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# ANALYSIS OF THE POTENTIAL ENERGY SAVINGS FOR 14 OFFICE BUILDINGS WITH VAV SYSTEMS

Jingjing Liu
Graduate Research Assistant

Juan-Carlos Baltazar, Ph.D.
Associate Research Engineer

David E. Claridge, Ph.D., P.E.
Professor/ Director

Energy Systems Laboratory, Texas Engineering Experiment Station
Texas A&M University, College Station, TX

## ABSTRACT

At the beginning of an existing building commissioning (EBCx)/energy retrofit project, some form of screening is usually applied to determine whether there is sufficient potential for savings to justify a formal EBCx assessment/energy audit. In this study, an improved methodology for potential energy savings estimation from EBCx/retrofit measures, based on Baltazar's methodology (2006), is proposed to perform this type of screening. The improvements are included on optimization parameters, space load calculation, simulation of buildings with multiple types of HVAC systems, AHU shutdown simulation, among others.

The improved methodology was used to estimate annual potential energy cost savings for 14 office buildings in Austin, TX with either single duct VAV (SDVAV) systems or dual duct VAV (DDVAV) systems. The estimates are based on very limited information about the buildings and the built-in HVAC systems as well as one year of utility bills. From this analysis, the methodology has predicted an average total potential savings of 36% for SDVAV systems with electric terminal reheat, 22% for SDVAV systems with hot water reheat, and 25% for DDVAV systems. To validate these results, the estimated potential savings are compared with savings proposed in respective EBCx assessment reports. Based on the comparison of the report estimates and the potential savings with the improved methodology, it was found that "generalized" factors of assessment predicted energy cost savings to estimated potential energy cost savings could be found. The factors identified in these cases were 0.68, 0.66, and 0.61 for each type of system - SDVAV w/electric reheat, SDVAV w/hot water reheat, and DDVAV, respectively.

## INTRODUCTION

Today, as energy prices increase, saving money on energy bills through an existing building commissioning (EBCx) or an energy retrofit project is attractive to many commercial building owners. At the beginning of such a project, some form of screening is often applied to determine whether there is sufficient potential for savings to justify implementation of commissioning measures or at least a deeper EBCx assessment. If screening results are positive, the assessment/audit is performed and the potential for energy savings in the building is evaluated before the owner/operator decides that further work is likely to produce significant energy savings meeting the owner's economic criteria.

Baltazar (2006) proposed a methodology for estimating the potential energy savings in commercial buildings, which is considered appropriate for this type of pre-screening. At its core is a procedure for obtaining the minimum energy use cost required to maintain indoor thermal comfort. This methodology was applied to several existing buildings that have been retrofitted and/or commissioned. The measured savings in one of the buildings was about 85% of the estimated potential savings, close enough to suggest value for this approach. This methodology seems suitable for screening purposes and is promising in realizing the necessary changes in variable values to optimize the energy use cost. However, to make it a useful tool in EBCx assessments or energy audits, it is desirable to uncover the actual relationship between savings that are achievable in EBCx practice and the potential savings identified by the methodology. In this study, Baltazar's methodology is improved in several ways and is used to estimate the potential energy savings for 14 office buildings in Austin, TX with VAV systems. The predictions are compared with savings proposed in EBCx assessment reports, and preliminary generalized factors are found between the two.

## POTENTIAL ENERGY SAVINGS ESTIMATION METHODOLOGY

## Baltazar’s Methodology for Potential Energy Savings Estimation

Baltazar’s methodology (Baltazar and Claridge, 2007) defines the potential energy savings in each outside air temperature bin as the difference between the actual energy cost during a particular period, preferably a whole year, and the minimum energy cost needed to maintain comfortable indoor conditions using the existing air-side HVAC systems in the building under the same weather conditions (Eq.1). Here the minimized energy cost is comprised of individual costs of electricity, cooling and heating. The electricity cost consists of two parts: (1) lighting and equipment consumption which is estimated from measured/benchmark data and remains constant, and (2) fan power consumption which is simulated. (Eq.2)

