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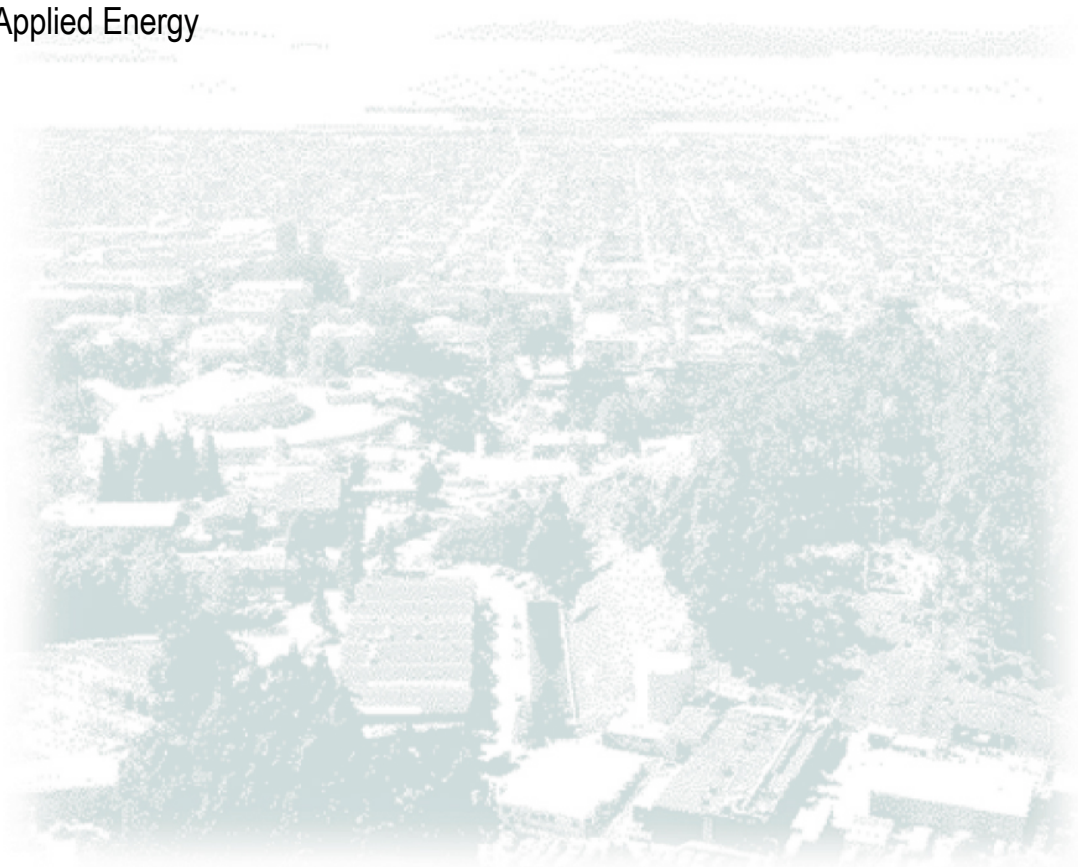
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Monitoring-based HVAC Commissioning of an Existing Office Building for Energy Efficiency

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Abstract

The performance of Heating, Ventilation and Air Conditioning (HVAC) systems may fail to satisfy design expectations due to improper equipment installation, equipment degradation, sensor failures, or incorrect control sequences. Commissioning identifies and implements cost-effective operational and maintenance measures in buildings to bring them up to the design intent or optimum operation. An existing office building is used as a case study to demonstrate the process of commissioning. Building energy benchmarking tools are applied to evaluate the energy performance for screening opportunities at the whole building level. A large natural gas saving potential was indicated by the building benchmarking results. Faulty operations in the HVAC systems, such as improper operations of air-side economizers, simultaneous heating and cooling, and ineffective optimal start, were identified through trend data analyses and functional testing. The energy saving potential for each commissioning measure is quantified with a calibrated building simulation model. An actual energy saving of 10% was realized after the implementations of cost-effective measures.

Keywords: Commissioning, Benchmarking, Fault Detection and Diagnostics, Functional Testing, EnergyPlus, Trend Data

1. Introduction

The performance of HVAC systems may fail to satisfy design expectations due to improper equipment installation, equipment degradation, sensor failures, or incorrect control sequences. In addition, most buildings have energy-saving opportunities based on changes to their HVAC and lighting equipment. Both an energy audit and commissioning are processes that help understand building energy use and identify potential energy saving opportunities. Energy audits identify energy-saving opportunities that range from cost-effective operational changes to capital-intensive retrofits of the building and its systems. Commissioning is the process of making buildings work properly, which includes identifying and implementing energy-saving opportunities on existing equipment and operations, but does not include major capital investments on equipment. Audits include estimates of energy and cost savings, implementation costs, and resulting payback periods, but do not include implementation of the recommendations. Audits often include using control-system trend data or portable instrumentation, but seldom perform detailed system tests. Commissioning normally includes extensive control-system trend data and functional testing to verify proper system operations.

Energy-related problems are widely reported in building commissioning [1-5] and energy audits [6-8] literature over the last two decades. They all come to the conclusion that most buildings do not work properly. Annex 40 [9] and Annex 47[10] research projects developed tools for commissioning HVAC systems and methods for evaluating cost-benefit and persistence of existing building commissioning. These international research projects provide the bases for international dissemination and adoption of commissioning techniques. A recent study on commissioning [11] found that most issues identified through commissioning occurred in air handling systems, heating water plants, and chilled water plants. In new construction projects, the origin of these issues is roughly evenly split among design, construction/installation, and operation and maintenance (O&M) controls. For existing building projects, more issues were related to O&M controls (42%), with the second most common being design (31%). Mills [12]

reported 16% whole-building energy savings in existing buildings and 13% in new construction on average can be achieved through building commissioning.

