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METHODOLOGY FOR THE DETERMINATION OF POTENTIAL ENERGY SAVINGS IN COMMERCIAL BUILDINGS

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ABSTRACT

This paper describes a methodology to determine potential energy savings of buildings with limited information. This methodology is based upon the simplified energy analysis procedure of heating, ventilation and air condition (HVAC) systems and the control of comfort conditions. Numerically, the algorithm is a tailored, exhaustive search of all the independent variables that are commonly controlled for a specific type of AHU system. The potential energy savings methodology has been applied to several buildings that have been retrofitted and/or previously commissioned. Results from the measured savings for the Zachry Engineering Building (ZEC), of Texas A&M University, after being commissioned showed a close agreement to the calculated potential savings (~85%).

INTRODUCTION

Many study opportunities can be identified for using calibrated models to lower energy use in buildings. Calibrated models are used as a base case for innumerable operation conditions in a building. For example, the calibrated model may be used as a reference to diagnose misbehavior of significant variables, to alert of out of range operation conditions, and to assist in the optimization of HVAC systems operation (Liu and Claridge, 1998). Another study opportunity related to the calibration of an HVAC system model is the determination of potential savings from improved operation of such systems. A calibrated simulation could be used to estimate the potential savings from a proposed retrofit or to explore the potential savings from changing operational strategies of HVAC systems – similar to, or in replacement of, energy audits.

This paper describes a methodology for the determination of potential savings, its basis, and its components.

POTENTIAL SAVINGS ESTIMATION METHODOLOGY

The energy use in a commercial building is dependent on the outdoor environmental conditions, the building's physical characteristics, and the operation conditions of its systems. The main objectives of the operation of buildings' HVAC systems are either to provide overall comfort for their occupants or to preserve a comfortable ambiance for work. Comfort is an important factor that is related to productivity and health; buildings should be maintained with adequate levels of clean air, luminance, and temperature.

Thus, it is recognizable that the potential energy savings in a building may be obtained from the minimization of its energy loads and from complying with the comfort conditions required for the specific occupant activities and type of building. Therefore, the minimum energy needed to provide comfort conditions in a building may be obtained through an optimization algorithm.

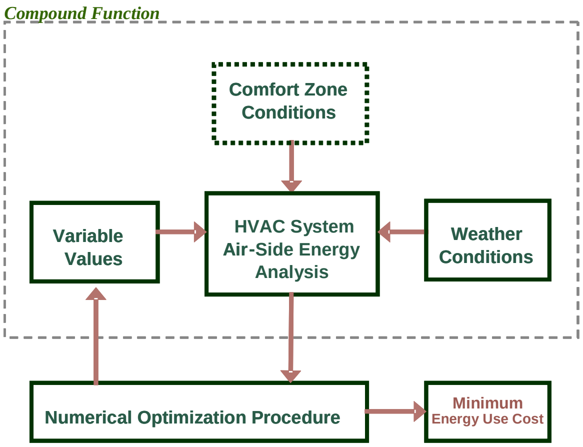

Figure 1 Block diagram of the methodology for determination of potential savings.

The potential energy savings can be defined as the difference between the actual energy use during the period of interest and the minimum energy use to obtain indoor comfort conditions under the same period's weather conditions.

$$\textit{Potential Energy Savings} = \textit{Energy Use}_{\text{ACTUAL}} - \textit{Energy Use}_{\text{MINIMIZED}} \quad \text{(Eq. 1)}$$

Figure 1 presents a block diagram of the developed minimization methodology. Two major components are identified: a numerical procedure for the minimization of the energy use and the compound function that thermodynamically represents the built-in HVAC system's performance. The compound function includes the simplified energy analysis modeling for any major-representative HVAC system in the building, the ambient conditions where the building is located, and the psychrometric definition of the comfort zone. The numerical methodology seeks and generates the parameter values that will produce the minimum building energy use.

The algorithm for the optimization consists of the ordered interaction between the HVAC system modeling and the numerical modules until the minimum is reached. Since the compound function is dependent on ambient conditions, which are time and location dependent, the minimization cannot be determined as in continuous functions. Thus, the methodology should be applied to representative ranges of these ambient conditions; the scheme fits perfectly to a bin sorting algorithm. The methodology to determine the potential savings will be applied to the total range of the ambient conditions – where the average outside dry-bulb temperature is the main variable and the outputs have to be integrated based on the bin temperature distribution.