$$\begin{aligned}\text{Potential Energy Savings} &= \text{Energy Cost}_{\text{ACTUAL}} \\ &\quad - \text{Energy Cost}_{\text{MINIMIZED}}\end{aligned} \tag{1}$$

$$\begin{aligned}\text{Energy Cost} &= (\text{ELE Cost}_{\text{LTEQ}} + \text{ELE Cost}_{\text{FANP}}) \\ &\quad + \text{CHW Cost} + \text{HHW Cost}\end{aligned} \tag{2}$$

The required outside air dry-bulb temperature bin data, mean coincident humidity ratios and the total of measured energy consumption to determine the potential savings can be prepared from hourly measured weather and consumption data.

The essence of this methodology is the procedure for determining the minimum energy use cost, which has two major components as Figure 1 demonstrates: the model is shown as a compound function in the figure, which thermodynamically represents the performance of the built-in HVAC system and the numerical procedure for energy cost minimization. The model takes weather conditions into account through a load calculation procedure and calculated load becomes part of the input for the air-side system simulation. Both the load calculation and system simulation follow the modified bin method (Knebel, 1983). The numerical procedure generates and seeks the parameter values which will produce minimum total energy use cost while meeting the indoor thermal comfort requirements.

Sequential exhaustive search is employed as the optimization method and is applied at representative equivalent ambient conditions obtained by “bin sorting”. Figure 2 illustrates the procedure for implementation of the methodology in determining the minimum energy cost for each bin. The total potential energy cost savings during the period evaluated are then the sum of savings found in each bin.

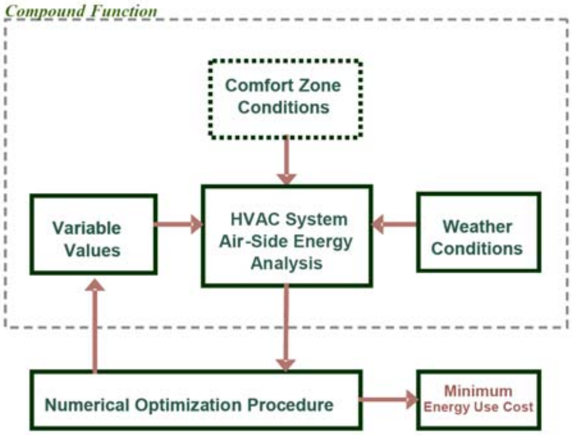


Figure 1 Block diagram of the methodology for potential energy savings determination (Baltazar, 2006)

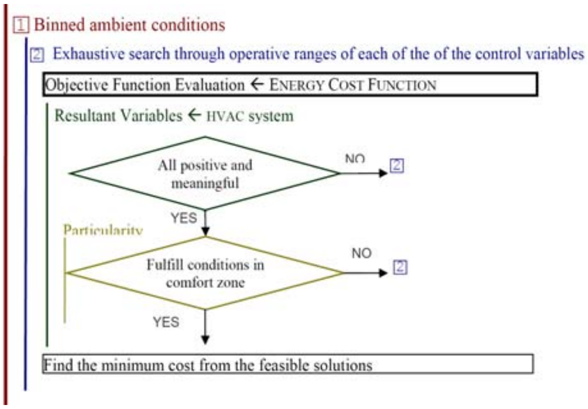


Figure 2 Flowchart of the methodology for evaluating potential energy savings in a building through binned ambient conditions. The total potential savings will be the sum of the individual products of the energy savings in each bin multiplied by its frequency. (Baltazar, 2006)

## Improvements on Methodology

In the potential energy savings estimation (PESE) toolkit developed for internal use, several major improvements have been made on Baltazar’s methodology as follows:

**Optimization parameters.** Four parameters are selected for optimization in Baltazar’s methodology: cold deck and hot deck (for dual duct systems) leaving air temperature set points; minimum supply airflow per square foot of floor area (for VAV systems); and the fraction of outside airflow in total design airflow. In this study, the volumetric outside airflow is optimized instead of optimizing outside air fraction because volumetric control is required in order to implement the optimization result; the minimum supply airflow is not optimized since the optimized value is always equal to the designated lower limit. In addition to the above changes, room temperature set points in the exterior and interior zones are included as additional optimization parameters, since space loads are dependent on these two parameters. In addition, options are provided in PESE to optimize any combination of these five parameters. This may be helpful in evaluating savings based on the existing control capability.