Both functional testing and passive testing can be applied in the process of existing building commissioning, such as retro-commissioning, re-commissioning, or on-going commissioning (or continuous commissioning®). Monitoring-based commissioning[13] is a measurement-based commissioning process incorporating energy information system and diagnostic tools, retro-commissioning, and ongoing commissioning. A cyclic process of monitoring-based building commissioning for existing buildings is illustrated in Figure 1. Collection of building information through architectural and mechanical drawings, equipment specifications, and Energy Monitoring and Control System (EMCS) control sequences is the first step of the process. Public benchmarking models are developed using various methods; they use indices of performance from a large number of reference buildings to build benchmarking data. Public benchmarking models can be used to assess if a building performs worse, similar to, or better than comparable buildings in the same region. Fault detection and diagnostics is the key step in the process of ongoing commissioning. Faulty operations in the system can be detected by trend-data analyses, functional testing, and/or fault detection and diagnostic tools. Trend data analysis [14, 15] is a top-down approach to verify system performance and detect faults in systems, subsystems and components. Functional testing [16] uses a bottom-up approach to test performance of components, subsystems, and systems for a range of various operating points and diagnose the causes of any particular faults. There are many important research efforts [17-24] contributing to automatic fault detection and diagnostics and development of robust fault detection and diagnosis tools to reduce the time and expense of commissioning. In the fourth step, a list of energy-saving measures are prioritized and implemented for the HVAC systems. Then energy savings can be analyzed based on actual energy use. Finally the process of monitoring-based commissioning repeats step 1 to restart the commissioning process towards a cycle of continuous improvement.

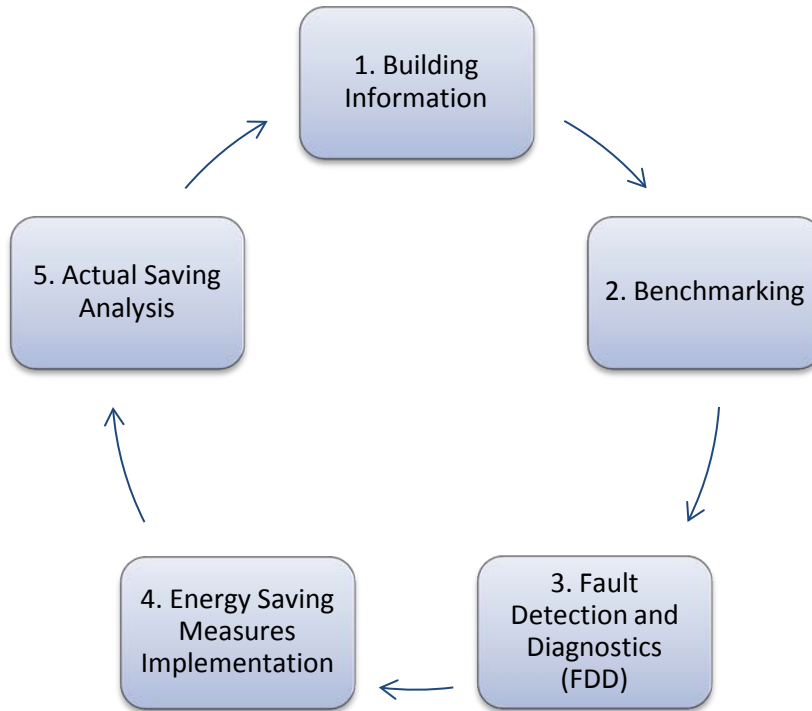


Figure 1. Monitoring-based commissioning flow chart

This study demonstrates the complete process of monitoring-based HVAC commissioning for an existing office building. Monitoring data and functional testing are employed to detect faulty operations, and a calibrated energy simulation model is used to prioritize the implementation plan of energy-saving measures. Lessons learned through the process and further research opportunities are reported.

2. Building description

An existing office building, Building 90 at the Lawrence Berkeley National Laboratory, constructed in 1959, was used as a case study for commissioning. The commissioning process started with understanding building systems. Both architectural and mechanical drawings, equipment specifications and EMCS control sequences of HVAC systems in the building are important information to collect for building commissioning. If it is an old building, it is very likely that some of the documentation is not available or otherwise not up-to-date. The following description is based on a review of existing documentation and site visits, including meetings with experts on this building.

There are four floors and one occupied basement in the building. The external walls and floor have minimal insulation, and the windows are single pane. The average occupancy number per day is roughly 350 people. The building operates from 7 am–6pm Monday through Friday. The lighting in office spaces is predominantly 4-foot fluorescent T8 lamps with electronic ballasts. The lighting control is based on infrared and ultrasonic motion sensors or manual switches. Miscellaneous electric plug loads scattered throughout the building are controlled by individual building occupants (e.g., computers’ monitors, task lighting) or shared by a group of occupants (e.g., printers, copiers).

Figure 2 shows the system diagram for the main air handling systems within the building. These systems serve the main three floors of the building. There are three main air handling systems, labeled as Blowers (BL) 1, 2, and 3, serving floors 1-3. These air handlers were originally designed as constant-volume systems to provide heating and ventilation with 100% outside air only, and have been retrofitted by installing return air ducts, variable frequency drives (VFDs) for supply and return fans, and direct expansion (DX) cooling coils. Each BL system has a 4-stage cooling coil which consists of four Direct Expansion (DX) sections, each connected to a stage of condensing units with evaporative condensers. Each BL system also has a heating coil, a supply fan, a reheat coil (RHC) for each zone it serves, a combined return fan, and a combined return and exhaust path. Three rooftop packaged heat pump units serve the 4th floor. Several packaged units and ductless split systems serve conference rooms together with central systems.

