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Informed Building Retrofit based on Simulation and Data Analysis

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ABSTRACT

With the availability of the many energy efficient technologies, significant reduction in energy consumption can be expected through retrofit of existing buildings. To achieve a cost-effective retrofit, however, a good understanding of the building system is necessary. In this study, two office buildings under retrofit in the Philadelphia area have been evaluated based on measured data and simulation outputs. The results showed that even with limited data points available, some inefficient operations and designs could be identified when combined with simulation of the integrated building systems. Thermal comfort could also be improved with appropriate redesign or controls of the buildings evaluated. By incorporating the hard constraints of the existing systems, the corresponding retrofit measures can be more cost effective. A sensitivity analysis of some key design and operation parameters provided further potential energy savings with relaxed system constraints.

1. INTRODUCTION

Office buildings account for 17% of energy consumption of all commercial buildings in the US (US Energy Information Administration, 2006). Increasing energy efficiency of office building operation is necessary to reduce energy consumption and improve environment quality. This has become increasingly imminent in recognition that over 60% of existing office buildings were built more than 30 years ago and that significant advancements in related technologies for high efficiency equipment and controls have been achieved during this time period. Many efforts have been made in both public and private sectors aiming to improve energy efficiency and reduce cost of building retrofits. Guidelines and best practices have been developed to cover a wide range of retrofits for major commercial building types (ASHRAE, 2012) (PNNL, 2011) (IEA 2009). As the first key step of a retrofit, it is essential to understand the current status of the building systems by reviewing system design documentation and any previous renovations completed for the building. Energy audit and field measurements are valuable inputs for examination of the system conditions. With data collected from design documents and field measurements, models of the integrated building envelope and HVAC systems should be created at the early stage for tradeoff analysis among different retrofit options. System simulation can provide valuable references of energy and comfort profiles as well as zoning and control options of various scenarios, which are often cost prohibitive or infeasible to achieve through physical installation or instrumentation. This analytical approach was applied in retrofit evaluation of two office buildings in Philadelphia: the Philadelphia Business & Technology Center (PBTC) and Building 101 in the Navy Yard. With practical constraints incorporated into the models, simulation results demonstrated the benefits of informed decision making in the early stage of retrofit planning.

Constructed in the 1930's, the PBTC is a building of 6 floors with an estimated total floor area of 40,000 m^2. A section of the fourth floor with approximately 1,000 m^2 of office space was first selected to undergo a retrofit of the HVAC system for improvement of energy efficiency and thermal comfort. As shown in Figure 1, the floor area is divided in two sections, each with a two-stage vertical packaged direct expansion (DX) air conditioning (AC) unit and a steam coil in a dedicated mechanical room. Two separate steam coils are used for heating of the perimeter areas. The steam heating coils are driven by a boiler for the whole building and are turned off during April 15–October 15. Air from the AC unit is delivered to the conditioned spaces through ducts and returns in the plenum through an opening in the internal wall to the mechanical room. Outdoor air enters the mechanical room through an opening in the external wall and is mixed with return air in the room before entering the unit.

Figure 1: HVAC Air Loop Layout of PBTC (Shaded: Unoccupied Rooms)

Installed 30 years ago, each of the pre-retrofit 15-ton AC units supplied conditioned air with a constant speed fan to the office rooms through fixed diffusers, although nearly half of the area is unoccupied as shown by the shaded areas in Figure 1. Both AC units were manually turned on and off each day and were controlled based on return air temperature during operation. There have been complaints about thermal comfort and indoor air quality in the pre-retrofit building. During a quick walk-through of the building, it was found the outdoor air inlet was a small fixed opening in the wall and air flow rate could not be adjusted.

Built in 1911 as a US Marine Corps barracks, Building 101 was changed into an office building in 1999. It has four floors, three above ground and one under ground, with a total conditioned area of about 7000 m^2. The HVAC system consists of a gas boiler for heating and three independent air-cooled condensing units for cooling of the north, the middle and the south sections separately. The gas boiler provides hot water for coils in the air handling units (AHUs) and the variable air volume (VAV) boxes as well. Each of the condensing units is coupled with a direct expansion AHU for cooling and a hot water coil for heating. VAV boxes with reheat are used as terminal units for the main zones in the building.

