs is a tool linking HVAC, lighting, security, fire safety, and other systems so as to make a building operate more efficiently and effectively. BASs is now used in more than half of all buildings in the U.S. larger than 100,000 square feet. Though it can be a heavy expense for the building owner of an existing building, it can save an average of 10 percent of overall building energy consumption (M.R. Brambley et al., 2005).

A BAS system usually consists of sensors, controllers, actuators, and software (Figure 2-6). HVAC control strategies can be implemented into BAS by programming with computer language. The three most adopted processes for programming are line-programming, menu-based programming and block programming. With control strategies programmed correctly, all the components work together to function as designed.

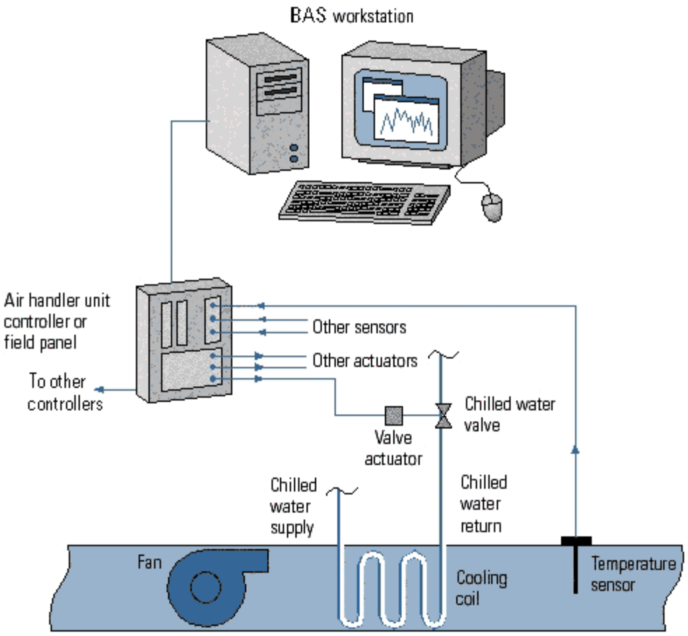


Figure 2-6: Building Automation System

The first generation of HVAC automation and control applications dates back to 1950s, when reasonably accurate pneumatic sensors and controllers started to come out. Later the use of electromechanical relays in ladder logic to switch dampers became standardized. Eventually, the relays became electronic switches, as transistors eventually could handle greater current loads. By 1985, pneumatic control could no longer compete with this new technology. By the year 2000, computerized controllers were common. Today, some controllers can even be accessed by web browsers remotely, which need no longer be in the same building as the HVAC equipment. However, for those building more than 20 years old, there are still pneumatic HVAC systems in operation.

Compared with pneumatic controls, DDC has significant savings from maintenances. Pneumatic systems require constant monitoring and recalibration. Drifting, or falling out of calibration usually occurs in pneumatic equipment because of the interaction between air and mechanical devices. They do not occur in DDC systems because digital signals are more accurate and reliable. It has been reported that system maintenance savings can reach 40% or more (Energy Office, Michigan Department of Consumer & Industry Service, 2002).

Energy Service of Colorado (ESCO) has done a detailed experiment to demonstrate the savings obtained by replacing outdated pneumatic control with DDC. In this 17 stories building, air distributions are controlled pneumatically on all floors. The ninth floor was retrofitted with DDC control independently. The eighth floor was chosen to compare since it has the same footprints, air distribution system, occupancy, and temperature requirement. At the same time, HVAC electrical distribution panel meters were installed on both floors. Electricity usage was monitored for a month without heating and another with heating. DDC reduced KWH usage by 50% in heating month and 45% in non-heating month. Demand was reduced by 58% in heating month and 40% in non-heating month (shown in figure 2-7 and 2-8).

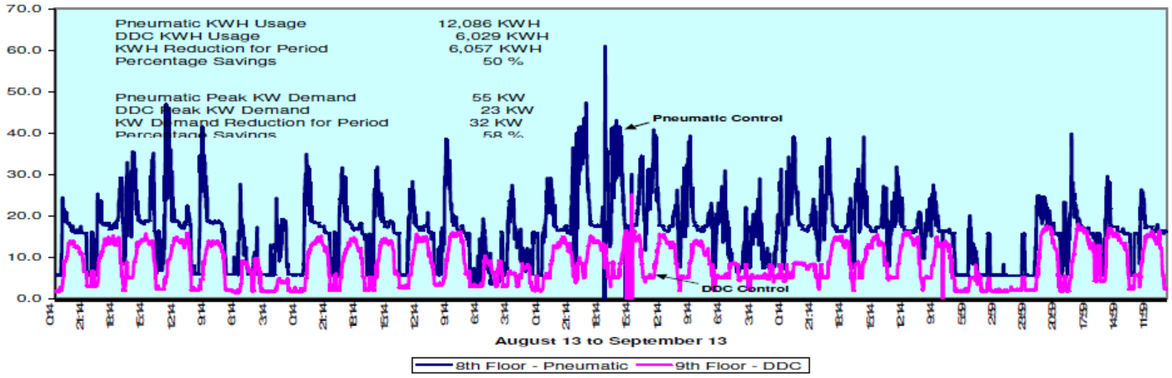


Figure 2-7: DDC vs. Pneumatic electricity usage profile when heating is disabled (DDC vs. Pneumatic VAV Control, ESCO)

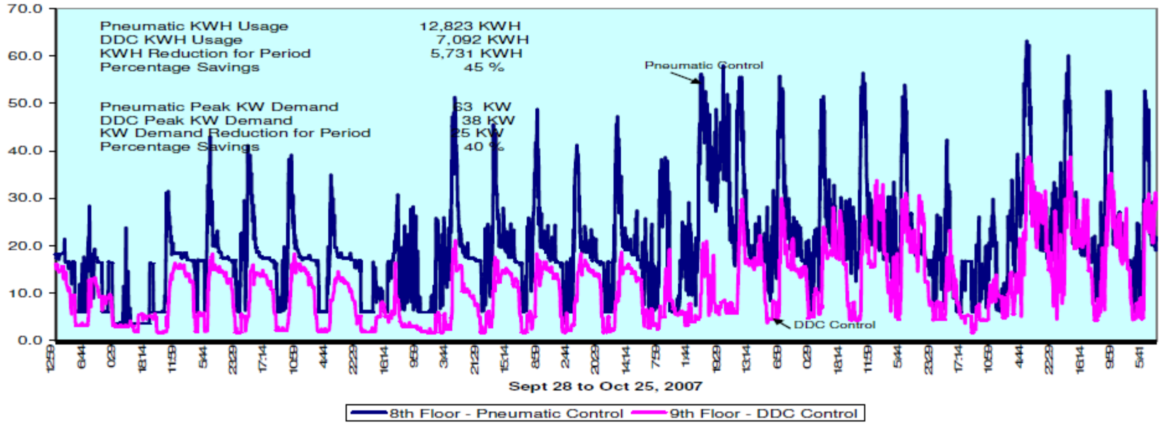


Figure 2-8: DDC vs. Pneumatic electricity usage profile when heating is enabled (DDC vs. Pneumatic VAV Control, ESCO)

VFD

Variable frequency drive (VFD), also known as VSD (Variable Speed Drive) and ASD (Adjustable Speed Drive), is a system for controlling the rotational speed of an alternating current (AC) electric motor by controlling the frequency of the electrical power supplied to the motor. VFD is being increasingly used in HVAC applications. Common places where VFD is effectively used are air handlers, pumps, chillers and tower fans.

One of the advantages of VFD is the capacity control to match the system demand and thus saves energy. Traditionally, throttling valves, vanes, or dampers are employed to control capacity of a constant speed pump or fan. However, these devices increase the head, thereby forcing the fan or pump to ride the curve to a point where it produces less flow (Figure 2-9). As the power consumption is the product of head and flow, energy savings are achieved by reduced flows despite of increased head. In contrast, when using VFD to reduce capacity, both the head and flow are reduced and this maximizes the energy savings.

A hospital in the Milwaukee metropolitan area retrofitted several air-handling units of its HVAC system with VFDs replacing inlet guide vanes. The total power of retrofitted supply-air and return-air fans amounts to 330 HP. The new systems operate 24 hours a day. They are saving approximately $36,800 each year (cutting annual costs from $61,800 to about $25,000) based on an energy cost of $0.05 per kilowatt-hour (kWh).

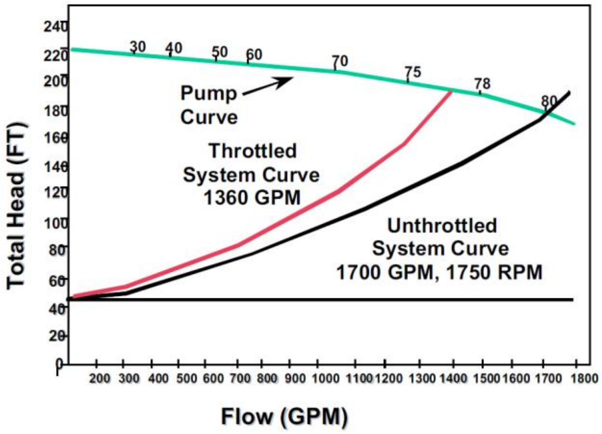


Figure 2-9: Capacity control using throttling devices

CAV to VAV conversion

Compared with CAV systems, VAV systems have two obvious advantages: (1) the fan capacity control, especially with modern electronic variable speed drives. This reduces the energy consumed by fans. (2) Dehumidification is greater with VAV systems than it is with CAV. CAV increases the discharge air temperature to satisfy part load cooling capacity, but involves humidity issue at the same time. VAV is able to modulate the supply air flow rate to achieve partial cooling load without sacrificing the discharge air temperature.

In a LoanSTAR report (Haberl, et al., 1996), savings due to CAV to VAV retrofits were analyzed based on the performance on 13 sites. Figure 2-10 shows the measured savings compared to the estimated savings for the calendar year 1993. There is a great difference in terms of retrofit effect among different buildings. The best retrofit effect was that more than three times the estimated savings was achieved (GAR). In contrast, five sites (FNA, BUS, ZEC, UNV and WEL) have measured savings less than 50% of the audit estimated savings. A further analysis based on the hourly electricity usage before/after retrofits was carried out to investigate this difference. It revealed two common features impacting the system performance with retrofit. First, the extent to which the system is oversized determines the significance of CAV to VAV retrofit potential. Among those sites where measured savings were within 100 to 200% of the audit estimated savings, the fans are oversized by as much as 3 to 6 times what is being used by the majority of hours of the post-retrofit VAV system. The ratio is only about twice for the rest of the sites. The second feature is about the schedule. In those sites showing good retrofit effects, CAV air-handler systems were mostly operated 24 hours per day in the pre-retrofit period.

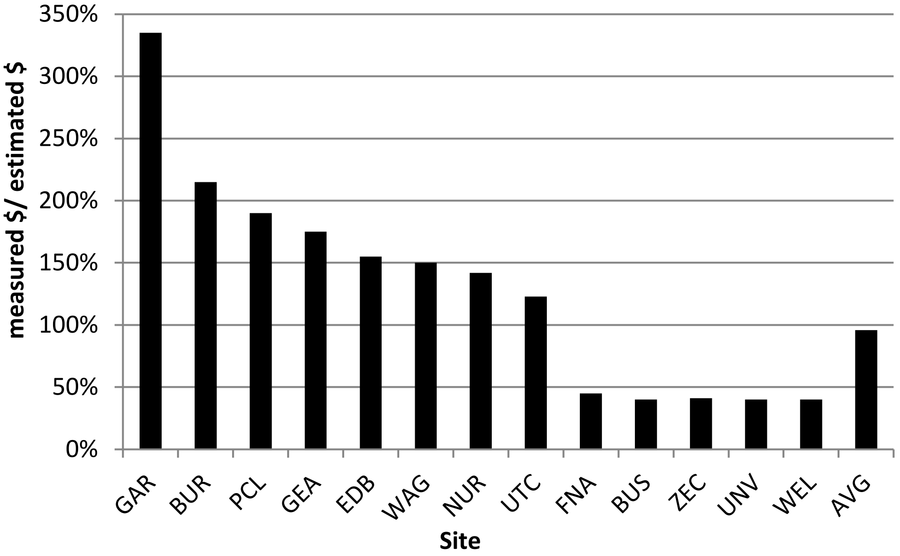


Figure 2-10: Measured savings compared to estimated annual savings for CV to VAV retrofits for 14 sites (An Evaluation of Energy-Saving Retrofits from the TEXAS LoanSTAR Program, Haberl, et al., 1996)

Others

In 1988, Texas LoanSTAR — Loans to Save Taxes and Resources — was implemented as a retrofit program for energy efficiency in buildings. The loans are targeted toward public buildings: state agencies, local governments, and school districts. The size of the original investment — $98.6 million — makes LoanSTAR the largest state-run energy efficiency and conservation program in the United States. Today it is still among the best documented and most successful energy efficiency programs in the United States.

In December 1993, LoarSTAR program had a milestone report on the energy savings of retrofits in 34 LoanSTAR sites representing 50 buildings (Reddy, 1994). An impartment goal of that report was to investigate various energy conservation retrofit measures (ECRMs) in the LoanSTAR program. Table 2-34 shows detailed data regarding the costs, savings and payback of difference ECRMs. It was noted that the primary retrofit in most of the buildings was the conversion of constant air volume (CAV) units to variable air volume (VAV) units. Lighting and

EMCS retrofits are the second most important type of retrofits, followed by boiler and chiller retrofits.

Table 2-4: Summary of ECRMs for building monitored in the LoanSTAR program as of December 1993 (An Overview of Measured Energy Retrofit Savings Methodologies Developed in the Texas Loan STAR Program, Reddy, et al., 1994)

ECRM Recommendations	Implementation Costs ($)	% of Total Imp. Costs	Savings ($)	% of total savings	Simple Payback (yrs)
HVAC System Retrofits	10,504,625	32.3	3,256,227	34	3.2
Boiler & Steam Retrofits	1,439,646	4.4	1,116,516	11.7	1.3
Motor/VSD/VSP Conversion	4,679,163	14.4	1,172,166	12.3	4
Chiller & Chilled Water Retrofits	1,936,886	6	362,643	3.8	5.3
Lighting Retrofits	4,841,987	14.9	1,605,062	16.8	3
EMCS	3,368,158	10.4	736,918	7.7	4.6
Pumping System Retrofits	1,752,647	5.4	655,057	6.8	2.7
Others	3,997,383	12.3	6,626,914	6.9	6
Total	3,250,495	100	9,566,880	100	3.4

2.3 Building Control Optimization

The building HVAC control systems have undergone a long history, along with the increasing complexity of HVAC design, development of control theory and automation technology. At the very beginning, draft dampers (followed by thermostat control of the dampers) controlled heating. The use of mechanical stokers for coal firing required another step in the use of control. Later oil burners were introduced, making the concept of combustion safety control necessary. This involved the sensing and proof-of-flame in the proper time sequence of introducing draft, fuel, and ignition.

As the steam and hot water radiators were introduced to provide heat, there came the concept of zone control and individual room control (IRC). Zone control was categorized as closed loop control using zone thermostats and open loop control with outside conditions setting the rate of heat delivery to the zone. Both of these forms of control were used to regulate the delivery of heat.

The ways of regulating heat included valves to control the flow of steam or hot water, controlling pumps to circulate hot water, and controlling boiler operation. When IRC was used, the central supply was maintained and radiator valves were controlled by room thermostats.