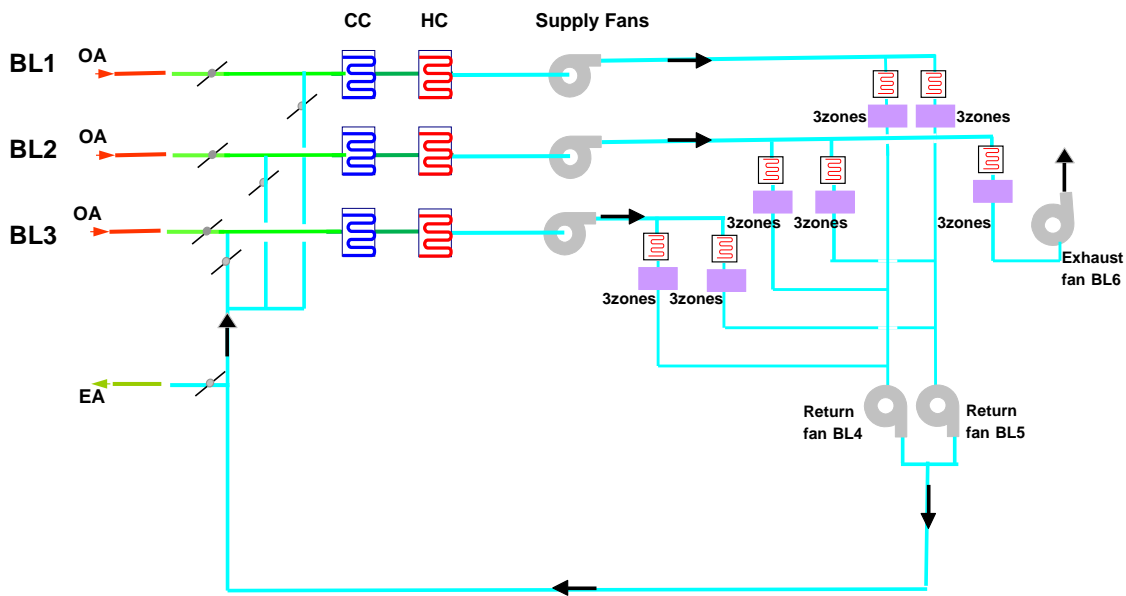


Figure 2. Main Air Handling System loops

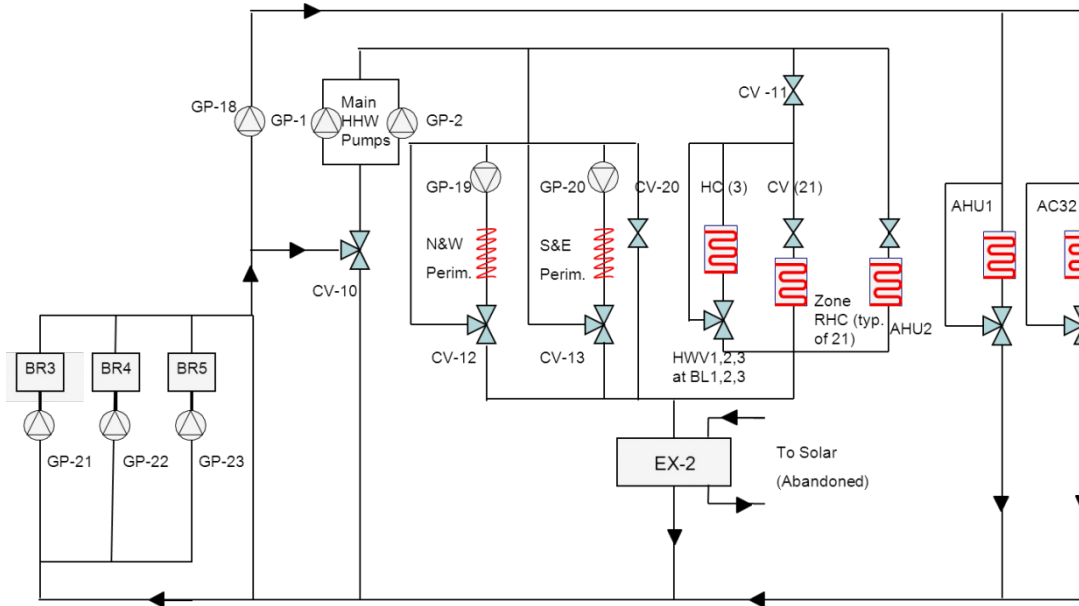


Figure 3. Heating Hot Water System

The system diagram for a heating hot water (HHW) system within the building is shown in Figure 3. The HHW system supplies heating hot water to preheat coils in air-handler units, reheat coils of thermal zones, and finned tube baseboard heating in perimeter zones. The primary HHW loop contains three pumps (GP-21, GP-21, and GP-23) and three boilers (BR3, BR4 and BR5); the secondary loop contains the main heating hot water pumps (GP-1, GP-2) and several control valves and smaller pumps (GP-18 for basement loads; GP-19 and GP-20 for perimeter heat; the latter two forming a partial tertiary configuration). A solar hot water system was added at one point, but it is now nonfunctional and has been abandoned in place.

3. Benchmarking for building energy use

Building energy benchmarking helps a building owner, operator, or commissioning provider determine how well a building is performing, compare a given building's energy consumption to that of other similar buildings, and set targets for improved performance. There are several widely adopted benchmarking tools, such as Portfolio Manager [25] and EnergyIQ [26]. Portfolio Manager, developed by the U.S Environmental Protection Agency's Energy Star, can rate

facilities’ energy performance on a scale of 1-100 relative to similar buildings nationwide. The rated building is compared against a peer group with similar characteristics, climates, and operations. In this benchmarking tool, Commercial Building Energy Consumption Survey (CBECS) performance data forms the basis of the comparative peer group. A rating score indicates that the building performs better than the score’s percentage of all similar buildings nationwide. EnergyIQ [27] is an “action-oriented” benchmarking tool developed by LBNL, which leverages both CBECS and California Commercial Energy Use Survey (CEUS) performance data to provide comparative rankings and decision-support information to help inform efficiency improvements.