One issue related to energy performance of the HVAC system before retrofit was that the outdoor air fraction was constant throughout the year, causing more energy consumption when the outdoor air flow could have been increased to reduce the mechanical cooling load and when the outdoor air flow should have been decreased to reduce heating load during unoccupied periods. In addition, a single setpoint of indoor air temperature was used for both occupied and unoccupied hours, leading to excessive energy consumption when the building was unoccupied.

2. SIMULATION AND ANALYSIS

2.1 Case Study 1: PBTC

The retrofit plan for the PBTC is to replace the old AC units (SEER 8.3) with high-efficiency units (SEER 15) with a variable speed fan and install zone air flow dampers controlled by an occupancy sensor in each zone. When a zone is unoccupied, the supply air damper will be closed. The supply fan will be controlled by duct static pressure that is affected by open/close of the terminal dampers. Energy consumption can therefore be saved with the new AC units and more accurate occupancy-based zone control.

Sensors and an energy management system (EMS) were installed to enable pre- and post-retrofit monitoring of system operation. In addition, valuable information could be obtained for verification of the integrated system model for more accurate evaluation of retrofit options. The AHU instrumentation included power, temperatures (outdoor air, return air, supply air, condenser entering and leaving air), outdoor air flow, return air flow, and return air CO2. Space condition monitoring included temperature, relative humidity, and CO2. Plenum temperatures, outdoor air temperature, and solar irradiance were also measured.