MATHEMATICAL FORMULATION OF THE POTENTIAL SAVINGS METHODOLOGY

As mentioned above, the methodology for the determination of potential savings may be formulated as an optimization scheme. Also, due to the functional dependence on ambient conditions, the optimization should be executed throughout that weather bin distribution, assuring an equivalent and appropriate representation of the problem.

The potential energy savings methodology is based on two main parts: the definition of the optimization scheme and the numerical algorithm to solve it. While an optimization algorithm seeks a solution in the feasible region that has the minimum value of the objective function, the optimization scheme is the mathematical formulation of the objective function and the specification of the constraints that define the feasible region. In this study, the mathematical representation for the potential savings methodology may be expressed as follows:

Objective Function:

minimize C_T

where $C_T = C_{HHW} + C_{CHW} + C_{EF}$

C_T is the total cost of energy use in the building, C_{HHW} is the cost of the heating loads, C_{CHW} is the cost of the cooling load, and C_{EF} represents the electricity cost of the electricity that fans utilize to move the air at specific outdoor conditions.

Subject to the following constraints:

a) System of equations, with n variables x, that model a specific HVAC system (See Baltazar-Cervantes, 2006)

$$F(x_i) = 0 \qquad i=1\ldots n$$

b) Primary or control variables, x_j, values must fall within practical ranges

$$x_{j,1} \geq x_j \geq x_{j,2} \qquad j=1\ldots m$$

where the subscripts *1* and *2* correspond to the lower and upper limits for each of the operation variables ($n > m$)

c) Secondary or resultant variables, x_k, must have a positive value that is physically reasonable

$$x_k \geq 0 \qquad k=1\ldots q$$

where $q = n - m$

d) In addition to meeting these conditions, comfort parameters, temperature (T) and humidity ratio (w), must fall within the comfort conditions "zone" limits

$$\{T_z, w_z\} \in \textit{Comfort conditions "zone"}$$

where the subscript z refers to the zones in the building, which for a simplified modeling are grouped as interior and exterior zones.

The boundaries of the comfort conditions "zone" utilized in this procedure are those defined in *ASHRAE Standard 55* (ASHRAE, 2001). These boundaries are illustrated in Figure 2 and described in a section below.

The number of variables to be evaluated, control and resultants, depends on the HVAC system assumed or identified in a building, e.g. In contrast to the modeling of a SDCAV systems, the one for a DDVAV . must consider both the cold deck and hot deck temperature schedules in the minimization.

From the solution of this optimization problem, the minimum heating and cooling requirements can be calculated. It should be remembered that the results are related to a particular ambient condition, and in order to obtain the total minimized energy use loads, the procedure should be repeated for all the environmental conditions at the building location – the optimization must be performed for each bin of weather data.

Comfort Conditions "Zone" – Psychrometric Description

The comfort conditions have been specified to provide an acceptable thermal environment for occupants wearing typical indoor clothing while engaged in near sedentary activity. These conditions are generally plotted on a psychrometric chart in terms of bounded areas as depicted in Figure 2. From a thermal point of view, a comfortable environment is one which at least 80% of the active persons would find acceptable (ASHRAE 1992 and 1995). Due to the changes in clothing for seasonal weather, the comfort zones are specified for winter and summer clothing and insulation levels of 0.5 and 0.9 clo[1], respectively. The warmer and cooler temperature borders of the comfort zones are affected by humidity and coincide with the lines of constant effective temperature[2] (Kreider and Rabl, 1994). Spaces below 68 °F and 30% relative humidity in the winter and zones above 78 °F and approximately 60% relative humidity in the summer are expected to produce discomfort in larger portions of the population (see Figure 2). Low relative humidity environments dry out the skin and mucous membranes, and high humidity limits the body's ability to shed excess heat. High humidity is also favorable to mold growth.

The parameters used to indicate whether the state of a process, or condition, falls in the comfort areas may be two of the following variables: the relative humidity, the humidity ratio, and the operative temperature. Evidently, knowing the physical properties of the humid air can also be used in the verification of comfort conditions; but for simplicity and for concordance with the way the HVAC system is modeled, thermodynamic states are used in this study.

Bin Data for Air Conditioning Calculations

The energy use necessary to generate indoor comfort conditions in a building is dependent on the ambient conditions. .Therefore, as has been previously mentioned, the minimization methodology should be managed through representative conditions obtained from those outdoor variables. The most common algorithm to obtain representative equivalent ambient conditions is "bin sorting". Thus, the optimization should be carried out for each bin of weather conditions data.