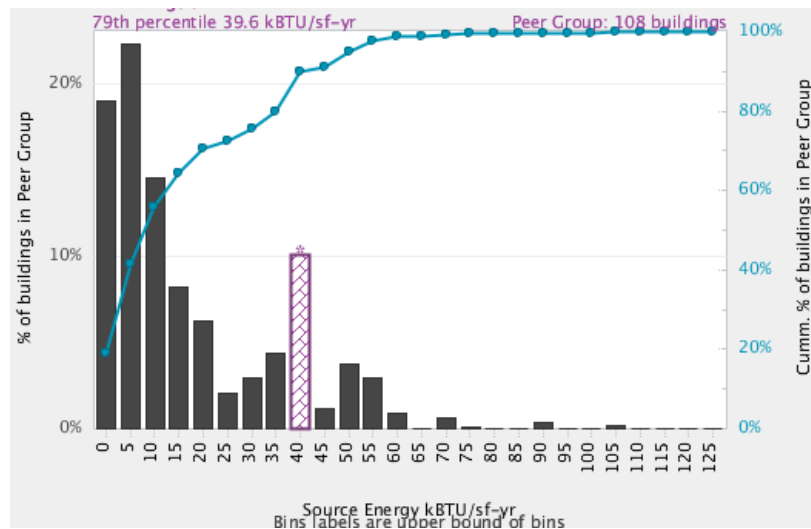


Figure 4. Benchmarking using EnergyIQ for Building Natural Gas Energy Consumption

Both Portfolio Manager and EnergyIQ are used to assess building performance using 12-month utility data ending May 31, 2010. The site energy use intensity (EUI) of this building is 268 kWh/m²/yr (85 kBtu/ft²/yr). Portfolio Manager and EnergyIQ reported significantly different scores due to the fact that they use different performance databases. Portfolio Manager reported a percentile score of 70 for the building energy use, which indicates that its source EUI of 643 kWh/m²/yr (204 kBtu/ft²/yr) is lower than 70% of comparison buildings nationwide.

Benchmarking using EnergyIQ reported that the whole building source EUI of 580 kWh/m²/yr (184 kBtu/ft²/yr)—not the same as the source EUI reported by Portfolio Manager due to different site-to-source conversion factors—is higher than 69% of comparison buildings in CEUS. A further benchmarking of individual fuel type shows that the electricity use is higher than 57% of comparison buildings while the gas EUI is higher than 79% of comparison buildings in CEUS

(see Figure 4). This rating suggests inefficient operation when the building is in heating mode. These benchmarking results help to set directions and goals for building commissioning efforts.

4. Detection of abnormal operations

Abnormal operations can be detected by trend data analyses, functional testing, or automatic fault detection and diagnostic tools. Trending capability of energy monitoring and control systems is important for the commissioning of HVAC systems. Analyzing trend data is a critical step in the process of building commissioning to identify faulty operations in HVAC system for buildings. If trending capability within control systems is not available, an alternative is to set up stand-alone data loggers or portable meters to collect system performance. In this study, both trend data analysis and functional testing were applied to detect abnormal operations.

4.1 Supply and return fans

The status of supply fan BL1 is shown in Figure 5. On the Y-axis, “1” indicates that BL1 is running, and “0” indicates that BL1 is off. The status profile for BL1 is typical for the other supply and return fans. It can be seen that the supply fan is running during 44% of the unoccupied hours (i.e. 913 hours of 2099 hours). There are two reasons that fans were running during unoccupied hours: 1) bypass, 2) most-open valve. 1) There is a bypass button for each thermal zone. During unoccupied hours, if the button is activated, the fan system for that zone will be commanded to run for one hour. 2) The reheat coil valve will be commanded to open when the heating setpoint during the unoccupied hours cannot be met. If the most-open valve position is greater than 25%, the fan system for that zone will be commanded to run. Also, it was found that the control algorithm for optimal start was ineffective, and the HVAC system always is always commanded to start at 4:00 am during weekdays.

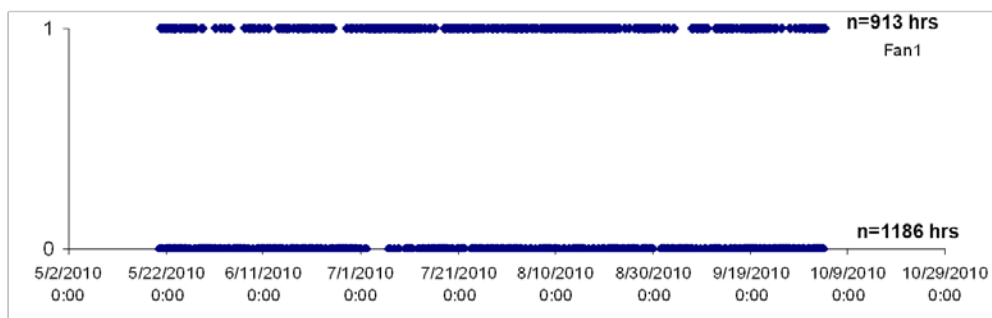


Figure 5. Status of supply fan BL1 during unoccupied hours

4.2 Boiler performance

There are three main boilers, labeled as BR3, BR4, and BR5, in the heating hot water system (Figure 3). As shown in Table 1, BR3, BR4, and BR5 take-on the role of lead, lag and last boiler alternatively. The lead boiler is called when any of the secondary pumps GP-1, 2, or 18 are turned on. The lag boiler is called when the lead boiler supply hot water temperature is below 54.5°C (130°F) or if hot water return temperature of the lead boiler is 5.5°C (10°F) below heating hot water return setpoint. The last boiler is called when hot water supply temperature of both lead and lag boilers are both less than 48.9°C (120°F), or if lag boiler hot water return temperature is 11.1°C (20°F) below the heating hot water return setpoint.