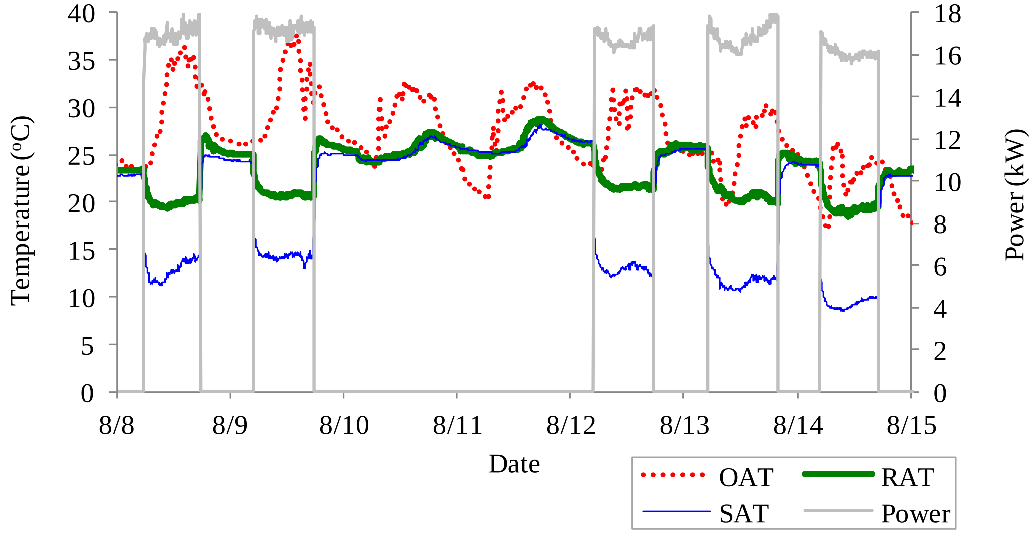


Figure 2: Measured Data of Air Temperatures and Power Input of AC Unit 2 in PBTC

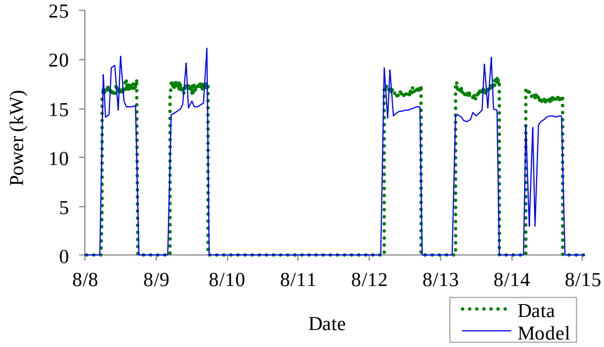
Preliminary evaluation of the measured data from the ongoing M&V provided some insights into the pre-retrofit system operation. For example, data collected between August 1 and September 16, 2013 showed that AC Unit 2 (data were not available for the AC Unit 1 at the time of data acquisition) was running non-stop at the low stage once it was turned on, even when the outdoor air temperature (OAT) became moderate during some time periods. Return air temperature (RAT) was maintained around 19˚C with an average supply air temperature (SAT) of 11˚C, as shown in Figure 2 for a week in August.

In order to estimate the potential energy savings with the new higher efficiency AC units controlled based on more accurate space occupancy, models were developed in TRNSYS 17 for the integrated system of the building envelope and HVAC equipment.

To calculate equipment performance over a wide range of off-design conditions, detailed vapor compression system models were created for both the old and the new AC units. Equipment configurations and design values from the manufacturer's catalog were used in creating the models of heat exchangers, compressors and fans.

Controls for staging of the AC units and on/off of the heating coils were developed to maintain the corresponding return air temperatures during occupied hours. The new AC units run at low stage when the return air temperature is between 24-26˚C and at high stage when the temperature is over 26˚C. Steam coils are controlled to deliver air at 35˚C once the return air is below 21˚C.

Before the analysis of retrofit options, the TRNSYS model was examined by comparing electric energy consumption of AC Unit 2 and indoor air temperature between simulation results and measured data. As shown in Figure 3, the overall profiles are consistent between simulation outputs and measured data, but the model under-predicted electric energy by about 9.2%. Indoor air temperature calculated by the model deviated from data by -0.9˚C during occupied periods and +1.9˚C during unoccupied periods on average. The higher energy consumption from data may be due to the degradation of the AC unit over the years. The indoor air temperature swing by simulation across measured data could be caused by an underestimate of the building thermal mass. It should be noted that this comparison was done for a check of general agreement between simulation outputs and measured data of cooling electric power and temperature profiles. A full calibration and validation of the model was not applicable because of the uncertainties in system controls, system degradation and building envelope data. These differences may be reduced if more detailed information about the AC unit controls and building envelope were available.



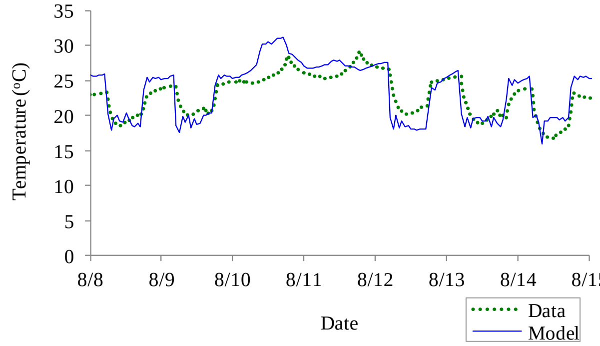


Figure 3: Comparisons of Power and Indoor Air Temperature between Data and Simulation

With this preliminarily verified model, annual simulation was performed for the integrated system with the old low-efficiency AC units and the new high-efficiency AC units separately. Simulation with different design cooling capacity of the AC unit indicated that a 12-ton unit is sufficient for each section of the area to maintain the indoor air condition with an approximate oversizing factor of 20%. This led to a 20% reduction of the design capacity of the 15-ton pre-retrofit unit. Excessive oversizing of the pre-retrofit unit was also indicated by the continuous operation of the unit at low stage even at a low return air temperature of about 19°C on average during operation as shown in the measured data in Figure 2.

