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A METHODOLOGY TO DEVELOP MONTHLY ENERGY USE MODELS FROM UTILITY BILLING DATA FOR SEASONALLY SCHEDULED BUILDINGS: APPLICATION TO SCHOOLS

A Thesis

by

WENYAN WANG

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 1998

Major Subject: Mechanical Engineering

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ABSTRACT

A Methodology to Develop Monthly Energy Use Models from Utility Billing Data for Seasonally Scheduled Buildings: Application to Schools.

(December 1998)

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The measured energy savings from retrofits in buildings in the Texas LoanSTAR program are determined as the difference between the energy consumption predicted by a baseline model and the measured energy consumption during the post-retrofit period.

Savings measurement for buildings such as primary and secondary schools is very difficult due to the special operating schedules of these buildings. Currently, savings are often determined by simple pre-post utility bill comparison; they may also be determined with two separate models for the baseline: a 3-P model for non-summer months, and a mean model for the summer months. (Landman 1996).

This thesis proposes a methodology for developing baseline models of energy use for buildings such as schools which have important daily and seasonal variations in occupancy. The method utilizes utility billing data, but also explicitly incorporates occupancy rate, permitting a generalized model which retains the distinction between energy use levels during occupied and unoccupied days of the year. The proposed

methodology has been evaluated against the one proposed by Landman for 10 schools in Texas.

The major results are summarized below:

1. The CV (Coefficient of Variation of the Root Mean Square Error) values for the proposed methodology are much smaller than those of the 3-P mean model method, while the average absolute percent error is somewhat smaller for the proposed method, implying that it is suitable for developing baseline models for buildings such as schools that experience large seasonal changes in occupancy patterns. Although this method is a little more complicated it allows a more intuitive and unified model to be identified than the standard 3-P model.

2. Using daily data from the Dunbar Middle School, it is illustrated that the effect of the schedule on energy use is sometimes comparable to that of outside temperatures for heavily scheduled buildings. This suggests that selection of data periods for baseline model identification should be done with great care.

3. The proposed 4-P multiple-linear regression model is recommended. It was found to be somewhat more accurate than the 3-P mean model approach recommended by Landman.

DEDICATION

To my father Yulin Wang, and my mother Menglan Han, the parents of unshakable strength: The strength to raise us children during difficult times; The strength to stand by me during difficult times. And to my husband Binsheng Lui whose love and encouragement are my inspiration.

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NOMENCLATURE

A	=	the energy consumption at the change point temperature T_{cp} (°F)
a	=	multiple linear regression coefficient (W/ft²)
B	=	the temperature slope
b	=	multiple linear regression coefficient
C	=	the change point temperature T_{cp} (°F)
c	=	multiple linear regression coefficient
d	=	multiple linear regression coefficient
E	=	electricity use (W/ft²)
e	=	multiple linear regression coefficient
f	=	multiple linear regression coefficient
g	=	multiple linear regression coefficient
I	=	indicator variable
ki	=	occupancy rate for each month
q	=	heat gain (W/ft²)
T	=	temperature (°F)

Subscripts

cp	=	change point
cpoc	=	change point for occupied day
cpun	=	change point for unoccupied day

db	=	dry-bulb
dp	=	dew-point
i	=	internal
mean	=	mean
m	=	get from multiple linear regression
oc	=	occupied day
sol	=	solar
tot	=	total
un	=	unoccupied day
wb	=	wet-bulb
0	=	first parameter for multiple linear regression
1	=	second parameter for multiple linear regression

CHAPTER I

INTRODUCTION

Energy use in commercial buildings accounts for 16% of total energy use in the United States (EIA 1992). Since most buildings were constructed when energy was inexpensive, at least 30% of the energy use in the buildings sector is wasted due to inefficient equipment and operation (Bevington and Rosenfeld 1990). This wasted energy can be saved in a highly cost-effective manner by operational improvements and retrofits. For example, the Texas LoanSTAR Program measured a 24% energy consumption reduction in 64 commercial buildings where retrofits with an average payback of 3 years were performed (Claridge 1994).

The analysis of energy consumption data is a valuable tool for the management of building operation:

- it can help detect malfunctioning equipment (by identifying episodes of abnormally high consumption);
- it is essential for energy audits in order to improve the estimates of expected savings, and to verify the savings achieved by retrofit (Haberl and Komor 1990)

Such an analysis requires an understanding of the factors that influence the energy consumption. Basically one needs a model of the building that can predict the

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This thesis follows the format of *ASHRAE Transactions.*

consumption for any operating conditions of interest.

In the LoanSTAR program, most retrofit evaluation programs, energy savings are determined as the difference between the energy consumption predicted by using a baseline model and the measured energy consumption during the post retrofit period. The baseline can be developed using different approaches, such as simplified HVAC system models calibrated with the data taken before or after the retrofit (Knebel 1983; Katipamula and Claridge 1993), and statistical regression models based on data taken before the retrofit (Fels 1986; Ruch et al. 1992; Claridge et al. 1992; Ruch et al. 1993; Kissock et al. 1992; Kissock et al. 1993). The regression model approach is the simplest and most widely used. A number of regression models and simplified simulation models were developed in the LoanSTAR program (Reddy et al. 1994). The selection of the appropriate model is determined by how much and what types of monitored data are available.

Regression models based on daily data are often used when daily data are available. These models regress daily energy consumption data against daily average outside temperature to develop empirical baseline models for commercial buildings' energy consumption. Daily models are used to determine daily baseline energy consumption under post retrofit weather conditions.

Monthly regression models are generally developed using utility billing data. The energy consumption is regressed versus the average ambient temperature during each billing period. This technique is easier than daily regression and can also be used when hourly or daily data are not available. (Wang 1996)

The most suitable regression models are generally selected based on the values of the coefficient of determination (R^2) and the coefficient of variation of the root mean square error (CV-RMSE). These two statistical indices provide an indication of the goodness-of-fit of the model to the data measured during the pre-retrofit period. The difference between the annual consumption determined from the model and the measured annual consumption is defined as the annual prediction error (APE).

However, the baseline models which use only temperature as an independent variable only capture changes in energy consumption due to changes in temperature. For seasonally scheduled buildings such as schools, a proper retrofit saving determination should explicitly account for any changes in schedule. Retrofit savings of schools are currently evaluated using simple pre-post utility bill comparison, or a procedure suggested by Landman (1996 a, b). The latter procedure considers the influence of weather on the energy use and uses a simple mean model for summer consumption, but does not consider schedule differences between the baseline year and post retrofit periods. By explicitly considering occupancy rate, a model can be generalized in a way which retains the distinction between energy use during occupied and unoccupied days.

CHAPTER II

REVIEW OF BASELINE MODELING FOR RETROFIT SAVINGS MEASUREMENT

Several approaches are used currently to determine energy retrofit savings. They can be divided into methods which determine the baseline consumption using:

- Calibrated simulation models such as the DOE-2 program (Hsieh 1988; Bronson et al. 1992; Reddy et al. 1994; Bou-Saada and Haberl 1992);
- Analysis of utility billing data;
- Simplified HVAC system models calibrated to data taken before or after the retrofit (Katipamula and Claridge 1993);
- Statistical regression models based on data taken before retrofit (Fels 1986; Ruth et al. 1992; Claridge et al. 1992; Ruth et al. 1993; Kissock et al. 1992; Kissock et al. 1993).
- Other methods for modeling hourly energy use, such as Fourier series (Dhar 1994) and regressed bin models which have been applied in the LoanSTAR program.

DOE-2 is a building energy simulation program primarily used for design simulations for new construction. However it is also used to evaluate the impact of energy conservation retrofits on exiting buildings. This is generally accomplished by simulating the building using the design characteristics of the building and then modifying the simulation inputs to evaluate the impact of retrofit measures and estimate savings as the difference between the pre- and post-retrofit simulated energy use.

Simplified HVAC system simulation models (Katipamula and Claridge 1992; Liu and Claridge 1995) based on the ASHRAE TC4.7. Simplified Energy Analysis Procedure (Knebel 1983) can also be calibrated to measured consumption data to establish a baseline model. These calibrated HVAC system models have also been successfully used to identify potential O&M (operation and maintenance) savings and determine real energy savings in several types of commercial buildings (Liu and Claridge 1995). This simplified system simulation method requires much less information than the DOE-2 program and offers suitable accuracy for determining savings. The time taken for the simulation and the accuracy achieved depends greatly on the user's knowledge and experience.

Simulation and calibration need a lot of building, schedule and internal load information; they require substantial user knowledge and experience, and the process takes considerable time. Therefore, when measured data are available, direct utility bill comparison (DUBC) or weather normalized analysis using statistical regression models are used more widely.

Direct utility bill comparison (DUBC) is the simplest method for savings' determination. The savings for any month are estimated as the difference between the unadjusted pre-retrofit and post-retrofit utility bills for any month assuming that the billing period does not change. This method can result in 10-20% baseline error when the post-retrofit weather is substantially different from the pre-retrofit weather, because it neglects weather changes. This drawback can be overcome by developing statistical regression models that correlate the energy consumption to the corresponding weather.

Usage of statistical regression models to establish baseline performance is straight-forward and often suitable for savings determination when measured daily or monthly energy consumption data are available for 12 months for both pre- and post-retrofit periods. In this approach, weather dependent regression models are developed from the pre-retrofit data to serve as a baseline model for the building energy consumption. These models are then used to predict the amount of energy the building would have consumed during the post-retrofit period if no retrofits were implemented. The difference between the baseline energy use and the monitored energy consumption in the post-retrofit period is the energy saved (Claridge et al 1990; Kissock et al. 1992). The regression models can be divided into two categories: single variable (SV) models and multiple variable (MV) models.

Single variable models:

Here the outside air dry-bulb temperature is taken to be the only regression variable. The models for weather dependent use include two-parameter (2-P), three-parameter (3-P), and four-parameter (4-P) models. The functional forms of these models are as follows:

2-P model: $E = a + bT_{db}$ (2.1)

3-P model: $E = a + b(T_{db} - T_{cp})^-$ for heating (2.2a) and $E = a + b(T_{db} - T_{cp})^+$ for cooling (2.2b)

4-P model: $E = a + b_1(T_{db} - T_{cp})^+ + b_2(T_{db} - T_{cp})^-$ (2.3)

In these equations, a is the energy consumption at the change point temperature T_{cp}, (it accounts for the energy consumption at zero temperature for a 2-P model) and b, b_1 and b_2 are the temperature slopes. Equation 2.2a is the 3-P heating regression model and Equation 2.2b is the 3-P cooling regression model. The notation $( )^+$ and $( )^-$ indicates that the quantities within the parentheses should be set to zero when they are negative and positive respectively. In this thesis we consider only electricity use for cooling, so only equation 2.2b is used.