The use of fans to provide ventilation and heated air was controlled by dampers, which functions by modulating the source and volume of air. Pneumatic controls were the mainstream form of unit ventilators at that time and several simple variables were controlled including minimum outside air ratio, discharge air volume, low-temperature limit, and thermostats with lower night settings activated by compressed supply pressure level. The increased usage of air conditioning resulted in more complex control sequences in larger systems and the popularity of central monitoring and control.

The development of computers and microprocessors has caused great changes in the HVAC controls industry. Minicomputers were installed to provide centralized control with on-site data. Then, microprocessors were used for remote data-gathering panels to gather data and provide direct digital control. Computers are now used as on-site central controllers with operator interfaces and as computer assisted engineering (CAE) tools in the design of system programs, databases, and documentation. Microprocessors are still used in remote data gathering, yet also in small unit controllers and in smart thermostats. With the help of advanced processors and consequent more convenient data monitoring and accessing tools, complicated control strategies are able to be implemented to squeeze energy saving from almost everywhere in buildings nowadays.

Generally, building control optimization is to minimize building energy consumption and to maximize comfort based on the current building conditions and requirements by means of optimized sequence of operation. The design intent is considered only as a reference, not as the performance target. This is because (1) the building designer rarely has enough information to specify optimal operation of the design, and (2) the building function and use have often changed significantly from original expectations (Claridge, et al. 2003).

Continuous Commissioning

Control optimization is mostly embedded into the process of Continuous Commissioning^{SM} (CC^{SM}). CC^{SM} is an ongoing process to solve operating problems, improve comfort, optimize energy use and identify retrofits for existing commercial and institutional buildings and central plant facilities. (Liu, 2002). It was first used by engineers at the Texas Engineering Experiment Station's Energy Systems Lab (ESL) at Texas A&M University. The term of CC^{SM} came from "recommissioning" or "O&M process" in early papers on how to identify and implement operational improvements. Later the name of CC is used to emphasize the continuing interaction with building operators in order to have a finely tuned building. Compared with conventional commissioning process, CC^{SM} is focused on energy savings through optimized control strategies.

The first buildings to undergo a CC^{SM} process were in the Texas LoanSTAR program (Liu, et al, 1994). During that period of time, measures to improve energy efficiency were simple and mostly referred to as O&M measures, such as turning off lights and equipment when possible, using efficient temperature settings, etc.

Nowadays control optimization is increasingly used to improve building energy efficiency and is more complicated than it used to be. Since the emergence of CC, a lot of studies regarding various control strategies have been carried out in the Energy System Laboratory (ESL) at Texas A&M University and University of Nebraska-Lincoln. In the book of "Continuous Commissioning Guidebook for Federal Managers" (Mingsheng Liu, et al, 2002), control strategies are elaborated from the aspects of AHU systems, water/steam distribution systems, central chiller and heating plants, thermal storage systems, etc.

There are two differences between conventional commissioning and continuous commissioning. Firstly, continuous commissioning, as its name implies, is an ongoing process throughout the life of buildings, while conventional commissioning is more of a onetime check to bring building operation to original design intent. Secondly, continuous commissioning focuses on advanced control sequences to meet the current conditions and requirements, but conventional commissioning is to bring the building back to original design.

Optimized Airflow control of VAV systems

Conventionally, building pressure are controlled by fan tracking (FT) method, direct building pressure control (DBP) method, and the volumetric tracking (VT) method. In FT method, the return fan speed is set up slightly aging the supply fan speed. This method works well in high load. However, in partial load the return fan may draw unduly high air volume from the building and resulting in bad building pressure control.

DBP method directly monitors the building pressure value across and maintains the setpoint. This method fails to work well when the pressure reading is not accurate due to large pressure difference variation.

In VT method, both the supply and return airflows are measured by meters. The return air fan speed is modulated to maintain the supply and return airflow difference as required. But in practical applications, accurate measurement of flow rate is very hard, especially when the building lacks appropriate length of straight ductwork.

Based on VT method, Liu (2002) proposed an innovative way to get the accurate flow measurement without meters. VFD signals and the fan pressure head are used instead. By implanting the fan curve characteristics into the control algorithm, calculation runs inside the controller to determine the correct airflow reading given by the value of VFD speed and fan head. Then VT method is also programmed into the controller to maintain the building pressure. This method is also used in the case demonstration part of this research.

Optimized pump speed control

Conventionally, chilled water pump speed is controlled to maintain the water loop differential pressure (DP) set point. The DP may be constant, or may be reset based on the outside air temperature, the system operation schedule or even by building facility management staff manually. However, none of the above ways can ensure an appropriate reset value due to the varying of chilled water loop load.

Zheng (2005) developed a new chilled water pump control algorithm in variable water flow direct return systems. In this method, the first step is to identify the most resistant loop. Then let the valve in this loop fully open. Pump speed is then adjusted to maintain the supply air temperature of the AHU on that loop. This control strategy was applied in a real project. Measured actual DP is much lower than the original set point (figure 2-11). This control greatly method saves pump head and pump electricity consumption. Calculated chilled water pump electricity savings are shown in figure 2-12.

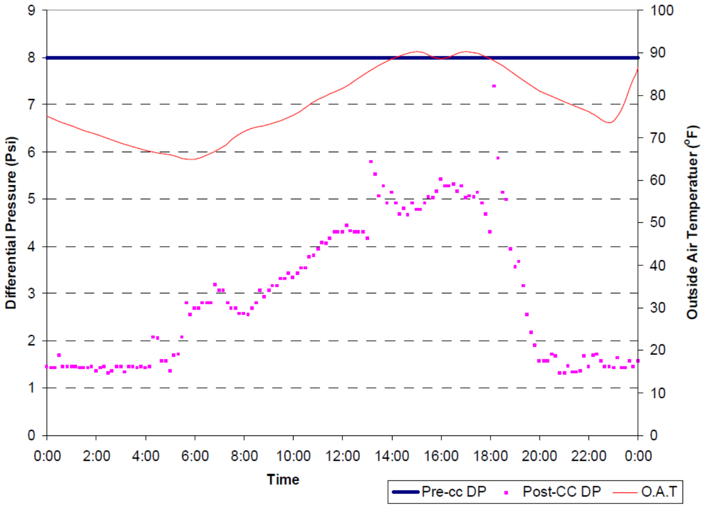


Figure 2-11: Reduced DP in the most resistant chilled water loop with new control strategy (Source: Supply Air Temperature Control Using a VFD Pump, Zheng and Liu, 2005)

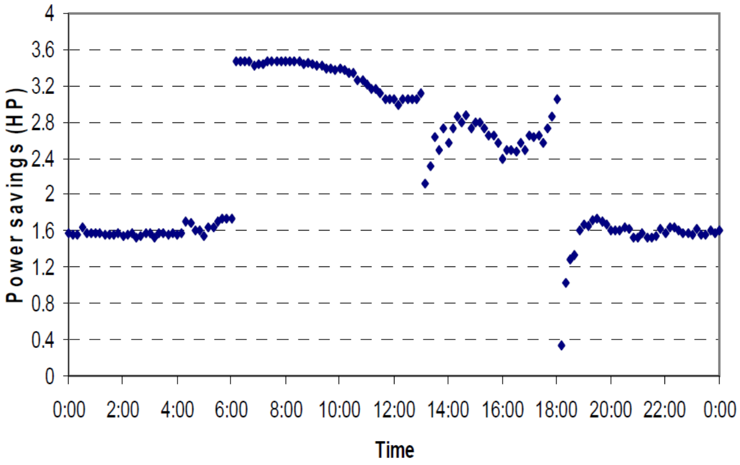


Figure 2-12: Calculated chilled water pump electricity savings with new pump control strategy (Source: Supply Air Temperature Control Using a VFD Pump, Zheng and Liu, 2005)

Overall Concepts

In actual control optimization process, it is commonly found that the control methods vary greatly among different buildings. Energy savings may turn out unexpected as well. Despite some unforeseeable factors impacting the result, there are some general concepts that can be followed during control optimization process.

1. No “one size fits all” sequences of operation.

Buildings vary with respects to their size, function, occupancy, located environment, equipment, design, age of buildings, etc. As a result, it is impossible to duplicate a set of control strategies that works for one building to another. The appropriate way of control should be very specific and building-oriented.

2. Need to be designed for the application (including the personnel)

This concept refers to the building function and occupancy-oriented control strategies. For example, in those hospitals and school buildings, indoor air quality is strictly required to be maintained above a certain level and should be given the top priority of control. Economizer is thus sacrificed in some cases to achieve better indoor environment, instead of energy saving.

3. Involve operations personnel in process

Due to “smart” building management systems and advanced automatic control technology, less and less human’s physical effort is involved in the operations of building performance. However, the building still cannot run totally depending on those automatic controls themselves. This is because (1) Building performing conditions vary greatly and it is impossible to program the control logic in every circumstance based on current technology. So, additional manual adjustments are needed periodically. (2) Potential faults and malfunctioning happen occasionally. While the building management systems cannot sense those failures and still run as programmed in design condition, the building will definitely lose thermal comfort and energy efficiency. This can be avoided if operations personnel notice the problem in time.

4. Commissioning can be a catalyst for control optimization

The work scope of control optimization is only limited to change/improve the way how the system is operated with existing condition. So, whether the existing condition is good or bad has a direct impact on the effect of control optimization. For example, if the chilled water valve was stuck, there is no way to control the supply air temperature at set point, no matter what sophisticated control algorithm is behind the set point reset. In this case, commissioning is very necessary tool to eliminate those “obstacles” for control optimization. This point of view will be discussed in details in chapter 3.

Chapter 3 Integrated process

In this chapter, a detailed procedure of integrated process is presented. The second part of this chapter analyzes how commissioning, retrofits and control optimization interact and facilitate each other in the integrated process.

3.1 Integrated Process

This integrated process has three phases, including preliminary assessment phase, energy study and planning phase and implementation phase.

3.1.1 Phase Ⅰ

This phase is for preliminary assessment of the energy saving potential of the targeted building. Usually a walkthrough by the commissioning engineers accompanied by the building technicians is needed. Commissioning engineers examine physical parameters, such as fan speed, pump speed, chillers and boilers performance data (temperature, pressure, and capacity), economizer performance, AHU supply air temperature, etc. Besides, through interviews with building technicians and occupants, subjective sense about the thermal comfort condition is collected. In the end of this phase, commissioning engineers submit a report to the building owners about the general building performance and estimate whether there is energy saving potential or not. Upon the building owner’s agreement and sponsorship, a further energy study plan is proposed as the work scope of phase Ⅱ.

3.1.2 Phase Ⅱ

This phase is for detailed study of the targeted building’s energy performance and plan of energy saving measures, including retrofit and control optimization.

Step 1: Setup the performance baseline. This step is similar to that in CC^{SM}. Existing building performance is evaluated from the standpoints of comfort conditions and energy performance. Comfort problems of feeling too hot or too cold, noise, humidity or odors are documented and quantified if measurement is available. Energy baseline includes whole building electricity, cooling energy and heating energy bill. As heating and cooling energy use are normally weather dependent, weather file is an important referred parameter when documenting building energy performance.

Step 2: Acquire existing control sequence information and set up trending for key parameters. A comprehensive study of the existing HVAC system operation is conducted. Common systems are AHUs, chillers, boilers, terminal boxes, RTUs, heat pumps, cooling towers, etc. Trending for both analog and binary values should be set up. A well collected set of data will help commissioning engineers troubleshoot the system and pinpoint those areas that can be optimized.

Step 3: Conduct field measurement and evaluate the existing performance. Field measurement cannot be replaced by BAS trending for two reasons: (1) it is never guaranteed that sensors are as accurate as they were right after installed after a period of usage. Field measurement is more reliable and can calibrate the accuracy of those sensors. (2) It is commonly found sensors can be missing or misallocated, even for those important parameters. As a result, filed measurement as well as short-term on-site trending is necessary as a proper tool to get accurate system performance data. With the help of those data, the performance of the existing HVAC system is evaluated. For example, hunting usually indicates improper configuration of control parameters and fine tuning is needed for better comfort condition, system stability and longer equipment life.

Step 4: Develop list of deficiencies. This is like the master of list of findings in the commissioning process. But it is more energy efficiency orientated compared with conventional function oriented commissioning findings. A typical list may include AHU economizer condition and fan speed control, chiller system schedule and operation, boiler schedule and operation, terminal units airflow control and set up, lighting efficiency, etc.

Step 5: Develop mechanical design requirements and control system upgrade specifications. The team developed a list of recommended solutions to the building owner based on the results of step 4. The list covers measures from conventional commissioning, retrofits and control optimization.

Step 6: Calculate the costs and savings. Predicted costs based on the working scope developed in step 5 are calculated. Also, the amount of savings and simple payback period due to proposed retrofit is estimated. With costs and savings estimation in hand and budget plan, building owners choose certain measures in the proposal for implementation. Then the process goes to phase Ⅲ.

3.1.3 Phase Ⅲ

This phase is for implementation of major retrofit, control optimization and follow-up work.

Step 1: Implement mechanical retrofit and follow-up commissioning. Mechanical contractor implements the retrofit in a way that minimizes the impact on system performing stability and occupants' thermal comfort. After mechanical retrofit is complete, the commissioning engineer takes a performance check to ensure the retrofitted part is compatible with the rest of the system and can function as proposed.

Step 2: Implement control system upgrade and follow-up commissioning. Control contractor installs and upgrades the control hardware and develop basic control program to integrate all components in existing systems. The program ensures the systems safe operation. The commissioning engineers perform a function check to make sure the control is completely upgraded and fully functioning.

Step 3: Program optimized control sequence and upload. After control contractor completes control upgrade, the control developer designs advanced optimal control algorithms which are beyond the typical control system program. The new version control sequence is built by control engineers and uploaded to the control system. The program must be uploaded unit by unit. Once again, a comprehensive test must be performed to ensure the new program functions as proposed. The programs may be fine-tuned. Control optimization may not be ended in phase Ⅲ. It can be adjusted continuously during a periodic follow ups.

Step 4: Fine tuning and follow up services. In the follow up period, the commissioning engineers work with the team (technician, facility operating staff) to solve minor problems. Adjustments may be made on the control sequences so that the system runs efficiently in all working conditions. Normally a four-season follow up is recommended. Commissioning engineers also provide training to the operating staff. Documented HVAC control are presented to operating staff so they may fully understand what kind of changes have been done and how they are going to work. How to operate and trouble shoot guide are important as well to ensure sustainable operation.

3.2 The Roles of Commissioning, Retrofits and Control Optimization in the Integrated Process

As the previous section is focused on procedures of the integrated process, this section discusses how the integration emphasizes commissioning, retrofits and control optimization. Again, a phase by phase framework for analysis is used.

3.2.1 Phase Ⅰ

The integrated process starts with work that is similar to commissioning. The team takes a walkthrough to evaluate the extent to which the system is operated as initially designed. Through interviews with facility operation staffs, commissioning engineers can find the problems of unsatisfying thermal comfort and high energy bill.

Though retrofit and control optimization is not physically implemented until phase Ⅲ, the potential of implementation is preliminarily considered in phase Ⅰ. For instance, more often than not an over 20 years old boiler indicates low efficiency and it is the right time for replacement. For complicated system with a large number of components, old pneumatic systems usually indicate the incapability of comprehensive energy management and running advanced algorithm. Disabled economizer during cool days indicates some possible mistakes in control program or improper operation by the facility operating staff. With these “hints” of retrofit and control optimization in mind, the team can better predict the potential of energy saving.

3.2.2 Phase Ⅱ

The tasks of commissioning in this phase begin with detailed study of the energy performance. Energy bill analysis, one-time measurement and long term trending with data loggers are measures to obtain the energy performance information. By looking at the energy bill, the team can understand the energy consumption characteristics better and figure out ways to reduce energy use from an overall perspective. Measured physical data provides useful information about specific equipment running condition and specific zone comfort level.

Retrofit in phase Ⅱ is in the planning scope. Different from the preliminary assessment of retrofit potential in phase Ⅰ, detailed retrofit plan is developed in this phase. The retrofit plan includes the specifications of the HVAC components to be retrofitted, design and sizing of new installations, control system update choice, control points to be added and connected, and estimated costs of each retrofit measure.

Control optimization in phase Ⅱ is also in the planning scope. Based on the existing system type and functions and potential future retrofitted system, the team developed unit-specific optimized control sequence. Instead of the control method in conventional commissioning, optimized control goes beyond what normal system can do, and implant state of art control strategies into the existing control system.

When planning retrofits and control optimization, the team cannot design the two plans separately, because they are so closely related to each other. On the one hand, the scope of retrofits and control optimizations should always be matched. Retrofitted components define the scope of control optimization by their new characteristics and compatibility with the rest of the system; the goal of control determines the scope of retrofits since no control can function well without basic "hardware" equipment. On the other hand, they facilitate each other to achieve the best effect. Optimized controls ensure retrofitted equipment work in the most efficient condition and extend their ability to serve the building. Retrofits meet the basic "hardware" requirement of optimized controls and maintain the quality of control.

3.2.3 Phase Ⅲ

At the beginning of phase Ⅲ, mechanical and control retrofits are implemented as previously planned. Upon retrofits completion, commissioning engineers take performance check to determine whether the retrofitted equipment functions as proposed. If not, trouble shooting is needed to ensure the function. Commissioning of control system retrofit is to ensure all control points are added and connected correctly. It is also necessary to check if basic control has been programmed into the controller and the system runs well. This is very important before implementation of control optimization.

After the retrofit and its commissioning, control optimization starts. This is the last major step to achieve energy saving, as well as a task that requires most technical knowledge. As mentioned in last chapter, control strategies should be very specific according to the building condition and equipment performance.

Commissioning work during and after control optimization process includes verification of the system's accurate response to different working conditions as programmed, verification of retrofitted and non-retrofitted components' full function upon the demand of control, collecting occupants' sense of the thermal comfort and humidity under new control, trending the physical parameters data and analyzing the system's stability and flexibility, analyzing the energy consumption bill, training of facility management staff, etc.

3.3 The Interrelationship of Commissioning, Retrofit and Control Optimization

In the integrated process as described in the last section, commissioning, retrofit and control optimization are not independent parts, instead they have impact on each other. Understanding the interrelationship among them may help building engineers with better design of energy saving measures for existing buildings.

Commissioning and retrofit

Commissioning identifies those inefficient components within HVAC system, which might be in need of retrofit. Also, commissioning verifies the effect of retrofit after it is complete by means of functional performance check. It can find the defect of retrofit in time and prevent further problems.

Commissioning and control optimization

A complete commissioning scope includes identifying the existing sequence of control. In this way commissioning sets the "target" for optimization. It is impossible to figure out a better control sequence without knowing how the system is currently controlled. In addition, by checking the system performance under optimized control sequence, commissioning ensures the optimization works as designed after it is programmed into the controller.

Retrofit and control optimization

In industry practice, retrofit and control optimization do not always have to work together. However, more energy savings can be achieved if integrating them both. Retrofit and control optimization is like the "hardware and software" repair on the building system. A high level of control requires not only the mechanical components work at normal conditions, but also a complete set of control points and modern control systems, which are often achieved by control upgrade. On the other hand, control optimization extends the capability of retrofitted system. This is because even after retrofit is completed, the HVAC system may still lack good management of all components and thus the overall system may not be running at maximum efficiency.

Chapter 4 Demonstration

In this chapter, a case study on a real commercial building is presented. Building energy performance with conventional commissioning and retrofits measures are simulated. Also, the integrated process developed in chapter 3 is practically implemented on this building. Conventional measures and integrated process are compared in terms of energy performance improvements, costs and benefits.

4.1 Building Information

The study is conducted on a small commercial building at Omaha, Nebraska. This is an energy efficiency project conducted by Energy System Laboratory (ESL) team at University of Nebraska-Lincoln and the Omaha Public Power District (OPPD) staff. The project started in May, 2008 and most of the work was completed by June, 2011.

This is a 3-story office building built in 1980's. The total floor area of is 32,884ft^2 (10,961 ft^2 per floor). The office hour is 7:00 a.m. to 6:00 p.m. Monday through Friday and 7:00 a.m. to 2:00 p.m. on Saturdays. There are approximately 150 occupants and 76 PCs. The HVAC system is operated 24/7.

Figure 4-1: Building outside look

HVAC system and facilities identification

There is a dual-duct variable air volume air handling unit (AHU) serving the whole building. One VFD is installed on the supply fan while the return fan uses inlet guide vane to modulate the air flow. The supply fan has a 25 HP motor with the design air flow at 18,000 CFM and return fan has a 20 HP motor with the design air flow at 18,000 CFM. A manual damper is installed on the hot deck, which is open all year around for air circulating. The terminal units are all pressure independent dual-duct variable volume terminal boxes.

The chiller system consists of a 90 ton air-cooled chiller and a 3 HP constant speed chilled water pump. The brand new Trane chiller has two compressors in mechanical room and twelve constant speed condensing fans on the roof. There is no chilled water valve on chilled water pipe. Chilled water is only provided for the cold deck of AHU.

The boiler system includes two natural gas fired hot water boilers and two 2 HP constant speed hot water pumps. Each of the two boilers has a heating capacity of 650 MBH. The hot water is only provided for the hot deck of AHU.

The control systems for AHU, chiller system, boiler system and terminal units are all pneumatic and in local level.

4.2 Conventional Processes

Based on the existing building condition, conventional commissioning and retrofits measures are developed by the author. Control optimization, as a relatively innovative measure, is not discussed in this section.

4.2.1 Commissioning

According to the building facility staff, this building has not been commissioned in the past few years and has a number of problems. So a retrocommissioning process is highly recommended from a conventional point of view.

Retrocommissioning process developed by CCC is used for commissioning analysis in this research. CCC defines the retrocommissioning process as four phases: planning phase, investigation phase, implementation phase and hand-off phase. As the commissioning process is generally similar for most buildings, it is not discussed in details. Here only the major findings in the investigation phase and implementation measures are emphasized (table 4-1).

Table 4-1: Major findings and implemented measures of retrocommissioning process in the studied building

	Master of list finds	Implementation Measures
Chiller	Hunting and low Delta T between CHWS and CHWR	1. Check and fully close cooling coil bypass 2. clean/replace fouled coil (not implemented)
Boiler	Boiler run when supposed to stop	1. calibrate outside air temperature sensor 2. adjust the schedule
AHU	High speed reading with supply VFD	Reset static pressure setpoint
	Negative building pressure	1. Check relief damper 2. Optimize relief damper control
	OA damper closed when economizer should be used	1. Investigate OA damper control 2. Adjust economizer schedule
	Cold deck temp higher than designed	1. Check and fully close cooling coil bypass 2. clean/replace fouled coil (not implemented)
	Hot deck supply temp higher than design	1. Replace heating valve 2. Reset hot deck temperature
Terminal box	High minimum flow	Adjust minimum flow setpoint
	Constant warm issues in hospital reception	1. Investigate flow distribution 2. ductwork modification(not implemented) 3. relocate thermostats(not implemented)
	Terminal box dampers stuck	Fix dampers

Table 4-1 summaries those findings by the project team during the integrated process that fall into commissioning category. A real retrocommissioning process may have a more complete master list than this table shows. This table provides important information that will be referred to when simulating benefits of commissioning in the following part.

4.2.2 Retrofits

Actually there are not many retrofit measures implemented on this building due to a number of reasons. This building is basically maintained well and has reasonably good design. Some modifications have already been done before the project, like one VFD is already installed on the supply fan and the new chiller is in good shape. The financial budget may be another reason for limited retrofit options.

Finally the project team decides to do two retrofits. An extra VFD is installed on the hot deck fan. All pneumatic controls for AHU, Chiller system, boiler system and terminal box units are upgraded to full DDC. Upgraded components are listed in table 4-2. Added control points are in table 4-3

Table 4-2: DDC upgrade list

Sub system	Components	Numbers
Control system	BCU	1
	MP581 controllers	5
	Expansion modules	11
	Control points	140
AHU	DDC damper actuators	6
	DDC valve actuators	1
	DDC pressure sensors	4
Terminal Box	DDC zone thermostats	27
	DDC TBX damper actuators	54

Table 4-3: Added control points

	Digital Input	Digital Output	Analog Input	Analog Output
AHU	8	8	10	6
TBX	0	0	54	54
Sum	140			

4.2.3 Simulation of Conventional Processes

4.2.3.1 Building energy model

To estimate the benefits of commissioning and retrofits, building energy simulation is used as the tool. In this research, TRACE 700, developed by TRANE, is chose as the simulation software.

Firstly the building model before the efficiency project is developed as the baseline. Physical values and system configurations are obtained by on-site measurement and building blueprint. As for those missing information, approximated values are given under the instruction of ASHRAE Standard 90.1-2007. Table 4-4 shows some basic modeling input parameters.

Table 4-4: Some major inputs for building modeling

Inputs	Values
Conditioned Area	32990 ft^2
Wall U factor	0.75 $Btu/(hr{\cdot}ft^2{\cdot}F)$
Windows U factor	0.6 $Btu/(hr{\cdot}ft^2{\cdot}F)$
Roof U factor	0.0406 $Btu/(hr{\cdot}ft^2{\cdot}F)$
Floor U factor	0.088 $Btu/(hr{\cdot}ft^2{\cdot}F)$
Lighting density	1 W/ft2
Infiltration	0.6 ACH
Miscellaneous Loads	300 watts/workstation
People Density	218 ft^2/person

After the building baseline model is built and adjusted, verification is conducted by comparing the modeled building energy consumption with real building energy consumption. The comparison result is shown in figure 4-2. Errors between modeled annual energy use and real annual energy use are 0.41% for electricity and 5% for gas.

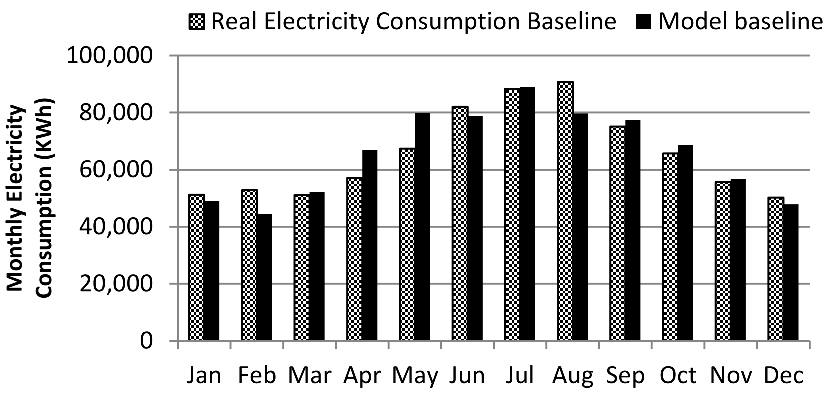


Figure 4-2: Simulated electricity baseline vs. real electricity consumption baseline

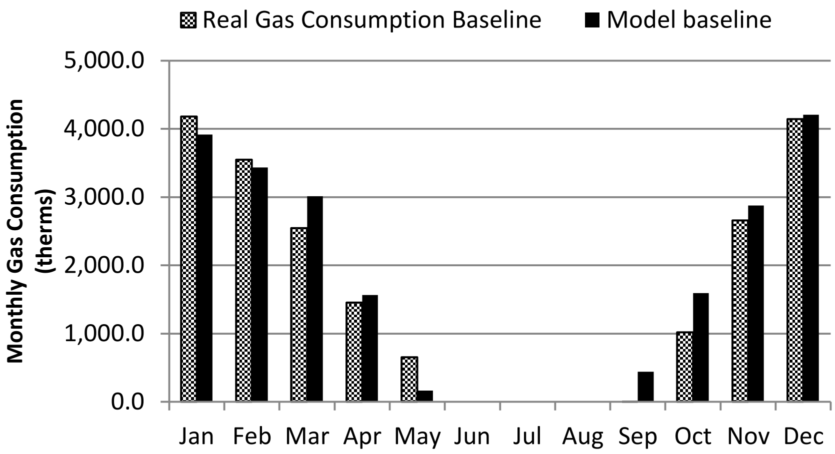


Figure 4-3: Simulated gas baseline vs. real gas consumption baseline

Though much effort is spent adjusting the baseline model, there is still a certain extent of error between the model and to real case. The reasons can be: (1) the existing building has internal problems such as fouling coil and stuck heating valves. Such detailed equipment's characteristics are not allowed for users to edit in TRACE 700. So their impact on the building energy performance is difficult to quantify or simulate. (2) The standard weather profile used by TRACE 700 may not consist with the baseline year. A little difference with weather condition results in deviance from the baseline to some extent.

4.2.3.2 Simulation of Commissioning

In order to simulate the energy performance improvement only due to commissioning, baseline model configurations are changed according to the commissioning measures developed in section 4.2.1. The consequent energy consumption reduction is assumed to be the benefit of commissioning. Simulated results are shown in figure 4-4 and figure 4-5.

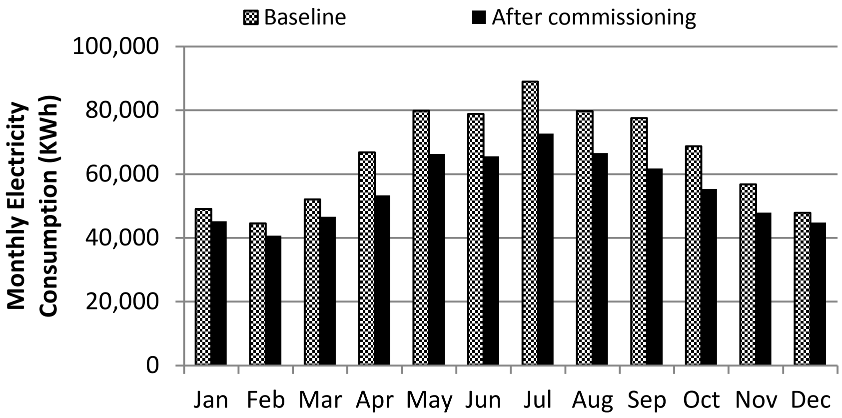


Figure 4-4: Electricity consumption before and after commissioning

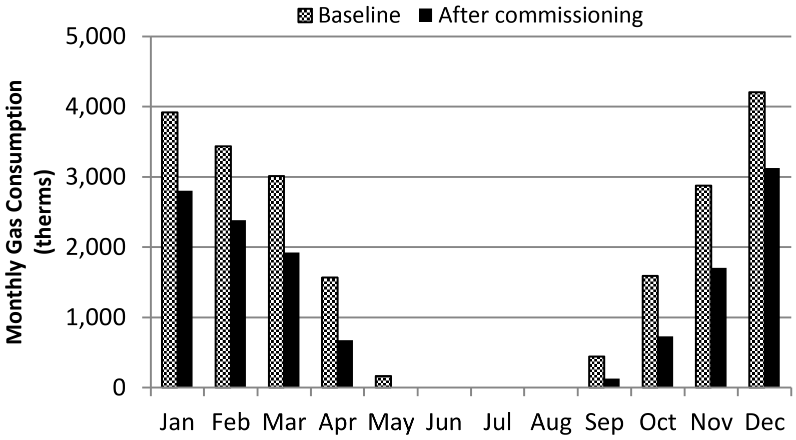


Figure 4-5: Gas consumption before and after commissioning

Simulation results show that after conventional commissioning process, annual electricity consumption is saved by 123,534 KWh (15.6%). Annual gas consumption is saved by 7,740 therms (36.5%).

4.2.3.3 Simulation of Retrofits

Retrofit measures implemented on the studied building include installation of VFD and pneumatic to DDC upgrade of control system and mechanical equipment. The author does not directly simulate the DDC upgrade. This is because on the one hand the benefits of pneumatic to DDC conversion vary greatly depending on how the existing pneumatic systems are maintained and calibrated; on the other hand the TRACE 700 does not have built-in pneumatic/DDC options. As a result, software simulation is only for installation of VFD. Simulation is run after changing the fan configuration from “fan with inlet guide vane” to “fan with VFD” in TRACE 700. Baseline is the energy consumption after commissioning process. Electricity consumption after the installation of VFD is shown in figure 4-6.

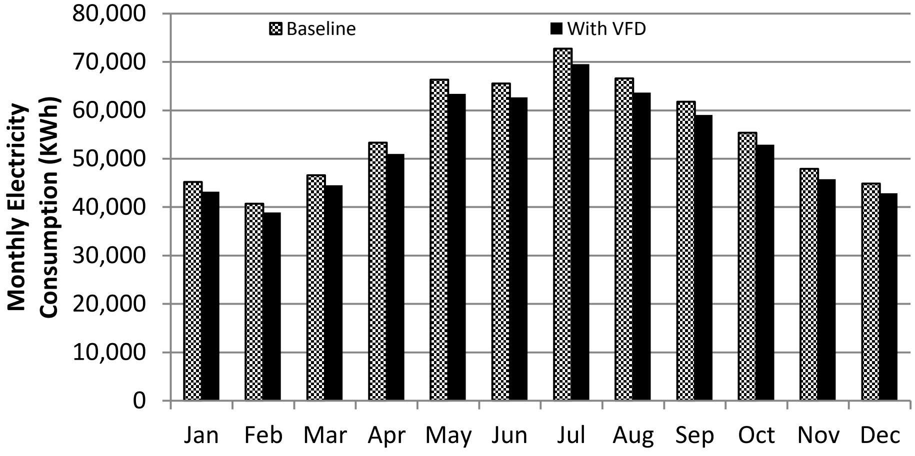


Figure 4-6: Electricity consumption before and after installation of VFD

Annual electricity consumption is reduced by 29,343 KWh (4.4%) after installation of VFD. As for gas consumption, the simulation results show no saving. This can be explained that the original hot deck fan has inlet guide vane installed already, which is able to modulate the airflow across the heating coil. So the heating coil load does not change even the VFD is added.

Regarding energy savings due to pneumatic to DDC conversion, Brambley (2005) did a comprehensive market assessment. Gauging the range of energy savings from more than twelve literatures, he arrives at the conclusion that installation of EMCS (refers to complete DDC upgrade) typically appear to achieve energy savings between 5% and 15%. The savings can be bigger for older or poorly maintained buildings. Considering the existing building condition, 10% is a reasonable value for savings estimation.

Adding another 10% of savings to the simulation results of VFD installation, electricity and gas consumption after retrofits is shown in figure 4-7 and figure 4-8. Eventually, annual energy savings from retrofits is 93,096 KWh (14.0%) for electricity and 1,307 therms for gas (10%).

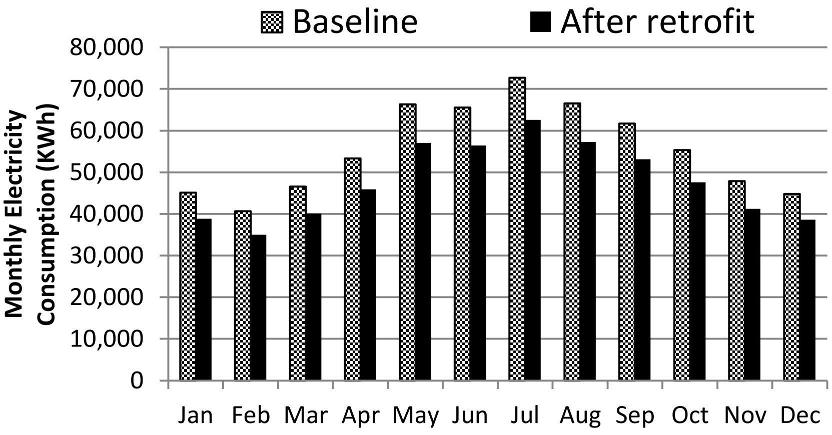


Figure 4-7: Electricity consumption before and after retrofit

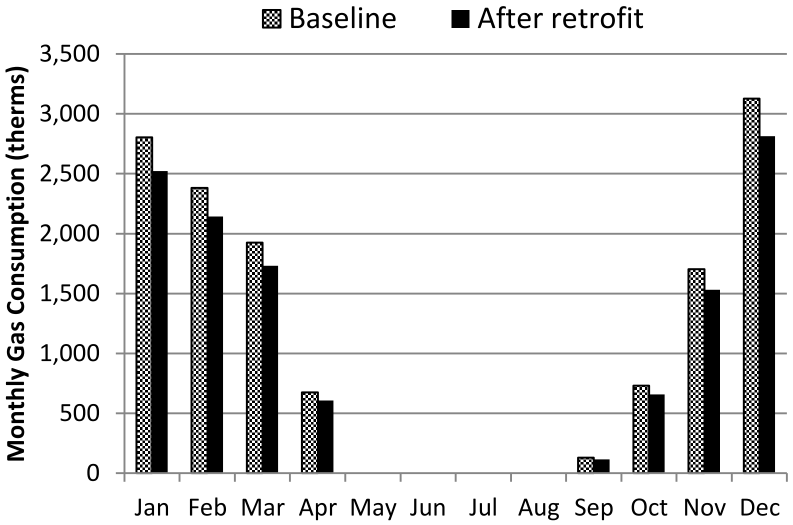
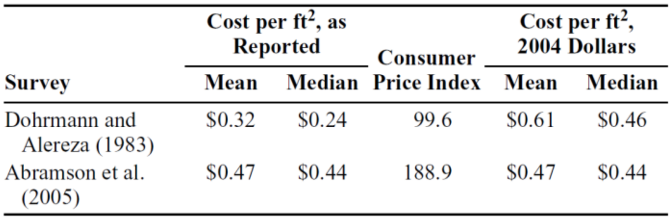


Figure 4-8: Gas consumption before and after installation of VFD

Besides reduced energy consumption, the pneumatic to DDC upgrade has another benefit as reducing the system maintenance costs. In ASHRAE research project TRP-1237, Abramson (2005) collected HVAC maintenance costs from 100 facilities. His results are compared with estimates reported by Dohrmann and Alereza (1983) in table 4-5.

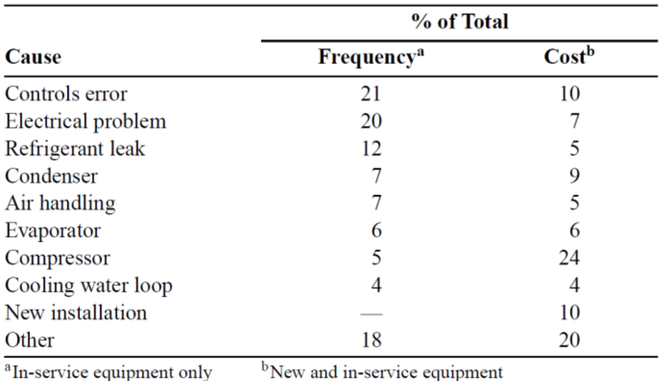
Table 4-5: Comparison of maintenance costs between studies (2007 ASHRAE Handbook-HVAC Applications, Chapter 36)



Survey	Cost per ft^2, as Reported		Consumer Price Index	Cost per ft^2, 2004 Dollars	
	Mean	Median		Mean	Median
Dohrmann and Alereza (1983)	\$0.32	\$0.24	99.6	\$0.61	\$0.46
Abramson et al. (2005)	\$0.47	\$0.44	188.9	\$0.47	\$0.44

According to the fault data for air conditioners collected by Breuker and Braun (1998) and Breuker eta al. (2002), control errors account for 10% of the total repair costs for HVAC systems (table 4-6).

Table 4-6: Normalized frequency of occurrence and repair costs for air conditioners (2007 ASHRAE Handbook-HVAC Applications, Chapter 38)



Cause	% of Total	
	Frequency^a	Cost^b
Controls error	21	10
Electrical problem	20	7
Refrigerant leak	12	5
Condenser	7	9
Air handling	7	5
Evaporator	6	6
Compressor	5	24
Cooling water loop	4	4
New installation	—	10
Other	18	20

^{a}In-service equipment only ^{b}New and in-service equipment

The pneumatic control system maintenance costs for the studied building are thus estimated as:

$$Maintenance\ cost = 0.47\$/ft^2 \times 32800ft^2 \times 10\% = 1541.6\$$$

During the first year after DDC control was installed, the only maintenance of DDC is for a room thermostat drift correction, which takes 150 \$. Thus, maintenance cost savings from pneumatic to DDC upgrade is 1391\$/year.

4.2.3.4 Combination of Commissioning and Retrofits

Combined savings from commissioning and retrofits are calculated in this section. By such calculation, the author intends to analyze the difference between implementation of commissioning and retrofits separately and together.

Assuming the commissioning and retrofits are implemented in one process, the baseline is still the building energy consumption before commissioning. Energy saving is simply the sum of that from commissioning and retrofits in above simulations. The results are shown in figure 4-9 and figure 4-10. Annual electricity consumption is reduced by 216,630 KWh (27.4%) and gas is reduced by 9,087 therms (42.8%).

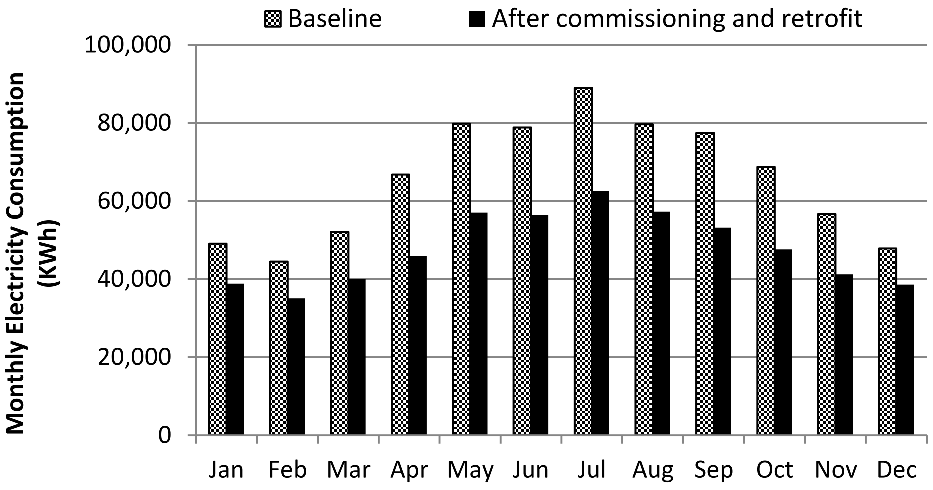


Figure 4-9: Electricity consumption before and after combining commissioning and retrofit

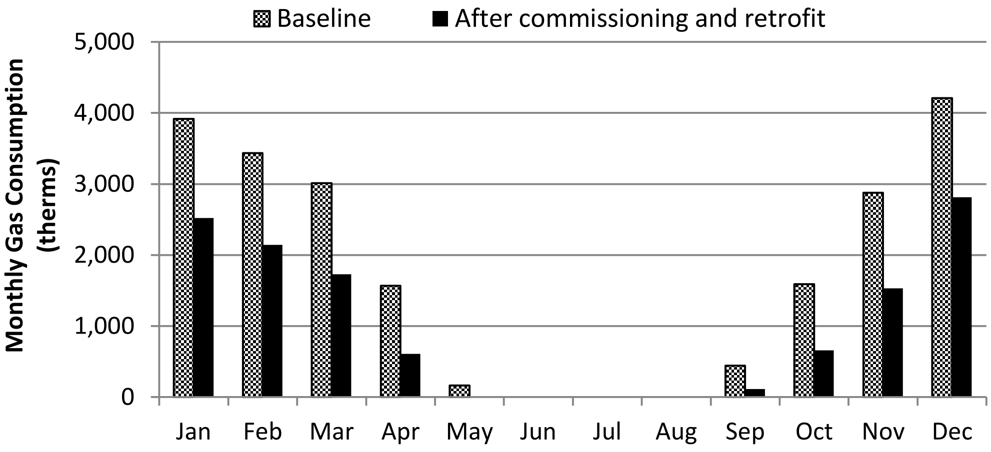


Figure 4-10: Gas consumption before and after combining commissioning and retrofit

Annual maintenance costs is reduced by 1391$ in this process, as calculated in last section.

4.3 Integrated process

As detailed integrated process and procedures have been discussed in chapter 3, this section only emphasizes the findings or specific measures in all three phases.

4.3.1 Phase Ⅰ - Preliminary Assessment

In the preliminary assessment phase, major findings are listed as follows.

Control system

- Old pneumatic control has high risk of control failure, and may increase maintenance and operation difficulties.
- Pneumatic control does not allow advanced control algorithm and prevents the system from running at most energy efficiency.

AHU

- The building manager mentions negative building pressure in winter time, which causes the cold air sucked in from the main entrance. The measured building pressure in the main entrance is at -0.06 in. water. This may also cause humidity issue in summer time.
- The return fan of the AHU is using inlet guide vane, which results in higher energy consumption at partial load compared with using VFD.
- Since the return fan needs to overcome the system resistance in hot deck, the return fan head is as high as 4.25 in. water.
- The economizer doesn't work well. The operator mentioned that when outside air temperature is higher than 47^{o} F, the outside air damper is fully closed. During the walk through there is no outside air intake. This will cause the indoor air quality problem as well as the negative building pressure.
- There is a bypass duct across the cooling coil. The bypass air mixes together with the air going through the cooling coil. However, this will cause humidity issue in summer time.

Chiller system

- The building operator mentioned that chiller is enabled when outside air temperature is higher than 47°F.
- During the walk through the chilled water supply and return temperature difference is only 3°F, while the chilled water return temperature is as low as 47°F. The low return water temperature will decrease the chiller efficiency.

Boiler system

- There is a bypass valve across boiler hot water supply and return pipe. Under partial load condition the high hot water return temperature will decrease boiler efficiency.

Based on the findings in phase Ⅰ, the studied building has potential solutions for several problems and energy efficiency improvement.

- Solve thermal comfort issues related to cold air infiltration in winter time and lack of fresh air intake in summer time.
- Solve the humidity issue due to negative building pressure as well as the blending of cold deck air.
- Improve chilled water system and heating system performance and efficiency.
- Potentially reduce entire facility energy consumption by 29% to 33%. The potential annual savings is in the range of **$16,000 to $18,000.**

4.3.2 Phase Ⅱ - Energy Study and Planning

4.3.2.1 AHU

The schematic diagram of AHU is identified and shown in figure 4-11.

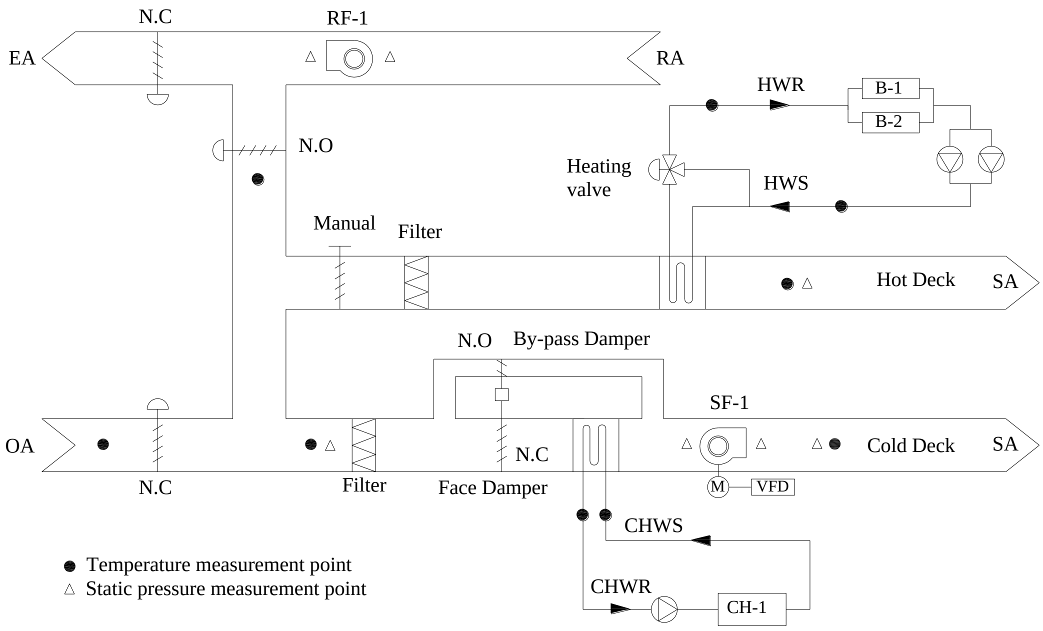


Figure 4-11: Schematic diagram of AHU-1

a) *Existing control sequences and drawbacks*

Outside air damper control: The outside air damper is modulated to maintain the mixed air temperature at 65 ºF. 65 ºF is absolutely too high to use free cooling as much as possible.

Relief air damper control: The relief air damper is modulated to maintain the building pressure set point at +0.05 in. water. Inaccurate pressure reading prevents this method from working well.

Chilled water coil face and by-pass dampers control: The chilled water coil face and by-pass dampers are modulated to maintain the south and west space temperature. This may result in mixed air bypassing the coil without dehumidification.

Fixed static pressure set point: Static pressure may be too high or too low when the building loads change.

b) *Major Observation and important system information*

- The hot deck damper is open all year around.
- There is negative pressure issue in the building. The static pressure in the entrance door is about -0.13 in. water. Through interviewing the operator, there is cold issue in the first floor which may be caused by building negative pressure.

c) *Measurement and analysis*

On-site one-time measurement shows that the cooling energy consumption is 256 MBH and the heating energy consumption is 193 MBH at some point. Obviously, unduly simultaneous heating and cooling waste exists caused by excessive airflow. Actually, much less cold airflow is needed to maintain the room temperature.

Trended data shows the outside air damper is closed when the outside air temperature is higher than 60 ºF, which means mechanical cooling energy is consumed unnecessarily. Also, no fresh air intake may lead to indoor air quality issue.

The cold deck temperature is about 60 ºF when the outside air temperature is higher than 70 ºF, which may cause humidity issue.

d) *Commissioning measures*

- Disable the bypass for cooling coil
- Optimize the economizer control

e) Retrofit plan

Mechanical retrofit

- Fully open the inlet guide vane and install a 20HP VFD on the return fan
- Add/replace sensors for supply air, return air, mixing air, differential pressure for supply and return fan, static pressure for hot and cold deck

Control retrofit

- Install TRANE MP581 controller and extension board for AHU control
- Add/connect points to connect the mechanical retrofitted components
- Replace the existing pneumatic actuators with five DDC actuators for the outside air damper, return air damper, relief air damper, hot deck damper and three-way heating coil valve.

f) Control optimization plan

- Implement the CC® supply fan speed control
- Implement the CC® return fan speed control algorithm for building pressure control
- Disable hot deck in when it reaches high cooling load
- Develop load based static pressure reset algorithm for the hot deck and cold deck

4.3.2.2 Terminal Boxes

The schematic diagram of terminal box unit is identified and shown in figure 4-12.

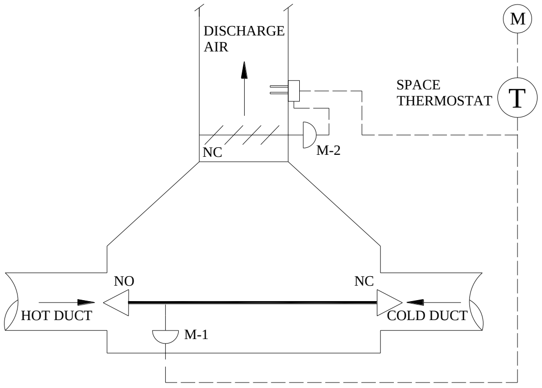


Figure 4-12: Schematic diagram of the terminal box

a) Existing control sequences and drawbacks

High load: Only cooling or heating air is served. Discharge damper is modulated to maintain room temperature.

Low load: Maintain discharge damper position at minimum position. Modulate interlinked mixing damper to maintain room temperature.

The existing control sequence works well by eliminating much simultaneous heating and cooling. No optimization options are identified.

b) Measurement and major observation

One time measurement is conducted on two selective terminal boxes. The minimum air flow is 78% and 40% respectively. This will result in waste of heating and cooling energy as well as fan power.

The trending data of two room temperatures shows they both change along with outside air temperature, which indicates neither of the boxes functions properly.

c) Commissioning plan

- Minimum airflow set point calibration and optimization
- Sensor calibration
- Damper functional test

d) Retrofit plan

- Replace pneumatic signal room sensors with new Trane DDC zone sensors.
- Replace pneumatic damper actuators with DDC ones.
- Install TRANE MP580/581 controllers for terminal box control.

4.3.2.3 Chiller

The schematic diagram of chiller system is identified and shown in figure 4-13.

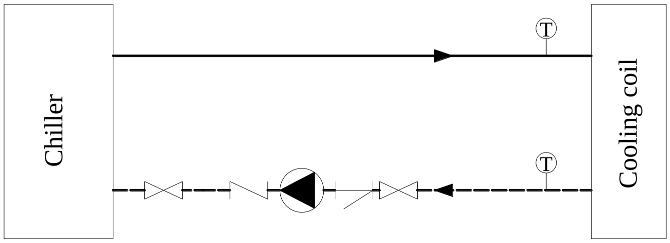


Figure 4-13: Schematic diagram of chilled water System

a) Existing Control Sequence and drawbacks

Chiller schedule: The chiller is enabled when the outside air temperature is higher than 56 °F and disabled when the outside air temperature is lower than 53°F. It works well for the studied building to take advantage of free cooling.

Chilled water supply temperature reset: It is reset by the built-in controller with an interface panel, either manually or automatically based on outside air temperature. Both methods are at local level and lose control of cold deck supply temperature.

b) Measurement and major observation

- The chilled water supply temperature varies within the range of 46-52 ºF. High supply water temperature may cause humidity issue.
- The chilled water supply temperature is hunting at some points.

c) Retrofit plan

- Connect chiller to the BCU controller for DDC control.

d) Control optimization plan

Reset the chilled water supply temperature to maintain the supply air temperature of the cold deck

4.3.2.4 Boiler system

The schematic diagram of boiler system is identified and shown in figure 4-14.

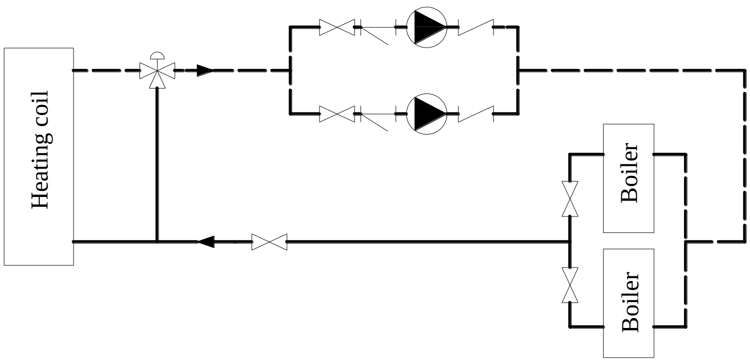


Figure 4-14: **Schematic diagram of boiler plant**

a) Existing control sequences and drawbacks

- *Boiler schedule:* Boiler#1 is enabled when the outside air temperature is below 47°F and disabled above 57°F. Boiler#2 is enabled when outside air temperature is below 20°F and disabled above 30°F. 10 °F dead band is big. With smaller dead band control can be more accurate and energy savings can be saved.
- *Hot water supply temperature set point:* Fixed set point at 110 °F is used. This method results in gas waster in partial load.

b) Measurement and major Observation

- The boiler is running when the days are warm, which causes gas waste.
- The real operation of the boiler is inconsistent with schedule programmed.
- The temperature difference between supply and return hot water is very small. This results in low boiler efficiency.

c) Retrofit plan

- Replace the pneumatic actuator on the hot water valve with DDC actuator.
- Connect the boiler with TRANE 580 controller for start/stop control.

d) Commissioning plan

- Optimize the operating schedule of the boilers
- Put reset function for hot water supply temperature

4.3.3 Phase Ⅲ- Implementation of Integration Measures

The implementation phase begins in the fall of 2009 and is mostly completed by the winter of 2010. Some new problems found in this phase cost more work than expected.

4.3.3.1 AHU

Retrofit and follow up commission

Retrofit on both mechanical and control system of AHU was successfully implemented as scheduled. However, a few problems arose in the follow up commissioning. For example, a point is found missing when connecting chiller and the Building Control Unit (BCU). Consequently, the chilled water supply temperature loses control in the first few weeks in the summer of 2009.

New control sequences

Economizer Control: When the outdoor air temperature is below 65^0F (adjustable), enable the economizer control and modulate the mixed/outside air damper to maintain the mixed air temperature at ($T_{supply,stpt}$ - 3^0F); when the outdoor air temperature is over 65^0F, keep minimum outside air intake.

Return Fan Control: When the hot deck is enabled, modulate return fan speed to maintain the hot deck supply static pressure; when the hot deck is disabled, modulate return fan speed to maintain constant difference of intake air volume and relief air volume, so that the building has positive pressure.

Relief air damper control: When hot deck is enabled, the relief damper is modulated to maintain positive building pressure; when hot deck is disabled, the relief damper is left at minimum position.

Air flow rate algorithm:

$$\boldsymbol{Q} = \frac{\left(-a_1 \pm \sqrt{a_1^2 - 4a_2\left(a_0 - \frac{H}{\omega^2}\right)}\right)\omega}{2a_2} \qquad \textbf{Equation 1}$$

Where Q is the flowrate (CFM), H is the fan head (in. wr), ω is the fan speed ratio (%), a1, a2 and a3 are three physical parameters based on the fan curve measurement. Deduction to this equation can be found in the appendix A. This equation is used for air flowrate calculation for both supply fan and return fan.

Static pressure reset:

Static pressure for both cold deck and hot deck is reset based on the flow rate and fan speed. This reset method is developed by Liu (2002). Optimized static pressure set point can be obtained by equation 2:

$$\boldsymbol{P_s = P_{s,min} + \frac{Q}{Q_{design}}(P_{s,max} - P_{s,min})} \qquad \textbf{Equation 2}$$

Where $P_{s,max}$ *and* $P_{s,min}$ are the maximum and minimum static pressure respectively (in. wr), which can be obtained by on-site measurement. Q_{design} is the air flow rate in design condition (CFM).

Follow up commissioning

One of the commissioning findings is that the hot deck temperature is always higher than the set point. In the meanwhile, the low temperature difference between the hot water supply and return, as considered due to low heating load and bypass in phase Ⅱ, is not solved. By observing the hot water valve position data and the corresponding hot deck temperature, it is suspected the heating valve is not functioning at all. Eventually, the mechanical engineer investigates the valve and finds out the valve is stuck. After a new valve is installed in the middle of December, the hot deck temperature is under control and saves a large amount of gas usage compared to previous winter.

The fouling of cooling coil is another problem found in the commissioning process in phase Ⅲ. It is brought to the building technician's attention that in hot summer time the cold deck temperature is hardly maintained below 60℉. Also, the temperature difference between the chilled water supply and return is small. Obviously there is not enough heat transfer on the coil side. On-site measurement shows extremely high pressure drop across the coil, which is almost three times of the design value. According to the building technician, the coil has never been cleaned over the past few years. So it is believed that the fouling of the cooling coil results in degraded heat transfer coefficient. Another consequence is extra fan power to overcome the coil resistance. Cleaning work is thus recommended on the coil. Coil replacement may also be recommended if the performance cannot be improved just by cleaning.

4.3.3.2 Terminal Boxes

Retrofit and follow up commission

Retrofits on the terminal boxes include pneumatic-DDC conversion for room thermostats, terminal box controllers, mixing damper actuators and discharge damper actuators. After retrofits are complete, selective room thermostats are calibrated. Discharge and mixing dampers for all terminal boxes have performance checks. Five of them cannot function well and are repaired (Appendix B).

New control sequences

The existing control sequences work very well with terminal boxes, so there are no big modifications, except decreasing the minimum discharge damper position.

Heating mode:

(1) When room temperature is lower than the set point plus 1 ^{o}F deadband (adjustable), fix the mixed air damper at 0% position (Hot deck 100%, Cold Deck 0%) and modulate discharge damper to maintain the room temperature.

(2) When discharge air damper is at the minimum position (10%), modulate the mixed air damper to maintain the room temperature.

Cooling mode:

(1) When room temperature is higher than the set point plus 1 ^{o}F deadband (adjustable), fix the mixed air damper at 100% position (Hot deck 0%, Cold Deck 100%) and modulate discharge damper to maintain the room temperature.

(2) When discharge air damper is at the minimum position (10%), modulate the mixed air damper to maintain the room temperature.

Follow up commissioning

During the follow-up commissioning period, complaints from reception staffs at the first floor hospital are reported. The reception area, supposed to be served by thermostat #1.6, has constantly warm issues. After the commissioning engineers spend weeks investigating this issue, eventually two reasons are found attribute to this problem. The first reason is two diffusers up on the reception desk are served by thermostat #1.8, though it is far on the other side of the hospital. Since #1.8 is usually in heating mode, warm air comes out of these two diffusers heating up the reception area. The second reason is the design CFM for this area is not enough, especially for intensive workers and computers there. A further duct work renovation is then provided by the commissioning engineers as a solution. The renovation plan is attached in appendix C.

Fine tuning of the terminal boxes include adjustments on the proportional gain and integral gain to make the terminal boxes run smoothly and responding rapidly enough.

4.3.3.3 Chiller

Retrofit and follow up commissioning

Control retrofit includes new DDC control on the chiller and chilled water pump through the Tracer MP581 controller and BCU. Commissioning includes verification of chiller's start/stop command from the controller and being correctly monitored.

New control sequences

- Minor adjustments on the schedule. The chiller system is enabled when the outside air temperature is over 50°F.
- Cooling coil bypass is disabled
- The supply chilled water set point is reset to maintain the cold deck supply air temperature.

Follow up commissioning

In the follow-up commissioning process, short cycling of the chiller happens frequently when the cooling load is low (figure 4-15). This is due to the built-in setup of the chiller, in which the chiller goes to standby mode when the chilled water supply and return temperature difference is below 4 degree. VFD on the chilled water pump is recommended to solve this issue by reducing the chilled water flow rate in partial load condition. Unfortunately, this recommendation has not been accepted by the building owner.

