IMPACT OF NIGHTTIME SHUT DOWN ON THE PREDICTION ACCURACY OF MONTHLY REGRESSION MODELS FOR ENERGY CONSUMPTION IN COMMERCIAL BUILDINGS

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ABSTRACT

Regression models of measured energy use in buildings are widely used as baseline models to determine retrofit savings from measured energy consumption. It is less expensive to determine savings from monthly utility bills when they are available than to install hourly metering equipment. However, little is known about the impact of nighttime shut off on the accuracy of savings determined from monthly data. This paper reports a preliminary investigation of this question by comparing the heating and cooling energy use predicted by regression models based on monthly data against the predictions of calibrated hourly simulation models when applied to a medium-sized university building in Texas with (i) DDCAV system operating 24 hours per day, (ii) DDCAV system with nighttime shut down, (iii) DDVAV system operating 24 hours per day, and (iv) DDVAV system with nighttime shut down.

The results of the four cases studied indicate : 1) when the AHUs are operated 24 hours/day, the annual prediction error of the cooling regression models is less than 0.5% of the annual cooling energy consumption; however, 2) when the AHUs are operated with nighttime shut down, the annual prediction error of the cooling models becomes as high as 6% of annual energy consumption. It should be noted that the cases considered here include only single end-uses of energy and have not investigated energy-use data which includes multiple end-uses.

Modified regression models are therefore recommended when AHUs are not operated 24 hours per day and the temperature pattern is significantly different between pre and post retrofit years.

INTRODUCTION

The North American Energy Measurement and Verification Protocol (DOE, 1996) presents three methods, Options A, B, and C, for measuring energy savings from retrofits in commercial buildings. Option C: Whole-Facility Or Main Meter Measurement determines savings as the difference between the energy consumption predicted for the post-retrofit period using a baseline model and measured energy consumption during the post-retrofit period. Single variable daily regression models, which regress daily energy use against daily mean ambient temperature, have been used for the baseline model in the majority of buildings in the LoanSTAR Program (Claridge 1994). However, when monthly utility bills are available, it will generally be less expensive to use monthly utility data for retrofit savings measurement than to record hourly or daily data. However, little is known about the prediction accuracy of the monthly regression models and the impact of nighttime shut down on the accuracy of savings determined from monthly data. Therefore this paper reports a preliminary investigation of this question by comparing the heating and cooling energy use predicted by regression models based on monthly data against the predictions of calibrated hourly simulation models when applied to a medium-sized university building in Texas.

When monthly utility bills are used for retrofit savings measurement, software which may be used to determine baseline models and savings includes PRISM (Fels et al. 1986) and EModel (Kissock et al. 1994). This study uses the EModel software for developing baseline monthly regression models since it includes a set of models applicable to a wider range of commercial buildings than the PRISM.

The functional form of the model most appropriate for the monthly data being analyzed in this study is (Ruch and Claridge 1992):

$$E = \beta_0 + \beta_1 (T_{cp} - T_{db})^+ + \beta_2 (T_{db} - T_{cp})^+ \quad (1)$$

where E is the daily average energy consumption for each month or billing period, T_{db} is the mean temperature for each month, T_{cp} is a change point temperature, β_0 is the energy consumption at the change point temperature T_{cp}, β_2 is the slope above T_{cp} and β_1 is the slope below T_{cp}. The notation $( )^+$ indicates that the quantities within the parentheses should be set to zero when they are negative.

Accuracy and reliability of regression models used for analysis of building energy data are generally assessed by comparing statistical indices such as the coefficient of determination (R^2), the root mean square error (RMSE), the coefficient of variation of the root mean square error CV (RMSE), and the mean bias error (MBE) (Katipamula et al. 1995).

Since the temperature range and temperature distribution for pre- and post-retrofit years may be different, these statistical indices may not correctly represent the prediction accuracy and reliability of the regression models. To investigate the prediction capability of the regression models, this study uses two years of weather and energy use data. The first year of data is used for developing models and the second year of data is used to evaluate the prediction accuracy of the regression models.

METHODOLOGY

The difference between the predicted and measured energy consumption of a building is due to a combination of the prediction error and "noise" due to operational changes and occupancy changes. Therefore, in this study, synthetic data from simulations is used to eliminate the "noise" found in measured data. The following procedure is used to identify prediction error in this study:

1. Develop HVAC system simulation models based on a case-study building.
2. Simulate cooling and heating energy use for a mild weather year, aggregate to monthly values and develop monthly regression models based on the simulated data.
3. Predict energy use with the regression models and simulate energy use with the simulation models for an extreme weather year.
4. Determine prediction error as the difference between regression model predicted and simulated energy consumption.

HVAC SYSTEM SIMULATION MODELS

The simulation model used in this study is AModel (Liu and Claridge 1995) which is based on the ASHRAE TC4.7 simplified energy analysis procedure (Knebel 1983). This program has been used successfully to identify potential energy savings from commissioning in several types of commercial buildings (Liu and Claridge 1995). This hourly simulation emphasizes the air-side systems and requires much less envelope information than many hourly programs. It has successfully predicted the savings from numerous system and control changes.

To ensure that the simulation results are reasonable, a simulation of the dual-duct variable air volume (DDVAV) case was calibrated to the measured cooling and heating energy consumption of the Nursing Hall at the University of Texas at Austin.

This building has a steel frame and reinforced concrete floors, exterior walls of pre-cast panel with single pane tinted fixed windows and a concrete roof. The total conditioned floor area is 96,000 ft^2. It houses nursing classrooms and lecture halls, work shops, lounges and professors' offices. The HVAC system for this building, which operates 24 hours/day, consists of two DDVAV air handling units (2x100hp) without pre-treat units or economizers.

The measured 1994 hourly cooling and heating energy use data for this building were used for calibrating the simulation models.

Figures 1 and 2 compare the calibrated simulated and measured cooling energy consumption for 1994. The figures show daily values of the simulated and measured consumption as well as the residuals, or difference between daily simulated and measured values. The annual fitting error or MBE is 0.87% and the CV-RMSE is 7.24% (on a monthly basis).

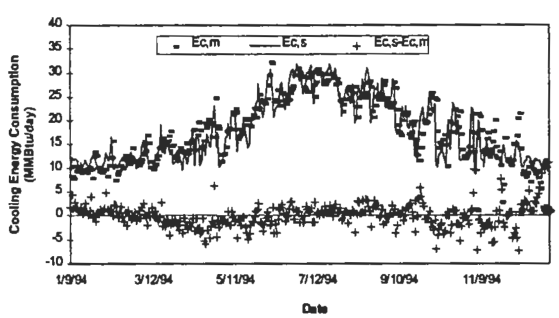

Figure 1. Time Series Plots of Calibrated Simulated and Measured Cooling Energy Consumption and Residuals (Ec,m - measured cooling energy consumption and Ec,s - simulated cooling energy consumption)

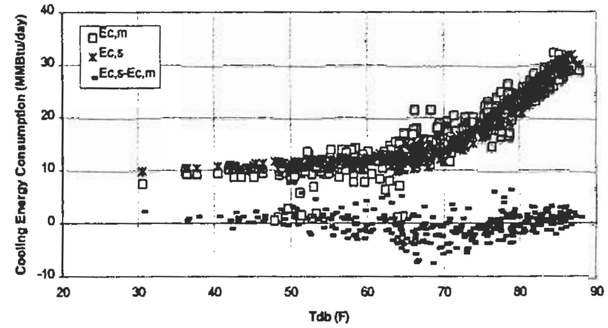

Figure 2. Calibrated Simulated and Measured Cooling Energy Consumption and Residuals versus Outdoor Temperature

Figures 3 and 4 compare the calibrated simulated values and measured heating energy consumption for 1994 in the same manner. The annual fitting error or MBE is 3.15% and the CV-RMSE is 10.12%. The MBE and CV-RMSE values for the heating simulation are higher than the values for the cooling simulation due to a change in domestic hot water usage during the summer and the lower average value of the heating consumption. Since the objective of this calibration is to develop reasonable characteristics for a building, typical operating practices were simulated to assure that the simulation results are reasonable; short-term operating changes were not simulated.

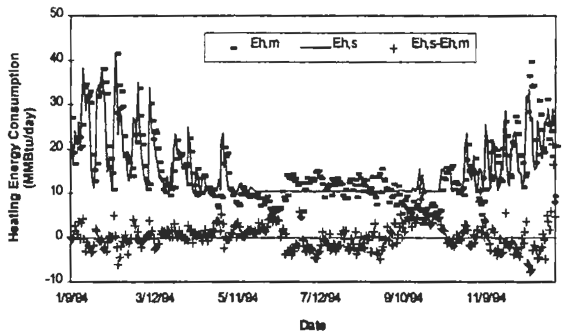

Figure 3. Time Series Plots of Calibrated Simulated and Measured Heating Energy Consumption and Residuals (Eh,m - measured heating energy consumption and Eh,s - simulated heating energy consumption)

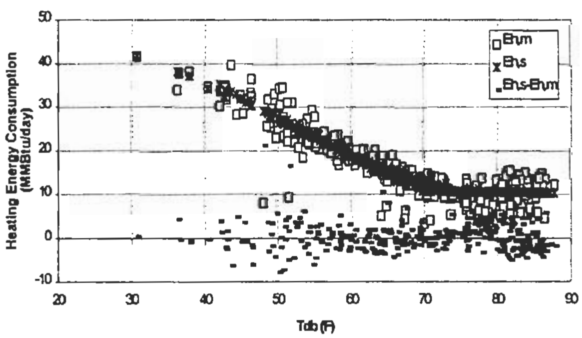

Figure 4. Calibrated Simulated and Measured Heating Energy Consumption and Residuals versus Outdoor Temperature

To investigate the impact of system types (DDCAV and DDVAV systems), and operating schedules (24 hour/day & nighttime shut down operation), the calibrated simulation models were modified to represent these cases, as shown in Table 1. Case 1 represents the DDCAV system with 24 hour/day operation and Case 2 represents the DDCAV system with nighttime shut down. Case 3 represents the DDVAV system with 24 hour/day operation and Case 4 represents the DDVAV system with nighttime shut down.

Table 1. Summary of the Cases Studied

HVAC System	24 Hour Operation	Nighttime Shut Down
DDCAV	Case 1	Case 2
DDVAV	Case 3	Case 4

SIMULATED ENERGY CONSUMPTION DATA AND MONTHLY REGRESSION MODELS

The hourly cooling and heating energy consumption were simulated using the simulation models for each of the four cases using 1994 weather data. 1994 had fewer days of extreme weather than any other year in the last decade (Wang, 1995). The simulated hourly data were totaled for each month to get monthly cooling and heating energy consumption. These simulated monthly values were then fit with four-parameter regression models which are summarized in Tables 2 and 3 below. The regression models give MMBtu/day consumption as a function of dry bulb temperature. R^2 and CV were determined by EModel (Kissock, 1993; Kissock et. al. 1994).

Table 2. Summary of Monthly Cooling Models

Case	Model	R^2	CV
Case 1: DDCAV, 24 hour operation	11.8936+0.3058(Tdb-68.3) if Tdb<68.3 (F) 11.8936+1.1810(Tdb-68.3) if Tdb≥68.3 (F)	1.00	3.2
Case 2: DDCAV, night shut off	4.9262+0.1413(Tdb-66.332) if Tdb<66.332 (F) 4.9262+0.5171(Tdb-66.332) if Tdb≥66.332 (F)	0.99	5.6
Case 3: DDVAV, 24 hour operation	9.8596+0.2973(Tdb-68.300) if Tdb<68.300 (F) 9.8596+1.1402(Tdb-68.300) if Tdb≥68.300 (F)	1.00	3.7
Case 4: DDVAV, night shut off	4.3675+0.1329(Tdb-66.988) if Tdb<66.988 (F) 4.3675+0.5198(Tdb-66.988) if Tdb≥66.988 (F)	0.99	5.5

Table 3. Summary of Monthly Heating Models

Case	Model	R^2	CV
Case 1: DDCAV, 24 hour operation	1.9235-0.7173(Tdb-66.988) if Tdb<66.988 (F) 1.9235-0.1076(Tdb-66.988) if Tdb≥66.988 (F)	1.00	8.5
Case 2: DDCAV, night shut off	0.6294-0.2291(Tdb-66.988) if Tdb<66.988 (F) 0.6294-0.0365(Tdb-66.988) if Tdb≥66.988 (F)	0.97	20.8
Case 3: DDVAV, 24 hour operation	2.2111-0.6626(Tdb-66.332) if Tdb<66.332 (F) 2.2111-0.1065(Tdb-66.332) if Tdb≥66.332 (F)	0.99	8.8
Case 4: DDVAV, night shut off	0.6063-0.2077(Tdb-67.644) if Tdb<67.644 (F) 0.6063-0.0327(Tdb-67.644) if Tdb≥67.644 (F)	0.97	19.8

PREDICTION ERROR OF THE MONTHLY REGRESSION MODELS

The regression models were evaluated by comparing the energy consumption predicted by the regression models with the values predicted by the calibrated simulation models with weather data from 1985. The 1985 weather year contained the largest number of extreme weather days in the last decade (Wang, 1995). The prediction accuracy of the regression models was judged by the annual differences between the predictions of the regression models and the simulation models as well as the coefficient of variation of these differences.

The annual percent difference (error) of a regression model is defined as:

$$E_{ae} = \frac{E_{a,r} - E_{a,s}}{E_{a,s}} * 100 \qquad (2)$$

where $E_{a,r}$ is the annual consumption predicted by the regression model and $E_{a,s}$ is the annual consumption predicted by the corresponding simulation model.

The coefficient of variation, CV(%), on a monthly time scale was calculated for the monthly regression models as:

$$CV(\%) = \frac{RMSE}{\overline{E}} * 100 \qquad (3)$$

where RMSE is the root mean square error which is:

$$RMSE = \sqrt{\frac{\sum_{j=1}^{j=n} \left| E_j - \hat{E}_j \right|^2}{n-p}},$$

E_j is the energy use in month j from the simulation model, and n=12 represents the total number of months in the high energy consumption year, $\hat{E}_j$ is the energy use in month j, predicted by the regression model, and p is the number of parameters in the model.

$\overline{E} = \frac{\sum_{j=1}^{j=n} E_j}{n}$, is the mean monthly energy consumption for the year, based on the simulation model.

$\hat{E}_j = D_j * \overline{E_j}$, where D_j is the number of days in month j, and $\overline{E_j}$ is the monthly average daily energy use in month j, predicted by the monthly regression model.

Cooling Consumption Prediction Accuracy

Table 4 summarizes the annual cooling consumption predicted by monthly regression models and simulation models for 1985 and presents the annual prediction errors for each case.

Table 4. Annual Prediction Error of the Monthly Cooling Regression Models

Case	Annual Cooling Consumption MMBtu)		Annual Prediction	CV-RMSE
	Predicted by Regression Models	Predicted by Simulation Models	Error or MSE	(%)
Case 1: DDCAV, 24 hrs/day	6016	6021	0.1	4.9
Case 2: DDCAV, nighttime shut down	2779	2943	-5.6	8.2
Case 3: DDVAV, 24 hrs/day	5249	5227	-0.4	5.4
Case 4: DDVAV, nighttime shut down	2678	2513	-6.1	9.0

Heating Consumption Prediction Accuracy

Table 5 summarizes the annual heating consumption predicted by the monthly regression models and simulation models and presents the annual prediction error of the regression models.

Table 5. Annual Prediction Error of the Monthly Heating Regression Models

Case	Annual Heating Consumption (MMBtu)		Annual Prediction	CV RMSE
	Predicted by Regression Models	Predicted by Simulation Models	Error or MSE	(%)
Case 1: DDCAV, 24 hrs/day	1788	1721	-3.7	11.7
Case 2: DDCAV, nighttime shut down	520	550	5.7	17.5
Case 3: DDVAV, 24 hrs/day	1723	1652	-4.1	-12.3
Case 4: DDVAV, nighttime shut down	510	537	5.2	15.9

As we can see, the monthly regression models have consistently higher prediction error when the system is shut down during the nighttime, even when the monthly model has high R^2, low CV and low MSE.

In the next section, the modified regression models are developed for the shut down cases.

MODIFIED MONTHLY REGRESSION MODELS AND THEIR PREDICTION ACCURACY

The regular monthly regression models were developed using the daily average temperature for each utility period. Using the average temperature gives equal weighting to the influence of all hourly temperatures on the energy consumption. When the HVAC system is shut down at night, the daytime weather has the major influence on the daily energy consumption. Therefore, for these cases, it is more reasonable to regress the energy consumption against the average temperature during the operating hours for the corresponding period.

Modified monthly regression models were developed, based on the average temperatures during the operating hours, for cases 2 and 4. The modified models are summarized in Table 6. The annual prediction errors determined for these modified models are presented in Figure 5.

Table 6. Modified Monthly Regression Models for Nighttime Shut Down Cases

Case	Models	R^2	CV %	Annual Prediction (%)
Case 2	$Ec=6.6569+0.1875(67.044-Tdb)^{+}+0.6756(Tdb-67.044)^{+}$	1.00	3.4	0.3
DDCAV, Night Shut Off	$Eh=0.9091-.3662(67.04-Tdb)^{+}-.0462(Tdb-67.044)^{+}$	1.00	14.6	-3.9
Case 4	$Ec=5.8505+.1736(67.7082-Tdb)^{+}+.6794(Tdb-67.708)^{+}$	1.00	3.7	0.6
DDVAV, Night Shut Off	$Eh=0.9718-0.341(67.044-Tdb)^{+}-0.0458(Tdb-67.044)^{+}$	0.99	13.8	-4.1

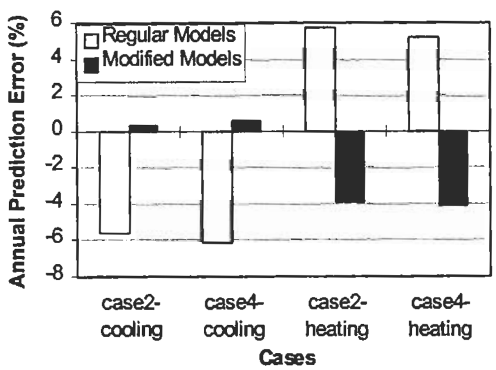

Figure 5. Prediction Error of Regular and Modified Heating and Cooling Models for Night Shut-Down Cases.

Figure 5 compares the annual prediction errors of the modified models and the regular models . The modified cooling regression models reduce the annual prediction error to 0.6% from -6.1 % . The modified heating regression models reduces the annual prediction error to 4.1% from 5.7%.

CONCLUSIONS

The results of the four cases studied indicate that when the AHUs operate 24 hours per day, the annual prediction error of the regular cooling regression models are less than 0.5% of the annual cooling energy consumption. However, when the AHUs operate with nighttime shut down, the annual prediction error of the regular cooling models is as high as 6.1% of annual energy consumption.

Modified regression models based on average temperature values during the operating periods are recommended when AHUs operated less than 24 hours/day and the temperature pattern of pre- and post-retrofit years are different. The modified cooling regression models reduced the annual prediction error to 0.6% from -6.1%. The modified heating regression model reduced the annual prediction error by about 1/3.

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