# A BIN METHOD FOR CALCULATING ENERGY CONSERVATION RETROFIT SAVINGS IN COMMERCIAL BUILDINGS

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## ABSTRACT

The calculation of measured energy savings from energy conservation retrofits is an important step in the verification of the success of a retrofit (Claridge et al. 1992). Several methods for calculating the savings from energy conservation retrofits to HVAC systems in the LoanSTAR program have been proposed, including linear and change-point linear empirical models and calibrated simulation models. Simple least squares linear regression is easiest to use and understand, but is incapable of describing non-linear temperature dependencies of a building's energy use. Change-point linear models are more complex than the simple linear regression and cover a broader range of buildings. However, there are some buildings for which change-point linear models do not fit the data adequately.

This paper presents a first look at an hourly bin method for calculating energy savings from energy conservation retrofits to HVAC systems based on hourly whole-building electricity, sub-metered motor control center use and thermal energy measurements. A general procedure for determining the appropriate number of bins is described and the bin method is applied to data from several agencies participating in the LoanSTAR program. Results are compared to existing savings calculation procedures for two buildings.

## INTRODUCTION

A fundamental requirement for the promotion of energy conservation retrofit measures is the ability to reliably and accurately appraise how much energy has been saved (Claridge et al. 1992). Significant improvements have been reported regarding the refinement of the analysis methodologies and related tool development. However, there is still a need for the development of new methodologies in order to produce a simple, robust procedure that is easily understood by the HVAC engineering community.

Three types of modeling approaches are currently used to calculate retrofit savings: regression models (Fels 1986; Ruch et al. 1992; Claridge et al. 1992; Ruch et al. 1993; Kissock et al. 1992; Kissock et al. 1993), calibrated simulation models (Hsieh 1988; Bronson et al. 1992; Bou Saada and Haberl 1993), and simplified systems models (Katipamula et al. 1992; Katipamula et al. 1993)

Regression methods are most often used because they are simple to develop, easy to use, and retain the ability to calculate the associated uncertainty. The simplest is the two-parameter linear model, which is used to regress the hourly, daily or monthly weather-dependent energy use against temperature. The physical basis for this correlation is the fact that the building envelope and ventilation heating-cooling loads are a strong function of the average outdoor dry bulb temperature. Studies have also been performed with change-point regressions of energy consumption against ambient temperature in residential (Fels 1986) and commercial (Claridge et al. 1992) buildings. These studies suggested that buildings that have thermostatically controlled HVAC systems usually exhibit behavior that can be explained with a change-point regression model driven by ambient temperature.

As of May 1993, 75% of the retrofit savings models in the LoanSTAR program used daily one, two, three, or four parameter linear models which were usually regressed against the average daily ambient temperature. In a few cases, a second variable (e.g., whole-building electricity or air-handler electricity) was used to account for internal heating gains. Many of the models used weekday-weekend separation of the data to account for occupancy schedules. In the remainder of the cases hourly regression models (8%), calibrated simplified system models (8%), or monthly utility billing data models (8%) were used[1]. These models were used to predict retrofit savings for cooling (75%), heating (83%), air-handler electricity (83%), lighting (17%), and electric demand (13%), as shown in Table 1 (Turner et al. 1993). In certain cases, although the retrofit savings were adequately described by the regression model, there is room for improvement. In this paper the concept of an inverse hourly bin modeling approach is proposed for those buildings where the

1 The monthly utility billing data models incorporated an hourly calibration to the post-retrofit data (Liu 1993).

**Table 1. Summary of the existing LoanSTAR program models for retrofit energy savings from 24 buildings: model types and calculation methodologies (Turner et al. 1993).**

**SAVINGS CALCULATION METHODOLOGIES**

| | Daily Regression Models | Hourly Regression Models | Utility Billing data and Hourly Energy Use | Simplified Systems Models |
|---|---|---|---|---|
| ZEC | x | | | |
| EDB | x | | | |
| UTC | | | | x |
| PCL | | | | x |
| WAG | x | | | |
| WEL | x | | | |
| BUR | x | | | |
| NUR | x | | | |
| WIN | x | | | |
| RAS | x | | | |
| PAI | x | | | |
| WCH | x | | | |
| GAR | x | | | |
| GEA | x | | | |
| UNV | | x | | |
| BUS | x | | | |
| FNA | x | | | |
| MSB | x | | | |
| SHS | | | x | |
| VHS | | | x | |
| SIM | x | | | |
| DMS | x | | | |
| TDH | x | | | |
| WMH | | x | | |

**TYPES OF SAVINGS**

| | Cooling | Heating or Gas | Air Handler Electricity | Lighting Electricity | Electric Demand |
|---|---|---|---|---|---|
| ZEC | x | x | x | | |
| EDB | x | x | x | x | |
| UTC | x | x | x | | |
| PCL | x | x | x | | |
| WAG | x | x | x | | |
| WEL | x | x | x | | |
| BUR | x | x | x | | |
| NUR | x | x | x | | |
| WIN | x | x | x | | |
| RAS | x | x | x | | |
| PAI | x | x | x | | |
| WCH | x | x | x | | |
| GAR | x | x | x | | |
| GEA | x | x | x | | |
| UNV | x | x | x | | |
| BUS | x | x | x | | |
| FNA | x | x | x | | |
| MSB | | | | x | |
| SHS | | x | x | | x |
| VHS | | x | x | | x |
| SIM | | | | x | |
| DMS | | | | x | |
| TDH | x | x | x | | |
| WMH | | | | | x |

regression-based models do not describe the pre-retrofit baseline energy use adequately[2].

## METHODOLOGY

An inverse hourly bin method analysis works best with at least nine months of hourly pre-retrofit energy consumption data from a building before the retrofit is installed (Stram 1986, Kissock et al. 1993). For the bin method used in this paper, hourly Whole-Building Electricity use (WBE), Air-Handler Unit electricity use (AHU), Whole-Building Chilled Water energy use (WBCW), and Whole-Building Hot Water energy use (WBHW) data were used. Prior to the application of the bin method it is necessary to identify the pre-retrofit, construction and post-retrofit periods, as well as special periods such as holidays or, in the case of many educational buildings, semester and non-semester periods.

In general, the approach used to apply the bin method varies depending on whether the data being considered are weather dependent or non-weather dependent. In the discussion that follows an overview of how the method was applied is presented. A detailed description of the procedure is currently under development and will be reported in the future.

2 The phrase inverse model follows the definition set forth by Rabl (1988). An example of a typical inverse model is a least squares linear regression model. DOE-2, BLAST or a bin-method analysis for design are examples of a forward model.

### Non-Weather dependent retrofit savings calculations

The calculation of retrofit savings in non-weather dependent energy use includes energy conservation retrofits and other energy consuming systems that are primarily influenced by schedule-dependent loads. In a typical before-after measurement analysis a baseline energy method is determined and then used to predict energy use in the post-retrofit period. Energy savings can be determined by modifying the procedure suggested by Claridge et al. (1992).

$$E_{save,tot} = \sum_{i=1}^{n}\sum_{j=1}^{m}\left(E_{pre_{i,j}} - E_{post_{i,j}}\right)$$

where

$E_{pre_{i,j}}$ = the bin model predicted average hourly pre-retrofit electricity use during hour (j) of day (i) in the post-retrofit period.

i = distinct day type varying from i=1 (all seven days per week the same), to i=365 (every day of the year different).

j = 1 to 24 hours in each day.

$E_{post_{i,j}}$ = measured hourly post-retrofit energy use for hour (j) of day (i).

In general, the non-weather dependent approach takes several passes through the data until the 24-hour profiles during the base-line period have been adequately characterized. Figure 1 illustrates the application of the 24-hour binning method to the Education Building at the

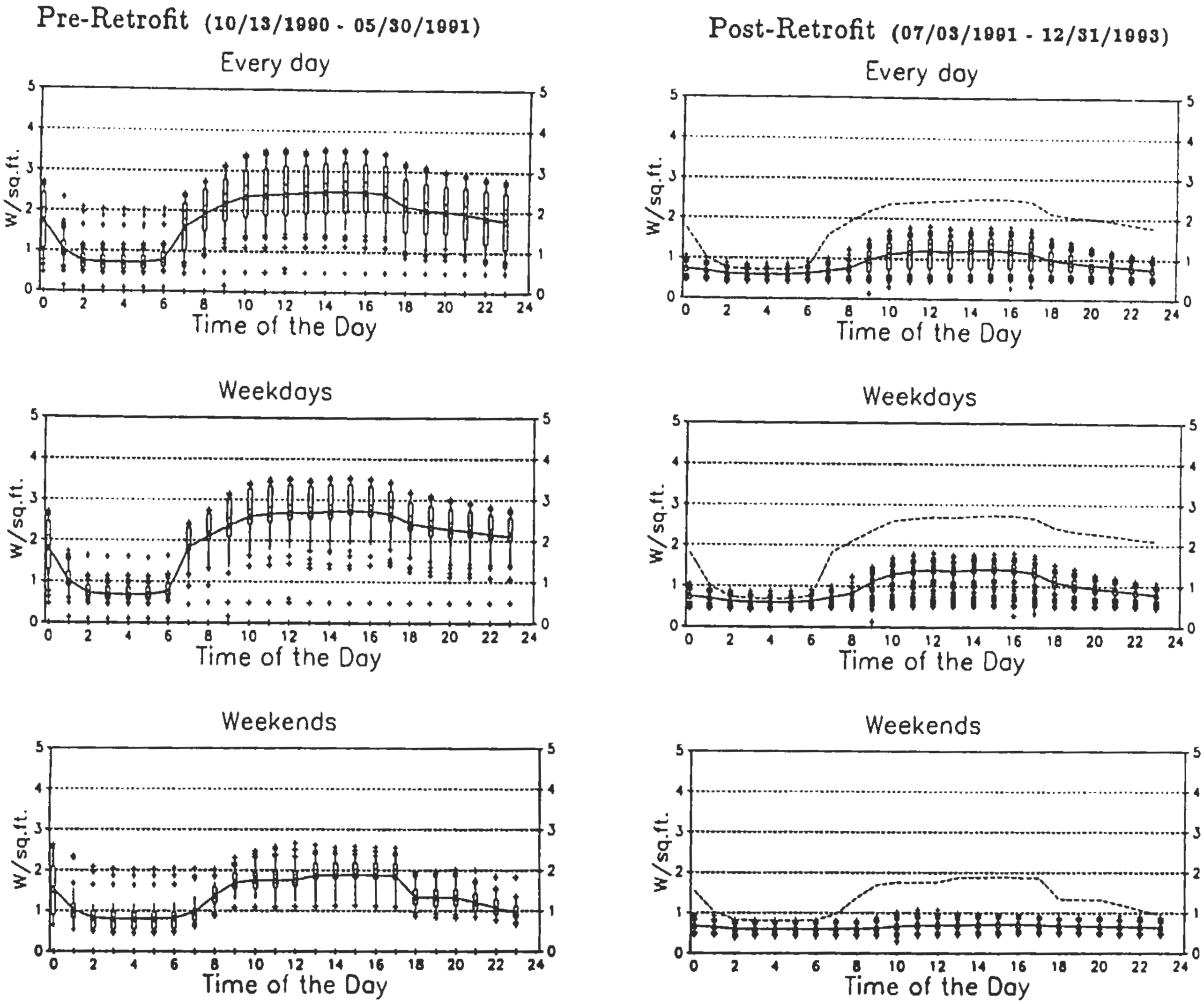


**Figure 1. Hourly 24-hour bin profiles of whole-building electricity use for the EDB building.**

University of Texas at Austin campus. The left side of the figure shows the average seven day (i.e. "every day"), weekday and weekend profiles for the pre-retrofit baseline period beginning October 13, 1990 and lasting through May 30, 1991. The right side illustrates the seven day average 24-hour profiles of the post-retrofit period beginning July 3, 1991 through December 31, 1993. In Figure 1 the 24-hour profiles are illustrated using box-whisker-mean plots where the top and bottom of the whisker represents the $90^{th}$ and $10^{th}$ percentiles, respectively. The top and bottom of the box represents the $75^{th}$ and $25^{th}$ percentiles. The hash mark towards the middle of the box is the median, and the connected triangles represent the mean value of each hourly bin. The superimposed dashed line in the post-retrofit period represents the respective sevenday, weekday and weekend consumption during the base-line period (Abbas 1993).

Once the 24-hour non-weather dependent profiles have been adequately characterized, the energy savings from the retrofit can be calculated by comparing the post-retrofit energy use to the respective hourly mean values of the weekday or weekend baseline profiles. Visual inspection of the graphs on the right side of Figure 1 reveals that there are significant differences in the hour by hour savings as well as differences between weekdays and weekends. Several criteria can be used to determine whether or not the 24-hour profile has adequately characterized the baseline or pre-retrofit period. One criterion that seems promising is to consider minimizing the hourly inter-quartile range. In most cases this will include the removal of anomalous days from the data set. For example, days where the entire 24-hour consumption falls below (or above) the $10^{th}$ (or $90^{th}$) percentile. Quite often these represent holidays in the weekday data which should have been flagged as weekends. Clearly, one or

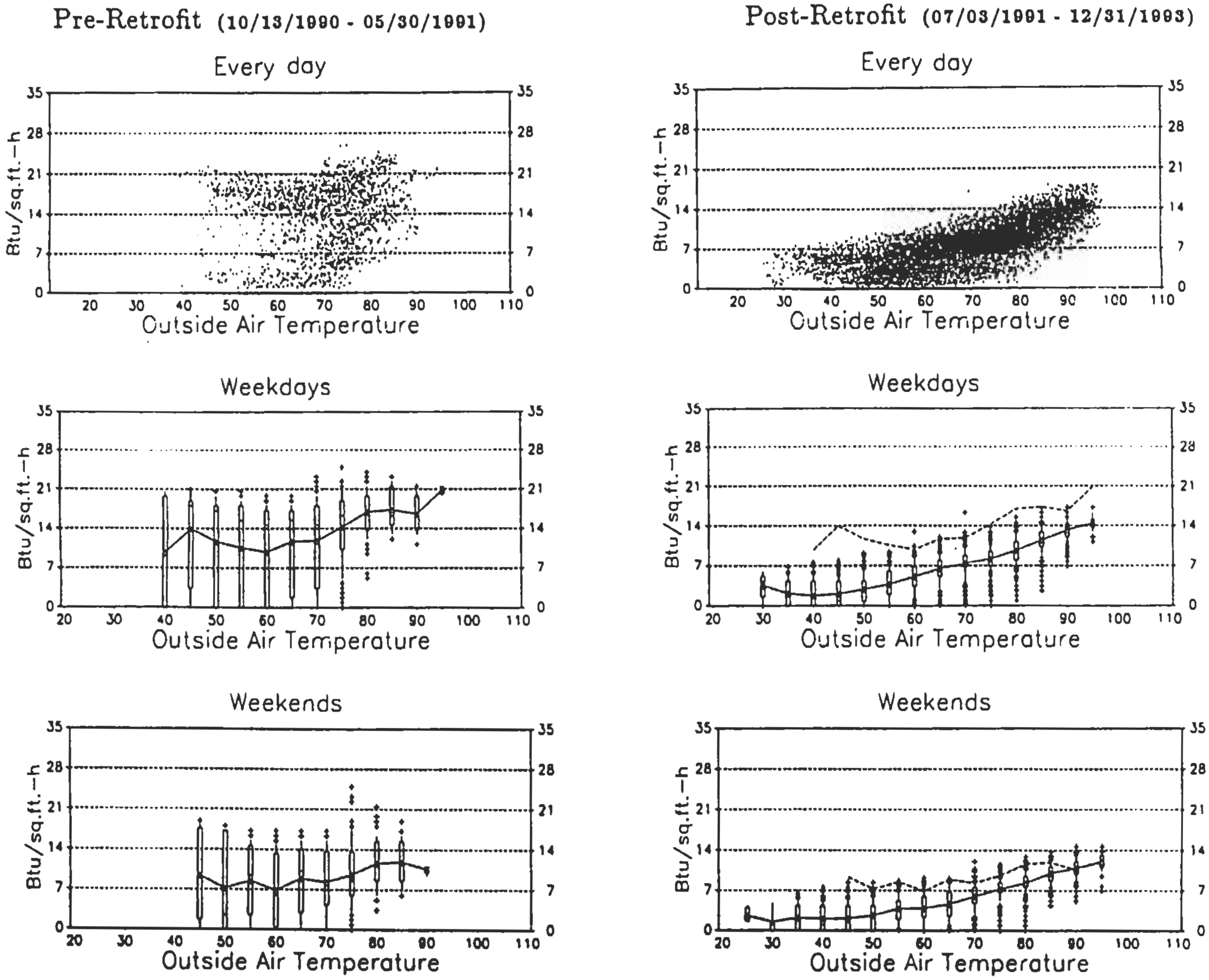


**Figure 2. Hourly temperature bin profiles of whole-building cooling energy use for the EDB building.**

more of the days remain in the pre-retrofit data shown in Figure 1.

**Weather dependent retrofit savings calculation**

Figure 2 illustrates the results of the application of a temperature binning procedure to the pre-retrofit chilled water energy use at the education building. In a similar fashion to Figure 1 pre-retrofit chilled water energy use is shown on the left side of Figure 2 and post-retrofit chilled water energy use is shown on the right side.

Using the bin method the pre-post weather dependent savings are determined from

$$E_{save,tot} = \sum_{i=1}^{n}\sum_{j=1}^{m}\left(E_{pre_{i,j}} - E_{post_{i,j}}\right)$$

where

$E_{pre_{i,j}}$ = the average pre-retrofit consumption for model (i) and temperature bin (j) as predicted in the post-retrofit period.

$E_{post_{i,j}}$ = the post-retrofit consumption falling within temperature bin (j) for days corresponding to model (i).

i = 1 to n different models (e.g. i=2 for weekday-weekend models)

j = 3° C(5.4° F) temperature bin expressed at the mid-point temperature (e.g. 4.5°C to 7.5°C is shown as temperature bin 6°C)[3].

In the case of the chilled water consumption for the education building inspection of Figure 2 reveals that although weekday-weekend bins appear to be adequate for the post-retrofit period (i.e., the inter-quartile range is

[3] The selection of 3°C bins was chosen to align with the ASHRAE bin weather data (Degelman 1984).

small) additional binning is required for the pre-retrofit period. The final model chosen for the baseline chilled water bin model incorporated an on-off model that closely followed the electricity use of the motor control center.

In general the selection of the weather dependent bin model begins with one temperature-bin model for all seven days and adds additional binning groups until the inter-quartile range reaches an acceptable value. Some examples include weekday, weekend and in some cases on-off bins.

**CASE STUDY 1 : ZACHRY ENGINEERING CENTER**

The Zachry Engineering Center (ZEC), located at Texas A & M University, contains 30,000 $m^2$ (324,000 $ft^2$) of classroom, office, computer center and laboratory facilities comprising four stories with an underground parking garage. It was constructed in the early 1970s. The building is a heavy structure with 0.15 m (6-inch) concrete floors and insulated exterior walls made of pre-cast concrete and porcelain-plated steel. About 12% of the exterior wall area is covered with single pane, bronze-tinted glazing. The windows are recessed approximately 0.61 m (2 ft.) from the exterior walls, providing some shading. Approximately 288 $m^2$ (310 $ft.^2$) of northeast-facing celestory windows admit daylight into the core of the building (Bronson 1992, TECCP 1986).

The building is served by 12 dual-duct air-handling units located in the parking garage. Chilled and hot water for the cooling and heating coils are supplied to the building by the campus physical plant. Two multi-zone units and a dedicated centrifugal chiller serve a super-computing facility located within the building. Manual operation of the secondary chilled and hot water pumps also affects the systems cooling and heating capacity. Outside air dampers are permanently set to supply about 10% to 20% outdoor air (Katipamula 1992) and do not operate on an economizer cycle.

The primary retrofit to the building was to replace the existing Constant Air Volume (CAV) air distribution systems with a variable frequency, Variable Air Volume (VAV) air distribution system. During the retrofit the energy management and control system was also upgraded.

The ZEC was the first building instrumented under the LoanSTAR program. About 50 channels of hourly data have been recorded and collected each week since May, 1989. The important channels for the retrofit savings measurement are the air-handler electricity consumption and the whole-building heating and cooling energy use. The air-handler electricity consumption is contained in the Motor Control Center (MCC) electricity use, which represents all of the air-handler units and various pumps. Cooling and heating energy use are determined by monitoring the flow rate and temperature difference of each stream as it enters and leaves the building.

**Air-Handler Electricity savings**

The daily MCC electricity consumption, which is the total electricity consumption by all the air-handler units and chilled water pumps, during the pre-retrofit, construction and post-retrofit periods is shown in Figure 3. As expected, the Constant Air Volume (CAV) air-handler electricity energy use is nearly constant in the pre-retrofit period, and therefore was modeled using a one-parameter model (or average 24-hour model). The pre-retrofit period mean energy use was found to be 350.5 kWh/h average or 8,411 kWh/day. The retrofit savings were determined by subtracting measured energy use in the post-retrofit period from the constant energy use predicted by the pre-retrofit base-line model.

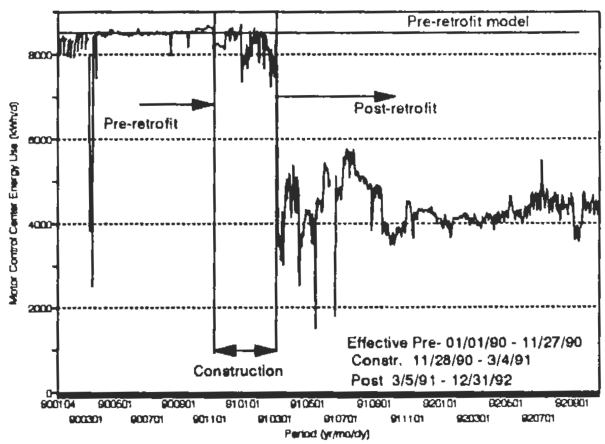


**Figure 3: Pre-retrofit, Construction and Post-retrofit period motor control center electricity consumption for the ZEC.**

**Cooling and Heating Energy savings**

The daily pre-retrofit cooling energy use, bin-predicted cooling energy use, and residuals (i.e., measured - predicted) are shown as a time series plot in Figure 4. The same pre-retrofit period data are plotted against the ambient temperature in Figure 5. The scatter plot shows that cooling energy varies linearly with ambient temperature. The plot also shows consumption predicted by the linear, two parameter weekday-weekend model used in the LoanSTAR program and consumption predicted by the bin model.[4]

[4] In order to display the daily-average consumption from the bin-prediction model hourly bin predicted values are calculated, totaled over 24 hours and plotted as a single point against the average daily temperature.

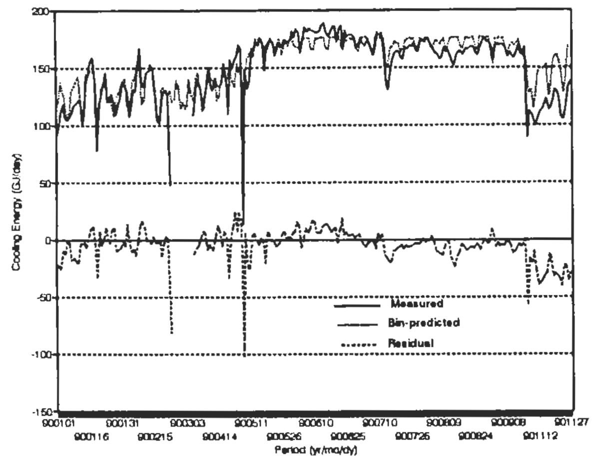


**Figure 4: Pre-retrofit cooling energy consumption for the ZEC building during the period Jan.1,1990 through Nov.27,1990.**

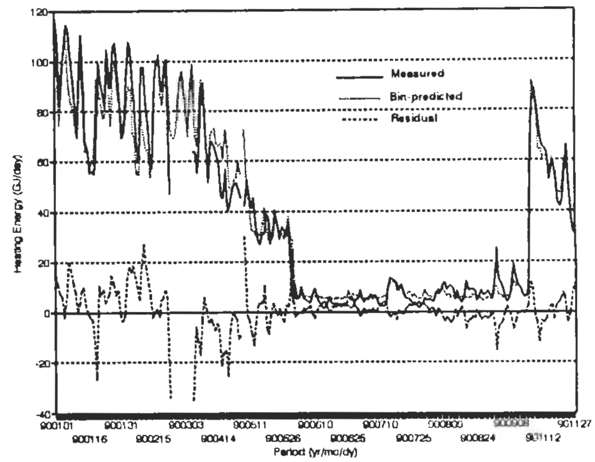


**Figure 6: Pre-retrofit heating energy consumption for the ZEC building during the period Jan.1,1990 to Nov.27,1990.**

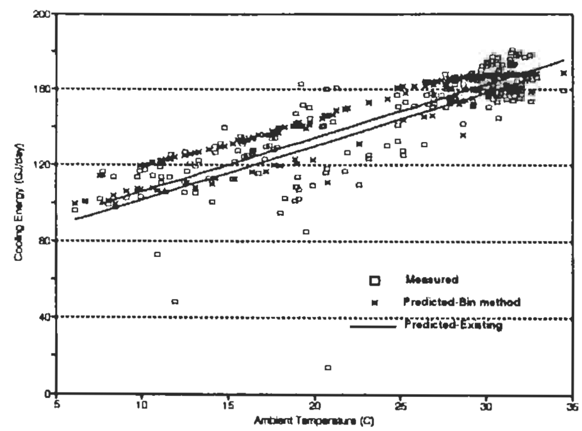


**Figure 5: Cooling energy consumption for the pre-retrofit period versus average daily temperature for the ZEC building during the period Jan.1,1990 to Nov.27,1990.**

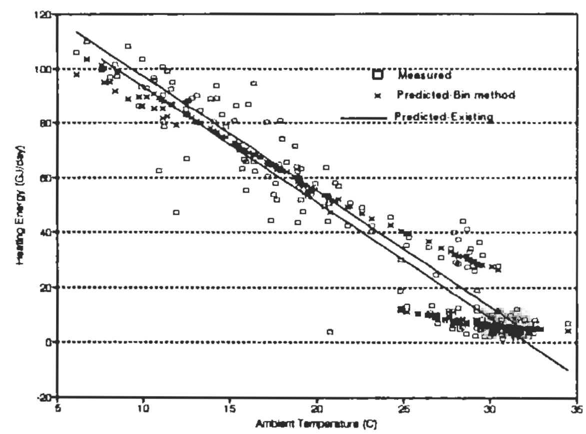


**Figure 7: Daily heating energy consumption for the ZEC versus daily mean temperature during the period Jan.1,1990 through Nov.27,1990**

Figures 6 and 7 show the heating energy consumption for the pre-retrofit period at the ZEC building. The heating energy use for the building also exhibits a linear variation with ambient temperature.

$R^2$, Coefficient of Variation (CV), and Mean Bias Error (MBE) statistical parameters were used to evaluate the performances of bin method prediction and the existing LoanSTAR savings models. Table 2 shows these parameters for the modeling of the ZEC MCC, cooling and heating loads.

The calculated monthly savings for the calendar year 1992 are shown in Figure 8. The cooling energy savings predicted by the bin method have higher values than the savings predicted by the existing LoanSTAR model for the months with lower mean temperatures (January - May, and October - December) and lower values during the months with higher mean temperatures (June - September). Conversely, the heating energy savings predictions from the bin method are lower than the existing model predictions during the months with high mean temperatures (June - September). The AHU electricity savings from both predictions were almost identical for the calendar year 1992, since both methods used an average daily value. For the entire year the bin-predicted chilled water savings were 27.8% higher than the existing LoanSTAR model, bin-predicted hot water savings were 5.8% lower and the MCC savings were 0.2% higher.

**Table 2. Comparison of parameters for both models used to calculate the ZEC energy savings.**

| Parameter | Evaluation Parameter | Bin method | Number of Bin Models | Existing model | Type of Existing Model |
|---|---|---|---|---|---|
| Air-handler | CV (%) | 4.6 | one bin | 5.8 | Constant |
| | $R^2$ (%) | N/A | | N/A | daily |
| | MBE (%) | -0.08 | | -0.05 | value |
| Cooling | CV (%) | 7.2 | two bins | 10.3 | Weekday- |
| | $R^2$ (%) | 71.9 | | 66.7 | Weekend |
| | MBE (%) | 0.35 | | 0.001 | 2 parameter |
| Heating | CV (%) | 26.9 | three bins | 28.4 | Weekday- |
| | $R^2$ (%) | 91.2 | | 90.6 | Weekend |
| | MBE (%) | -0.98 | | 0.37 | 2 parameter |

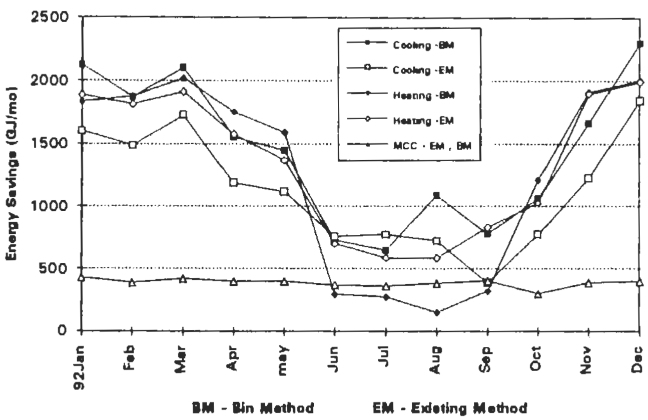


**Figure 8: Comparison of bin method savings to existing LoanSTAR method savings for the ZEC building.**

## CASE STUDY 2 : THE EDUCATION BUILDING, UNIVERSITY OF TEXAS, AUSTIN

The Education Building (EDB), located at the University of Texas at Austin contains 23,300 $m^2$ (250,000 $ft^2$) of gross conditioned space and consists of five stories of classrooms, office and administration facilities. It was constructed in 1976. The building is face brick on block wall construction. About 30% of the exterior wall area is covered with single pane, tinted glazing, which is shaded. The building has a flat built-up roof, and is occupied from 8 a.m. to 5 p.m. Monday through Friday.

The building is served by 11 dual-duct air-handling units, three constant air volume units and eight variable air volume units. Chilled and hot water for the cooling and heating coils are supplied to the building by the campus central energy plant. During the pre-retrofit period the air-handling units were operated during the occupied periods (i.e., about 18 hours per day, Monday through Friday). In the post-retrofit period the HVAC system operated 24 hours per day. The building has an economizer cycle that was not used during the pre-retrofit period (ESL 1993).

The primary retrofits were to replace the existing Constant Air Volume (CAV) air distribution systems with a variable frequency, Variable Air Volume (VAV) air distribution system and the incandescent lighting in the corridors with compact fluorescent lamps.

The EDB was instrumented as one of several buildings at the University of Texas at Austin campus under the LoanSTAR program. About 18 channels of hourly data are metered, including whole-building electricity, MCC, whole-building heating and cooling energy use, and a derived channel which represents the lights and equipment. The lights and equipment channel is derived by subtracting MCC electricity use from the whole-building electricity use. The pre-retrofit period was determined to be between October 14, 1990 through April 29, 1991.

### Lighting and Equipment Savings

The model chosen for the LoanSTAR program consisted of a one-parameter average daily weekday-weekend model. For the bin method the lights and equipment electricity consumption was described by weekday-weekend 24-hour bin values shown in Figure 1.

### Air-Handler Electricity Consumption

In a similar fashion to the lights and equipment retrofit savings the pre-retrofit MCC electricity use was described with a one-parameter average daily weekday-weekend model for the LoanSTAR program, and 24-hour weekday-weekend bin models.

The monthly lighting retrofit savings as measured by the derived lights and equipment channel are shown in Figure 13 for both methods. In the case of the EDB the one-parameter average daily LoanSTAR method and the bin method yield almost identical results.

### Cooling and Heating Energy savings

The pre-retrofit cooling energy use is shown in Figures 9 and 10. The LoanSTAR model utilized a four-parameter weekday-weekend change-point model. The measured, bin-predicted, and residual heating energy consumption for the pre-retrofit period is shown in a time series plot (Figure 11), and as a scatter plot versus daily mean ambient temperature (Figure 12).

In both the cooling and heating models (Figures 10 and 12) the bin method and change-point models appear to capture the non-linear variation. In both cases the bin-

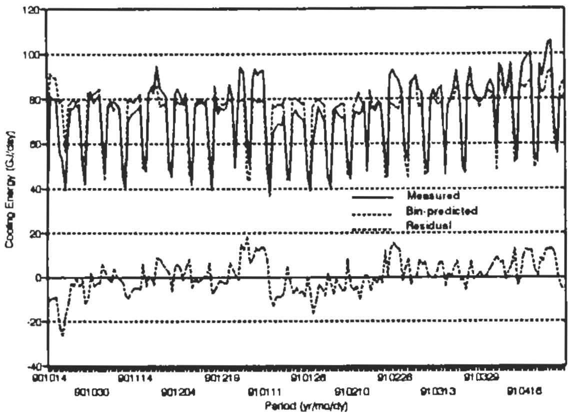


**Figure 9: Pre-retrofit cooling energy consumption for the EDB building during the period Oct.14,1990 through Apr.29,1991.**

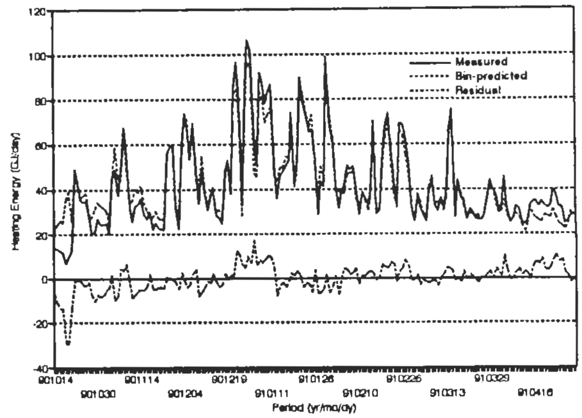


**Figure 11: Pre-retrofit heating energy consumption for the EDB building during the period Oct.14,1990 through Apr.29,1991.**

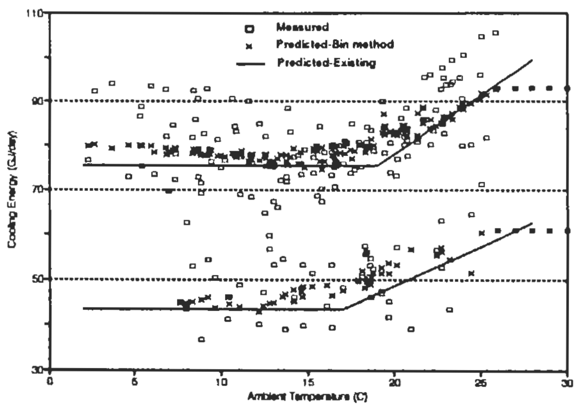


**Figure 10: Pre-retrofit cooling energy consumption versus daily mean temperature for the EDB building during the period Oct.14,1990 through Apr.29,1991.**

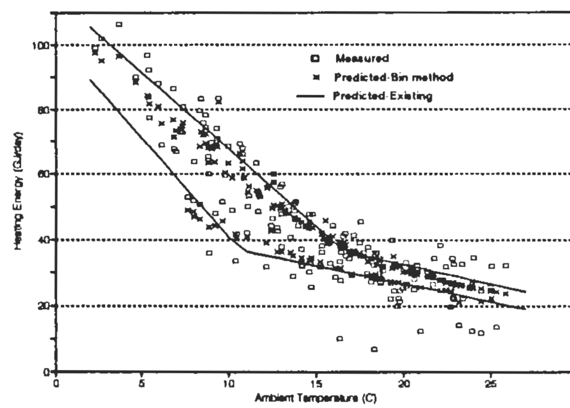


**Figure 12: Pre-retrofit heating energy consumption versus daily mean ambient temperature for the EDB building during the period Oct.14,1990 through Apr.29,1991.**

**Table 3. Comparison of parameters for both models used in the EDB building savings calculations.**

| Parameter | Evaluation Parameter | Bin method | Number of Bin Models | Existing model | Type of Existing Model |
|---|---|---|---|---|---|
| Light & Equipment | CV (%) | 3.1 | two | 3.7 | Weekday-Weekend 1 parameter |
| | R2 (%) | N/A | | N/A | |
| | MBE (%) | 0.66 | | 0.17 | |
| Motor Control Center | CV (%) | 6.6 | two | 5.8 | Weekday-Weekend 1 parameter |
| | R2 (%) | N/A | | N/A | |
| | MBE (%) | -0.54 | | -1.42 | |
| Cooling | CV (%) | 10.27 | three | 14.85 | Weekday-Weekend change-point |
| | R2 (%) | 78.4 | | 54.9 | |
| | MBE (%) | -0.44 | | 1.01 | |
| Heating | CV (%) | 14.23 | three | 17.43 | Weekday-Weekend change-point |
| | R2 (%) | 90.6 | | 85.9 | |
| | MBE (%) | 0.10 | | -0.05 | |

method happens to have the edge over the change-point models. This is evident from the higher coefficient of determination ($R^2$) for both heating and cooling energy use models and lower Coefficient of Variation (CV) values (Table 3). The change-point linear regression model has a zero slope for cooling energy use in the low temperature region (i.e., PRISM-CO or 3 parameter cooling model), while the actual data has varying slopes for this region. In this building during the cooling season the air-handler units are frequently shut down during the holidays and weekends. Hence, the air-handler shutdowns during these periods are separated as another day type. This allowed for the separation of data into an occupied weekday-weekend groups and an unoccupied group. Each of these three groups have binned in 3°C (or 5.4°F) bins to capture the variation of the energy consumption with the temperature.

Table 3 shows the evaluation parameters for the modeling of EDB building MCC electricity, lights and equipment electricity, cooling energy and heating energy models. The calculated monthly savings by both methods for the calendar year 1992 are shown in Figure 13. The energy savings predicted by the bin method agrees well with the savings predicted by the existing methods, except for the extreme cooling energy savings. The difference can be attributed to the different prediction method used in the existing change-point linear method versus the bin method for the temperature data that lies outside the pre-retrofit model data range. The bin method predicted cooling energy value was arbitrarily chosen as a constant for weekday and weekend and is shown by filled squares in Figure 10. By contrast, the prediction from a change-point linear model has an increasing linear variation with temperature, as shown in Figure 10. Unfortunately, this problem occurred in the analysis of the education building because the six month pre-retrofit data period did not include sufficient hourly data in the extreme cooling period necessary to fully characterize the building's cooling energy use.

Obviously, a method needs to be developed for extrapolating the bins into extreme conditions since a flat consumption is probably not reasonable. Since this extrapolation is automatically handled by a weekday-weekend change-point linear model the cooling savings predicted by the existing LoanSTAR model are probably more reasonable in this region of the cooling season.

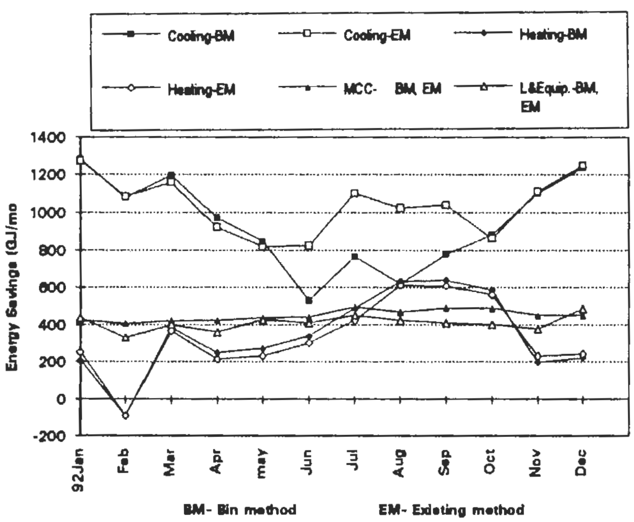


**Figure 13: Comparison of bin method savings to existing LoanSTAR method savings for the EDB building.**

For the entire year the bin-predicted chilled water savings were 9.4% lower than the existing LoanSTAR model; bin-predicted hot water savings were 4.3% higher; bin-predicted MCC electricity savings were 1.2% higher; and bin-predicted lights and equipment electricity savings were 1.3% higher.

## RESULTS AND DISCUSSION

The preliminary results from the comparisons of bin method predicted savings to savings predicted by linear and change-point linear models shows that the bin method appears to calculate similar savings. In certain cases the bin method may have the edge in capturing non-linear variations in the data that cannot be described by average daily regression models. In cases with insufficient data for developing mean bin consumption for extreme heating-cooling conditions other methods will need to be developed for extrapolating pre-retrofit consumption into extreme bins.

We suggest that the model selection should be based on the ability to predict the data with adequate accuracy evaluated from the coefficient of determination ($R^2$) and Coefficient of Variation (CV) and the simplicity of the model itself for savings calculations. In buildings where a one-, two-, three-, or four-parameter, change-point linear regression model fits the data well, then the change-point model should be used. However, for the buildings that exhibit non-linear behavior, the hourly bin method should be considered.

## FUTURE DIRECTIONS

This work suggests many other areas for future work. First, the choice of the appropriate form of equation for the CV needs to be resolved. This includes the determination of the number of parameters (p) for a bin model. Second, a robust procedure needs to be developed that will consistently give the optimum number of bins for a given data set. Third, the bin method needs to be expanded to include other weather variables such as humidity, solar heat and thermal mass. Finally, methods need to be developed for extrapolating mean bin values during extreme cooling-heating when a pre-retrofit data set contains insufficient data for doing so.

## ACKNOWLEDGMENTS

The Texas LoanSTAR program is funded through the Texas State Energy Conservation Office (SECO) of the Inter-governmental Division of the General Services Commission (Texas State Agencies Program). We gratefully acknowledge useful discussions with Dr. David E. Claridge, Dr. T. Agami Reddy and Dr. David Ruch.

Assistance from Ron Chambers in processing and updating the building archive database is also appreciated.

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**APPENDIX**

The three statistical indices used to evaluate the models are defined below (SAS 1990) :

1. The coefficient of determination, $R^2$ (%):

$$R^2 = \left( 1 - \frac{\sum_{i=1}^{n} \left( y_{pred,i} - y_{data,i} \right)^2}{\sum_{i=1}^{n} \left( \bar{y}_{data} - y_{data,i} \right)^2} \right) \times 100$$

2. The coefficient of variation CV (%):

$$CV = \frac{\sqrt{\dfrac{\sum_{i=1}^{n} \left( y_{pred,i} - y_{data,i} \right)^2}{n-p}}}{\bar{y}_{data}} \times 100$$

3. The mean bias error, MBE (%):

$$MBE = \frac{\dfrac{\sum_{i=1}^{n} \left( y_{pred,i} - y_{data,i} \right)}{n-p}}{\bar{y}_{data}} \times 100$$

where

$y_{data,i}$ is a data value of the dependent variable corresponding to a particular set of the independent variables,

$y_{pred,i}$ is a predicted dependent variable value for the same set of independent variables above,

$\bar{y}_{data}$ is the mean value of the dependent variable of the data set,

$n$ is the number of data points in the data set.

$p$ is the total number of regression parameters in the model (which was arbitrarily assigned as 1 for all models).