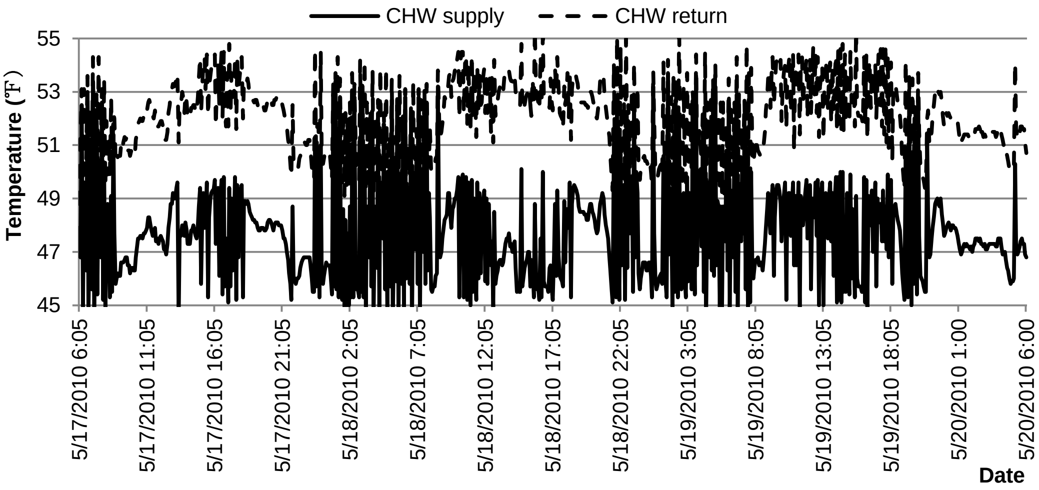


Figure 4-15: Short cycling of the chiller and small ∆T between chilled water supply and return

4.3.3.4 Boiler

Retrofit and follow up commissioning

After new DDC control with the Tracer MP581 controller is installed on the boiler, commissioning is taken to verify the boiler's start/stop command from the controller and being correctly monitored.

New control sequences

- The boiler is enabled when both conditions are met: 1. the outside air is below set point; 2. the return air is below 78℉.
- The hot water supply temperature is linearly reset based on the outside air temperature.

Follow up commissioning

After the new schedule is implemented, the building performs a lot better automatically. However, the boiler still has to be manually switched once in a while; especially when it is cold the boilers cannot be enabled. From the trending data, everything seems to work well and the boiler is running strictly on the programmed schedule, in which the outside air determines to enable or disable the boilers. After a few on-site investigations on this issue, finally the answer is narrowed down to the outside air sensor. Even just installed a few months ago, the new outside air sensor fails to provide the correct reading, with the error changes regularly with the time of a day (figure 4-16). This is because the sensor is closely attached to the west side wall of this building. When the wall generates or absorbs heat from the air, the heat impacts the reading of the sensor. Fortunately, there is another outside air sensor as part of the chiller's condensing unit on the roof. It shows decent accuracy after calibration and is used instead.

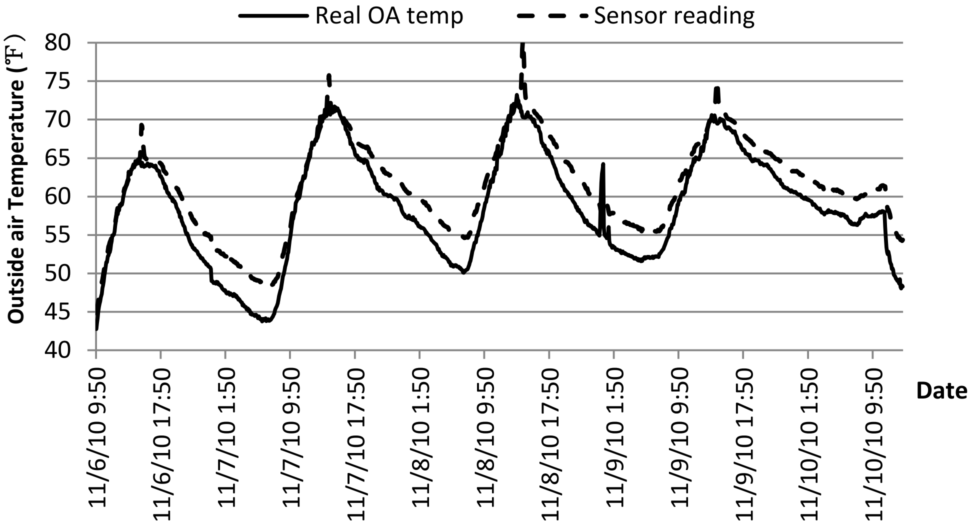


Figure 4-16: Outside air temperature sensor drift due to wrong placement

4.3.4 Results

The electricity consumption from June 2010 to May 2011 is collected as follows. The same time period in 2007 to 2008 is used for baseline allowing for similar weather condition.

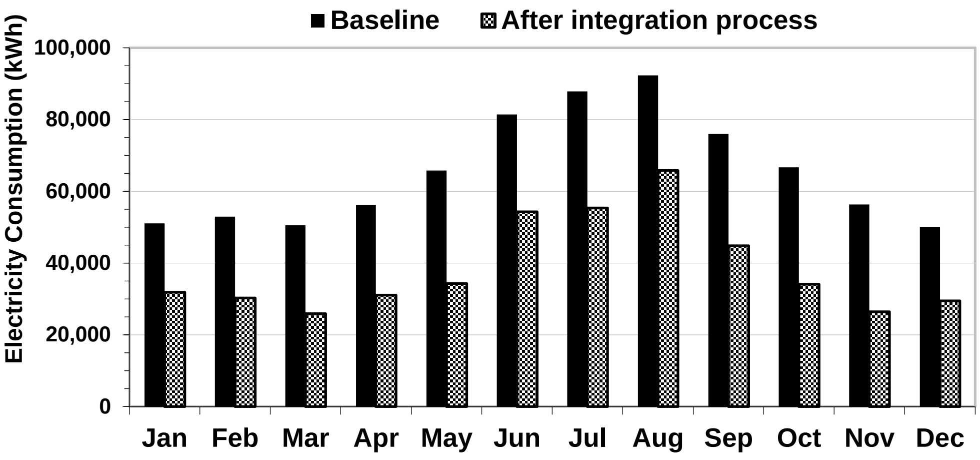


Figure 4-17: Measured electricity consumption before and after integrated process

The monthly electricity reduction ranges from 28% to 53%, with annual average savings of 41%. Total annual electricity cost is reduced by $27,393 (59.7%). It is found that the biggest monthly savings happen in transition season (November), and the smallest savings in summer (August) at the peak load.

Due to the malfunctioning heating valve and inappropriate boiler schedule control, extremely large amount of energy was wasted in the winter of 2009. The heating valve problem was not detected until the November of 2010 and new heating valve was installed in the middle of December. The gas usage reduction after valve replacement is obvious (figure 4-18).

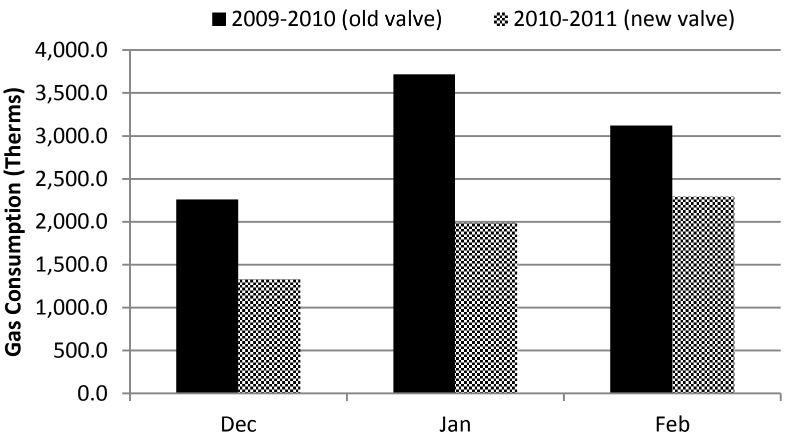


Figure 4-18: Measured gas consumption before and after valve replacement

Gas usage from October 2010 to February 2011 is collected and compared to the same period of 2007-2008 (figure 4-19). The monthly gas reduction ranges from 35% to 86%, with average savings of 61%. Total gas cost during five months period is reduced by $5,302 (34.1%).

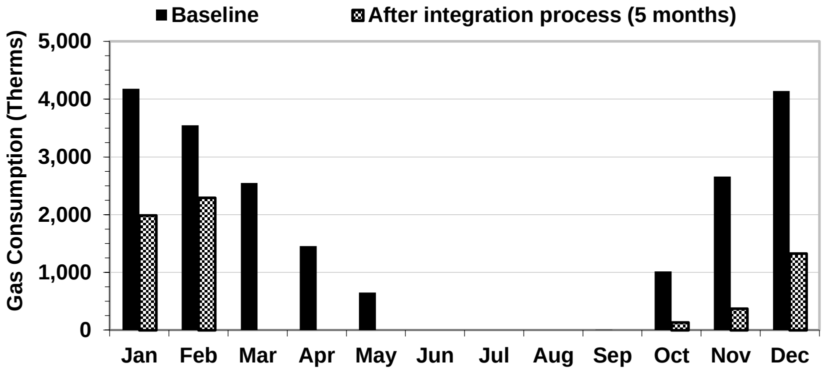


Figure 4-19: Measured gas consumption before and after integrated process

4.4 Costs and Benefits Comparison

Since the gas consumption data after integrated process is only available from October 2010 to February 2011, estimation has to be made for the rest of the year in order to calculate annual gas savings. Assuming the gas consumption is linearly related to the outside air temperature, the annual consumption trend is predicted using the five months data in hand (figure 4-20).

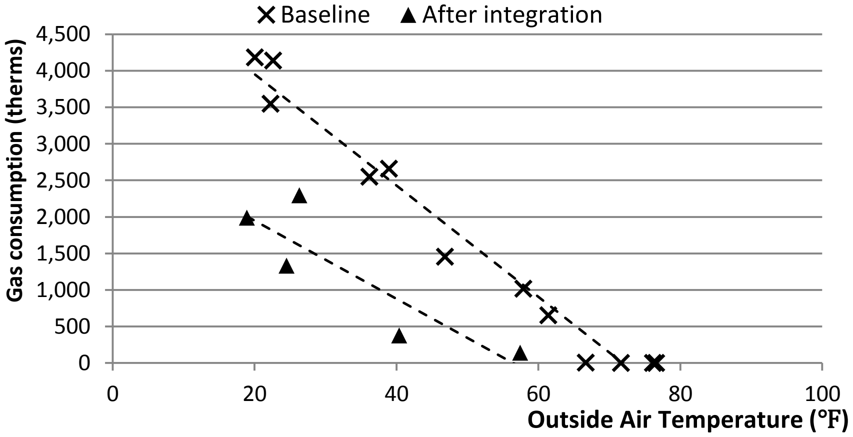


Figure 4-20: Gas consumption tendency with outside air temperature

Based on the monthly average temperature and the trend line in figure 4-20, annual gas consumption after integration is estimated and shown in figure 4-21. Annual gas consumption is reduced by 12,850 therms (69%).

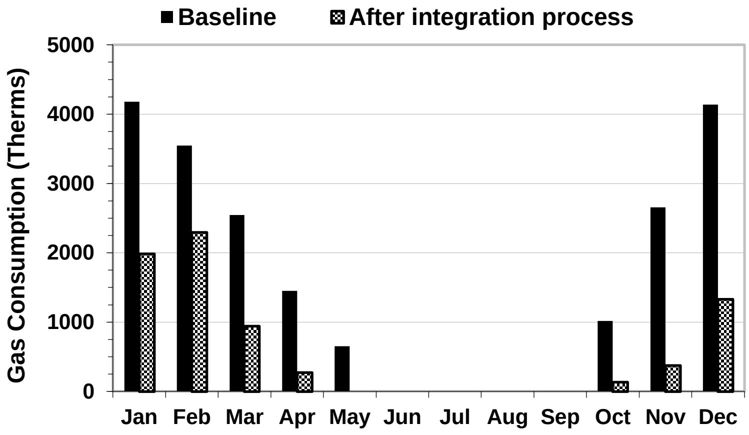


Figure 4-21: Gas consumption before and after integrated process

4.4.1 Costs calculation

The estimated costs for commissioning process are based on the work scope of commissioning on this building. Considering the building size and HVAC system, approximately 193 hours of commissioning job is needed. Assuming labor fee of 140 $/hour is charged, a total of 27,020$ is the commissioning cost. Besides, according to California Commissioning Guide for existing building, recommissioning process is recommended to implement every 5 years. Thus another three commissioning processes are taken into account during a 20 years span. The cost is assumed to keep pace with inflation rate, which is 3.2% in this case.

Retrofit cost is directed obtained from the project inventory. The cost of doing commissioning and retrofit together is then simply the sum of both processes. Integrated process cost is the real charge for the whole project.

The final costs of four processes are summarized in table 4-7.

4.4.2 Savings calculation

The savings are mainly calculated based on the electricity and natural gas reduction. First-year savings use 0.08$/KWh and 0.55$/Therm as current utility rate. Then energy escalation rate are calculated using Energy Escalation Rate Calculator (EERC), which is developed by NIST.

First-year maintenance savings of 1391$ are also included in both retrofits and integrated process as previously calculated in section 4.3. They are also expected to keep pace with inflation rate. First-year savings are shown in table 4-7.

4.4.3 Economic analysis

Table 4-7 shows the initial costs, first year savings and simple payback period of four types of processes.

Table 4-7: Costs, savings and payback of four processes

Process	Initial Costs ($)	1st year savings ($)	Simple payback period (years)
Commissioning	27,020	14,140	1.91
Retrofits	82,500	9,580	8.61
Cx+Retrofits	109,520	23,719	4.62
Integration	132,600	34,366	3.86

It is found that retrofits, if implemented separately from commissioning, have 8.61 years simple payback period, which is beyond the normal acceptance range. This is the reason why conventional retrofits cannot be implemented alone. However, if combined with commissioning, retrofits payback can be shortened to 4.62 years and easier to accept for most building owners.

As this simply payback ignores time value of money and the cash flows beyond payback period, more sophisticated economic analysis is needed to give a complete evaluation of different processes. In this study, four methods are employed for further economic analysis: Net Present Value (NPV), Savings-to-Investment Ratio (SIR), Internal Rate of Return (IRR) and Modified Internal Rate of Return (MIRR). Since separate retrofit process has too long simple payback period, it is not selected for further analysis.

The net present value (NPV) of a time series of cash flows, both incoming and outgoing, is defined as the sum of the present values of the individual cash flows. In the NPV method, the cash flows and discount rate are taken as the inputs and a price as output. Each cash inflow/outflow is discounted back to its present value and then summed as the NPV. Equation 3 is used for NPV calculation.

$$\boldsymbol{NPV = \sum_{i=0}^{n} \frac{CF_t}{(1+i)^t}}$$

Equation 3

Where t is the number of year of the cash flow; i is the discount rate; CF_t is the net cash flow (the amount of cash, inflow minus outflow) in year t.

In terms of decision making, NPV can be an indicator of how much value an investment or project adds to the firm. Normally a positive NPV is the criteria as acceptance. When comparing two mutually exclusive alternatives in financial theory, the one yielding the higher NPV should be selected.

In SIR method, savings and investments are both discounted separately on an annual basis, and then the discounted total cumulative savings (summed PV of savings) is divided by the discounted total cumulative investments (summed PV of investment).If the ratio is less than 1, the project does not pay for itself within the analysis period. The higher the SIR, the better the alternative. However, SIR method shows limited usefulness (Fuller, et al. 1995), especially when applied to projects with different sizes. It is appropriate only for accept/reject decisions and in this case it is consistent with NPV analysis.