The bin sorting algorithm is based on the classification of the data through well-defined ranges of a "key" variable. At the same time that the classification is carried out, the variables related in time and location to that key variable are separated in a corresponding way. At the end of the arrangement, the averages of the coincident data related to the guide variable are generated. This can be expressed as follows:

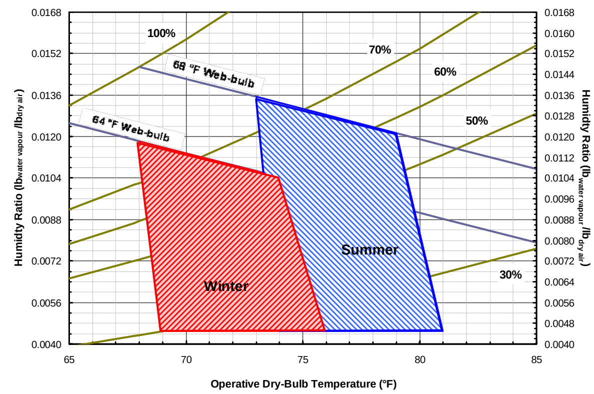

Figure 2 Acceptable ranges of operative temperature and humidity for people in typical summer and winter clothing during light, primarily sedentary activity (<1.2 met). The operative temperature ranges are based on a 10% dissatisfaction criterion (adapted from ASHRAE 1995)[3].

Set up an array of "bins", u, – one for each range of the key variable, generally the outdoor temperature. Examine each item of the dataset (y_{uv}) and use the value of the key variable to place it in the appropriate bin. Inspect each u-bin to count the m_u elements in it, where $m_u \geq 0$. For each of the related variables y_u related to the key variable, the averages are evaluated through

$$\bar{y}_u = \frac{\sum_{v=1}^{m_u} y_{uv}}{m_u} \qquad \text{(Eq. 2)}$$

The representation of ambient conditions by the common bin sorting, by any combination of the dry-bulb temperatures, wet bulb temperatures or humidity ratios, especially in hot and humid climates, has been questioned because any of the possible sets of those combinations, using a single-parameter bin representation, is deprived of extremes (Cohen and Kosar, 2000). Perhaps a joint-frequency bin representation could pick those extremes, but, for this

[1] 1 clo = 0.88 °F·ft^2·h/Btu (0.155 m^2 K/W)

[2] Effective temperature is the temperature of an isothermal black enclosure with 50% relative humidity where the body surface would experience the same heat loss as in the actual surface.

[3] 1 met = 18.4 Btu/h·ft^2 (58.2 W/m^2), Metabolic heat generation unit.

study that is intended to be used with limited data, the extremes could also very well be missed.

IMPLEMENTATION OF THE MINIMIZATION ALGORITHM TO DETERMINE THE POTENTIAL ENERGY SAVINGS

The formulation of the minimization problem to determine potential energy savings requires an algorithm which proves reliable and manageable in the total range of the ambient conditions available. The intrinsic formulation of some of the HVAC systems requires that the minimization be carried out with functions that may not be differentiable in a straightforward manner. Therefore, it may be convenient to establish a methodology that does not use derivatives.

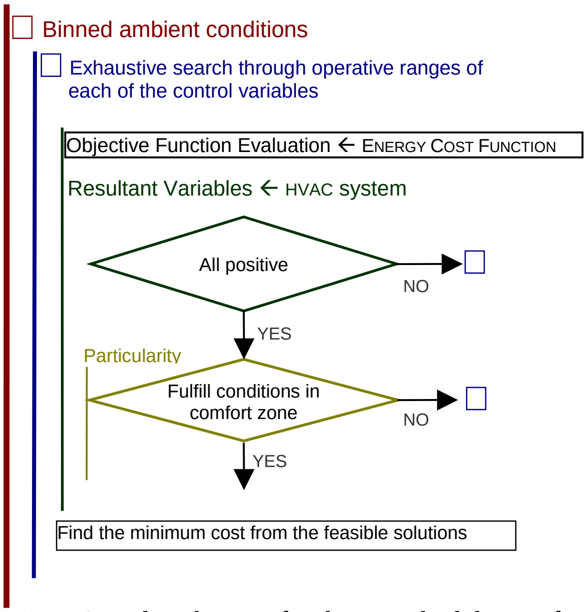

Figure 3 Flowchart of the methodology for evaluating potential energy savings in a building through binned ambient conditions. The total potential savings will be the sum of the individual products of the energy savings in each bin multiplied by its frequency.