**Space load calculation.** Baltazar (2006) calculated space cooling and heating load based on a fixed room temperature set point (e.g. 75°F) for the simulation. To effectively enable optimization of the room temperature set points, this study uses a space load calculation procedure based on the modified bin method that is linked with the optimization procedure, so that the space load is re-calculated dynamically as room temperature set points change in the optimization process.

**Simulation of buildings with multiple types of systems.** The PESE uses the fractions of exterior and interior zone areas served by each type of system as input parameters. They are applied to calculated whole-building exterior and interior zone space loads. Here, it is assumed that the space load is proportional to floor area. This assumption is consistent with buildings having a single system type serving an entire floor or several floors, or buildings having two different types of systems serving the exterior zone and interior zone respectively.

**Air-handling unit (AHU) shut-down simulation.** The cooling and heating energy use during unoccupied periods is typically comprised of two parts: the energy use during the AHU shut-down period (there is usually still a lower and upper limit on the room temperature that can result in AHU operation during the unoccupied period) and the energy use during start-up. Using energy balance, this energy use can be estimated to be approximately equal to the algebraic sum of the largest two components of the space load: the internal heat gain and the conduction load.

During the AHU shut-down period, the room temperature changes under the influence of internal heat gain and conduction through the building envelope. This challenges one of the major limitations of the modified bin method, which is based on time averaging techniques and does not take the thermal capacitance of the space into account. However, based on the measured data in an office building in Texas, where AHU shutdown has been implemented, it is found that the average room temperature during the unoccupied period has an approximately linear relationship with the average outside air temperature. This finding is used to estimate the average conduction load during the unoccupied period. It is noted that the relationship can vary from building to building depending on the building's size, construction, internal heat gain, etc.

## APPLICATION OF THE POTENTIAL ENERGY SAVINGS ESTIMATION METHODOLOGY TO 14 OFFICE BUILDINGS

The methodology described in the previous section is expected to predict a theoretical upper limit to the potential energy savings in a building. However, in order to make the methodology useful in real projects, it is desirable to determine the fraction of the estimated potential savings that may be achievable in EBCx practice. In this section, the methodology is used to estimate potential savings for 14 office buildings with VAV systems. The results are compared with savings predicted in EBCx assessment reports, and the use of generalized factors to improve the correlation between potential savings identified by this methodology and those identified in EBCx assessments is investigated.

### General Building Description

The 14 buildings selected for this study meet two criteria: (1) the building is mainly used as offices; and (2) most of the building is served by either single duct VAV or dual duct VAV systems.

These buildings were built between 1959 and 2000 with gross areas between 70,000 to 500,000 ft$^2$. Six of these buildings are equipped with SDVAV systems, while the other eight buildings have DDVAV system as the main HVAC system type. Among the six buildings which have SDVAV systems, three use electricity for terminal reheat instead of hot water. Therefore, the buildings are grouped into three categories: three buildings with SDVAV systems with electric reheat, three with SDVAV systems with hot water reheat, and eight with DDVAV systems.