Table 1. Control sequence for boiler staging

Boiler	Jan, Apr, July, Oct	Feb, May, Aug, Nov	Mar, June, Sep, Dec
BR3	Lead	Last	Lag
BR4	Lag	Lead	Last
BR5	Last	Lag	Lead

Figure 6 illustrates the results of trend data analyses for boiler performance in September. Boiler status for both BR3 and BR4 are trended, but the trend data for BR5 status is not available. Based on the control sequence for boiler staging, in September, BR5 should have served as the lead boiler, and if either BR3 or BR4 were found to be on, BR5 must also be on. There are a couple of issues identified by Figure 6. First, it is found that the supply water temperature of BR5 is around 26.7°C (80 °F) when the lag boiler BR3 is on. BR5 was later confirmed to be dysfunctional by building maintenance personnel. The second issue is that the supply water temperature of BR4 is always close to that of BR3 even when the status of BR4 is off. After we visited the mechanical room, two reasons for the inconsistency between supply water temperature and boiler status of BR4 were identified. The heating hot water primary loops of BR4 and BR3 are in parallel, and there is no check valve in the boiler primary loops so that it is likely that the heated water from

BR3 flows backwards through BR4 depending on the pressure balance of the plant loop. Both BR 3 and 4 supply water temperature sensors are located close to the supply branch. It is likely that the temperature of supply hot water from one boiler has been sensed by the supply water temperature of another boiler.

4.3 DX cooling

There are four stages of DX cooling in each of the main air handling units. Each stage of a cooling coil is triggered by outdoor air temperature. The open loop control is easy to implement and can avoid frequent cycling of DX cooling coils, compared to a closed loop control. According to the control sequence, the first, second, third and fourth cooling stages were triggered when outdoor air temperature was greater than 20, 21.1, 23.3, and 24.4°C (68, 70, 74, 76 °F), respectively. Figure 7 identified several periods for simultaneous heating and cooling through trend data analysis of DX cooling status, boiler status and outdoor air temperature.

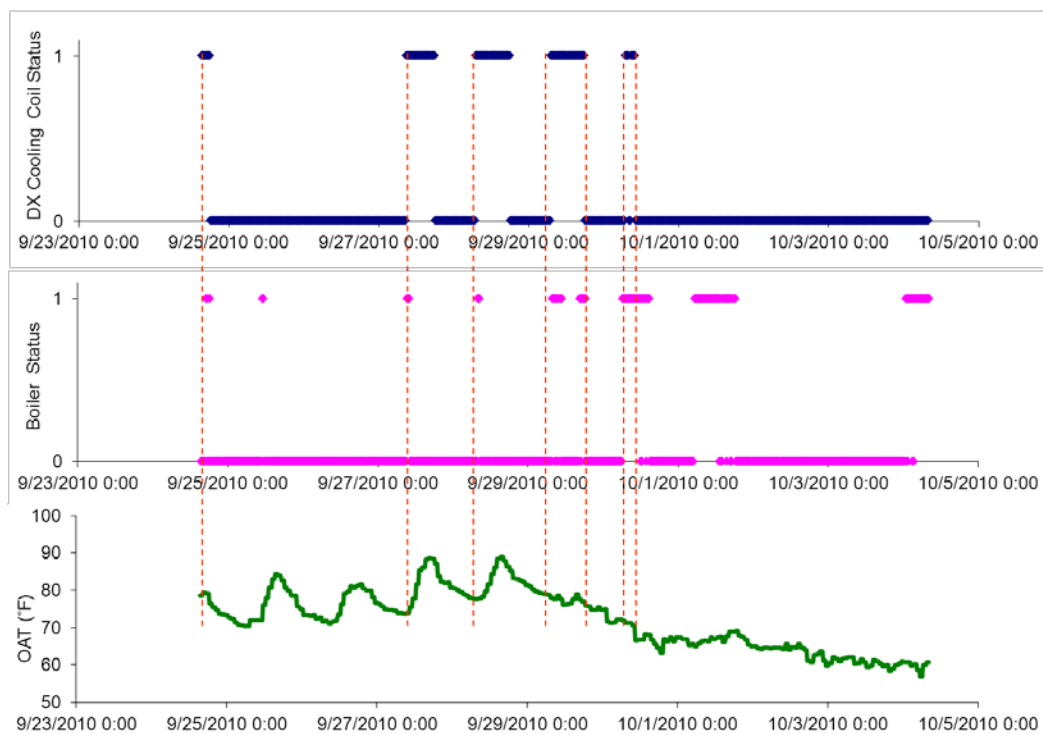


Figure 7. Simultaneous heating and cooling

4.4 Airside Economizer

In the current system, the airside economizer is not integrated with DX cooling coils. In such systems, the outdoor air dampers are set to a minimum position once free cooling cannot meet the required cooling capacity. The control sequence of the airside economizer was carefully reviewed. The existing control logic implemented in the EMCS and correct control logic for non-integrated economizer operation are summarized in Table 2.

Table 2. Control sequence for non-integrated economizer

	Driving Condition	Existing Logic	Correct Logic (Non-integrated)
Mechanical Cooling	OAT>DX cooling enable temperature	Modulate to 0%	Minimum Position
Free Cooling	OAT<DX cooling enable temperature	OAT>RAT	Minimum Position
		SAT<OAT<RAT	Modulate to 100%
		T	100%
	OAT<SAT<RAT	Modulate	Modulate
Heating	OAT< Lockout temperature	Modulate	Minimum Position
Schedule	Non-occupied hours except night ventilation	Modulate to 0%	0%

There are several issues identified for the implemented control sequence of airside economizer. When the system is in heating mode, the outdoor air damper modulates in a direction counter to its intended operation. As shown in Figure 8, when system is in heating mode, the outdoor air dampers were commanded to be fully open for most of the time based on the trend data from 01/11/2011-01/12/2011.

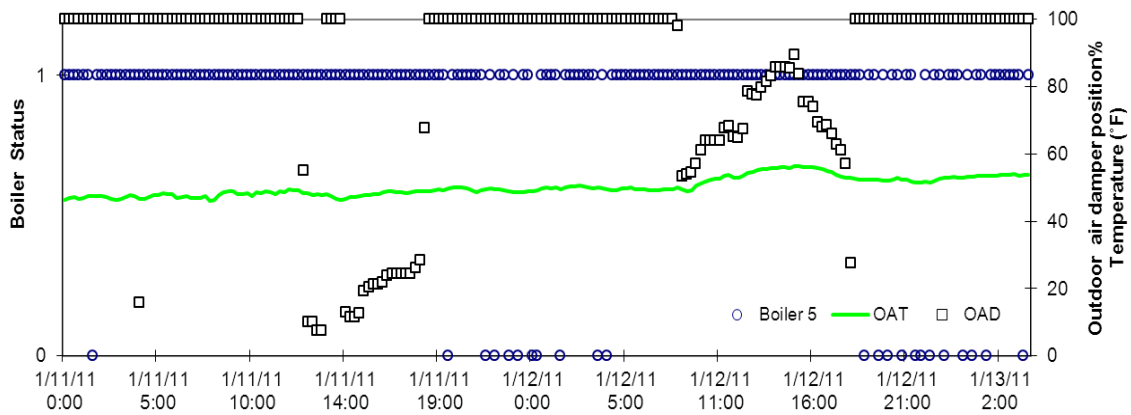


Figure 8. System in heating mode with fully open outdoor air damper

From the summary of control sequence for a non-integrated economizer, it shows that there is no setting for minimum outdoor air damper position for ventilation in mechanical cooling mode when outdoor air temperature is greater than return air temperature. Functional testing was conducted to estimate the outdoor air damper leakage based on temperature measurements and mass balance equation. A Testo high accuracy temperature sensor (± 0.05 °C) was used to measure the outdoor air temperature, return air temperature and mixed air temperature after the filters, when outdoor air damper control signal was overridden to be fully closed and return air damper control signal was overridden to be fully open during unoccupied hours. The temperature measurement was conducted when the system was in steady state. The estimated outdoor air damper leakage is 19%. Therefore, although the outdoor air damper is commanded to be fully closed, the amount of outdoor air leaking through the damper can serve the ventilation purpose. During unoccupied hours, this damper leakage results in energy penalties due to increased infiltration rates through the duct systems for both passive and active modes.

5. Energy saving measures

A calibrated EnergyPlus simulation model was developed based on monitoring data. A hybrid modeling approach, integrating real-time monitoring data and first principles, is applied to estimate the energy savings from the retro-commissioning case study, and prioritize the implementation plan. Creating such a model is convenient for analyzing savings opportunities and can potentially be used to setup baseline for diagnosis but it is not essential for the monitoring-based commissioning process. Building Optimization Analysis tool [28] can provide customized energy savings for EBCx measures based on site-specific inputs from users. The list of retro-commissioning measures listed in Table 3 was evaluated using the developed simulation model.

Table 3. List of energy saving measures

No.	Energy Saving Measures
1	Adjust room temperature setpoints
2	Adjust DX cooling coil stages
3	Night purge
4	Fix improper damper operation
5	Repair damper leakage
6	Implement optimal start

5.1 Information preparation

The collection of information on building systems for an energy simulation model is an important process, which directly influences the accuracy of the model to be developed. Resources for building information on envelope, HVAC equipment sizing and operation, and internal loads include drawings, equipment specifications, control sequence, testing reports, monitoring data, and engineering calculations. Equipment specifications provide design conditions (such as nominal capacity, efficiency, etc.) of HVAC components. The process of information preparation for existing buildings generally requires more effort than for new buildings as it is often found that documents for building systems are missing for existing buildings.

The building is classified as a medium-size (ca. 8316 m²) office building with a leaky shell. An infiltration rate that is typical for this type of building according to the construction year was used as an initial estimate, and then was further calibrated based on monitored data from the EMCS and EIS (Energy Information Systems). Design flow rates, fan pressure rise and speed of supply fan and return fans were obtained from previous test and balance reports as the catalog data for system fans were no longer available. EnergyPlus was used to size the capacities of reheat coils based on design days and sizing factor because the heating capacities of zone reheat coils (RHC) were unavailable. The HVAC operation control algorithm, operation schedules and set points were obtained from the sequence of operations document. The building has 41 submeters that monitor electricity and natural gas consumption at various levels. These submeters capture electricity usage for lighting and HVAC components, such as fans, individual packaged units, and condensing units, and natural gas consumption for boilers and water heater. Lighting and HVAC load profiles for weekdays and weekends for the EnergyPlus model are directly obtained from this monitored data, while plug load profiles for the model are obtained by subtracting lighting, and HVAC energy use from the building's main meter.

5.2 Model development

An EnergyPlus model was developed for the purpose of representing actual building performance and analyzing the impact of various energy conservation measures on the overall energy performance. The HVAC system defined in the EnergyPlus model represents building system characteristics to a large extent. However, due to the limitations of the simulation software, there

are certain features of the mechanical system for the building that could not be fully represented in the model. For example, the actual four stages of DX coils are connected in two parallel branches with each branch containing two coils in series, while the four stages of DX coils in the simulation model have to be connected in series; the HHW system actual configuration is primary-secondary-tertiary while EnergyPlus currently is limited to model a primary-only or primary-secondary system. So the plant loop of the building was simulated as a primary-secondary system.