Another aspect to be considered is that two constraints on the minimization problem for the determination of potential energy savings exist: one of linear form (one variable) and another of area configuration (two variables). In addition, the algorithm has to be repeated for each of the representative conditions of the binned ambient conditions, so the algorithm should be chosen to be as fast and simple as possible.

The used algorithm is a tailored, exhaustive search. Although the methodology is not sophisticated, it allows the control of the minimization constraints and the managing of the procedure sequence in a versatile manner. The diagram in Figure 3 illustrates the implementation for the methodology to determine potential energy savings.

The methodology is executed bin by bin, individually, until all of the representative conditions are evaluated. The total potential savings are then the sum of all the individual products of the potential energy savings found in each bin, multiplied by the frequency of each bin.

The frequency of each bin of ambient conditions plays an important role in the determination of the potential energy savings. Although the minimization can be obtained with limited data related to a particular period, the yearly potential energy savings are better obtained from ambient conditions that reflect the average, or the "typical", ambient conditions for the building location. One alternative is to use the meteorological year defined for use in major simulations such as DOE-2. Therefore, it is recommended in this study that the weather conditions be obtained from the TMY2 weather files so that the potential energy savings have a more solid base. In case the TMY2 file does not exist for a particular location, either the TMY2 weather file closest to that location or a weather year for the location with a complete record close to the period of analysis.can be used.

<u>Description of the Exhaustive Search</u>

As previously mentioned, the approach followed to determine the potential cost savings is based on a tailored exhaustive search. The procedure consists of an exhaustive evaluation of the constrained objective function, which depends on the HVAC system in the building, through the control variables. In this case, the term exhaustive refers to a total sweep under specific increments of the span of each of the control variables. The increments are sized in a way that the number of evaluations is not so large that the minimum can be missed or mistaken. In other words, the range of each control variable should be divided in a moderate increment size for generating a grid where a minimum can be clearly detected without expending an intense computational effort. When the minimum is found, the exhaustive search is reestablished for all the control variables with new narrowed ranges, generating a new, finer grid, around the reached minimum. The procedure is started again for the new grid to locate a new minimum in the new ranges. The procedure is continued until a defined criterion for steadiness in the minimum is fulfilled. Figure 4 depicts the sequence of the algorithm for a two-dimensional problem.

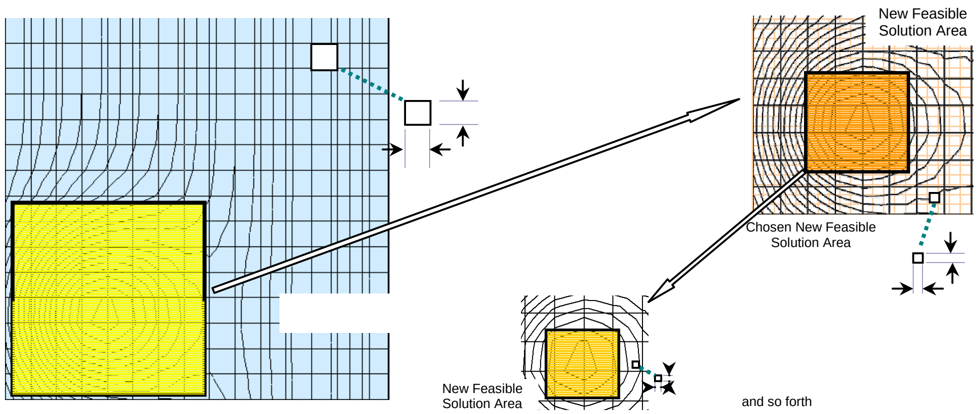

Figure 4 Representation of the sequential exhaustive methodology for a two-dimensional generic case.

APPLICATION OF THE METHODOLOGY

The Eller Oceanography and Meteorology (O&M) Building was selected to show how the methodology is applied. The Eller Building is the tallest building on the Texas A&M University campus; this building is fifteen-stories high and houses the Department of Meteorology and the Department of Ocean Engineering. It is a building with areas for diverse activities, including offices, laboratories, and classrooms. The total conditioned area is 180,316 square feet.

The building has 4 major DDVAV systems, and the heating and cooling loads are covered by the chilled water and the hot water of the campus' central utilities plant.