### Methodology Adjustments

Conducting potential energy savings estimation using the methodology introduced in the previous section requires hourly consumption data for electricity, cooling and heating. However, the only available consumption data in this project are one year of utility bills for electricity and natural gas. Nevertheless, the methodology still can be used to estimate the annual potential energy savings for these buildings with some adjustments as follows:

The annual potential energy savings are determined as the difference between the measured or estimated annual consumption and the minimized annual consumption obtained with the methodology. One year hourly weather data of dry-bulb and dew-point temperatures are used to prepare the bin data input. The minimum electricity, chilled water and hot water consumption in each bin are obtained by the methodology, and the annual total of each energy type are calculated. Then the chilled water and hot water consumption needs to be converted to electricity and natural gas consumption, respectively. The efficiencies used for chilled water and hot water generation here are 1 kW/Ton (chiller plant overall efficiency) and 0.8 (boiler efficiency). The same efficiencies are also used in converting the energy prices from electricity ($0.0753/kWh) and natural gas ($8.466/MMBtu) to chilled water and hot water as part of the input required by the methodology.

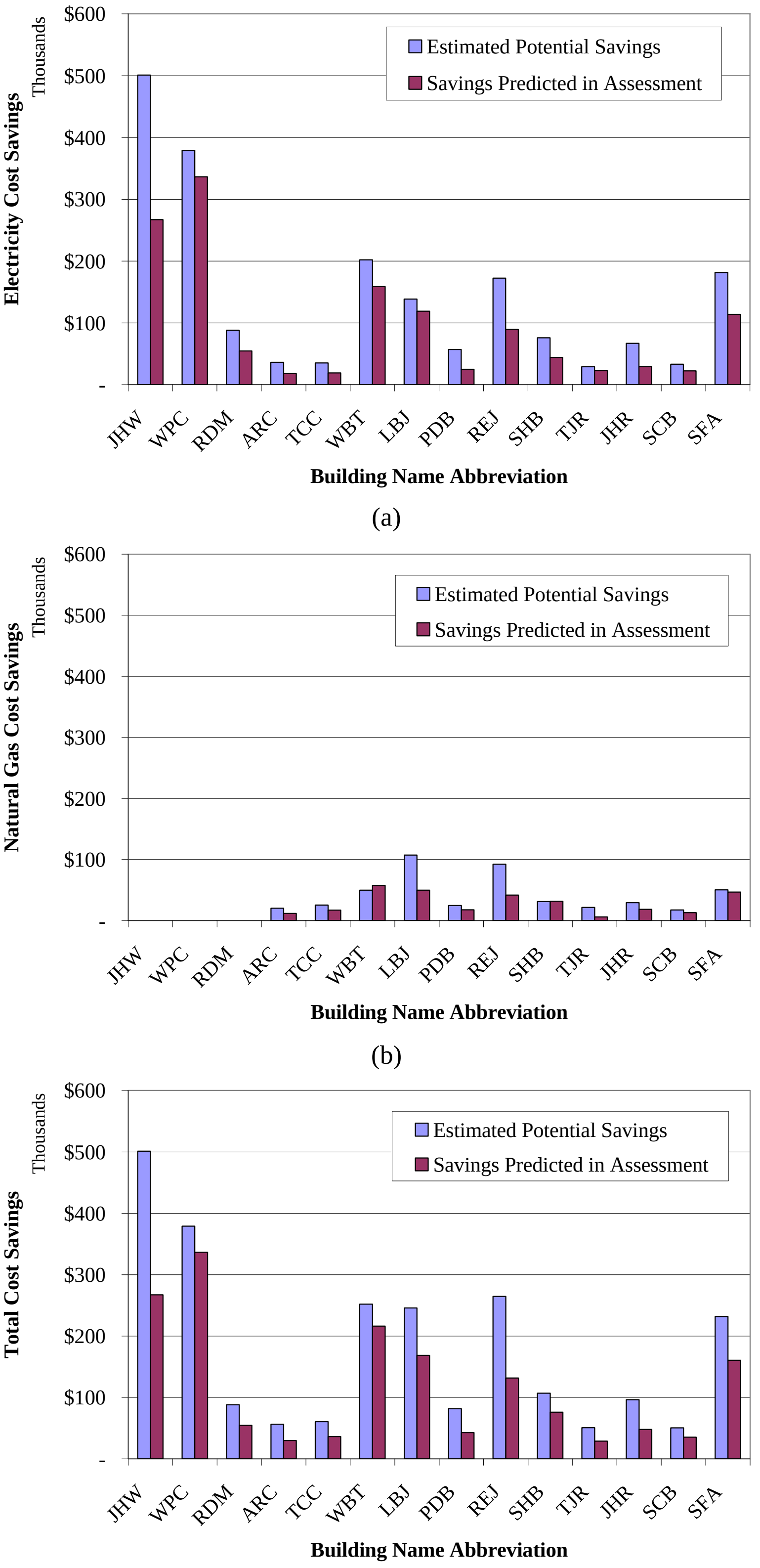
## Potential Energy Savings Estimation

The current annual total energy use per square foot of gross area is given in Table 1. The average annual usage is 31.57 kWh/ft$^2$/yr for electricity, 25.74 kBtu/ft$^2$/yr for natural gas, which are equivalent to 127.93 kBtu/ft$^2$/yr of energy consumption in total using simple conversion of kWh to kBtu. Before optimization, a simulation representing the current operation of each building is conducted using assumed system operation parameters. The simulation parameters are adjusted so that the simulated annual consumption approximately matches the annual total of utility bills. Then an optimization is performed with AHU shutdown, minimum airflow reset, and all applicable optimization parameters activated — room temperatures, cold deck and hot deck (only in DDVAV system) reset schedules and outside air intake.