Multiple variable regression models:

Multiple variable regression models consider the effects of variables such as specific humidity, solar radiation and internal loads in addition to the impact of outdoor temperatures. Suitable multi-variable regression models can be developed by incorporating the engineering principles that govern the HVAC system operation (Forrester and Wepfer 1984). An example of a simplified multi-variable regression model based on engineering principles can take the form (Katipamula et al. 1994):

$$E = a + b + cI + dIT_{db} + eIT_{wb}^{\ +} + fq_{sol} + gq_i \quad (2.4)$$

where a, b, c, d, e, f and g are the linear regression coefficients, T_{db} is again the dry-bulb temperature, T_{wb} is the wet-bulb temperature, q is the heat gain and I is an indicator variable that accounts for a change in slope due to the effect of outdoor temperatures at higher values (Kissock 1993).

CHAPTER III

METHODOLOGY

3.1 Introduction

Since the single variable regression models consider the measured energy consumption to depend only on outside air temperature, they are much simpler and more popular than multiple variable regression models for retrofit savings.

But multi-variable models have higher accuracy than single variable regression models. And for heavily scheduled buildings, the occupancy rate is another very important factor that affects the energy use.

How much of the total energy use depends on the residents' behavior? In a study of 209 similar homes, Goldstein, Schneider, and Clark (1985) found that 60% of the variation of energy use could not be explained by the measured variables and must be attributed to physical parameters not in the study or to nonphysical parameters included under the general term "lifestyle". A study in Norway, (Peterson 1994) found that 80-85% of the total variation in energy use was caused by the inhabitants. Meier, Rainer, and Greenberg (1992) contend that miscellaneous appliances account for more than 40% of the total electricity consumption for a typical modern house. Human behavior affects energy use in homes as well as the heavy occupied and scheduled commercial buildings.

The proposed model and the 3-P mean model will be evaluated using data from 10 schools in Texas. These ten schools are located in four different cities: Fort Worth, Victoria, Nacogdoches, and Galveston. Table 3.1 shows the location, size and the data years used to test the model for each of these schools. Weather data for the four different sites are available on a daily basis. The extreme year is the year with higher daily average temperature in summer and lower daily average temperature in winter than the baseline year.

Table 3.1
Summary of the Study Cases

School Name	Code	Site	Area (ft^2)	Baseline year	Extreme year
Sims Elementary School	SES	Fort Worth	62,400	FY93	FY95&96
Dunbar Middle School	DMS	Fort Worth	92,884	FY94	FY95&96
Stroman High School	SHS	Victoria	210,414	FY94	FY95&96
Victoria High School	VHS	Victoria	257.014	FY94	FY95&96
Nacogdoches High School	NHS	Nacogdoches	202,515	FY94	FY95&96
Chamberlain Middle School	CMS	Nacogdoches	66,778	FY94	FY95&96
Oppe Elementary School	OES	Galveston	80,400	FY94	FY95&96
Weis Middle School	WMS	Galveston	80,769	FY94	FY95&96
Parker Elementary School	PES	Galveston	81,742	FY94	FY95&96
Morgan Elementary School	MES	Galveston	76,798	FY94	FY95&96

THE PROPOSED MODEL

The proposed, methodology is intended to identify monthly baseline models of energy use for buildings such as public elementary and secondary schools, whose energy use is affected by seasonal occupancy changes. The model developed captures not only the relationship between the energy usage and the outside air temperature, but also the dependence on seasonal occupancy rate. The methodology involves a two stage process, a 3-P regression of the energy use data from non-summer months and a multiple linear regression for all 12 months. This approach will be "validated" with monitored data from 10 different schools in Texas. How such a model identification scheme is affected by outdoor temperature variation will also be studied by selecting extreme years at the same location and evaluating the predictive ability of the monthly models against that of daily models.

3.2 Mathematical Basis of the Proposed Model

The proposed model will consider the impact of the occupancy level as well as that of the outside air temperature. From equation 2.2b, the 3-P cooling regression model for school days is:

$$E_{oc} = A_{oc} + B_{oc}(T_{db} - T_{cpoc})^{+} \tag{3.1}$$

and the appropriate 3-P model for non-school days is:

$$E_{un} = A_{un} + B_{un}(T_{db} - T_{cpun})^{+} \tag{3.2}$$

These models can be combined to give the following model:

$$E_{tot} = E_{oc}k_i + E_{un}(1 - k_i) \tag{3.3}$$

where k_i is defined to be the fraction of the days in month i which are school days. Then the average daily consumption in month i is given as

$$E_{tot} = A_{oc}k_i + B_{oc}(T_{db} - T_{cpoc})^{+}k_i + A_{un}(1 - k_i) + B_{un}(T_{db} - T_{cpun})^{+}(1 - k_i) \tag{3.4}$$

Because there are 6 parameters to be identified from 12 data points (where 12 months of data are available) the estimation will be unsound. Thus, in order to simplify the model we will assume the two models to have the same slope and the same balance temperature. Then the model becomes a 4-P multiple linear regression model:

$$E_{tot} = A_{oc}k_i + A_{un}(1 - k_i) + B_m(T_{db} - T_{cpun})^+$$
$$= A_{un} + k_i(A_{oc} - A_{un}) + B_m(T_{db} - T_{cpun})^+$$

or:

$$E_{tot} = A_0 + A_1 k_i + B_m(T_{db} - C)^+ \quad (3.5)$$

where A_0 , A_1 , B_m and C are the four parameters of the model which need to be identified by regression. If we assume only that the two models have the same balance temperature, then the model becomes a 5-P model as:

$$E_{tot} = A_0 + A_1 k_i + B_{oc}(T_{db} - C)^+ + B_{un}(T_{db} - C)^+ \quad (3.6)$$

3.3 Procedures

A procedure is described which is used in this thesis to test the proposed method for developing baselines for the energy usage of buildings with heavily variable seasonal occupancy schedules as shown in Figure 3.1. The circled numbers in the figure correspond to the step numbers in the description shown below. Chapter VII presents a detailed example of the use of this methodology to baseline and predict consumption of Sims Elementary School.

(1) Selection of baseline time period

Obviously, any regression is of little value if the measured data are not correct. It has also been found that the accuracy of the regression model depends greatly on the quality of the measured data. If there are less than three months of measured daily data, the regression model may have uncertainty as high as 20% for monthly energy prediction (Kissock 1993). The regression should be developed with a full year of data that covers all four seasons, and all the building operation patterns. In such instances, the effect of limited data can be largely eliminated. (Wang 1996)

For normal baseline development the last 12-month set of data before the retrofit starts is used unless this data is known to be anomalous. To test the method, select one typical school year with mild weather among the last five years for which the hourly energy consumption and weather information are available in the LoanSTAR database. Use this year as the baseline year. Convert the hourly data into the average daily energy consumption and the daily average outside air temperature data for the year from the LoanSTAR data base.

Although humidity conditions also significantly impact the energy consumption, the weather years were determined based on the dry-bulb temperature since it was found that the correlation between humidity and dry-bulb temperature was very close from year to year.

For example, the monitored hourly data for FY94, that is from 08/93 to 07/94, was selected as the baseline year for nine of the schools.

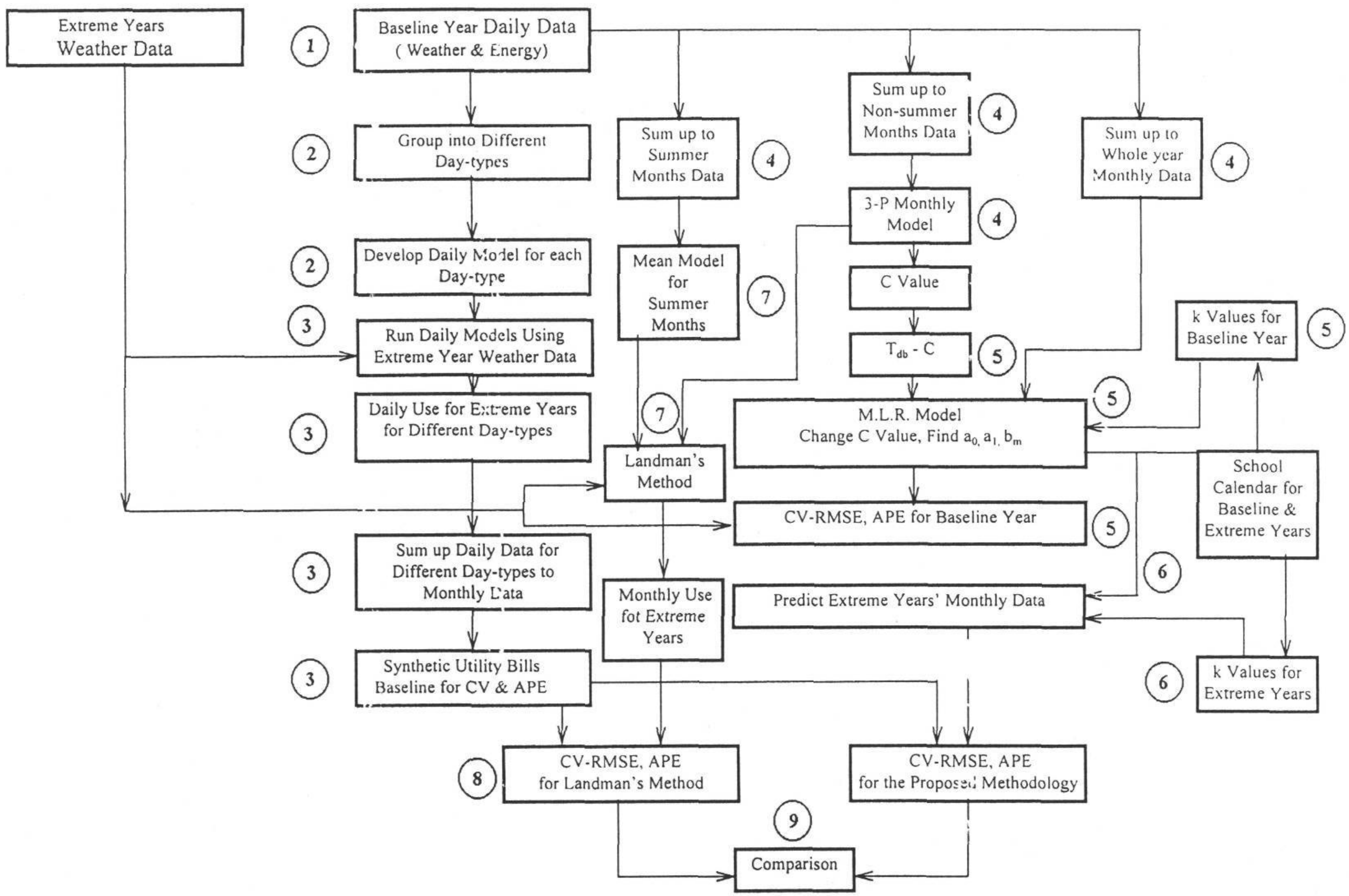


Figure 3.1 Flow Chart of the Various Steps Involved

(2) Group daily data and develop daily regression models

Group the daily data according to the school calendar to create “day types”. According to the school schedule and the time series energy usage, divide the daily data into two or three different groups, using criteria such as those of Katipamula and Haberl (1993) or Dhar et al (1992).