The building was commissioned in the first months of 1997, and the major adjustments then were tuning control valves, optimization of cold and hot decks, resets of static pressures, tuning of the minimum supply air and tune-up for chilled and hot water pumping.

The chilled water and hot water consumption data for the first eight months of the year 2000 are presented in Figure 5. The time series was used just until August due to a hot water use trouble pattern found in the first weeks of September of that year. In Figure 6, the same energy use patterns are plotted as a function of outside temperature for hourly, average daily, and the equivalent hourly binned data set.

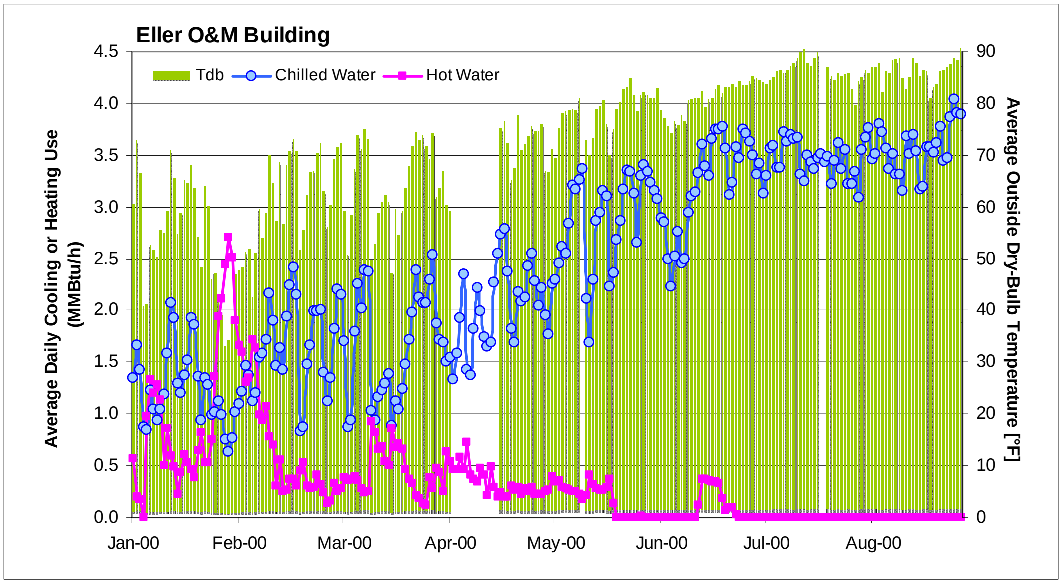

Figure 5 Average daily chilled and hot water consumption measured for the Eller O&M Building and daily average outside dry-bulb temperature for the period of January through August of 2000.

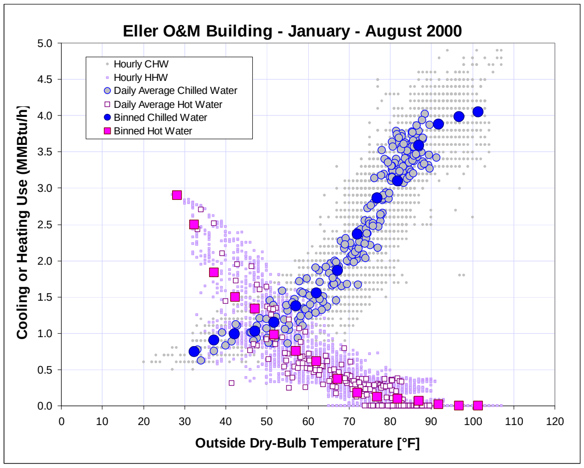

Figure 6 Average daily, hourly and binned chilled and hot water consumption values measured for the Eller O&M Building as a function of their corresponding outside dry-bulb temperature for the period of January through August of 2000.

To implement the potential savings methodology for any building, it is required to have at hand some values that are not going to be optimized, such as the UA, the equivalent interior and exterior area temperatures, the approximate fraction of exterior area with respect to the total, the equivalent number of occupants, and the design flow rate. As it is established for this study, limited information is available, so a calibration procedure is necessary to approximate these operative parameters. The calibration could be done in a automated way with the methodology presented in Baltazar-Cervantes, 2006. The need for this calibration is clear: It is not practical to optimize all those variables simply because the building is already built, and the purpose of this study is not, at least directly, to propose retrofit measures. On the other hand, it is not convenient to optimize occupancy for obvious reasons, and the design flow rate is specified according to the capacity of a particular system. Once the calibration is done, the methodology described above is applied.