Table 1 gives the estimated potential energy and cost savings. It shows that the SDVAV systems with electric terminal reheat have the greatest potential for savings, with an average of 36%. The total potential energy savings for the SDVAV systems with hot water reheat (22% on average) and DDVAV systems (25% on average) are nearly as large. The potential savings on electricity use and natural gas use are 16% and 95% on average for SDVAV systems with hot water reheat, and 18% and 97% for DDVAV systems.

Table 1 Estimated potential energy savings in the 14 office buildings, and comparison with savings predicted in EBCx assessment report

| Building Name | System Type | Annual Energy Usage (kBtu/ft$^2$/yr) | Potential Percent Savings (%) | Potential Energy Cost Savings ($) | Savings Predicted in Assessment ($) | Ratios of Assessment Predicted Savings to Potential Savings |
|---|---|---|---|---|---|---|
| JHW | SDVAV E.R. | 122.51 | 38 | 501,057 | 267,062 | 0.53 |
| WPC | SDVAV E.R. | 101.81 | 36 | 379,123 | 336,462 | 0.89 |
| RDM | SDVAV E.R. | 98.74 | 33 | 88,144 | 54,573 | 0.62 |
| ARC | SDVAV | 129.26 | 20 | 56,407 | 29,871 | 0.53 |
| TCC | SDVAV | 137.45 | 23 | 60,538 | 36,214 | 0.60 |
| WBT | SDVAV | 108.51 | 25 | 252,016 | 216,267 | 0.86 |
| LBJ | DDVAV | 162.57 | 27 | 245,787 | 168,557 | 0.69 |
| PDB | DDVAV | 154.04 | 19 | 81,646 | 42,664 | 0.52 |
| REJ | DDVAV | 129.15 | 37 | 264,716 | 131,567 | 0.50 |
| SHB | DDVAV | 129.26 | 24 | 106,909 | 75,916 | 0.71 |
| TJR | DDVAV | 129.01 | 21 | 50,594 | 28,683 | 0.57 |
| JHR | DDVAV | 129.26 | 23 | 96,354 | 47,837 | 0.50 |
| SCB | DDVAV | 137.45 | 28 | 50,449 | 35,287 | 0.70 |
| SFA | DDVAV | 122.09 | 22 | 231,853 | 160,570 | 0.69 |



(a)

(b)

(c)

Figure 3 Comparison of estimated potential electricity (a), natural gas (b), and total (c) cost savings with savings predicted in the EBCx assessment report in the 14 office buildings

## Comparison with EBCx Assessment

The estimated potential energy cost savings are compared with savings predicted in the EBCx assessment report for each building. For each of these buildings, the ratio between the predicted savings in the assessment report and the potential savings is determined. Then, a generalized factor for each type of system is obtained as an indicator of the fraction of the estimated potential energy cost savings that may be achieved in EBCx assessments for office buildings with VAV systems in the future.