The IRR method calculates a discount rate that makes the net present value (NPV) of all cash flows (both positive and negative) from a particular investment equal to zero. Given the cash flow in the nth year, the net present value NPV and IRR (r) has the relation as described in equation 4:

$$\boldsymbol{NPV = \sum_{i=0}^{n} \frac{CF_n}{(1+r)^n} = 0}$$

Equation 4

In this study, IRR is calculated using Microsoft Excel built in IRR function.

One of the advantages of IRR is that it gives a single rate or return, which is more intuitive to understand and compare given an expected interest rate. However, it still has some problems. First of all, it is not used to rate mutually exclusive projects, but only to decide whether a single project is worth investing. For example, project "A" may has a higher NAP even though its IRR is lower, because it has a higher initial investment. Secondly, in the cases of positive case flows followed by negative ones and then by positive ones again (usually called non-normal project), the IRR gives multiple values. It is not clear a high or a low IRR is correct. Thirdly, IRR assumes reinvestment of interim cash flows have equal rate of return of IRR. This may result in overstatement of IRR.

Another version of IRR is the modified internal rate of return (MIRR). This method is intended to solve the last two problems with IRR as mentioned previously. MIRR can be calculated with equation 5.

$$\boldsymbol{MIRR = \sqrt[n]{\frac{FV(positive\ cash\ flows, reinvestment\ rate)}{-PV(negative\ cash\ flows, finance\ rate)}} - 1} \qquad \textbf{Equation 5}$$

Where n is the number of the year when the cash flows occur, PV is present value (at the beginning of the first year), FV is future value (at the end of the last year). Again, Microsoft Excel built in MIRR function is used to calculate the MIRR value.

Like the IRR, MIRR is still not valid to rank projects of different sizes, such as a larger project with a smaller MIRR may have a higher NPV.

Economic analysis in terms of NPV, SIR, IRR and MIRR is conducted for a 20-years span after the implementation of each process. Detailed calculation procedures with Microsoft Excel based on annual period is shown in appendix F. Table 4-8 lists the major final results.

Table 4-8: NPV, SIR, IRR and MIRR values of three processes

Process	SIR	NPV ($)	IRR	MIRR
Cx	2.25	$89,000	47.7%	16.3%
Retrofits	1.29	$23,952	13.5%	12.6%
Cx+Retrofit	2.42	$155,299	25.0%	16.2%
Integration	2.90	$251,390	29.5%	17.2%

Table 4-8 shows that all processes have positive NPV and SIR over 1, so all processes can be accepted at first step. The SIR ratio shows the same results as simply payback, in which retrofit is the least economical alternative. If combined with commissioning, retrofit has much higher SIR and is thus easier to accept by building owners. During a 20-years span, integrated process has NPV of 251,390$, which is 2.82 times of commissioning-only process and 1.62 times of combined commissioning and retrofits process. This is because integrated process has most annual savings from both reduced utility costs and maintenance costs. High MPV results in a high SIR as well.

However, in terms of IRR, commissioning-only process shows highest return rate of 48%. This is because of its relatively low initial investment. It should be noted that commissioning-only process has cash flows with changing signs and falls into non-normal project category as previously discussed. Thus IRR is not an appropriate index for evaluation. In terms of MIRR, three processes are similar compared to each other. It reduced the error of IRR to some extent, but still is not an optimal measure for evaluation, because the three processes have different sizes.

Above all, NPV is the most effective financial tool for investment decision in this research. Integrated process proves to be the preferred alternative with the highest NPV.

4.4.4 Carbon footprint analysis

Climate change due to carbon dioxide becomes more and more important and will influence in the future. As a result, the reduction of carbon emission can be one of the benefits of building energy project as well. In this section, the carbon dioxide emission reduction is calculated as complementary analysis of different processes.

Electricity

CO^2 emissions from electricity generation are based on data from the EPA's eGRID emission factors. On average, electricity sources emit 1.722 lbs / kWh (Source: EPA eGRID)

Natural Gas

Emissions factors for natural gas are based on data from the Department of Energy's Energy Information Administration. Weighted national average emissions of natural gas is 11.7 lbs/therm (Source: US EIA, Voluntary Reporting of Greenhouse Gases Program)

CO^2 emission reductions from commissioning-only, combined commissioning and retrofits and integrated processes are thus calculated and the results are shown in figure 4-22.

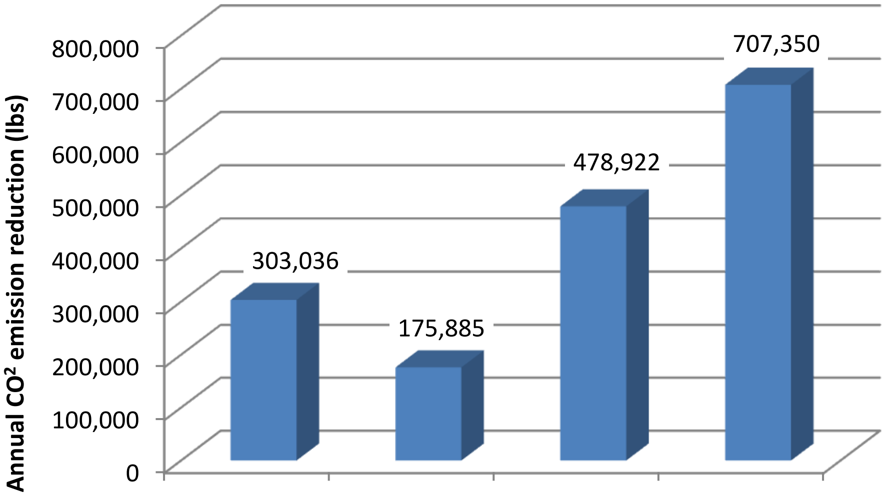


Figure 4-22: Reduced annual CO^2 emission of four processes

The figure above shows that integrated process reduces annual CO^2 emission by 707,350 lbs, which is 2.3 times of commissioning-only process, 4 times of separate retrofit process and 1.5 times of combined commissioning and retrofits.

4.4.5 Social impact analysis

One of the key parts of social impact is the job creation opportunities. Combined with commissioning, conventional retrofits can be accepted in a larger scale, because a shorter payback period is easier for building owners to accept. This results in tremendous employment opportunities in the manufacturing, design, installation, and maintenance market of building retrofits.

Integrated process has the highest initial investment of 132,600$, which is 4.9 times of commissioning-only process and 1.2 times of combine commissioning and retrofit process. From this perspective it obviously contributes most to the job market. Considering a high demand of building energy conservation in the U.S., it is very possible that integrated process is increasingly applied in building industry and thus more jobs must be involved in this domain in the future.

Chapter 5 Conclusions and Future Work

5.1 Conclusions

Commissioning and retrofits are two processes conventionally employed to improve the energy efficiency of buildings. Commissioning has been shown in numerous studies to be remarkably cost-effective. For existing buildings, the median normalized cost to deliver commissioning is \$0.30/ft^2, which leads to 16% median whole-building energy savings with payback times of 1.1 years. Retrofits have relatively higher initial investment and mostly implemented on chillers, boilers, VFDs, lighting and control system upgrade. The costs and savings vary depending on the type of retrofit.

Integrated process incorporates commissioning, retrofits and control optimization. Though a number of projects show that it can achieve significant amount of energy, there is still lack of comparison to conventional process.

To compare the conventional process with integrated process, a case demonstration is conducted on an existing building. In this demonstration, conventional commissioning and retrofit savings are simulated, and compared with measured integrated process savings. Economic analysis is conducted over a 20-years span. The following conclusions are drawn:

1. Retrofit, if implemented separately without commissioning, has long payback period and not economical at all. Thus, it can only be implemented together with commissioning. In that way, retrofits simple payback can be shortened to 4.62 years.
2. Integrated process can achieve first-year savings of 132,600\$ with simple payback of 3.86 years.
3. NPV is an effective tool for economic analysis in this study. Integrated process achieves NPV of 251,390\$, which is 2.82 times of commissioning-only process and 1.62 times of

combined commissioning and retrofits process. Thus, integrated process is the preferred alternative in this study.

5.2 Future Work

This research is done on a small commercial building with dual duct AHU and terminal boxes. In order to show the advantages of integrated process in a broader range, study can be carried out on other types of buildings and HVAC systems.

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Appendix A-Air Flow Rate Algorithm Deduction

Deduction of air flow rate algorithm (equation 2).

Equation 2 is deduced based on the fan curve and the fan law. The procedure is listed below.

At full speed, the fan curve can be expressed by a second order polynomial equation:

$$H = a_0 + a_1 Q + a_2 Q^2 \tag{a-1}$$

At partial speed, the fan head and the airflow is correlated using equation a-2 according to the fan law.

$$H_\omega = \omega^2 (a_0 + \frac{a_1 Q}{\omega} + a_2 \left(\frac{Q}{\omega}\right)^2) \tag{a-2}$$

Based on equation a-1 and a-2, when both the fan head and the fan speed are given, the fan airflow is deduced as:

$$Q = \frac{(-a_1 \pm \sqrt{a_1^2 - 4a_2\left(a_0 - \frac{H}{\omega^2}\right)})\omega}{2a_2} \tag{a-3}$$

Appendix B-Terminal Box Mixing Damper Performance Check Report

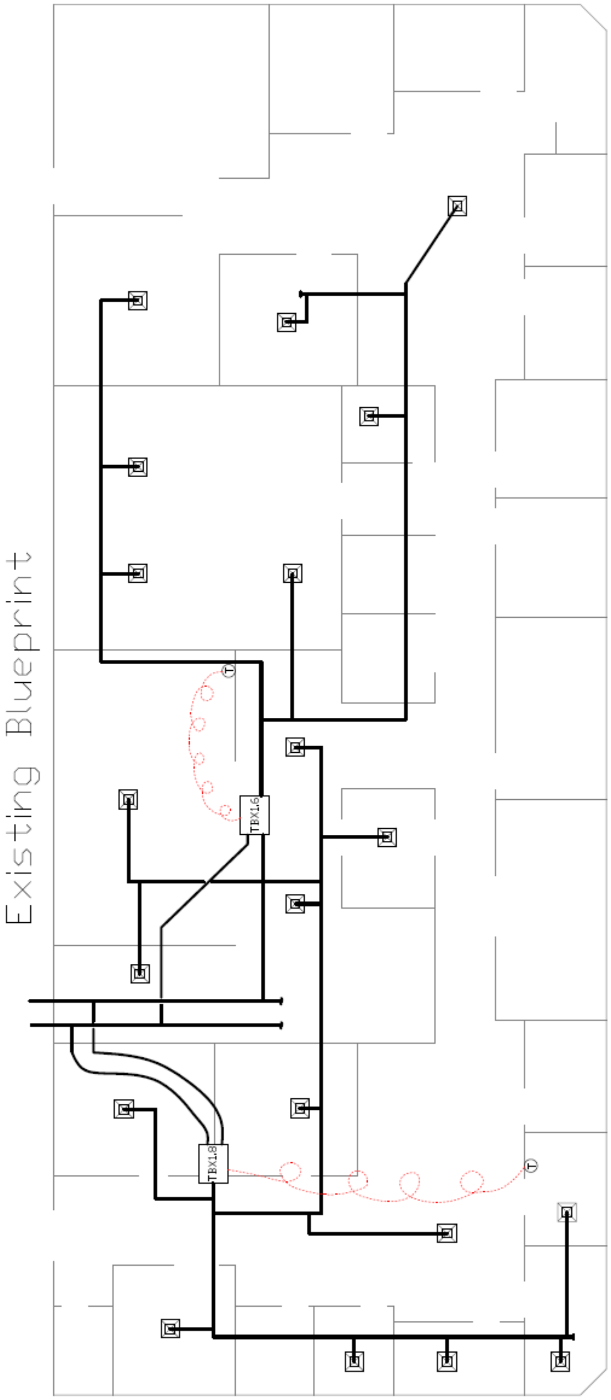
Terminal Box #	Mode	Mixing damper position	Discharge temp
MB1-1	Heating	0%	110
	Cooling	100%	60
MB1-2	Heating	0%	N/A
	Cooling	100%	N/A
MB1-3	Heating	0%	N/A
	Cooling	100%	N/A
MB1-4	Heating	0%	88
	Cooling	100%	58
MB1-5	Heating	0%	95.3
	Cooling	100%	61.4
MB1-6	Heating	0%	91.6
	Cooling	100%	61.5
MB1-7	Heating	0%	99
	Cooling	100%	57.3
MB1-8	Heating	0%	96.2
	Cooling	100%	59
MB1-9	Heating	0%	N/A
	Cooling	100%	N/A
MB2-1	Heating	0%	100.3
	Cooling	100%	57
MB2-2	Heating	0%	102.1
	Cooling	100%	57.3
MB-2-3	Heating	0%	113
	Cooling	100%	56.3
MB2-4*	Heating	0%	92
	Cooling	100%	61.6
MB2-5	Heating	0%	93.7
	Cooling	100%	57.5
MB2-6	Heating	0%	99.4
	Cooling	100%	60
MB2-7*	Heating	0%	N/A
	Cooling	100%	76

MB2-8	Heating	0%	98
	Cooling	100%	57.2
MB3-1	Heating	0%	95.3
	Cooling	100%	60.5
MB3-2	Heating	0%	115
	Cooling	100%	62.1
MB3-3	Heating	0%	100
	Cooling	100%	60.3
MB3-4*	Heating	0%	114
	Cooling	100%	80
MB3-5*	Heating	0%	96.5
	Cooling	100%	64.3
MB3-6	Heating	0%	112
	Cooling	100%	62.5
MB3-7*	Heating	0%	103
	Cooling	100%	69
MB3-8	Heating	0%	110
	Cooling	100%	57.5
MB3-9	Heating	0%	107
	Cooling	100%	58.5
MB3-10	Heating	0%	114
	Cooling	100%	62.3
MB3-11	Heating	0%	113
	Cooling	100%	58
MB3-12	Heating	0%	113
	Cooling	100%	65.5
MB3-13	Heating	0%	114
	Cooling	100%	60.8
MB3-14	Heating	0%	119
	Cooling	100%	58
MB3-15	Heating	0%	112
	Cooling	100%	61.3
MB3-16	Heating	0%	105
	Cooling	100%	61.9

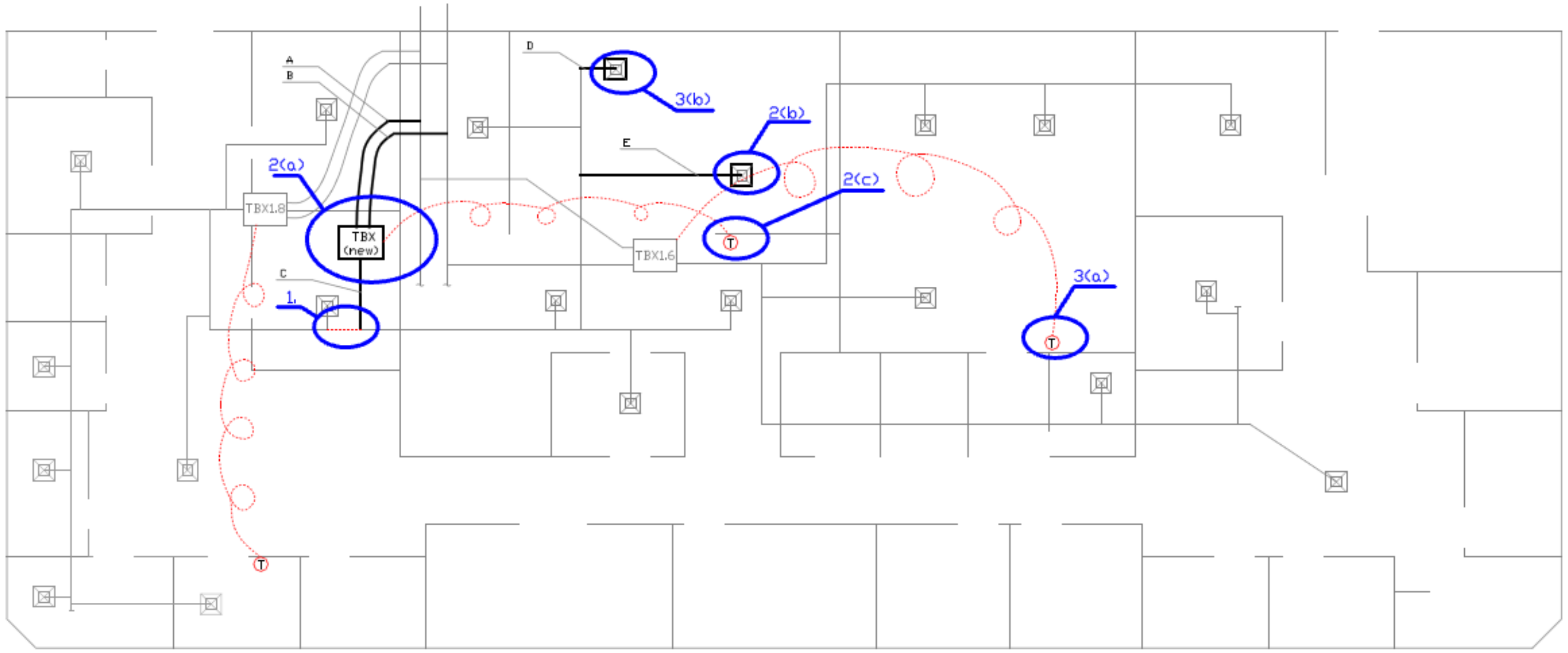
*Terminal boxes with mixing damper problems

Appendix C-Ductwork Renovation Blueprint

Ductwork renovation blueprint for the reception area at first floor hospital.



Modified Blueprint



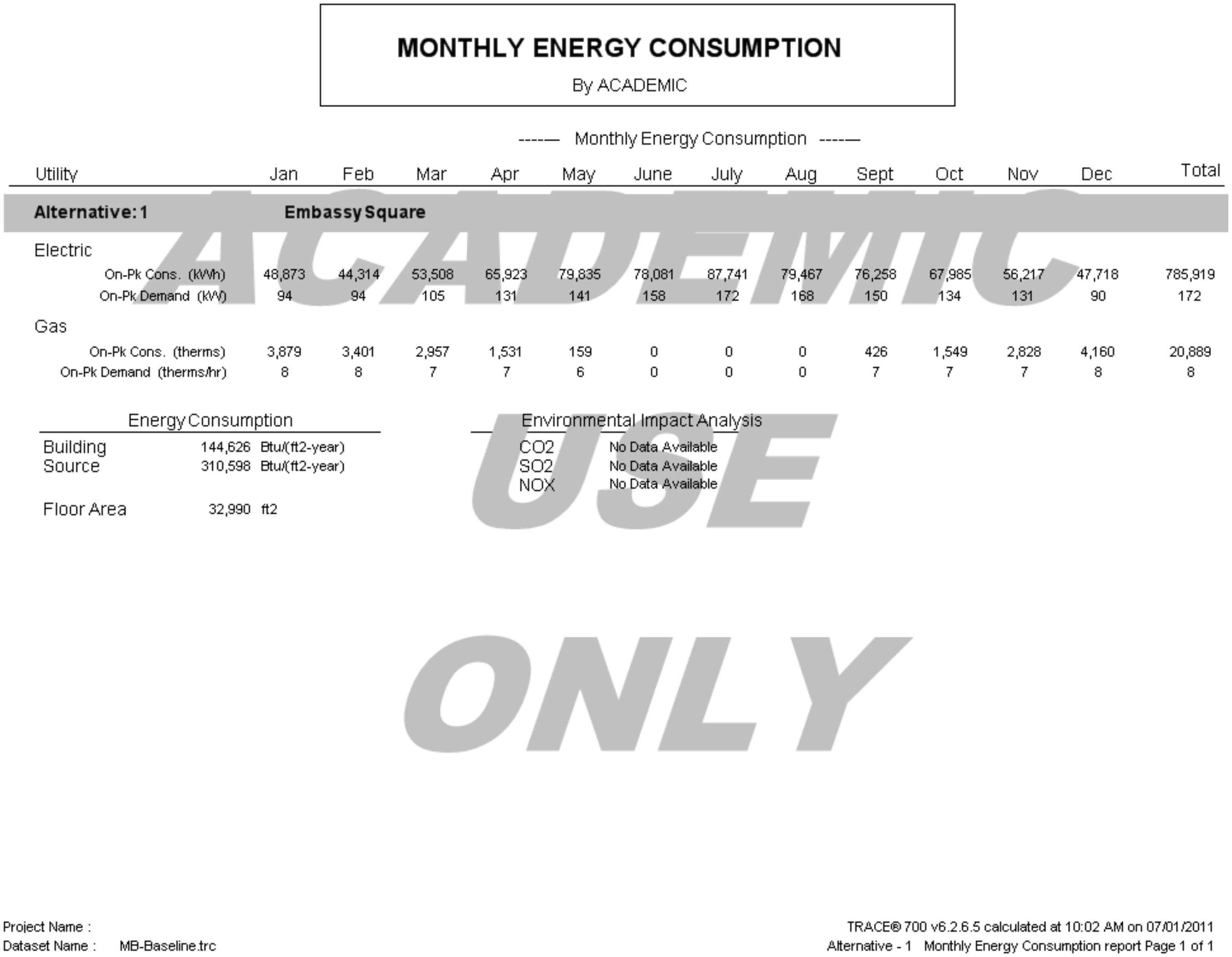
Job description:

1. Cut parts of existing TBX1.8 ducts, keep the remaining parts for new TBX use.
2. Install (a) a new TBX and hook it up to the remaining parts in 1, (b) a new thermostat and (c) one more diffuser.
3. Relocate (a) the thermostat of TBX1.6, (b) a diffuser

New Parts	Quantity	Size	Remark
TBX	1	750 CFM	
Diffuser	1	2ft × 2ft	
Thermostat	1		
Duct A	1	10''ø, Length: 16ft	Cold Deck
Duct B	1	8''ø, Length: 14ft	Hot Deck
Duct C	1	18''x10'', Length: 4ft	Rectangular, Galvanized
Duct D	1	6.5''ø, Length: 4ft	Round, flexible
Duct E	1	6.5''ø, Length: 8ft	Round, flexible

Appendix D-Baseline Model Simulation Report

Baseline model output



MONTHLY ENERGY CONSUMPTION

By ACADEMIC

------ Monthly Energy Consumption ------

Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Alternative: 1	**Embassy Square**												
Electric													
On-Pk Cons. (kWh)	48,873	44,314	53,508	65,923	79,835	78,081	87,741	79,467	76,258	67,985	56,217	47,718	785,919
On-Pk Demand (kW)	94	94	105	131	141	158	172	168	150	134	131	90	172
Gas													
On-Pk Cons. (therms)	3,879	3,401	2,957	1,531	159	0	0	0	426	1,549	2,828	4,160	20,889
On-Pk Demand (therms/hr)	8	8	7	7	6	0	0	0	7	7	7	8	8

Energy Consumption

Building	144,626	Btu/(ft2-year)
Source	310,598	Btu/(ft2-year)
Floor Area	32,990	ft2

Environmental Impact Analysis

CO2	No Data Available
SO2	No Data Available
NOX	No Data Available

Project Name :
Dataset Name : MB-Baseline.trc

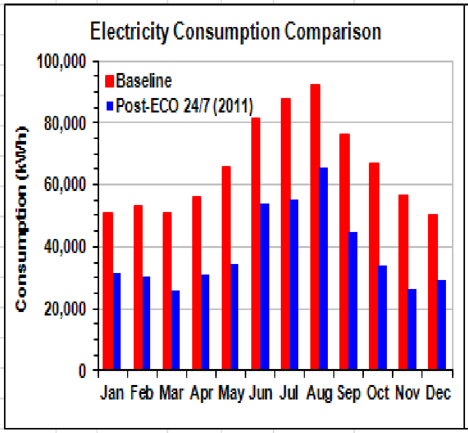
TRACE® 700 v6.2.6.5 calculated at 10:02 AM on 07/01/2011
Alternative - 1 Monthly Energy Consumption report Page 1 of 1

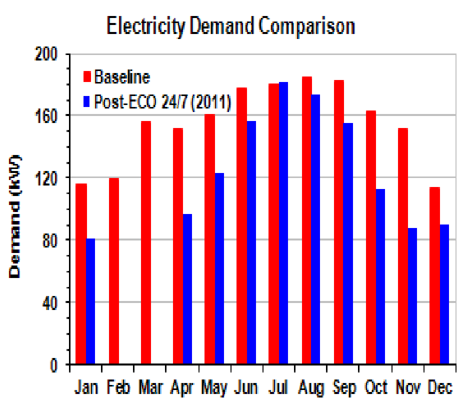
Appendix E-Building Energy Usage Datasheet

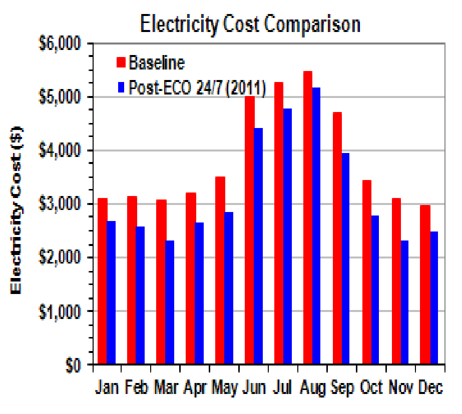
Electricity and gas bills and savings calculations

	Baseline					Post-Construction					Savings		
			Demand	Consumption	Cost			Demand	Consumption	Cost	Demand	Consumption	Cost
Month	Days	Year	kW	kWh	$	Days	Year	kW	kWh	$	kW	kWh	$
Jan	31	2008	115.8	51,040	$ 3,085.18	33	2011	80.8	31,840	$ 2,678.93	35.0	19,200	$ 1,615.44
Feb	29	2008	119.4	52,960	$ 3,132.03	29	2011		30,240	$ 2,586.84	N/A	22,720	$ 1,943.55
Mar	31	2008	155.8	50,560	$ 3,073.48	29	2011		25,920	$ 2,329.88	N/A	24,640	$ 2,214.82
Apr	29	2008	151.7	56,160	$ 3,210.09	30	2011	97.0	31,040	$ 2,634.42	54.7	25,120	$ 2,131.98
May	34	2008	160.0	65,760	$ 3,500.53	33	2011	123.8	34,240	$ 2,837.32	36.2	31,520	$ 2,611.93
Jun	29	2008	177.4	81,440	$ 4,973.84	28	2010	156.3	54,240	$ 4,420.19	21.1	27,200	$ 2,216.61
Jul	29	2008	180.5	87,840	$ 5,237.23	34	2010	181.3	55,360	$ 4,772.31	-0.8	32,480	$ 2,799.94
Aug	29	2008	184.6	92,320	$ 5,455.11	29	2010	173.8	65,760	$ 5,173.53	10.9	26,560	$ 2,089.55
Sep	29	2007	182.2	76,000	$ 4,680.95	29	2010	155.7	44,800	$ 3,933.14	26.6	31,200	$ 2,739.15
Oct	32	2007	163.4	66,720	$ 3,443.49	29	2010	113.0	34,080	$ 2,775.13	50.4	32,640	$ 2,657.87
Nov	31	2007	151.7	56,320	$ 3,107.35	34	2010	88.5	26,400	$ 2,316.34	63.2	29,920	$ 2,625.19
Dec	31	2007	113.1	50,080	$ 2,960.46	28	2010	90.1	29,440	$ 2,492.32	23.0	20,640	$ 1,747.33
Annual	364		184.6	787,200	$ 45,859.74	365		181.3	463,360	$ 38,950.35	3.4	323,840	$27,393.36
										Savings %	1.8%	41.1%	59.7%

*2010 Post-ECO 24/7 data







Appendix F-Economic calculation spread sheet

Cx		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Savings ($)	Energy		14140	14722	15329	15960	16617	17302	18014	18756	19529	20333	21170	22042	22950	23895	24879	25904	26971	28082	29238	30442
	Maintenance		-	-	-	-		-	-	-	-		-	-	-	-		-	-	-	-	-
	Total		14140	14722	15329	15960	16617	17302	18014	18756	19529	20333	21170	22042	22950	23895	24879	25904	26971	28082	29238	30442
Investment		-27020	0	0	0	0	-31629	0	0	0	0	-37024	0	0	0	0	-43339					
Cash flow ($)		-27020	14140	14722	15329	15960	-15012	17302	18014	18756	19529	-16691	21170	22042	22950	23895	-18460	25904	26971	28082	29238	30442
PV of savings		$160,309																				
PV of Investments		$71,308																				
Savings-to-investment ratio		2.25																				
NPV		$89,000																				
IRR		48%																				
MIRR		17%																				

Cx+retrofit		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Savings ($)	Energy		22328	23211	24129	25082	26074	27105	28176	29290	30448	31652	32903	34204	35556	36962	38423	39942	41521	43163	44869	46643
	Maintenance		1391	1436	1481	1529	1578	1628	1680	1734	1790	1847	1906	1967	2030	2095	2162	2231	2303	2376	2452	2531
	Total		23719	24646	25610	26611	27652	28733	29857	31024	32238	33499	34809	36171	37586	39057	40585	42173	43824	45539	47321	49174
Investment		-109520																				
Cash flow ($)		-109520	23719	24646	25610	26611	27652	28733	29857	31024	32238	33499	34809	36171	37586	39057	40585	42173	43824	45539	47321	49174
PV of Savings		$264,819																				
PV of Investments		$109,520																				
Savings-to-investment ratio		2.42																				
NPV		$155,299																				
IRR		25%																				
MIRR		16%																				

Integration		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Savings ($)	Energy		32975	34272	35626	37035	38499	40021	41603	43248	44958	46735	48583	50503	52500	54575	56733	58976	61307	63731	66250	68869
	Maintenance		1391	1436	1481	1529	1578	1628	1680	1734	1790	1847	1906	1967	2030	2095	2162	2231	2303	2376	2452	2531
	Total		34366	35707	37108	38564	40077	41649	43283	44982	46747	48582	50489	52470	54530	56670	58895	61207	63610	66107	68703	71400
Investment		-132600																				
Cash flow ($)		-132600	34366	35707	37108	38564	40077	41649	43283	44982	46747	48582	50489	52470	54530	56670	58895	61207	63610	66107	68703	71400
PV of Savings		$383,990																				
PV of Investments		132600																				
Savings-to-investment ratio		2.90																				
NPV		$251,390																				
IRR		30%																				
MIRR		17%																				

Retrofits		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Savings ($)	Energy		8188	8512	8848	9198	9562	9940	10333	10741	11166	11607	12066	12543	13039	13554	14090	14647	15226	15828	16454	17104
	Maintenance		1391	1436	1481	1529	1578	1628	1680	1734	1790	1847	1906	1967	2030	2095	2162	2231	2303	2376	2452	2531
	Total		9580	9947	10330	10727	11139	11568	12013	12475	12955	13454	13972	14510	15069	15649	16252	16878	17529	18204	18906	19635
Investment		-82500																				
Cash flow ($)		-82500	9580	9947	10330	10727	11139	11568	12013	12475	12955	13454	13972	14510	15069	15649	16252	16878	17529	18204	18906	19635
PV of Savings		$106,452																				
PV of Investments		$82,500																				
Savings-to-investment ratio		1.29																				
NPV		$23,952																				
IRR		13%																				
MIRR		13%																				