Figure 7 shows the partial performance of the methodology to determine the optimum cost based on the cold deck temperature for the outdoor temperature bin of 60-65°F. The optimized cost point is clearly identified and it is observed that the energy use patterns become asymptotical as the search continues.

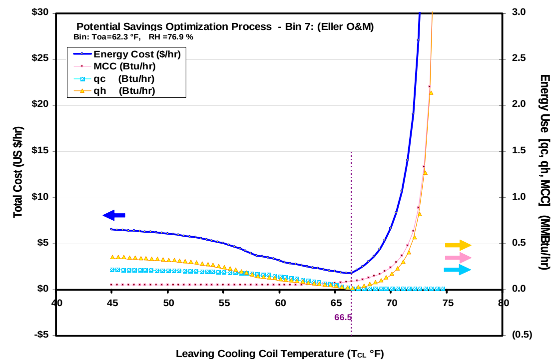

Figure 7 Performance of the potential energy savings methodology for the number seven bin of the Eller O&M Building energy use and ambient conditions data.

Potential Energy and Cost Savings for Eller O&M Building

The application of the methodology gives optimized patterns for heating and cooling as a function of the weather conditions at the building location. Thus, for the Eller O&M Building these patterns are presented in Figure 8. The zone bounded by the "actual" energy use of the year 2000 and the optimized energy use patterns represents the potential energy savings. These potential savings come from changes in the operation of the HVAC system's energy use which changes the heating and cooling patterns from the actual consumption to a minimum consumption in the way presented in Figure 9. Knowing the parameters that produce the minimized patterns, the economic quantification of the potential savings is made through the weather bin distribution of the building's location and the difference between the "actual" and optimized heating and cooling patterns, as tabulated in Table 1.

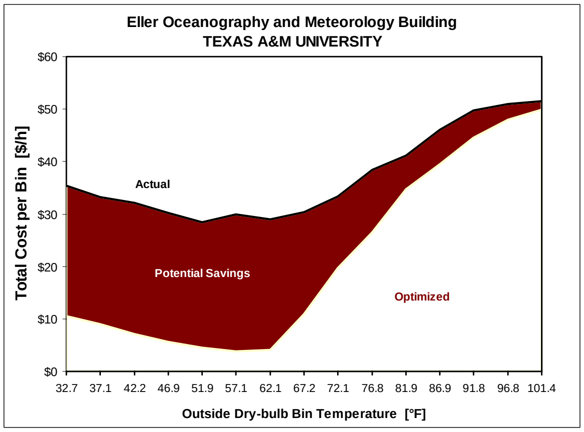

Figure 8 Potential dollar savings for the Eller Oceanography and Meteorology Building of Texas A&M University based on recorded energy use of the year 2000.

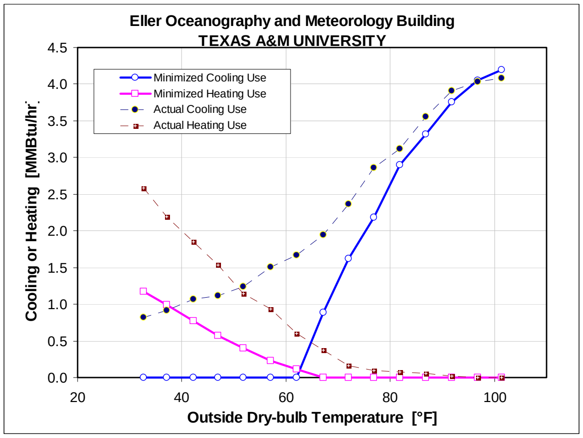

Figure 9 Actual and minimized cooling and heating patterns as a function of temperature for the Eller Oceanography and Meteorology Building at Texas A&M University, based on recorded energy use for the year 2000.

From Table 1, by using the binned weather for College Station, TX, of 1996, the year before any CC was carried out, and applying the obtained minimized energy consumption patterns, with their respective individual costs, it is possible to obtain the potential cost savings for the building. In this case this could produce approximately $133,362 if the changes in the system operation were applied.

In the same way as applied to the Eller O&M Building, the potential savings methodology has been applied to several buildings. Table 2 presents savings for one of those buildings, the Zachry Engineering Center that was commissioned by the Energy Systems Laboratory of Texas A&M University in different periods. This table includes the audit-expected savings, which for Zachry Engineering Center are the estimated savings for the measures proposed in an audit assessment conducted as part of the Texas Energy Cost Containment Program report (TECCP, 1986); the savings that occurred after some of the measures were applied. The same table presents the estimated potential savings and the ratio between the actual measured savings and the audit-expected. Table 2 also presents the ratio between the audit-expected and the estimated potential savings.

The Zachry Engineering Center, which was retrofitted during late 1990 and early 1991, houses offices, laboratories, and classrooms. The retrofits converted the dual-duct constant volume air handler and terminal boxes to variable volume systems and upgraded the control system. The expected audit savings, as pointed out by Claridge et al. (2001), were overestimated because the total cost of the fan electricity use and heating and cooling energy use were erroneously assumed by the energy auditors to be about 50% larger than actual use. The optimized and pre-retrofit energy use patterns and daily energy-use data for the year 1996 and 1997 are presented in

Table 1 Summary of the actual and optimized bin data and the potential savings for the Eller Oceanography and Meteorology Building of Texas A&M University, based on recorded energy use for the year 2000.

Cqc =11.293$/MMBtu; Cqh =7.9465$/MMBtu; CkWh =0.069$/KWh

									College Station, TX (Yr1996)		
Bin			Actual Use		Optimized		Costs			Tdb	Savings
		Toa	CHW	HHW	CHW	HHW	Optimized	Actual	#Data	Avge	Total
15	20								8	17.9	
20	25								40	22.5	
25	30								93	27.4	
30	35	32.7	0.82	2.58	0.00	1.18	$10.58	$35.43	196	32.2	$4,870
35	40	37.1	0.92	2.20	0.00	0.99	$8.95	$33.25	259	37.3	$6,292
40	45	42.2	1.06	1.85	0.00	0.77	$7.06	$32.11	317	42.2	$7,940
45	50	46.9	1.12	1.54	0.00	0.58	$5.60	$30.25	350	47.1	$8,630
50	55	51.9	1.24	1.15	0.00	0.40	$4.53	$28.47	419	52.1	$10,033
55	60	57.1	1.51	0.94	0.00	0.22	$3.83	$29.91	577	57.2	$15,053
60	65	62.1	1.66	0.60	0.00	0.12	$4.09	$29.00	662	62.0	$16,490
65	70	67.2	1.95	0.38	0.89	0.00	$10.97	$30.37	761	67.2	$14,765
70	75	72.1	2.36	0.16	1.62	0.00	$19.68	$33.40	1130	72.3	$15,505
75	80	76.8	2.86	0.10	2.19	0.00	$26.53	$38.47	1466	76.9	$17,514
80	85	81.9	3.12	0.07	2.90	0.00	$34.68	$41.18	950	81.8	$6,176
85	90	86.9	3.56	0.06	3.31	0.00	$39.49	$46.03	679	86.9	$4,446
90	95	91.8	3.91	0.02	3.76	0.00	$44.52	$49.72	481	91.9	$2,498
95	100	96.8	4.03	0.00	4.05	0.00	$47.94	$50.91	298	96.8	$887
100	105	101.41	4.08	0.00	4.20	0.00	$49.87	$51.47	74	100.7	$119
									8619		$131,216
									8760		**$133,362**

Table 2 Summary of the audit-expected savings and the determined potential for the Zachry Engineering Center of Texas A&M University.

Building Name	Location	Total Area	Hourly Data Available	Savings CHW+HHW+ELEC Measured†	Expected‡	Potential	*Measured / Expected*	*Expected / Potential Savings*
Zachry Engineering Center, TAMU	College Station, TX	324,400	6,367	$191,185	$232,900	$224,284	82.1%	103.8%

†Zachry Engineering Center savings come from the 1996 and 1997 annual consumption reports. ‡Expected cost savings are the audit estimated savings.

Figure 10 The data shows how the optimized patterns bound the energy use data, and in this case the heating closely follows the minimized pattern while the cooling has the same trend at high temperatures; however, for mild temperatures, where the optimized values suggest the use of economizers, the difference is substantial. Factors to consider in the optimized patterns are that they are obtained with the coincident mean conditions for humidity so just one point represents the bin conditions. For lower humidity conditions, the average of the energy use will be decreased proportionally to latent load cut corresponding to that humidity. Figure 10 includes a lower band in the optimized pattern that corresponds to the potential energy use when it is subtracted the effect of one standard deviation of the humidity data. This may explain why some points fall below the optimized curve, i.e. why the optimized values use an average humidity while the measured data covers some days with lower humidity. In this case, the results support the validation of the proposed potential savings methodology.