Figure 3 also illustrates comparisons of electricity, natural gas, and the total savings. It shows that the estimated potential savings is larger than the total savings predicted in the assessment report in each of the buildings. The amount of savings predicted in the assessment report is given in Table 1 with the ratio to estimated potential savings provided. The average ratios in each group of buildings are used as the generalized factors for each type of system, as shown in Table 2. The range of ratios in each group is also provided. The generalized factors of total energy savings are 0.68 for SDVAV systems with electric reheat, 0.66 for SDVAV systems with hot water reheat, and 0.61 for DDVAV systems. The generalized factors for electricity and natural gas are 0.61 and 0.81 for SDVAV systems with hot water reheat, and 0.61 and 0.66 for DDVAV systems. Larger variations are observed on the ratios for natural gas than those for electricity, because savings on electricity weight more in the optimization considering that its price (22.069/MMBtu) is much more expensive for the same amount of energy.

It should be noted that the savings predicted in the assessment report are largely based on simulations and include savings from improvement on water-side of the system as well as common retrofit savings, such as installing VFDs on chilled water and hot water pumps, DDC upgrade, etc. This explains the large values of ratios in building WPC and WBT, where significant retrofit measures are reported in the assessment. Therefore, the ratios obtained above are expected to be smaller if only savings on the air-side are compared. Nevertheless, the predicted savings from AHU shutdown and improvements on the air-side dominate the total savings in the assessment report for most buildings.

Table 2 Averages and ranges of ratios of savings predicted in the EBCx assessment report to estimated potential energy savings in the 14 office buildings

| System Type | Electricity | | Natural Gas | | Total | |
|---|---|---|---|---|---|---|
| | Average | Range | Average | Range | Average | Range |
| SDVAV with electric reheat | 0.68 | 0.53-0.89 | | | 0.68 | 0.53-0.89 |
| SDVAV with hot water reheat | 0.61 | 0.50-0.78 | 0.81 | 0.59-1.15 | 0.66 | 0.53-0.86 |
| DDVAV | 0.61 | 0.44-0.86 | 0.66 | 0.28-1.02 | 0.61 | 0.50-0.71 |

## CONCLUSIONS

In this paper, the methodology for potential energy savings estimation from EBCx/retrofit measures proposed by Baltazar is improved in several important aspects and is implemented in a spreadsheet based prototype program for testing. Then the methodology is used to estimate annual potential energy savings in 14 office buildings with VAV systems. The estimations of the improved methodology are compared with savings predicted in the commissioning assessment report. The results show it may be helpful to study the correlation by using generalized factors of assessment predicted energy cost savings to estimated potential energy cost savings. The generalized factors identified in this application are 0.68 for SDVAV systems with electric reheat, 0.66 for SDVAV systems with hot water reheat, and 0.61 for DDVAV systems. The basis of this study could be the base to find a correlation between measured savings and estimated potential savings in a large number of buildings with EBCx measures implemented.

## REFERENCES

Baltazar-Cervantes, J.C. 2006. *Development of an Automated Methodology for Calibration of Simplified Air-Side HVAC System Models and Estimation of Potential Savings from Retrofit/Commissioning Measures.* Mechanical Engineering Department, Texas A&M University, College Station, TX.

Baltazar, J. C. and Claridge, D., 2007, “Methodology for the Determination of Potential Energy

Savings in Commercial Buildings", *Proceedings of the 7th International Conference for Enhanced Building Operation (ICEBO 2007)*, ESL - IC - 07/11 - 11, San Francisco, CA., October 31 - November 2, 2007.

Knebel, D. E. 1983. *Simplified Energy Analysis Using the Modified Bin Method*. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers.