ENERGY AND COST SAVINGS OF RETRO-COMMISSIONING AND RETROFIT MEASURES FOR LARGE OFFICE BUILDINGS

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ABSTRACT

This paper evaluates the energy and cost savings of 7 retro-commissioning measures and 29 retrofit measures applicable to most large office buildings. The baseline model is for a hypothetical building with characteristics of large office buildings constructed before 1980. Each retro-commissioning measure is evaluated against the original baseline in terms of its potential for energy and cost savings, while each retrofit measure is evaluated against the commissioned building. All measures are evaluated in five locations (Miami, Las Vegas, Seattle, Chicago and Duluth) to understand the impact of climate conditions on energy and cost savings. The results show that implementation of the seven operation and maintenance measures as part of a retro-commissioning process can yield an average of about 22% energy use reduction and 14% energy cost reduction. Additionally, widening zone temperature deadband, lowering VAV terminal minimum air flow set points and lighting upgrades are found to be the most effective retrofit measures.

INTRODUCTION

Office buildings consume approximately 17% of energy use in commercial buildings in the U.S. (EIA 2003). Almost 60% of existing office buildings were built before 1980. Many are past due for upgrades to aging building equipment, systems, and assemblies. Therefore, there are significant opportunities for energy efficiency improvements in existing office buildings. Available resources on office building retrofits are either general guides or specific case studies. General guides offer general procedures and guidance on building retrofits or the existing building commissioning process. No quantified results of energy and cost savings are provided for different measures. Specific case studies offer quantified savings based on measurement or simulation. In this case, however, only a few measures specific to a particular building and location are investigated.

This paper presents use of a building simulation to evaluate the energy and cost savings of retro-commissioning and retrofit measures. Starting from a hypothetical baseline building with representative characteristics of large office buildings constructed before 1980, seven retro-commissioning measures were evaluated individually and as a package against the baseline in terms of their potential for energy and cost savings. Then, based on the commissioned building, a total of 29 retrofit measures were evaluated. The measures are retrofits to the interior and exterior lighting, plug and process loads, heating, ventilation and air conditioning (HVAC) equipment and control, service hot water system, and building envelope. All measures are evaluated using the EnergyPlus simulation program version 6.0 in five locations to understand the impact of climate condition on energy and cost savings. The five locations and their representative climates include Miami (hot and humid), Las Vegas (hot and dry), Seattle (marine), Chicago (cold) and Duluth (very cold).

BASELINE BUILDING MODEL DEVELOPMENT AND BENCHMARKING

To evaluate the energy and cost savings of various energy efficiency measures, a baseline building model needs to be developed as a reference. This baseline building should represent the typical design and operating conditions for a pre-1980 vintage office building, which is the targeted building type for this study. The U.S. Department of Energy (DOE) has developed a reference building prototype for pre-1980 large office buildings. The DOE reference large office building is a high-rise building with 12 above-ground floors and a basement. The building has a total floor area of about 42,000 m^2. However, based on the commercial building energy consumption survey (EIA 2003), such a high-rise office building is not representative of office buildings with floor areas more than 10,000 m^2. Therefore, a low-rise large office building with a smaller area than the DOE reference model was developed to have typical, pre-1980 construction characteristics, as described in this section.

The building has four floors and a total floor area of 18,500 m^2. All floors have a floor-to-floor height of 3.96 m, including an air plenum with the height of 1.22 m. The building footprint has an aspect ratio of 1.5 and an overall window-to-wall ratio of 40%. With a window sill height of 1.1 m, the windows are distributed evenly in continuous ribbons around the perimeter of the building. Figure 1 shows an axonometric view of the large office building and the thermal zones defined in the simulation model. As can be seen in Figure 1, a computer server room is defined as an individual thermal zone in the core area on each floor. On the top floor, a big conference room is defined as another thermal zone in the core area. One perimeter zone on the ground floor is also defined as a conference room. The server rooms and the conference rooms, respectively, occupy about 0.9% and 3% of the total building area. The thermal zones are thus defined to account for the trade-off between model simplification and the needs of retrofit measure evaluation.

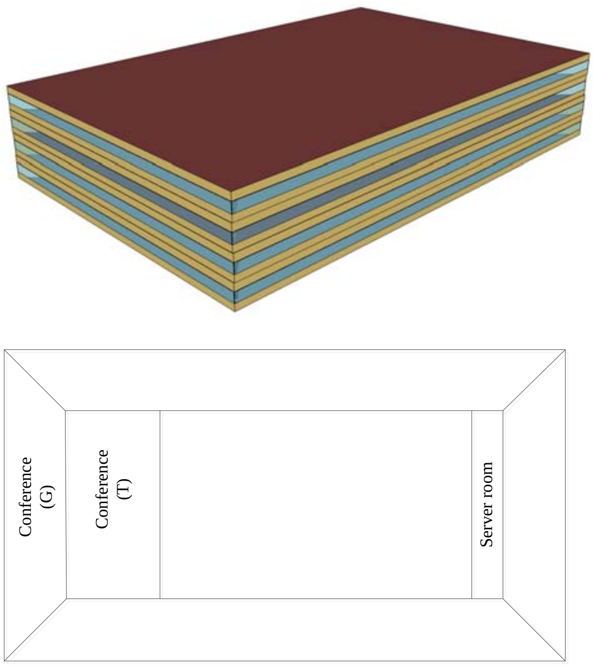

Figure 1: Axonometric view (top) and thermal zoning (bottom) of the large office building

The building has concrete block walls, a flat roof with insulation entirely above metal deck, and a slab-on-grade concrete floor with carpets. All exterior opaque assembly constructions are configured according to Appendix A in ASHRAE Standard 90.1 (ASHRAE 2010). The performance values of the exterior envelope are taken from the U.S. DOE reference building model for the pre-1980 vintage (Deru et al. 2011).

Although the baseline building represents the pre-1980 construction vintage, it was assumed that some building systems and equipment have likely been upgraded since the building was first constructed. These upgrades were considered to determine the appropriate baseline building characteristics. For example, the baseline interior lighting system is assumed to have been upgraded to comply with the ASHRAE Standard 90.1-1999 requirements. Hence, the lighting power density (LPD) of the baseline building is calculated as the area-weighted average of LPD values for different spaces. The area-weighted average LPD is then applied to all thermal zones. For exterior lighting power allowance, it is calculated as the sum of maximum power used for building façade, entrances and exits, and the parking area according to ASHRAE Standard 90.1-1999 to account for past upgrade.

To determine the plug load power density for those spaces other than computer server rooms, a break-down of plug loads was developed for the large office building in accordance with ASHRAE's recommended heat gains from various office equipment and appliances (ASHRAE 2010). Following the same procedure as used by Thornton et al. (2009), the plug load power density for the baseline building is calculated as 8.1 W/m^2. In contrast to the conventional spaces, the computer server room has a much higher equipment load, assumed at about 269.1 W/m^2 based on the monitored data from a real server room in a large office building. According to rules of thumb (Deru et al. 2011), a total of four elevators are used in the building. Each elevator is equipped with a 20-hp hydraulic motor. In addition, the elevator cab continuously consumes about 162 W for lighting and ventilation (Thornton et al. 2010).

The large office building is fully heated and cooled with a central HVAC system. There are two water-cooled, centrifugal chillers for cooling and two gas-fired, hot water boilers for heating. Two open cooling towers with constant speed tower fans are used as the heat rejection equipment. The chillers, boilers, and cooling towers are equally sized according to the EnergyPlus simulation program. The chiller and boiler efficiencies are set according to their capacities (Deru et al. 2011). Constant primary systems with headered pumps are used to distribute chilled water and hot water in the building. For the condenser water loop, a constant speed headered pump is used to circulate condenser water between the chillers and the cooling towers.

The large office building has a variable-air-volume (VAV) system on each floor for all spaces except for the computer server rooms. The VAV system is composed of a central air-handling unit (AHU), air ducts and VAV terminal boxes with hot water reheat coils. The AHU contains a mixing box, a hot water heating coil, a chilled water cooling coil, and a variable speed supply fan. The return and outdoor air flows are mixed and treated in the central air-handling unit, and then supplied to each zone through VAV boxes. The central heating and cooling coils operate to maintain the temperature set point of the discharge air from the AHU at 12.8°C. The AHU includes airside economizer control to reduce the need for mechanical cooling. The VAV system controls the zone air temperature by varying the airflow rate through the terminal box damper modulation. As the zone cooling load decreases, the damper of VAV box closes until the airflow rate reaches the minimum value, which is set at 50% of the design air flow. If the cooling load of a zone continues to decrease, the reheating coil valve of corresponding VAV box is modulated to maintain the space temperature set point.

For the computer server rooms, one water- or glycol-cooled direct expansion (DX) unit is used in each server room. In Miami, Las Vegas, and Seattle, water-cooled DX units are used with the central cooling tower as the cooling source. In Chicago and Duluth, glycol-cooled DX units are used with a dedicated fluid cooler as the cooling source.

Figure 2 shows the simulated energy end use intensity for the baseline building. The whole building energy use intensity (EUI) ranges between 970 and 1090 MJ/m^2/year. In comparison, the average EUI for existing office buildings with more than 10,000 m^2 built from 1945 is about 880 MJ/m^2/year (EIA 2003).

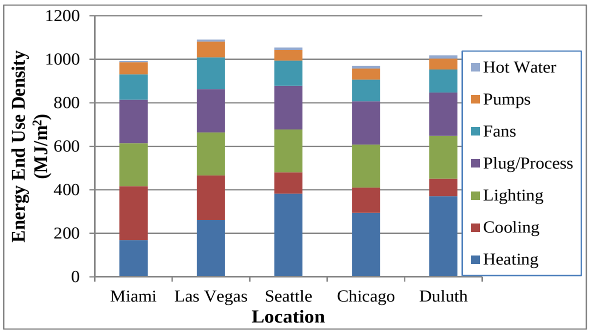

Figure 2: Baseline building energy end use intensity

RETRO-COMMISSIONING AND RETROFIT MEASURES

This section describes the retro-commissioning and retrofit measures investigated in this study. Because of space limitation, only a brief description is provided for each measure. The retro-commissioning measures are coded as RC and the retrofit measures are coded as RT. For more details, refer to Liu et al. (2011).

Retro-commissioning measures

Revise air filtration system (RC1). The baseline building assumes that both pre-filters and final filters are used in AHUs for air cleaning. This measure intends to replace both filters with an extended surface air filter, leading to a lower pressure drop across the filters. This measure was modeled by reducing the supply fan total static pressure by 45 Pa.

Supply air temperature reset (RC2). The AHU supply air temperature (SAT) is fixed at 12.8°C in the baseline. This measure resets the SAT based on outside air temperature (OAT): SAT=12.8°C when OAT> 23.9°C; SAT = 15.6°C when OAT<7.2°C; SAT is linearly interpolated when OAT is between 23.9°C and 7.2°C.

Reduce HVAC equipment runtime (RC3). In the baseline, HVAC equipment operates between 6 am and 10 pm weekdays and between 6 am and 6 pm on Saturdays. This measure reduces the scheduled HVAC operations hours to more closely match the occupancy schedule. Thus, the HVAC operation schedule is shortened to between 6 am and 7 pm weekdays and between 6 am and 3 pm on Saturdays.

Close outside air damper during unoccupied periods (RC4). The baseline assumes that the outside air damper opens whenever the supply fan is operating, including the early morning warm-up and cool-down periods before normal occupancy. This measure closes the outside air damper during unoccupied hours.

Reduce the AHU damper leakage (RC5). The baseline assumes that outside air and return air dampers do not have blade and jamb seals. As a result, only 70% outside air is supplied during 100% economizer operation. After adding seals, 95% OA is supplied during 100% economizer operation.

Shut down cooling plant when there is no cooling load (RC6). In the baseline, the chilled water plant (including chillers, cooling towers, and chilled water and condenser water pumps) operates whenever the main air handlers operate. After applying this measure, the chilled water plant operates only when there are cooling needs from the air handlers.

Reduce envelope leakage (RC7). Based on the DOE reference building model (Deru et al. 2011), the air infiltration rate is assumed to be 0.0043 $m^3/s/m^2$ of exterior envelope at 75 Pa pressure difference. This measure assumes that the air infiltration rate reduces by 10% from the baseline after weather stripping the exterior door, windows and crack caulking on exterior walls.

Retrofit measures

Interior lighting retrofit (RT1 through RT4). This measure involves four levels of incremental lighting upgrades. Starting from the baseline, the incremental changes of these four levels include lamp and ballast replacement for Level 1, lighting fixture replacement for Level 2, lighting system redesign for Level 3, and using high-performance linear fixture and light-emitting diode downlight for Level 4. The lighting fixtures used in different spaces and their efficiencies are based on the lighting subcommittee work for ASHRAE Standard 90.1 development. Following the same approach used to calculate baseline LPD, the LPDs are calculated for the above four levels of upgrades as 12.8 W/m^2 (RT1), 11.3 W/m^2 (RT2), 10.4 W/m^2 (RT3) and 9.2 W/m^2 (RT4), respectively.

Install occupancy sensors to control interior lighting (RT5). The baseline assumes that all interior overhead lights are manually controlled with a nighttime sweep. After applying this measure, occupancy sensors are installed to control general lighting in the following spaces: open offices, private offices, conference rooms, restrooms, stairways, and break rooms. Following the approach used by Thornton et al. (2009), the percentage of lighting energy savings from occupancy sensor control is calculated as 10.1%, which is used as the percentage of LPD reduction to model this measure.

Add daylight harvesting (RT6). This measure involves the installation of photocells to sense the space lighting level. The overhead lighting fixtures are dimmed continuously in the perimeter zones to maintain the desired illuminance set point at 300 lux. The continuous dimming control can dim down to 10% of the maximum light output with a corresponding 10% of the maximum power input.

Upgrade exterior lighting (RT7). This measure involves two aspects of effort: lighting retrofit and lighting control. First, lamps currently used for parking lots, entrances and building facades are replaced with more efficient ones. For example, the high pressure sodium lights used for parking lots are replaced with pulse start metal halide lamps. The change of lighting bulbs reduces the exterior lighting power from 33.6 kW to 22.4 kW. For control, the baseline assumes that all lights are based on astronomical time clock control, which means that the lights are on at 100% whenever it is dark outside. In contrast, this measure assumes that parking lights are lowered to 25% of the full power at 7 pm and remain at that level for the rest of the night. Other exterior lighting control remains unchanged.

Add advanced control for plug loads (RT8). This measure intends to turn off plug loads when they are not in use through the following techniques: 1) power management software for networked computers; 2) power strips with integrated occupancy sensors to control task lighting; 3) vending miser controls for vending machines; and 4) timer switches for coffee makers and water coolers. The advanced control of plug loads is simulated by changing the plug load schedule. The detailed procedure can be found in Thornton et al. (2009).

Control elevator cab lighting and ventilation (RT9). The baseline assumes that the cab lighting and ventilation are on continuously. This measure adds a motion sensor in each cab to turn off lights and ventilation when the cabs are unoccupied.

Add optimum start strategy for HVAC equipment (RT10). In principle, optimal start requires an adaptive control sequence to determine the time used to reach the space temperature set point. Because of the simulation program constraints, this measure was modeled by simply delaying the start time from 6 am to 7 am in shoulder seasons (March to May and September to November).

Revise air-side economizer damper control (RT11). In the baseline building, except for Miami, the air-side economizer is used in all other four locations: in Las Vegas and Seattle, the economizer control is based on fixed outdoor air dry-bulb temperature at 21.1°C; in Chicago and Duluth, it is based on fixed outdoor air enthalpy at 55.8 kJ/kg. With this measure, the economizer control is based on differential dry-bulb temperature in the above four locations.

Widen zone temperature deadband and add conference room standby control (RT12). In the baseline building, all spaces served by the VAV systems have thermostat set points at 21.7°C for heating and 22.8°C for cooling. This measure intends to upgrade the control of VAV terminal units from pneumatic to direct digital control (DDC). Then, the space temperature set points are widened to 20.6°C for heating and 23.9°C for cooling. For conference rooms, when they are unoccupied for more than 10 minutes, the temperature set points are widened further to 19.4°C for heating and 25°C for cooling. In addition, the minimum air flow is reduced from 50% to 15% of the zone design flow.

Lower VAV box minimum flow set points and reset duct static pressure (RT13). In the baseline, all VAV terminal boxes have the minimum air flow set at 50% of the maximum flow. The AHU supply fans maintain a constant static pressure at 1500 Pa. This measure reduces the minimum air flow to 40% of the maximum for all VAV boxes except those serving the conference rooms. The supply duct static pressure is reset based on VAV box damper positions.

Add demand-controlled ventilation (RT14). The baseline assumes that the outdoor air is always supplied at 15% of the supply flow. This measure controls the amount of outdoor air based on space ventilation needs.

Replace supply fan motor and Variable Frequency Drive (VFD) (RT15). The supply fan motor efficiency is assumed at 88% and the VFD efficiency at 70% for the baseline building. This measure replaces the fan motors and VFDs with premium efficiency: 91% for the motor and 92% for the VFD.

Shut down heating plant when there is no heating load (RT16). The baseline assumes that the heating plant (boilers and hot water pumps) operates whenever the AHUs operate. After applying this measure, the heating plant operates only when the AHUs run and the outside air temperature is less than 23.9°C.

Increase efficiency of condenser water system (RT17). The baseline assumes that the cooling towers with constant speed fans are cycled to achieve a constant condenser water supply temperate at 26.7°C. With this measure, VFDs are added to the cooling tower fans and the condenser water supply temperature is reset to the outside air wet-bulb temperature plus 5.6°C, but no less than 21.1°C.

Change cooling plant pumping system to variable primary (RT18). This measure upgrades the primary-only chilled water pumping system from constant flow to variable flow.

Replace cooling and heating plant pump motors (RT19). For all pumps used for chilled water, condenser water, and hot water, the motor efficiency increases from 88% for the baseline to 91% after the motor replacement.

Add a VFD to the leading chiller (RT20). The baseline building has two constant speed centrifugal chillers, each sized for 50% of the peak cooling load. This measure equips the lead chiller with a VFD, which increases the chiller's part-load performance.

Replace boilers and change the heating plant pumping system (RT21). This measure involves the following changes: 1) the current boilers at 76% thermal efficiency are replaced with condensing boilers at 90% efficiency; 2) the hot water pumping system is changed from constant primary to variable primary configuration; 3) differential pressure set point across the hot water loop is reset based on the heating coil valve positions; and 4) hot water supply temperature (HWST) set point is reset based on the outside air temperature. HWST is at 65.6°C when outdoor air temperature (OAT) is above 18.3°C; HWST is at 82.2°C when OAT drops below 4.4°C in Las Vegas, 1.7°C in Seattle, and -6.7°C in Chicago and Duluth. Linear interpolation is used when OAT lies in between the two boundaries. Note that in Miami, HWST is maintained at 65.6°C and no HWST reset is used.

Replace boiler burners with modulating burners (RT22). The baseline uses two-stage burner operation in the two boilers. This measure intends to replace the boiler burners with fully modulating ones with a minimum of 5:1 turndown ratio. The measure was modeled by using different boiler part-load performance curves in EnergyPlus.

Increase the efficiency of computer server room cooling units (RT23). In this work, water- or glycol-cooled DX units are modeled as closed-water-loop heat pumps. With this measure, the rated cooling efficiency of the water-loop heat pump units is improved from 10.9 energy efficiency ratio (EER) in the baseline to 16.4 EER for the new cooling units.

Replace windows (RT24). The windows are replaced with code-compliant ones. The new windows have the minimum thermal performance as required by the Standard (ASHRAE 2010).

Add exterior window shading (RT25). In the baseline, no exterior shading devices are used on the windows. This measure adds horizontal exterior shading devices with a 0.5 projection factor on the south windows. As recommended by (Thornton et al. 2009), exterior shading is not used in Duluth.

Add wall insulation (RT26). Wall insulation is added to meet the minimum requirement by the Standard (ASHRAE 2010).

Add roof insulation (RT27). Roof insulation is added to meet the minimum requirement by the Standard (ASHRAE 2010).

Replace the service hot water heater (RT28). The baseline has a gas-fired-storage water heater with 80% thermal efficiency. It is replaced with a condensing water heater with 95% thermal efficiency.

Replace the electric transformer (RT29). The electric transformer is used in the large office building to reduce the voltage from 480/277v to 208/120v. The transformer efficiency is 95% for the baseline and 98.5% for the new transformer.

ENERGY SAVINGS

Table 1 provides the percentage of onsite energy savings for retro-commissioning measures relative to the original baseline. NA is used in a cell if the corresponding measure is not applied in that location. This table shows that:

- Of the seven evaluated retro-commissioning measures, reducing HVAC equipment runtime (RC3) saves the most energy, followed by the measure of SAT reset (RC2). SAT reset has a large impact on energy savings because it can significantly reduce the reheat energy used by VAV terminal units. This is especially true for the baseline building, which has terminal minimum air flow at 50% of the design.
- Except for Miami, shutting down the cooling plant when there is no cooling load (RC6) can save more than 2% of whole building energy use. This measure is not as effective in Miami because there is cooling load almost all year around.
- The impact of reducing envelope leakage (RC7) is insignificant in locations with hot or mild climates.

Table 1: Percentage of energy savings relative to the baseline for retro-commissioning measures

RCs	Location				
	Miami	Las Vegas	Seattle	Chicago	Duluth
RC1	0.4	0.4	0.4	0.3	0.3
RC2	1.3	6.7	13.1	10.0	11.1
RC3	13.1	12.8	13.4	12.5	11.0
RC4	0.2	0.1	0.0	0.2	0.8
RC5	NA	1.1	1.3	0.4	0.7
RC6	0.5	3.2	2.4	2.7	3.1
RC7	0.0	0.0	0.1	0.2	0.3

Figure 3 shows the overall energy savings from the combined seven retro-commissioning measures. The modeled results show an average of about 22% of energy use reduction. This magnitude of energy savings from energy simulation is comparable to the measured energy savings from actual retro-commissioning projects (Mills 2011).

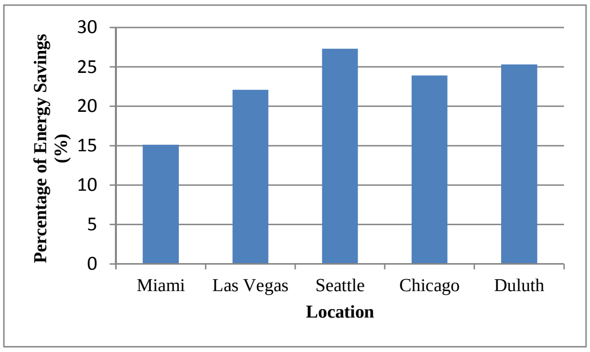

Figure 3: Percentage of energy savings from the packaged retro-commissioning measures relative to the baseline

Using the retro-commissioned building as the new baseline, each retrofit measure is evaluated in terms of the percentage of energy savings. Table 2 lists the results. This table shows that:

- After the control of VAV terminal units is upgraded from pneumatic to DDC, decreasing the terminal minimum flow set points (RT13) and increasing the zone temperature deadband (RT12) are the two measures with the largest energy savings. Depending on the location, both of them can achieve 8% to 13% of onsite energy savings. RT13 can significantly reduce the reheat energy and the fan energy after lowering the terminal minimum flow set points. RT12 has a large impact on both heating and cooling energy because of the widened temperature deadband.
- Shutting down the heating plant when there is no heating load (RT16) is an effective measure in hot climates. Simulation results show that this measure achieves more than 4% of whole building energy use in Miami and Las Vegas.
- Boiler replacement and the related heating system upgrades (RT21) achieve between 2.5% and 6.5% of whole building energy use. It is more effective in cold climates because of the dominated heating needs.
- Lighting retrofits (RT1 to RT8) are generally effective energy savings measures for all five locations. Depending on the location and the level of interior lighting upgrade, reducing LPD can reduce whole building energy use by between 1.1% and 5.0%.
- Except in cold climates, upgrading exterior envelope to ASHRAE Standard 90.1 minimum requirements (RT24 to RT27) usually has less than 1% of energy savings. This is mostly because

all HVAC equipment sizes are fixed when investigating these measures. The benefits of load reduction on sizing are not considered.

- Because of the small percentage (~1%) of whole building energy use is for service hot water, upgrading the hot water heater reduces the building energy by less than 0.3%.

Table 2: Percentage of energy savings relative to the commissioned building for retrofit measures

RTs	Location				
	Miami	Las Vegas	Seattle	Chicago	Duluth
RT1	1.8	1.5	1.3	1.4	1.1
RT2	3.3	2.8	2.2	2.5	2.1
RT3	4.0	3.5	2.7	3.0	2.5
RT4	5.0	4.4	3.3	3.6	2.9
RT5	1.7	1.4	1.2	1.3	1.0
RT6	2.0	1.6	0.4	0.7	0.3
RT7	2.3	2.2	2.4	2.5	2.5
RT8	2.2	1.9	1.5	1.6	1.2
RT9	0.1	0.1	0.1	0.1	0.1
RT10	0.8	0.6	0.7	0.6	0.5
RT11	NA	0.1	0.0	0.3	0.0
RT12	9.3	10.3	10.6	9.1	7.9
RT13	11.7	13.1	11.9	10.0	8.5
RT14	0.6	0.5	0.0	0.2	0.8
RT15	2.7	3.4	2.9	2.6	2.7
RT16	7.1	4.2	0.2	1.1	0.1
RT17	0.9	1.9	0.5	0.6	0.3
RT18	1.3	1.4	0.5	0.6	0.4
RT19	0.2	0.2	0.1	0.1	0.1
RT20	1.7	1.5	0.5	0.7	0.3
RT21	2.5	3.8	5.7	5.0	6.5
RT22	0.2	0.3	0.3	0.4	0.5
RT23	1.0	1.1	1.2	1.3	1.2
RT24	-0.6	-0.4	2.2	0.3	3.8
RT25	0.6	0.6	-0.4	-0.2	NA
RT26	NA	0.6	0.8	0.9	2.2
RT27	0.0	0.7	0.9	1.0	2.2
RT28	0.1	0.2	0.2	0.3	0.3
RT29	0.9	0.9	1.0	1.0	1.0

ENERGY COST SAVINGS

Energy costs for the baseline and each case after implementing a retro-commissioning and retrofit measure are calculated by the EnergyPlus simulation program. Energy costs include electric energy costs, electric demand costs, and gas energy costs. The electricity and gas rates from the major utility companies in the five locations are used in the cost calculation. Table 3 lists the percentage of energy cost savings for retro-commissioning measures relative to the original baseline. This table shows the following:

- Similar to the energy savings in Table 1, reducing HVAC equipment runtime (RC3) saves the most energy cost, followed by the measure of SAT reset (RC2).
- A measure may have different impacts on energy and cost savings, as can be seen by comparing Tables 1 and 3. Because natural gas costs less than electricity, measures saving more heating energy and therefore natural gas (e.g., RC2) usually lead to a higher percentage of energy savings than cost savings.

Table 3: Percentage of energy cost savings relative to the baseline for retro-commissioning measures

RCs	Location				
	Miami	Las Vegas	Seattle	Chicago	Duluth
RC1	0.4	0.6	0.4	0.4	0.4
RC2	0.7	3.4	7.1	4.6	4.4
RC3	7.2	7.6	8.2	7.3	5.9
RC4	0.2	0.1	0.0	0.1	0.3
RC5	NA	0.9	1.5	0.2	0.5
RC6	0.4	2.9	2.6	3.0	3.8
RC7	0.0	0.0	0.1	0.1	0.1

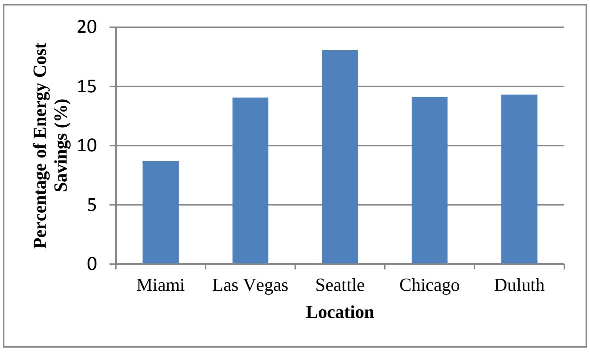

Figure 4: Percentage of energy cost savings from the packaged retro-commissioning measures relative to the baseline

Figure 4 shows the overall energy cost savings from the package of seven retro-commissioning measures. This figure indicates that implementation of operation and maintenance measures as part of a retro-commissioning process can yield an average of about 14% of energy cost reduction.

Table 4 lists the percentage of retrofit-related energy cost savings relative to the commissioned building. This table leads to similar observations as those from Table 2. However, the percentage of cost savings is more prominent than the percentage of energy savings for those measures saving electricity (e.g., RT1-RT6).

Table 4: Percentage of energy cost savings relative to the commissioned building for retrofit measures

RTs	Location				
	Miami	Las Vegas	Seattle	Chicago	Duluth
RT1	2.7	2.3	2.6	3.0	3.0
RT2	5.1	4.5	4.9	5.5	5.7
RT3	6.4	5.7	6.2	6.8	7.2
RT4	8.2	7.4	8.0	8.8	9.3
RT5	2.6	2.2	2.5	2.9	2.9
RT6	4.5	3.8	3.2	3.8	4.0
RT7	1.5	1.7	2.1	2.4	2.5
RT8	2.0	2.1	2.1	2.8	2.8
RT9	0.1	0.1	0.1	0.1	0.1
RT10	0.4	0.3	0.4	0.3	0.2
RT11	NA	0.0	0.0	0.4	0.2
RT12	5.6	7.7	5.8	5.1	4.1
RT13	7.9	9.0	9.1	7.6	7.3
RT14	0.7	1.0	0.0	0.1	0.2
RT15	3.0	4.1	3.4	3.1	3.5
RT16	4.7	3.4	0.9	1.7	1.3
RT17	0.7	2.0	0.8	0.8	0.5
RT18	1.3	1.6	0.6	0.7	0.4
RT19	0.2	0.2	0.1	0.1	0.1
RT20	1.5	1.8	0.8	0.7	0.4
RT21	2.1	2.8	3.9	3.2	3.8
RT22	0.1	0.1	0.1	0.1	0.1
RT23	0.9	1.1	1.2	1.3	1.4
RT24	1.6	3.1	2.1	0.8	1.9
RT25	0.9	0.9	0.5	0.4	NA
RT26	NA	0.5	0.4	0.3	0.7
RT27	0.2	0.8	0.5	0.4	0.3
RT28	0.1	0.1	0.1	0.1	0.1
RT29	0.9	0.9	1.1	1.1	1.2

CONCLUSION

This paper applied building simulation to evaluate the energy and cost savings of 36 retro-commissioning and retrofit measures potentially applicable to most large office buildings. The modeled results show that implementation of operation and maintenance measures as part of a retro-commissioning process can yield an average of about 22% of energy use reduction and 14% of energy cost reduction. Widening zone temperature deadband, lowering VAV terminal minimal air flow set points and lighting upgrades are effective retrofit measures to be considered. The findings from this work can help to screen and prioritize energy conservation measures if the studied building has similar characteristics as the baseline building in this paper.

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