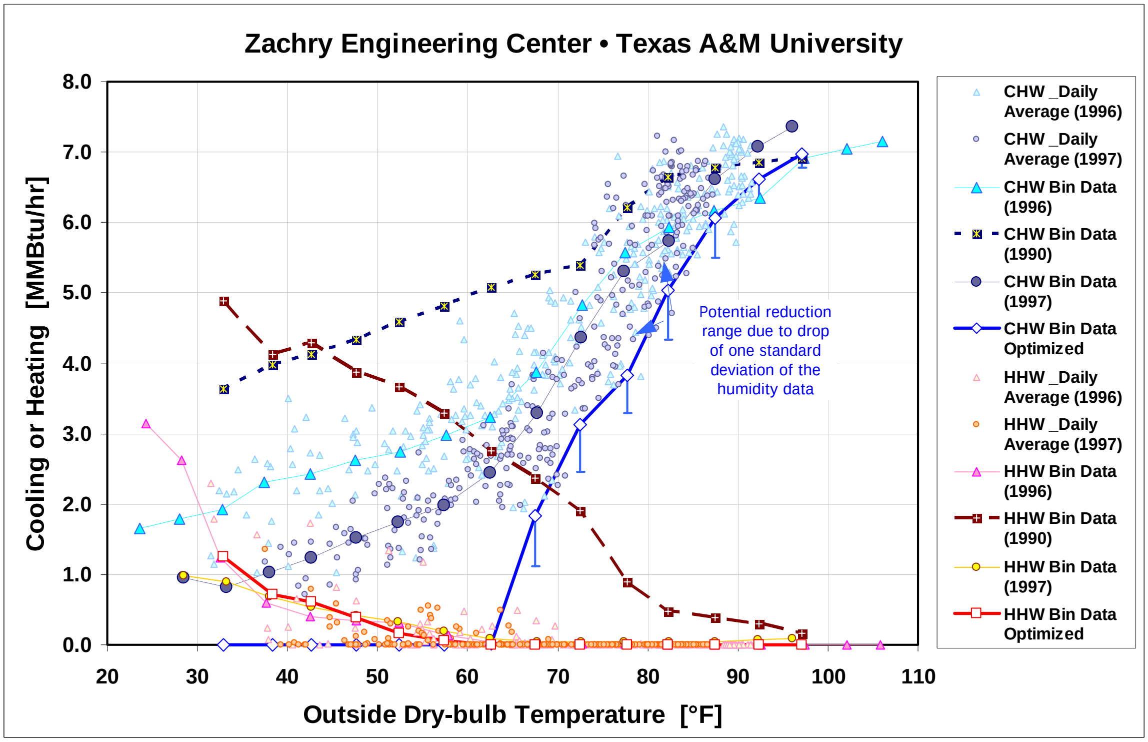

Figure 10 Energy use in the year 1990, 1996, optimized and post-CC® at Zachry Engineering Center at Texas A&M University.

CONCLUSIONS

The potential energy savings methodology presented in this study is based on the minimization of energy use over the span of ambient conditions at the building location. Because of the building energy use dependency on the ambient conditions and its cyclic variability over a calendar year, the methodology was applied for each representative bin obtained from the building location's weather data.

In general, from the buildings studied, just four were commissioned; the ratios of the audit-expected to the computed potential savings were still low, except for Zachry Engineering Center building, where the audit savings were overestimated.

Based on the cases studied herein, the potential savings methodology, for the cooling energy use part, seems to predict potential savings better at higher outside air temperatures than for mild or lower ambient temperatures. This is because many buildings do not have an economizer, which thermodynamically always gives important savings, as the methodology indicates. This suggests that the consumption data should be analyzed for the presence or absence of an economizer in the building before applying the methodology to estimate potential savings.

The results of the proposed methodology can be used for a commissioning team, to predict the potential energy savings, and additionally to have a starting point for the changes that need to be done on the HVAC operation conditions to reach a minimum energy use.

The methodology for the determination of potential energy savings, to the contrary of the calibration process, can not absolutely be verified because there are no known buildings that work under comfort conditions with a proved minimal energy use. As with any new methodology, the methodology proposed in this study, for the evaluation of potential energy savings, needs to be applied to other buildings where deeper operational changes have been carried out – similar to the Zachry Engineering Center Building.

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