5.3 Calibration

The developed EnergyPlus model was calibrated using monthly utility data and the hourly monitored energy use from the submeters. The general procedure for model calibration is as follows:

- i. **Collection of historical weather data:** Customized weather files for the EnergyPlus model were created using weather data from a local weather station.
- ii. **Quality control of monitored data:** Data recorded by real-time monitoring systems provided valuable actual building performance. However, it was not uncommon for data to be missing or incorrect. Engineering judgment and meter commissioning were required to assure the quality of monitored data.
- iii. **Selection of calibration periods:** An entire year was used as a calibration period. In addition, for detailed calibration, the monitored data were compared to the simulation data for 1 month each (January and August) to represent the heating and cooling seasons, respectively. Monitored data for the two time periods were compared to the simulation results for the equipment for the same time periods.
- iv. **Energy use calibration at the component level:** Calibration of the simulation model was conducted at the component level in addition to the whole-building level. Input parameters of the simulation model for each component are re-examined and adjusted according to the deviation of hourly energy use comparison between measurement and simulation. The calibration at the component level focused on major equipment including boilers, three main supply fans serving first through third floor, and the AC-24 and AC-25 heat pump units serving the fourth floor.
- v. **Energy use calibration at the whole-building level:** Finally, the building simulation model was calibrated based on the overall energy-use comparison at the whole-building

level between hourly/monthly monitored data and simulation. Input parameters at the building level were fine-tuned.

5.4 Saving estimation

The prediction of the energy simulation model for the office building was significantly improved through the calibration process. Input parameters at both component and building levels were verified and modified during the calibration process which helped the building simulation model to better predict the energy usage. Comparison of the results of the calibrated simulation with the actual measured data yielded normalized mean bias error (NMBE) values of 8.0% for electricity and 5.1% for natural gas relative to annual energy consumption, and within 10% relative to hourly calibration data. The calibration results meet the requirement of whole building calibrated simulation performance in ASHRAE Guideline 14 [29].

The potential energy conservation measures (ECM) identified through the commissioning process are listed as follows. Each measure is evaluated using the developed calibrated EnergyPlus model.

i. ECM #1: Adjust room temperature setpoints

Reducing zone (room) heating setpoint, without sacrificing thermal comfort, can reduce natural gas consumption for space heating. Various runs to decrease room heating setpoints by 0.5, 1.6 and 2.8°C (1, 3 and 5°F) relative to the current room temperature setpoints were analyzed and energy savings were predicted.

ii. ECM #2: Adjust DX cooling setpoints for four cooling stages

Optimized DX cooling setpoints can lead to reduced DX cooling power consumption, better thermal comfort, and reduced reheat energy. The building manager received complaints for cold spots from occupants based on the original DX operation. There are four stages for the DX cooling coils, which are controlled by outdoor air temperature. Two sets of DX cooling setpoints (20.5/22.2/25/28.9°C, 21.1/23.3/26.1/30°C) are selected for analysis, compared to the original setpoints (20/21.1/23.3/24.4 °C) to address thermal comfort issues, and energy savings are evaluated using EnergyPlus simulations.

iii. ECM #3: Night purge

Night purge is designed to reduce cooling energy consumption during hot days by means of cooling the building's thermal mass during the previous night when it is cooler outside. Outdoor cool air is brought into the building by the ventilation fans to pre-cool the building mass. This measure is effective if the cooling energy savings are greater than the required fan energy for

night purge. In the energy simulation, the night purge operational strategy is only evaluated for the 12 hottest days of the year. For a selected day, fan operation starts at midnight and room temperature setpoints during the night purge are adjusted to avoid additional heating energy during morning warm-up.

iv. ECM #4: Correct improper damper operation for economizer

During the retro-commissioning process, it was identified that the outdoor air damper is 100% open when the system is in heating mode. Bringing in 100% outside air during heating will result in energy waste. Correcting improper damper operation is achieved by positioning the outdoor air damper at minimum position to meet the ventilation requirement; the EnergyPlus simulation is used to predict energy savings.

v. ECM #5: Repair damper leakage

An outdoor air damper leakage of 19% was identified through functional testing (See section 4.4). During unoccupied hours and morning warm-up, the outdoor air damper can be fully closed to save heating energy. The developed simulation model is used to quantify the energy penalty for damper leakage.

vi. ECM #6: Implement optimal start for morning warm-up

Without sacrificing thermal comfort, a delay in start up of HVAC system can achieve higher energy efficiency if it was starting earlier than needed. In the original operation, the occupied period is assumed to start at 6 am on weekdays; the warm-up start time is 2 hours prior to occupancy, regardless of weather. This measure changes the assumed occupancy start time to 7 am, and determines the warm-up start time according to an optimal start algorithm. The algorithm calculates morning warm-up period by taking into account worst zone temperature and outside air temperature; the maximum warm-up time can be two hours. Potential savings are estimated through the EnergyPlus simulation.

vii. ECM #7: Reset room temperature setpoints during morning warm-up for hot days

During hot weather periods, there is a significant diurnal temperature swing, with the result that morning warm-up energy use is followed by cooling energy use in the afternoon. In order to achieve higher energy efficiency, this measure resets the warm-up set points to minimize heating energy in the morning and thereby reducing cooling energy needed during hot days. Potential energy savings are estimated using the simulation model.

Simulations were performed for each ECM to estimate annual savings and a combined case. The original building operation was used as a baseline to estimate energy savings for ECMs.

The estimated annual energy saving for each measure and the total combined saving in terms of source energy for overall natural gas and electricity as a percentage of baseline energy consumption are shown in Figure 9. Each measure can lead to 0.7% -6.9% savings of annual source energy. Among all the measures, correcting the improper outdoor air damper operation and implementing optimal start are the most beneficial strategies. The total source energy savings of 15% can be achieved by implementing all the listed energy saving measures. Note that the overall energy savings are less than the sum of the energy savings from individual measures because of interacting effects among the measures.

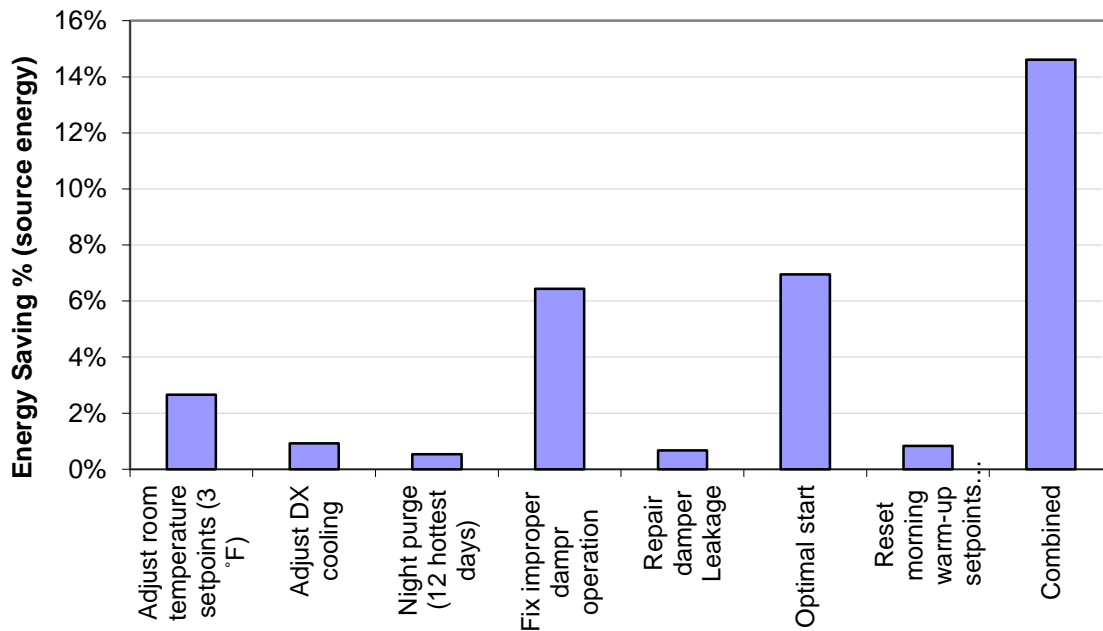


Figure 9. Estimated annual source energy saving percentage for energy saving measures

6. Actual saving analysis

The energy saving measures, such as adjustment of room temperature setpoints, DX cooling control, outdoor air damper control and optimal start, were implemented in the actual HVAC system. Hourly electricity and gas consumption were tracked to evaluate the effect of these

measures on actual energy consumption. Since building operations are typically different for weekdays, and weekends or holidays, the measured data are classified into two categories—data for occupied hours and unoccupied hours. The period for baseline is from 02/01/2010 to 02/28/2011 (13 months) and the period for ongoing commissioning is from 09/01/2011 to 02/28/2012 (~6 months). Regression models [29], describing the relations between electricity and natural gas usage, and outdoor air temperature, were developed for both occupied and unoccupied hours. For unoccupied hours, 51% of natural gas energy was saved (Figure 10) that can be mainly attributed to the implementation of an improved morning warm up algorithm. The natural gas energy saving is 4.3% for occupied hours. There were 1.4% and 5% electricity energy savings for occupied and unoccupied hours, respectively. Based on the analysis, the overall source energy savings as a result of recommissioning exercise were a total of 10% the baseline energy consumption.

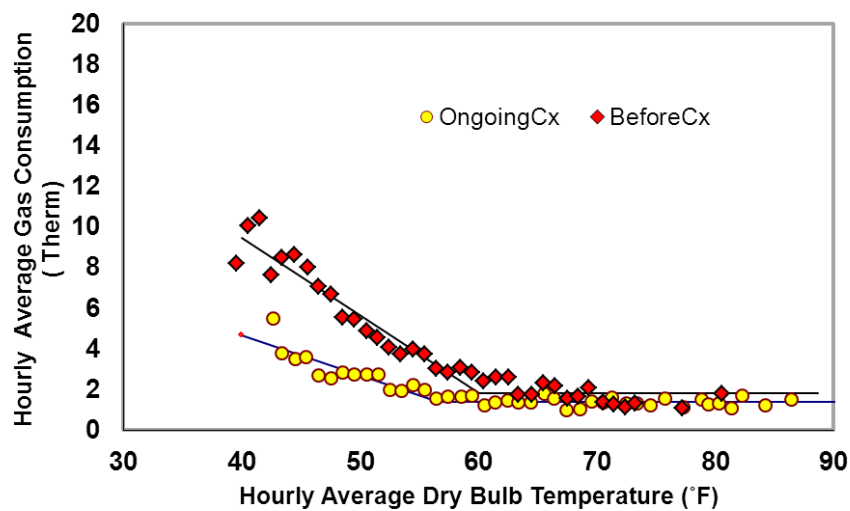


Figure 10. Regression model of hourly natural gas consumption for unoccupied hours

7. Conclusion

This paper demonstrates a case study of monitoring-based commissioning of an existing office building. The developed EnergyPlus model can be used as a reference model for on-going commissioning to ensure the persistence of energy savings. The predicted energy use at various levels (whole building, system, subsystem) can be compared to actual monitored data to help identify the potential faults. An actual energy saving of 10% was realized through the process

of ongoing commissioning. The following opportunities were identified for further research and development:

- To support persistence of commissioning benefits, commissioning would be required throughout a building lifecycle. Automating the process of commissioning would be a critical step to save labor, time and cost required by manual commissioning. It could also improve the effectiveness of commissioning.
- Improve the algorithm for automatic fault detection and diagnostics (FDD) using a hybrid method (a combination of rule-based, and model-based methods). Incorporating the FDD tool into building automation systems (BAS) or energy information systems (EIS) would promote the wide adoption of FDD technology. Included in this effort should be extending previously developed FDD methods and tools to address advanced systems and low-energy buildings.
- With the increasing installation of sub-meters and sensors in existing buildings, large amounts of actual building performance data have become available. Advanced data visualization, which interprets building performance data, is important to supplement fault diagnostics and prioritize work plans for building operators and facility managers.
- Development of retrofit and retro-commissioning tools, incorporating building simulation and existing retrofit databases, to quantify and improving the costs and benefits of commissioning.

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