To estimate the annual energy consumption of the actual pre-retrofit operation with the 15-ton units, return air temperature setpoints of 18°C and 20°C were assumed for the first and second stage cooling based on observation of measured data. To understand the impact of the temperature setpoint alone, system operation was also simulated with return air temperature setpoints of 24°C and 26°C for the first and second stage cooling. In the system after retrofit, with a variable speed fan and terminal air flow control, the AC units were simulated to maintain thermal comfort in the occupied zones only. Currently, nearly half of the floor area is not occupied, which results in a reduction of supply air flowrate by about 43%, as shown in Figure 4.

Based on simulation outputs with the corresponding TRNSYS models, annual energy consumption of three design and operation options have been compared against the pre-retrofit baseline. As summarized in Figure 5, with full occupancy of all the spaces, by adjusting the indoor air temperature setpoint for cooling from the pre-retrofit 18/20 °C to 24/26°C (option 1), annual electric energy can be reduced by 38%; using the new high-efficiency AC units (Option 2), annual HVAC electric energy will decrease by 58%. If only the occupied spaces are conditioned (Option 3), not only cooling electric energy can be reduced by 78% but heating gas will also be saved by 51% compared to the pre-retrofit system.

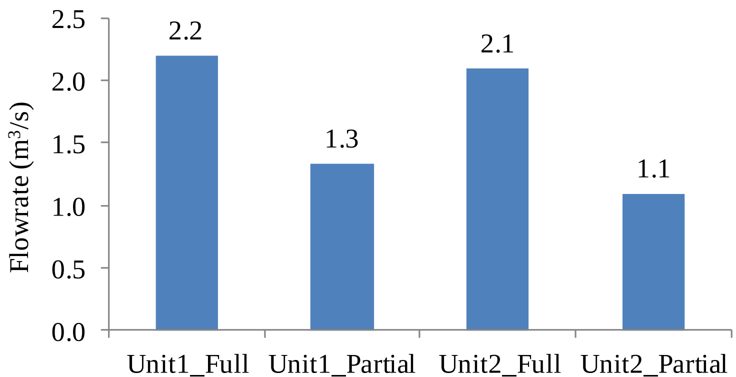


Figure 4: Supply Air Flowrates for Full and Partial Occupancies

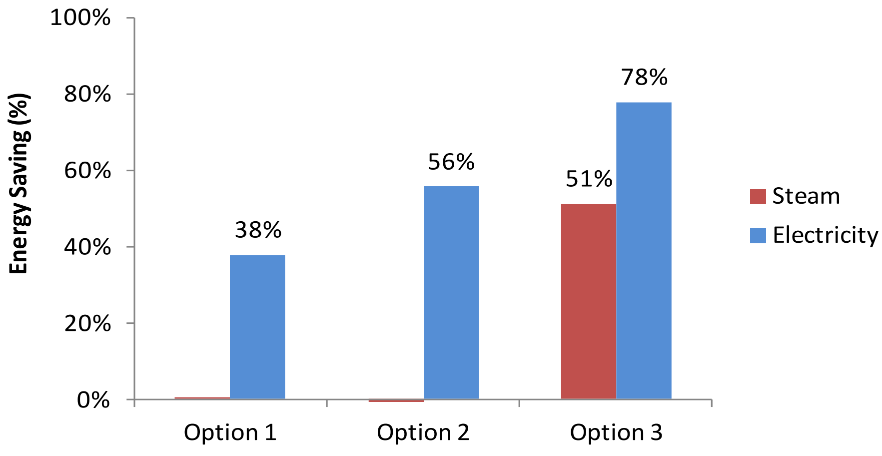


Figure 5: Annual Energy Savings of Different Retrofit Options for Building PBTC
Option 1: Old AC Units, Full Occupancy, Return Air Temperature Setpoint 24/26°C;
Options 2 & 3: New AC Units, Return Air Temperature Setpoint = 24/26°C, full & partial occupancy.

For all the cases evaluated above, outdoor air flow was maintained at the design value because of the fixed size of the opening in the wall for outdoor air. Electric energy may be further reduced by using an economizer. However, this is constrained by the building structure for an enlarged outdoor air opening and an opening for exhaust air. In addition, ductwork may need to be installed for reliable control of outdoor air. The extra cost may not be justified for this specific retrofit.

2.2 Case Study 2: Building 101

This case study was performed to evaluate the energy impact of outdoor air controls and indoor air temperature setback as two of the most cost effective means for energy performance improvement by introducing selected control options into the EnergyPlus model. The integrated system model for the pre-retrofit baseline was created in EnergyPlus 7.2.

A preliminary verification of the integrated system model was conducted by comparing energy consumption trends between the simulation outputs and measured data using instrumentation similar to that described for PBTC. For the time period of March 1 – March 11, 2012, the model predicted 11% and 14% more electric energy consumption for the whole building and AHU-1, respectively, than indicated by the measured data. Note this comparison was only used to understand the deviation of model prediction from data as a full validation was not feasible due to limited data availability.

In the pre-retrofit system, outdoor air flow fractions were fixed around 16%, 10% and 6% for AHU-1, 2 and 3, respectively, throughout the year. Air side economizers can be used in the AHUs to reduce energy consumption by varying the flowrate of outdoor air. Air side economizers are widely used in air conditioning systems today to lower energy consumption (ASHRAE, 2010). The ideal control would be using a dry bulb limit for dry coil operation and an enthalpy limit or differential enthalpy for wet coil operation (Taylor, 2010). For a specific application, however, control options and the limits of the economizer should be evaluated to achieve optimal energy performance within the existing constraints.

For Philadelphia in Climate Zone 4a, an economizer is not required and differential dry bulb control alone is prohibited by ASHRAE Standard 90.1 due to the relatively high humidity of outside air. Feasible control options include fixed dry bulb or enthalpy based or a combination of the two. Enthalpy based controls should be used with caution because of the lower accuracy and higher cost of humidity sensors compared to temperature sensors (Taylor, 2010). For fixed dry bulb control, the actual optimal value needs to be determined given the fact that a lower value for the high limit reduces excessive energy consumption by reducing outdoor air which is more humid than return air. However, it may also miss some energy reduction potential under dry coil operation by eliminating outdoor air that is cooler than return air, and vice versa with a higher dry bulb limit. A tradeoff analysis based on annual energy simulation can be used to determine the optimal control of the economizer.

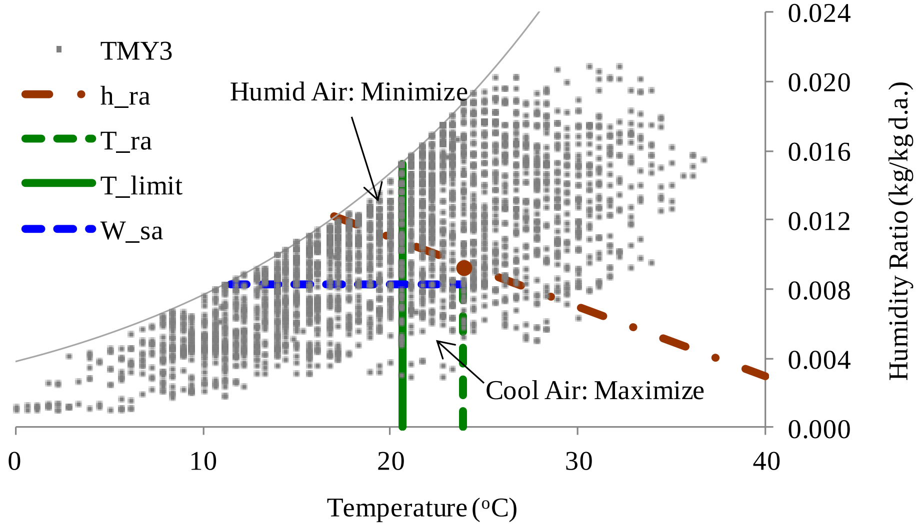


Figure 6: Economizer High Limit Options for Building 101

In addition to the selection of economizer controls, constraints of the existing building must be taken into account to obtain realistic energy savings predictions. In Building 101, outdoor air supply is limited by the physical size of the supply path. The maximum outdoor air fractions are about 20%, 20% and 26% for AHU-1, 2 and 3, respectively. With these limits included in the simulation, Table 1 summarizes the reduction of energy consumption of electricity for cooling and gas for heating with six different outdoor air controls compared against the pre-retrofit baseline. By turning off outdoor air supply during unoccupied hours without any additional sensor, electric energy for cooling and gas for heating can be reduced by 15% and 26%, respectively. By applying economizer controls with the scheduled minimum outdoor air supply, the cooling electricity reduction reached 17%-19%. With similar energy savings among all five economizer controls, the fixed dry bulb of 18.3°C becomes the most cost-effective option - it reduces cooling electricity by 2% more than the control with fixed dry bulb of 20.6°C, and it is essentially comparable (within 0.2%) to control schemes using additional humidity sensors, i.e., the enthalpy limit (one additional humidity sensor) or differential enthalpy control (two additional humidity sensors).

As another low-cost option, indoor air temperature setback was tested by increasing the cooling setpoint from 24°C to 28°C and decreasing the setpoint of heating from 21°C to 16°C during night time, weekends and holidays. As shown in Table 1, by applying the setpoint adjustment with the original fixed outdoor air flowrate, cooling electric and gas heating energy could be reduced by 9% and 17%, respectively. When combined with the economizer with fixed dry bulb of 18.3°C, 20% and 31% of cooling and heating energy were saved compared to the baseline. The relatively small saving of cooling by adding setback to the fixed dry bulb was mainly because of the reset of supply air temperature setpoint with outdoor air temperature.

3. DISCUSSION AND CONCLUSIONS

In this study, energy performance of the HVAC systems of two retrofit buildings in the Philadelphia area were analyzed base on preliminary data assessment and simulation outputs. The results demonstrated that understanding of existing conditions and constraints as well as the feasible technologies in a specific application is essential to a successful retrofit.

For building PBTC, even with the limited measured data, it was clear that the controls of the existing system should be modified to improve both thermal comfort and energy performance of the HVAC system. A field visit helped to understand the actual constraints including the size of the opening for outdoor air supply and the actual occupancy level of the area. Such information provided a realistic basis for model predication of system performance. In addition to the significant energy savings of system operation by control modifications, simulation of the annual load and the temperature profile led to a size reduction of the AC units by 20%, which helped to save both first cost and operational costs of the HVAC system.

Table 1: Annual Energy Savings for Cooling and Heating of Building 101

Control Options	Cooling Electricity	Heating Gas
No OA for Unoccupied Hours	15%	26%
Fixed Dry Bulb 18.3 ^{o}C	19%	26%
Fixed Dry Bulb 20.6 ^{o}C	17%	26%
Differential Enthalpy	19%	26%
Differential Enthalpy w/ Dry Bulb 18.3 ^{o}C	19%	26%
Differential Enthalpy w/ Dry Bulb 20.6 ^{o}C	19%	26%
Temerature Setback	9%	17%
Fixed Dry Bulb 18.3 ^{o}C w/ Setback	20%	31%

For Building 101, similar constraints were implemented for outdoor air flowrate in simulation. Among the outdoor air control options with different implications of cost and reliability, temperature setback with an economizer of fixed dry bulb of 18.3°C was identified as the most cost-effective option, which is slightly more efficient than the value of 20.6°C recommended by ASHRAE Standard 90.1 for Climate Zone 4a. To provide a reference of potential further energy savings, 'ideal' outdoor air flow control was simulated without the physical constraint of the air flow path, which showed 7% more cooling electric energy reduction than that with the current flowrate limits.

It should be noted that timely collection of data and knowledge of a retrofit building are critical for not only initial system assessment but also model generation and validation that can be utilized for evaluation of retrofit options. One challenge encountered in this study was the availability of quality data for system analysis and model validation, which is a common issue for building energy simulation, especially with old retrofit building systems.

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DISCLAIMER

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