For example, the criteria used might identify two day types, namely:

(1) school days during the school year.

(2) non-school days during the school year.

Another result might be the following three day types:

(1) school days during the school year.

(2) holidays longer than 2 days during school year.

(3) Remaining days (weekends and one day holidays).

Following Dhar etal. (1992), Duncan's multiple range test which is a mean comparison test for multiple groups of data, (it considers both mean and standard deviation of the groups to be compared) is then performed and the day-groups with statistically insignificant differences in mean energy consumption are aggregated together. The day-types thus achieved are the day-types used to calculate the “ synthetic utility bill ” for the extreme years.

Table 3.2
Results of Duncan's Multiple Range Tests for Identification of Day-types for Ten Schools in Texas

School		Group Mean (W/ft²)		Duncan Grouping
	Group 1	Group 2	Group 3	
SES	1.62	1.21	0.99	3 Groups
DMS	2.08	2.34	0.95	3 Groups
SHS	1.11	0.61	0.39	3 Groups
VHS	1.28	0.67	0.36	3 Groups
NHS	1.82	0.94	0.62	3 Groups
CMS	1.36	0.68	0.27	3 Groups
OES	1.85	0.58	0.36	3 Groups
WMS	2.25	0.49	0.5	2 Groups
PES	1.89	0.58	0.47	3 Groups
MES	2.37	0.69	0.37	3 Groups

Use the daily energy and weather data for each group of the day-types chosen above to develop a daily 3-P or 4-P linear regression model for the corresponding day type. A detailed example of this procedures shown at the beginning of Chapter VII.

(3) Calculate the " synthetic utility bill " for the extreme years

To determine the prediction error, at least two years of energy use data are desirable. The first year of data which is the baseline year selected in step 1, is used for developing the regression model. The second year of data is compared with the consumption predicted by the baseline regression model to determine the prediction error of the regression model. Unfortunately, it is very difficult to find buildings with two years of measured data which also maintained the same internal load profile schedule and the same operating schedule over both years. Therefore " synthetic utility bills " were created as follows.

To choose the extreme temperature years, first, plot the time series daily outside temperature data during several recent years for the city where the school is located. Choose the year with the highest daily average temperatures in summer and the lowest daily average temperatures in winter such as FY96 and the year with second highest daily average temperature in summer, and with the daily average temperatures lower than the baseline year in winter, for which FY95 is chosen. These two years were defined as the extreme temperature years. Further discussion will be given in Chapter V.

The extreme years should be chosen with the largest temperature variation available for each school. We then use the single variable linear regression models, to compare the influence of outside air temperature and that of schedule on energy use to determine which has larger impact. Assume the extreme years have identical schedules as the baseline year, that is the same k_i value for each month and the same 2 or 3 different day types. Run the 3-P or 4-P daily models with the extreme years temperature data as input. Sum up the predicted daily consumption for each month of the extreme years, divide by the number of days to get the average daily use for each month and use these values as the " synthetic utility bills " for the extreme years.

The other reason to create the " synthetic utility bills " for the extreme years instead of the measured utility data is that this study has found that the schedule affect has an influence on energy consumption that is comparable to that of the outside air dry-bulb temperatures for seasonally scheduled buildings. This is especially true during summer when some special activities occur, and often the school calendar can not catch it. When the developed models from the baseline year are used to predict the extreme years' energy consumption, it implicitly assumes that the baseline year and the chosen extreme years have the same schedule, which we know is general not true, especially during the summer time. But the " synthetic utility bills ", are based on the same schedule as the baseline year, by definition; by using these " synthetic utility bills ", we have removed the random operating factor from the data. Some figures and further discussion will be shown in Chapter VII.

(4) Develop 3-P non-summer month models

Sum up the daily data got from the database for each month of the baseline year, and divide by the number of days to get the monthly mean daily average energy use values. Use the average values for the 9 non-summer months to develop a monthly 3-P linear regression model following equation 2.2b in the form:

$$E = A + B(T_{db} - C)^{+}$$

where A, B and C are the linear regression coefficients: A is the intercept of E; B is the slope and C is the balance temperature.

(5) Develop 4-P M.L.R model

Calculate occupancy fraction (k_i) for each month i as:

the fraction of the total days in the month which are school days. It should be between 0 and 1.

$$k_i = \frac{\textit{Number of school days}}{\textit{Number of school days} + \textit{Number of non-school days}} \tag{3.7}$$

Landman has defined Electric Load Factor (ELF), Occupancy Load Factor (OLF) and People Load Factor (PLF) in his thesis, determined their numerical values for the schools investigated, and qualitatively use of these values in his analysis of the energy consumption. But he did not directly incorporate them into the models. In this thesis, we define the occupancy rate k_i in a manner similar to Landman's OLF,

$$\text{OLF} = \frac{\text{hours occupied (in billing period)}}{\text{total hours (in billing period)}}$$

except that k_i is defined at the daily level. The k_i values are explicitly incorporated in the proposed model, permitting a generalized model which retains the distinction between energy use levels during occupied and unoccupied days of the year. Thus the baseline model proposed accounts for the influence of school schedules directly.

Choose the C value of the 9 non-summer months model we identified in step (4). Use it to determine (T - C), for each of the 12 months of the current year. Develop a monthly multiple linear regression model for this year, the "Proposed Model" which is written as:

$$E_{tot} = A_0 + A_1 k_i + B_m(T_{db} - C)^+ \quad (3.8)$$

where A_0, A_1, B_m and C (initial value is obtained from step 4) are the multiple linear regression coefficients. $A_0 = A_{un}$; $A_1 = A_{oc} - A_{un}$. Because the initial value of C is obtained from step 4, change the C value by small increments, and finally select the value for which the smallest CV is obtained. Calculate CV-RMSE and APE (Annual Prediction Error). Plot k_i vs [E - $B_m(T_{db} - C)$]. If we observe a linear relationship, it indicates that the models are correct because from equation (3.8): $E_{tot} - B_m(T_{db} - C)^+$ is linear in k_i. Energy use can then be predicted using outside temperature and k_i values.

The regression models are evaluated by comparing the energy consumption predicted for the extreme years using the proposed regression models based on the baseline year and the " synthetic utility bills ". The prediction accuracy of the regression models' was judged by the annual and monthly differences between the regression models predictions and the synthetic utility bills data as well as the coefficient of variation of these differences.

If the regression models predict significantly different annual energy consumption from the synthetic utility bills, the regression models are unsuitable for baseline modeling, since savings based on these models would be highly uncertain. The uncertainty (and the APE) should be a small fraction of the expected savings. This suggests that models with APE above 5% will seldom be suitable as baseline models.

In such instances. Consequently, the usability of the regression model should be carefully investigated on a case-by-case bases.

The coefficient of variation of the root mean square error, CV-RMSE for the M.L.R. model of this example is computed as:

$$CV\text{-}RMSE = 100 \left(\frac{1}{Y_{mean}} \right) \left[\frac{SE}{(12 - 4)} \right]^{0.5} \qquad (3.9)$$

where $$SE = \Sigma \left(E_{measured} - E_{predict} \right)^2 \qquad (3.10)$$

The Annual Prediction Error (APE) is calculated as:

$$APE = 100 \frac{(E_{measured} - E_{predict})}{E_{measured}} \qquad (3.11)$$

where $E_{predict} = \sum_{i=1}^{12} E_{toti}$ and $E_{measured}$ is the corresponding annual predicted and measured consumption.

A sequential regression is performed by using the C values from step 4 as initial values in the proposed models in step 5. This is done because the Emodel software used can not simultaneously determine C and perform multiple regression as required by Equation 3.8. An initial value is needed by Emodel to develop such a model; however the summer months also tended to unduely affect the entire model.

(6) Calculate CV-RMSE and APE for the extreme years

Use the monthly M.L.R model with two the extreme years of temperature data to predict the consumption for the extreme years. Compare the predicted consumption from the M.L.R model with the "synthetic utility bills " from step (3); get CV-RMSE and APE for the extreme years.

Again as described in step(3), we compared the predicted data against "synthetic utility bills " instead of measured data, in order to remove the effects caused by random operation.

For the two years of data, CV-RMSE becomes:

$$CV\text{-}RMSE = 100 \left(\frac{1}{Y_{mean}} \right) \left[\frac{SE}{(24 - 4)} \right]^{0.5} \qquad (3.12)$$

(7) 3P-mean method

Landman (Landman, 1996) fits a 3-P model to the data for non-summer months, which we have developed in step (4), and a mean model for the data from the summer months.

The 3-P non-summer months model is of the same form as described earlier:

$$E = A + B(T_{db} - C)^{+}$$

The mean model is simply the mean monthly value of the summer months:

$$E = E_{mean} \qquad (3.13)$$

(8) Calculate CV-RMSE and APE for the extreme years using the 3P-mean method

Use the 3P-mean method to create a two-part model of the monthly data used in step (4) and use the extreme years' temperature data in the models to predict the extreme years' consumption. Calculate CV and Annual Prediction Error using the extreme year " synthetic utility bills " from step (3)

(9) Compare the results of the proposed method with that of the 3P-mean method

Compare the results of the 3P-mean method in step (8) with the results of step (6).

(10) In Step 5, we assumed that both B and C values for occupied and unoccupied period are the same. Here, we want to investigate the possibility that the occupied and unoccupied periods do not have the same slope (B value), but have only the same change point (C value). This corresponds to a 5-P monthly multiple linear regression model which may be written as:

$$E_{tot} = A_0 + A_1 k + B_{oc}(T_{db} - C)^+ + B_{un}(T_{db} - C)^+ \quad (3.14)$$

5-P models have been tried for the same ten schools, but the statistical parameters for k and (T - C) show that the estimation of 5-P models are not stable, i.e. uncertainty in some of the estimated parameters is larger than the estimated parameter values. So we can not use the 5-P monthly multiple linear regression models for these buildings.

CHAPTER IV

SCHOOL AND HVAC SYSTEM DESCRIPTIONS

The same schools are studied in this thesis as in Landman's thesis. The following descriptions of the schools and of their systems are adapted from Landman. (1996a).

4.1 Stroman High School (SHS) (adapted from Landman, 1996a)

Stroman High School is located in Victoria, TX. It consists of nine separate buildings with a total floor area of 210,414 square feet. Classrooms are heated and cooled by individual 2-pipe hydraulic fan coil units. The first floor is heated/cooled by an single duct air handler, and there are separate air handlers on the second through the fourth floors to supply conditioned outside air to each floor. Unit B is a two story which contains the auditorium, choir room, band room, and drafting classrooms. It is heated/cooled by air handlers through the band hall. Unit C is a single story building. Which is heated/cooled by hydraulic fan-coil units. Units D and E are in one contiguous building, a two story structure. HVAC is provided by hydraulic air handler in the library, and heating/ventilation units in the remaining athletic facilities. Unit F is a two story building. And is heated/cooled by hydraulic fan-coil units. Unit G is a single story shop building. The HVAC is provided by direct expansion units with gas furnaces.

Chilled-water and hot water for units A through G are provided by a 460 ton electric chiller and a 5.05 million Btu gas-fired steam boiler.

Air distribution is primarily through single duct multi-zone systems which maintain thermostat set points in the 75°F range for cooling and 70 - 72 °F for heating.

Electricity is purchased from Texas Utility Electric Company and natural gas from Loan Star Gas Company.

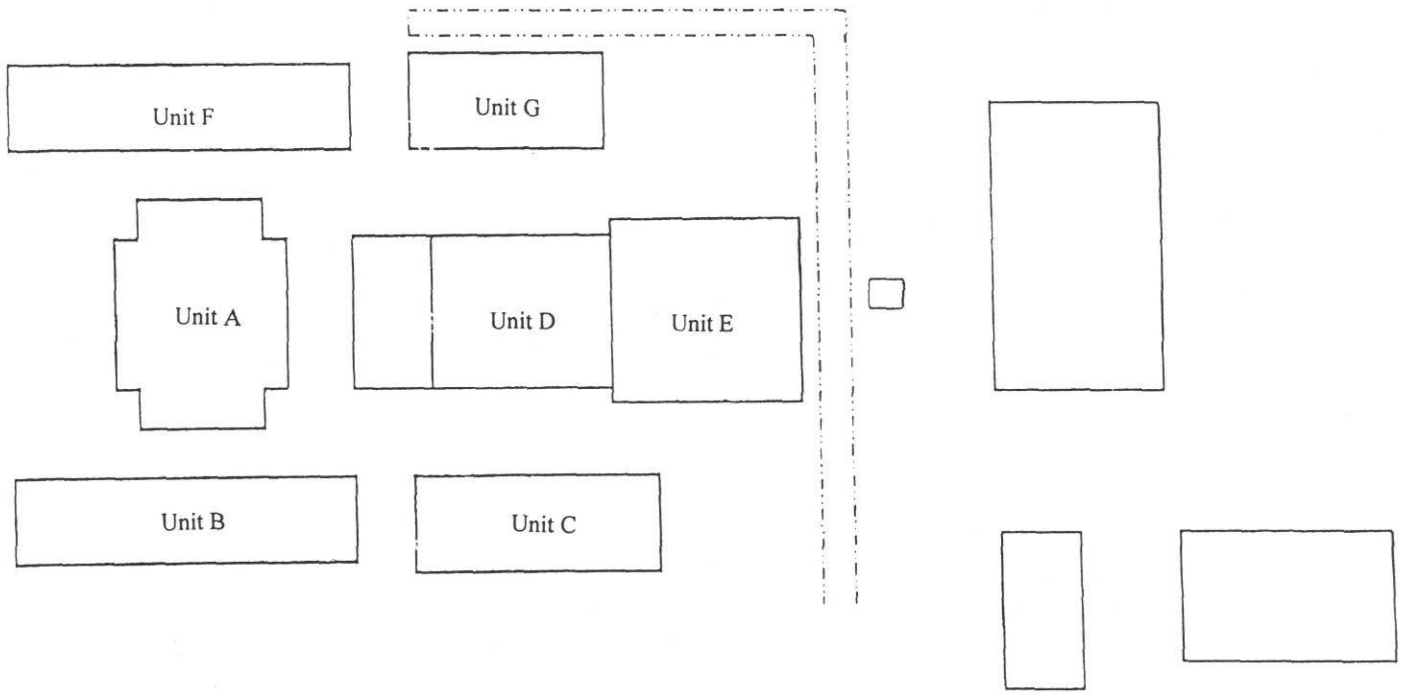


Figure 4.1 Floor Plan of Stroman High School (SHS) (adapted from Landman, 1996a)

4.2 Victoria High School (VHS) (adapted from Landman, 1996a)

Victoria High School is located in Victoria, TX. It consists of ten buildings with a total floor area of 257,014 square feet. The two largest buildings are the Main Building and the Academic Wing. Both of these buildings are two story, brick, slab on grade construction, with a flat roof. And are served by hydraulic fan-coil units. The chiller serving the Main Building is a 192-ton centrifugal chiller, with 25 horsepower chilled water and condenser pumps, and a 15 horsepower cooling tower fan. The chiller serving the Academic Wing is a 182-ton centrifugal chiller, with 20 horsepower chilled water pump a 15 horsepower condenser pump, and a 20 horsepower cooling tower fan.

The eight remaining buildings are all single story, served by rooftop units with direct expansion cooling and gas heating.

Air distribution is primarily through single duct air-handling systems providing cooling. Set point temperatures for cooling are in the 75°F range and heating temperatures are in the range of 70 - 72 °F.

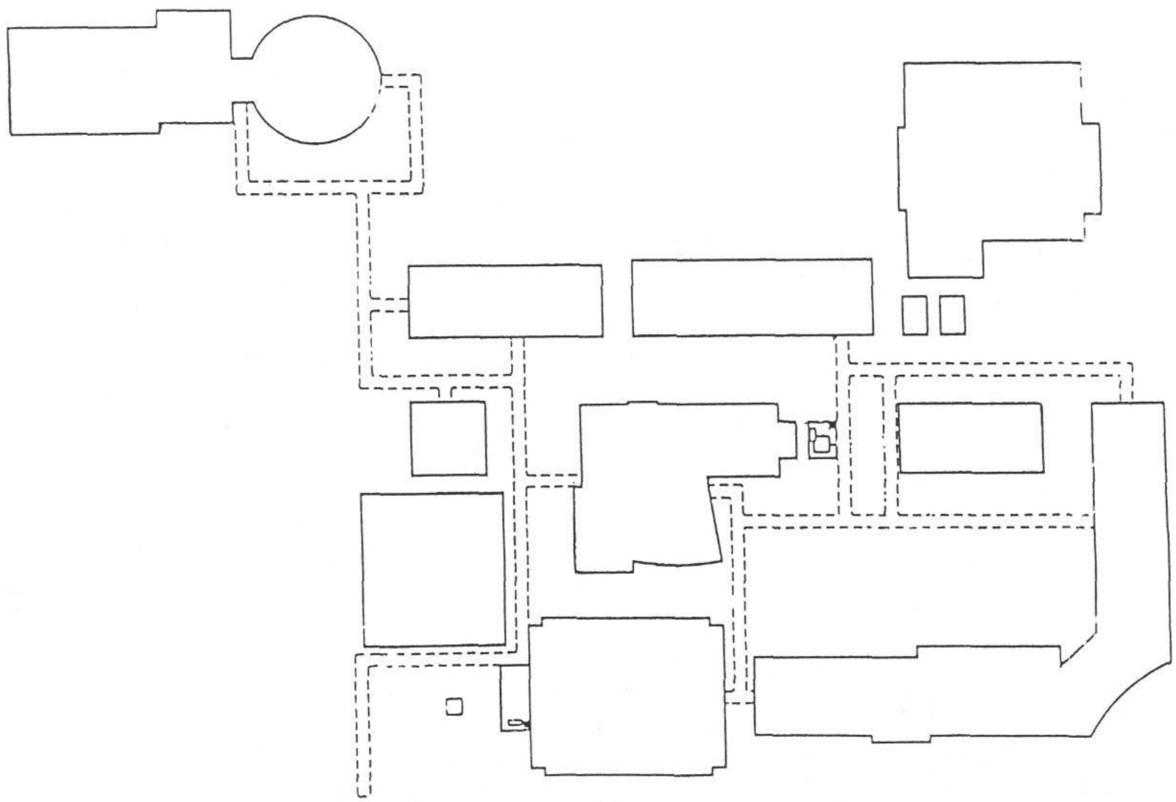


Figure 4.2 Floor Plan of Victoria High School (VHS) (adapted from Landman, 1996a)

4.3 Sims Elementary School (SES) (adapted from Landman, 1996a)

Sims Elementary School is located in Fort Worth, TX. It is a single story concrete building with single-pane tinted, operable windows and has a floor area of 62,400 square feet. There are approximately 54 rooftop units of various sizes that provide both heating and cooling throughout the building.

The school is operated from August through May with approximately 862 students and 50 faculty and staff. The maximum school occupancy is from approximately 7:00 a.m. until 3:00 p.m. The building has a lower occupancy during the weekend.

Thermostat set points in the 75°F range for cooling and 70 - 72 °F for heating.

Electricity is purchased from Texas Utility Electric Company and natural gas from Loan Star Gas Company.

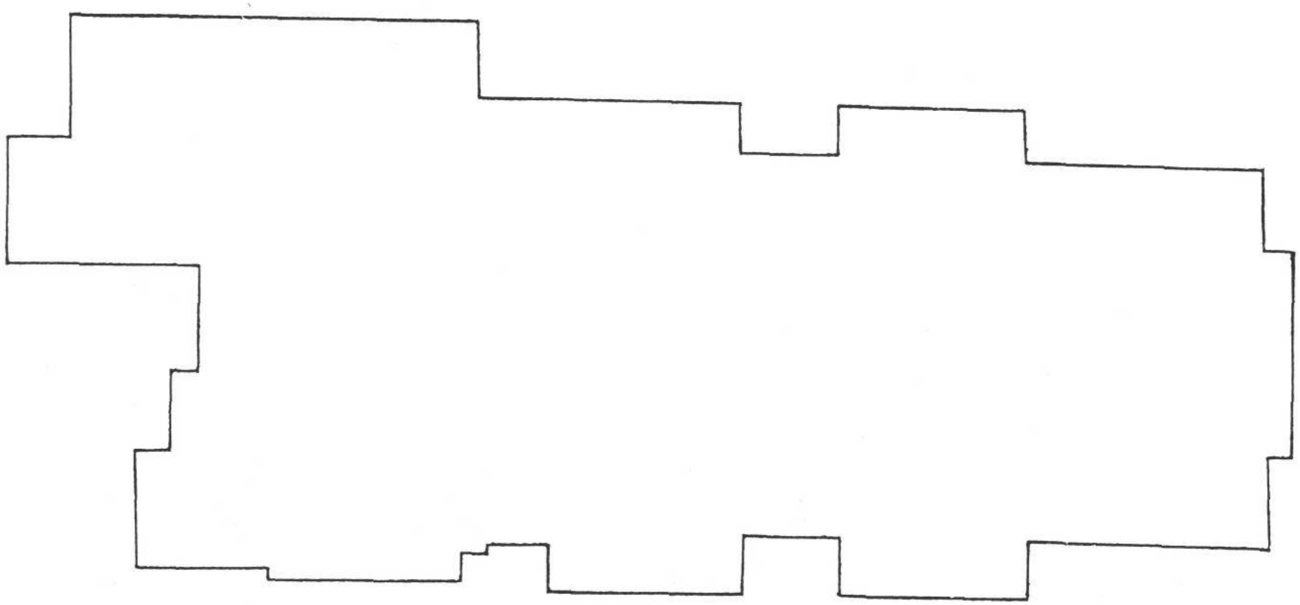


Figure 4.3 Floor Plan of Sims Elementary School (SES) (adapted from Landman, 1996a)

4.4 Dunbar Middle School (DMS) (adapted from Landman, 1996a)

Dunbar Middle School is located in Fort Worth, TX. There are three buildings: the main building which is a two-story structure with 92,884 square feet of gross conditioned area; an activities buildings of 6,128 square feet which is heated but not cooled; and a portable building that is both heated and cooled. The main building is heated by a 2,520 MBtu/hr centralized sectional steam boiler and cooled with two 110 ton chillers and air handling units. The activities building has gas-fired unit heaters.

The school is operated from August through May with approximately 774 students and 85 faculty and staff. The maximum school occupancy is from approximately 7:30 a.m. until 3:00 p.m.

Electricity is purchased from Texas Utility Electric Company and natural gas from Loan Star Gas Company.

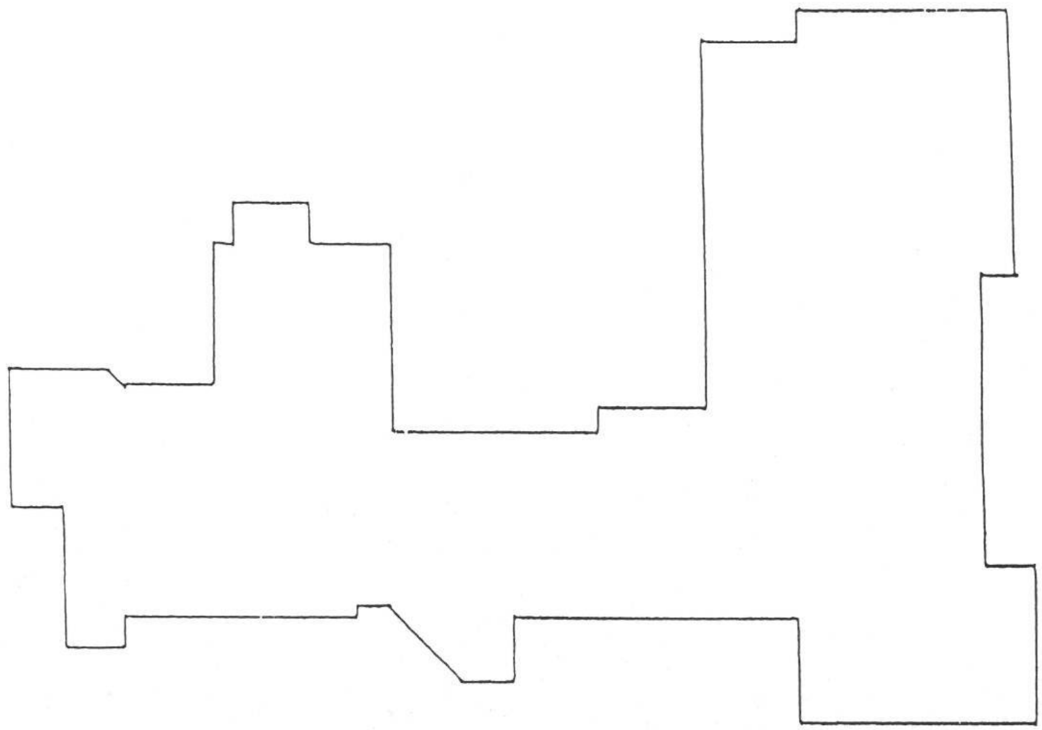


Figure 4.4 Floor Plan of Dunbar Middle School (DMS) (adapted from Landman, 1996a)

4.5 Nacogdoches High School (NHS) (adapted from Landman, 1996a)

Nacogdoches High School is located in the Nacogdoches Independent School District in Northeast Texas. It contains 206,750 square feet of space in three main buildings. The main building contains all but the band hall and the 600 wing of the school. The 600 wing is used for summer school in order to try to shut-off most of the school during that time. In the band wing, cooling units are operated year- round to prevent humidity from damaging any of the instruments. The main heating system is a new 6 million Btu/hr modular boiler system installed for the 1993 heating season. The main cooling system consists of four chillers providing 648 tons of cooling. The band wing is heated by three 120,000 Btu/hr forced air furnaces in the band hall and a 20 ton rooftop unit which provides heating and cooling for the old band hall located in the same building. Twenty- two constant volume air handling units provide heating and cooling for the main building during the day.

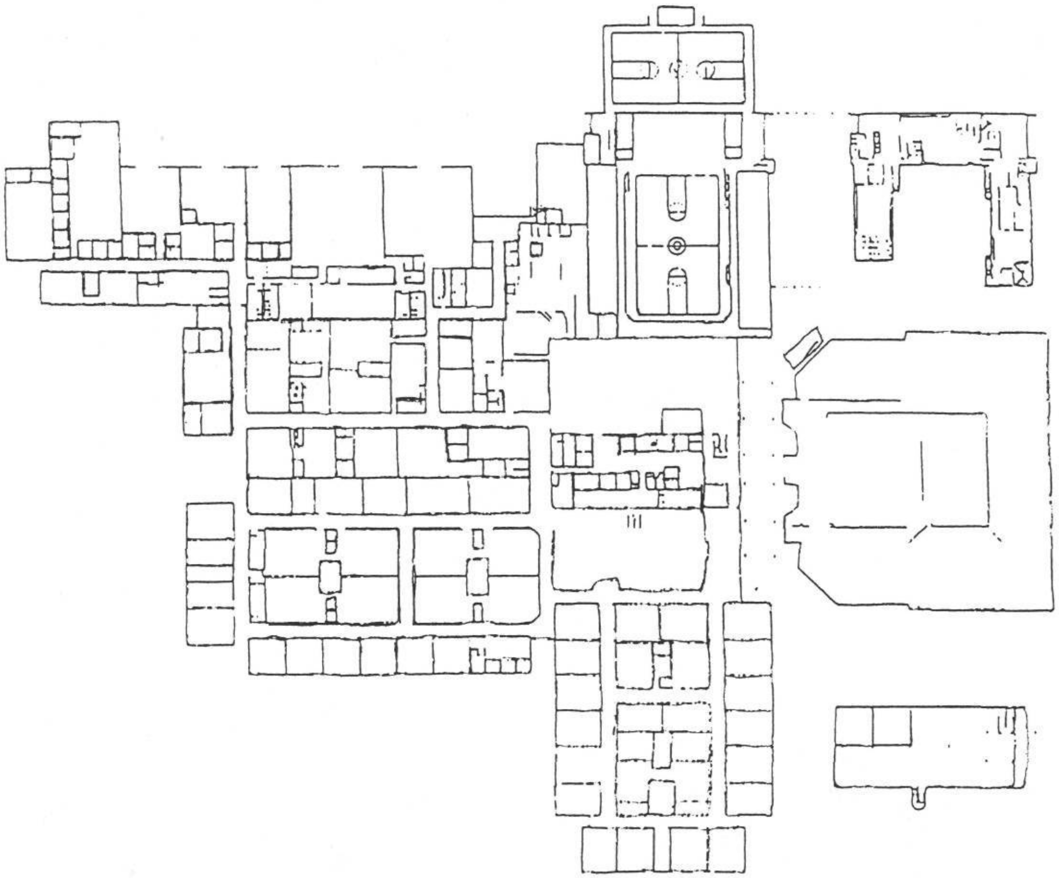


Figure 4.5 Floor Plan of Nacogdoches High School (NHS) (adapted from Landman, 1996a)

4.6 Chamberlain Middle School (CMS) (adapted from Landman, 1996a)

Chamberlain Middle School is located in Nacogdoches, TX. It is a single building on the T.J. Rusk campus. It is a two story brick structure with 66,778 square feet of area. This the only school among the ten schools which cooks meals on site, and also the only non-portable building to have electricity as the primary heating source. The first floor is cooled by 106 tons of split systems with 44 AHUs with electric heating located in each classroom. There is a 10-horsepower pump to circulate the water. The remainder of the building is heated and cooled by rooftop units with a heating capacity of 2.85 million Btu/hr and a cooling capacity of 90 tons.

The school is operated from August through May with approximately 1480 students and 300 faculty and staff. The maximum school occupancy is from approximately 8:00 a.m. until 4:00 p.m.

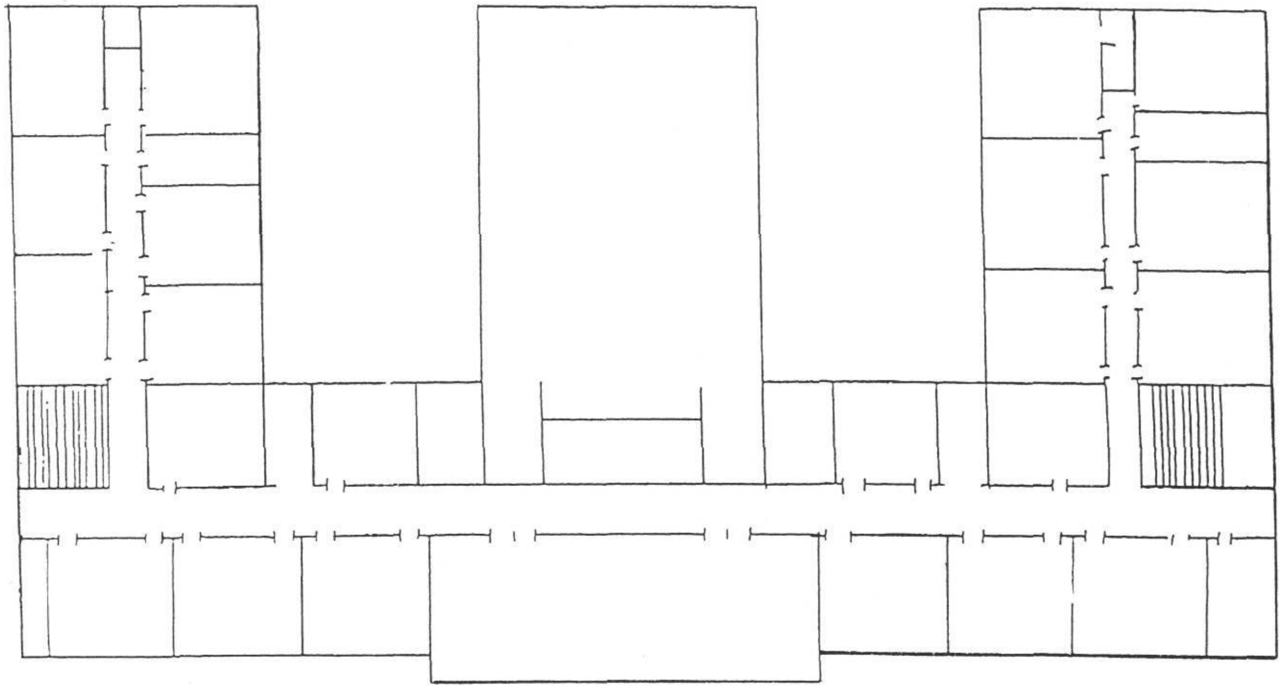


Figure 4.6 Floor Plan of Chamberlain Middle School (CMS) (adapted from Landman, 1996a)

4.7 Oppe Elementary School (OES) (adapted from Landman, 1996a)

Oppe Elementary School is located in Galveston, TX. It is a single story building of prefabricated concrete panel construction with small energy efficient windows. It has a total floor area of 80,400 square feet with a kitchen, cafeteria, gymnasium, library, and classrooms. Cooling is provided by a single 190 ton reciprocating air-cooled chiller with cool storage. Heating is primarily provided by a 2.3 million Btu/hr gas-fired hot water boiler. There are also 6 small heat pumps. Fan coil units contain air in each classroom and AHUs supply heating and cooling to the kitchen, cafeteria, gymnasium, library. This school also has humidity control in summer. The controls cause simultaneous heating and cooling which circle throughout the year with reheat coils. Offices are served by heat pumps.

The school is operated from August through May with approximately 624 students and 70 faculty and staff. The maximum school occupancy is from approximately 7:30 a.m. until 3:30 p.m.

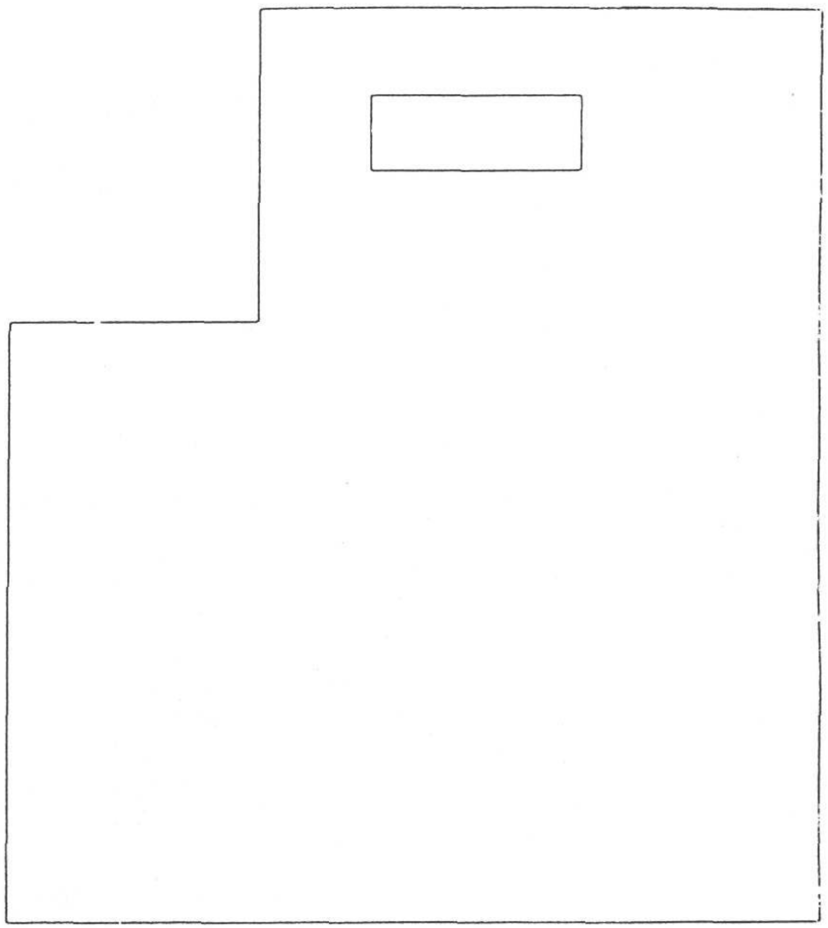


Figure 4.7 Floor Plan of Oppe Elementary School (OES) (adapted from Landman, 1996a)

4.8 Weis Middle School (WMS) (adapted from Landman, 1996a)

Weis Middle School is located in Galveston, TX. It is a single story building of prefabricated concrete panel type construction with small energy efficient windows. It has a total floor area of 80,769 square feet with a kitchen, cafeteria, gymnasium, library, and classrooms. Cooling is provided by two single 140-ton reciprocating air-cooled chillers with cool storage. Heating is primarily provided by a 3.25 million Btu/hr gas-fired hot water boiler. Fan coil units contain air in each classroom and AHUs supply heating and cooling to the kitchen, cafeteria, gymnasium, library. This school also has humidity control in summer. The controls cause simultaneous heating and cooling which circle throughout the year with reheat coils. Office are served by heat pumps.

The school is operated from August through May with approximately 827 students and 80 faculty and staff. The maximum school occupancy is from approximately 7:30 a.m. until 3:30 p.m.

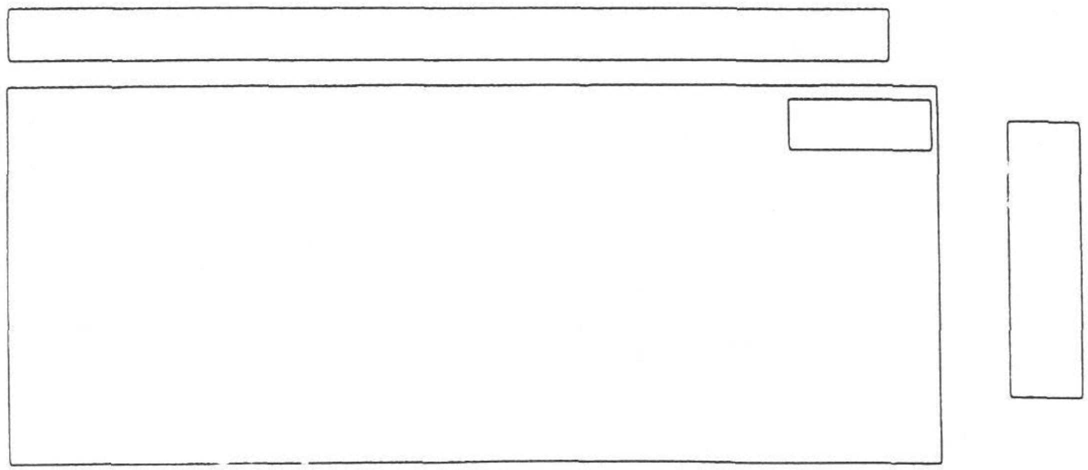


Figure 4.8 Floor Plan of Weis Middle School (WMS) (adapted from Landman, 1996a)

4.9 Parker Elementary School (PES) (adapted from Landman, 1996a)

Parker Elementary School is located in Galveston, TX. It is a single story building with tilt-wall concrete panel construction. It has a total floor area of 81,742 square feet with a kitchen, cafeteria, library, and classrooms. Cooling is provided by three 80 ton single reciprocating air-cooled chillers and four 15-ton split systems. The building has two mechanical penthouses with several multi-zone units. Each of these units serves several classrooms. Each zone of these muilti zone units is equipped with reheat coils. Heating is provided by a 3.25 million Btu/hr gas gas-fired hot water boiler which remains off during the cooling season.

The school is operated from August through May with approximately 609 students and 60 faculty and staff. The maximum school occupancy is from approximately 7:30 a.m. until 3:30 p.m.

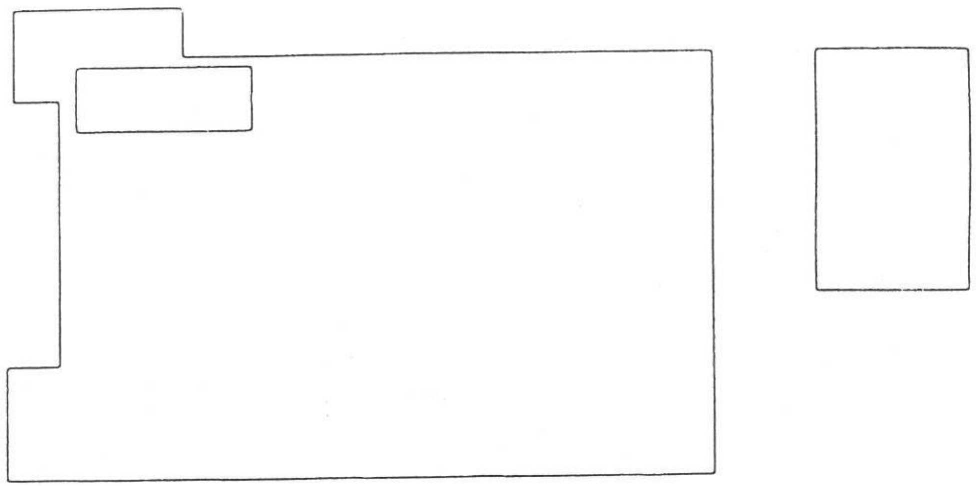


Figure 4.9 Floor Plan of Parker Elementary School (PES) (adapted from Landman, 1996a)

4.10 Morgan Elementary School (MES) (adapted from Landman, 1996a)

Morgan Elementary School is located in Galveston, TX. It is a single story building with tilt-wall concrete panel construction. It has a total floor area of 76,798 square feet with a kitchen, cafeteria, library, and classrooms. Cooling is provided by three 80 ton single reciprocating air-cooled chillers and four 15-ton split systems. Morgan Elementary School is similar to Parker Elementary School, however two mechanical penthouses with several multi-zone units. Each of these units serves multiple classrooms. Each zone of these muilti zone units is equipped with reheat coils. Heating is provided by a 3.25 million Btu/hr gas-fired hot water boiler witch remains off during the cooling season.

The school is operated from August through May with approximately 555 students and 370 faculty and staff. The maximum school occupancy is from approximately 7:30 a.m. until 3:30 p.m.

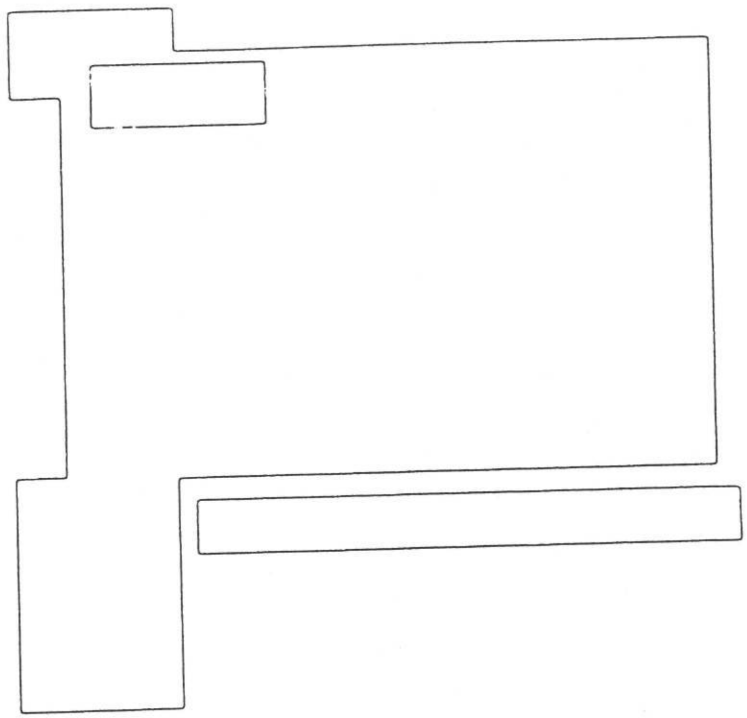


Figure 4.10 Floor Plan of Morgan Elementary School (MES) (adapted from Landman, 1996a)

CHAPTER V

SELECTION OF WEATHER DATA

Kissock et al. (1993) investigated the effect of season and length of data set on annual prediction accuracy. It was found that the average cooling prediction error of short data sets decreased from 7.3% to 3.0% and the average heating prediction error decreased from 27.5% to 12.9% as the length of sets of daily data increased from one month to five months. It was also pointed out that the temperature range of data sets was very important. Cooling models identified from months with above average temperature tend to over-predict annual cooling energy and vice versa. The converse seems to hold for heating models. The limited temperature ranges represented in short data sets can lead to large errors in energy use predictions. Since a regression model can only represent history, it will likely be in error when applied to a new case if the past history is short. For example, if the model was developed using summer data, large prediction error is likely if it is used for a winter period. According to statistical theory, a regression model can only be used within its historical temperature range, or the model can only be interpolated not extrapolated. For example, if the regression model is developed from data within a temperature range of 40°F to 85°F, it will likely have large error if it is used in a year with a temperature range of 25°F to 95°F. Therefore, even if the regression model is developed from a full year of data, it can still have large prediction error when it is used for an extreme year where the temperature range is larger than for the year from which the model is developed.

To investigate the impact of annual weather pattern or the temperature range on the model error, a baseline year which has mild weather that is not too hot in summer and not too cold in winter, and two extreme years which have the largest temperature ranges were chosen from the last five years. The baseline year has a narrower temperature range than the extreme years. If the model, developed using the data from the baseline year, accurately predicts the energy use in the extreme weather years, the model should be accurate for any other year. If the model is inaccurate in the extreme years, its application to other years should be investigated carefully.

FY94 was selected as the baseline year for nine schools. Two other years were selected among the most recent five years which contain the highest temperatures in summer and the lowest temperatures in winter. These two years are the ones which were defined as the extreme temperature years in Chapter III. Figures 5.1 show the time series behavior of the outside dry-bulb temperature for the four sites. While Figure 5.2. and Figure 5.3. show the monthly average temperature difference between one of the extreme years and the mild year used to create the models.

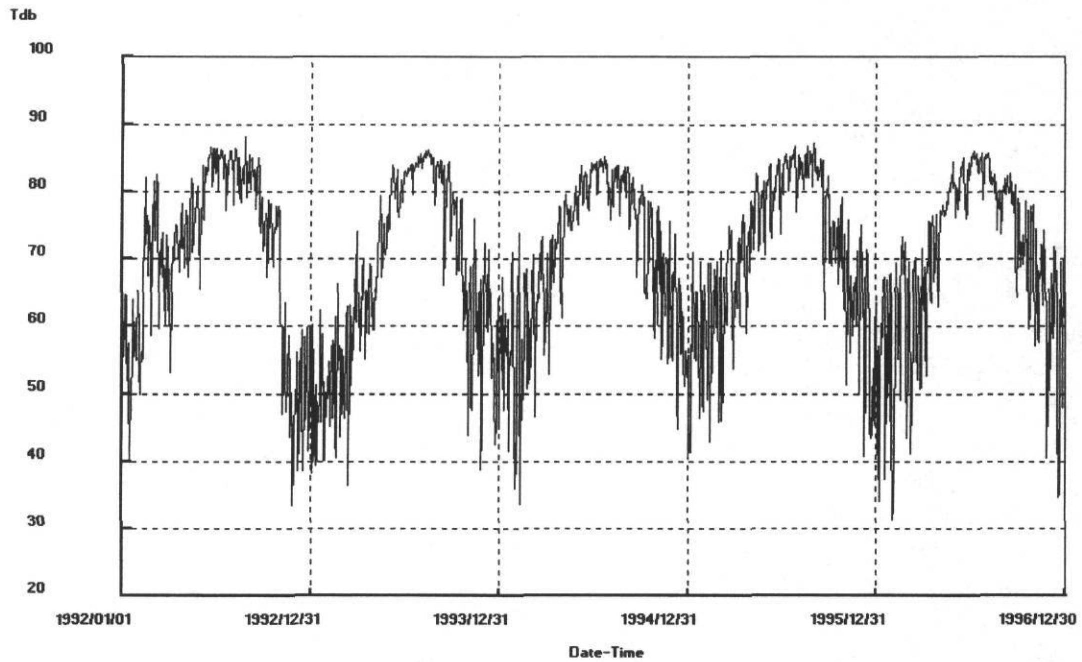


Figure 5.1a Daily Average Temperature Distribution for Fort Worth from 1992 through 1996

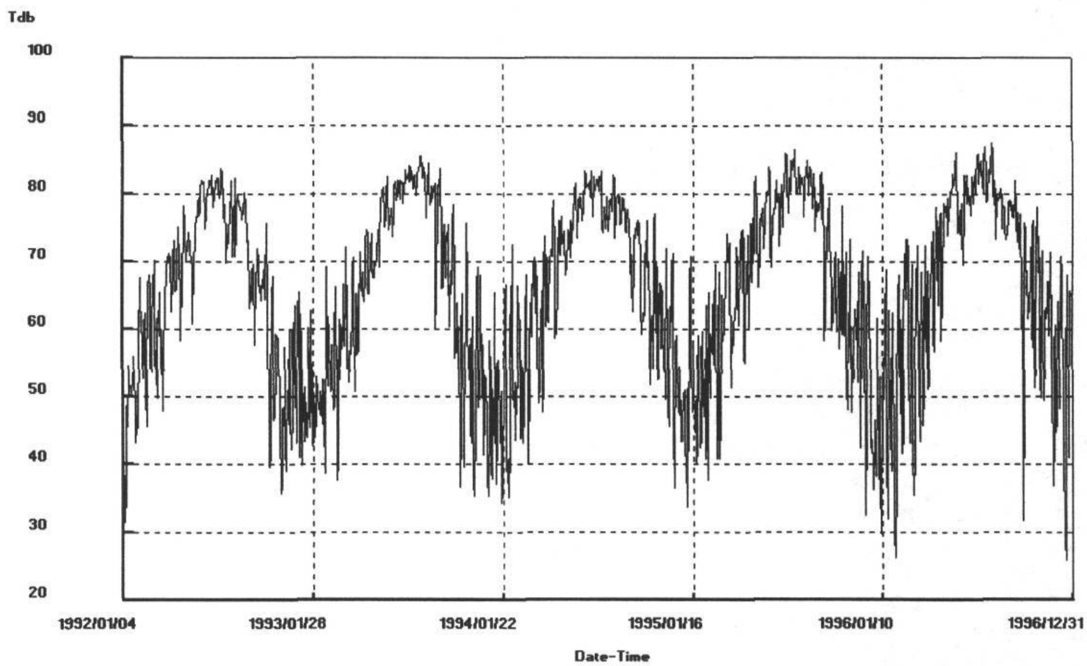


Figure 5.1b Daily Average Temperature Distribution for Nacogdoches from 1992 through 1996

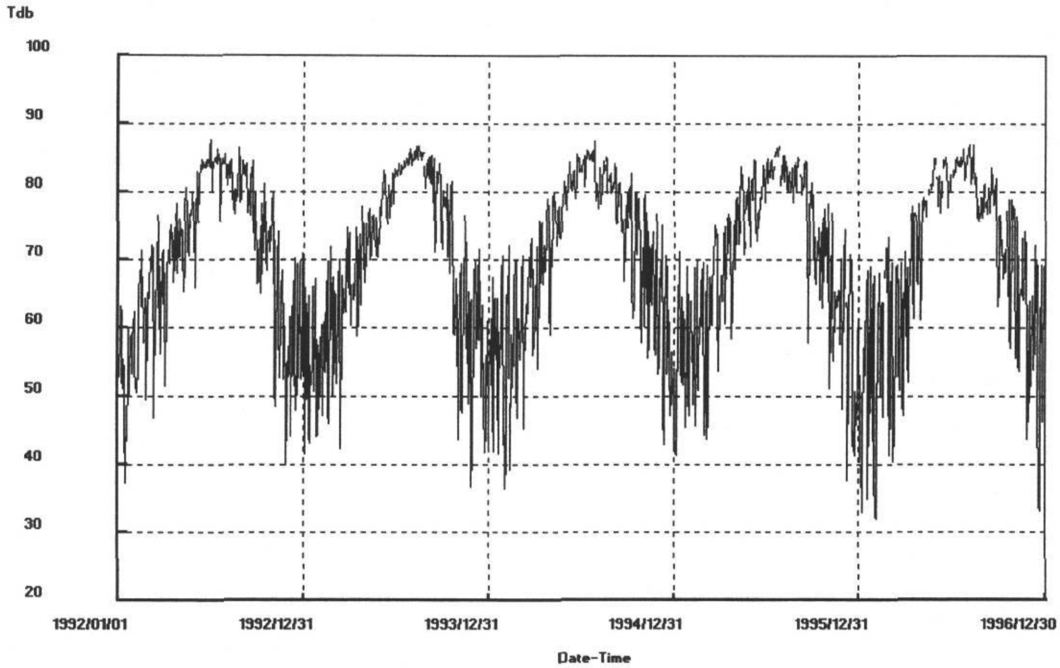


Figure 5.1c Daily Average Temperature Distribution for Victoria from 1992 through 1996

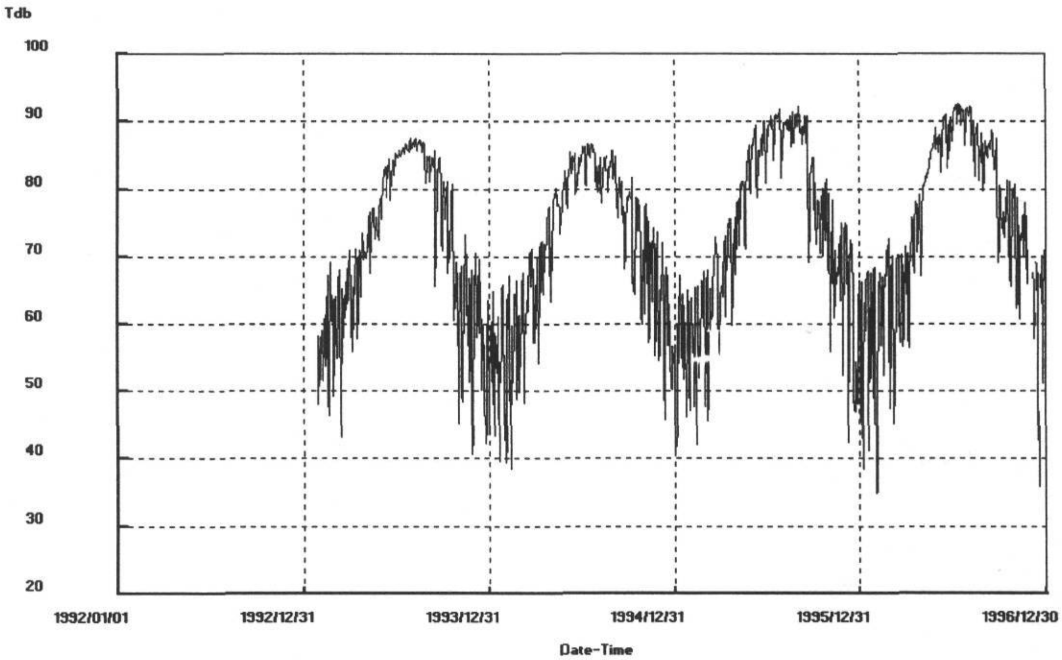


Figure 5.1d Daily Average Temperature Distribution for Galveston from 1992 through 1996

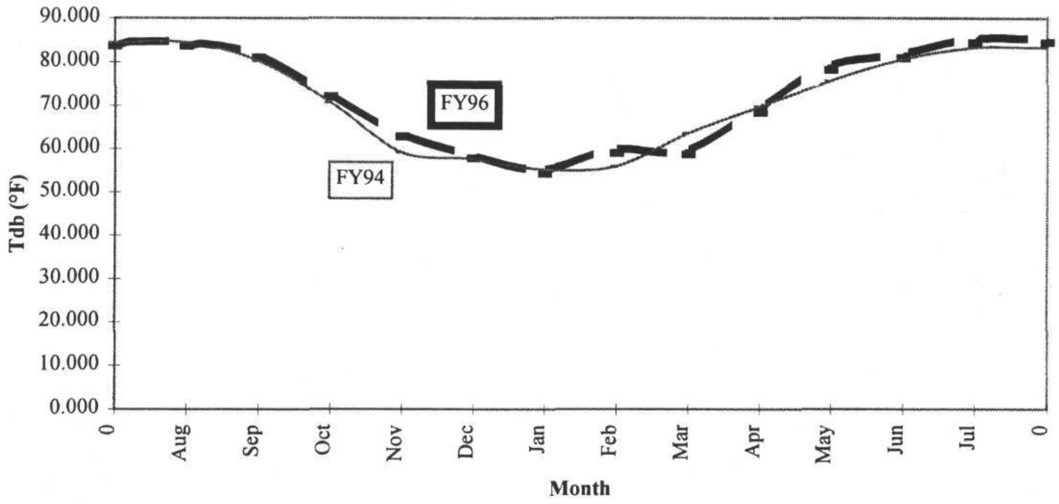


Figure 5.2 Monthly Average Temperature Distribution for Fort Worth for Two Different Years (FY94 & FY96)

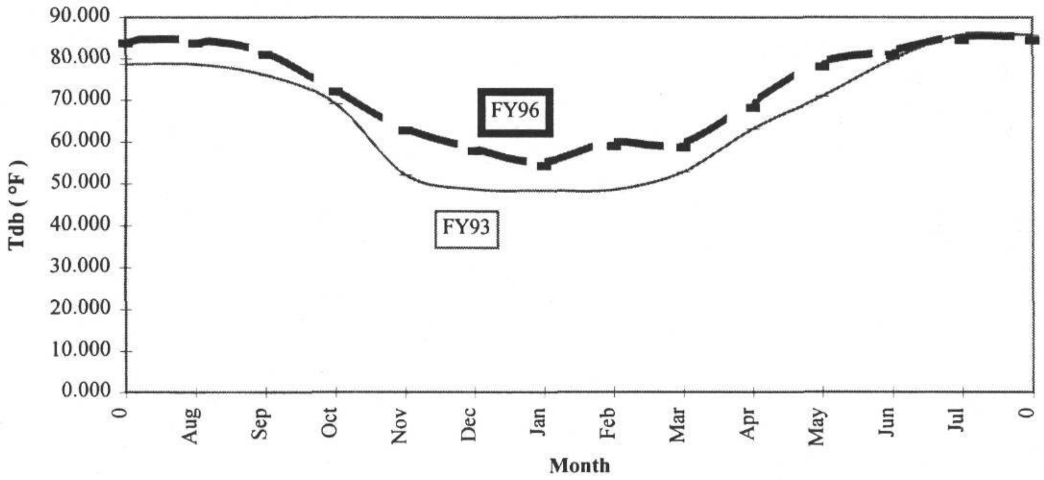


Figure 5.3 Monthly Average Temperature Distribution for Fort Worth for Two Different Years (FY93 & FY96)

Figures 5.2 and 5.3 clearly illustrate the difference in the monthly average temperatures for Fort Worth between the extreme years and the year selected to create the baseline models.

The outside air dry-bulb temperature is a very important variable which affects energy consumption. It is also the only variable used in single linear regression models. By choosing the extreme year temperatures to maximize temperature influence on energy usage, it will be possible to see how the schedule difference will affect the energy use for the seasonally scheduled buildings and which factor is more important for energy use prediction. Further discussion about this on Dunbar Middle School will be shown in Chapter VI.

CHAPTER VI

SCHEDULE EFFECTS ON DUNBAR MIDDLE SCHOOL

The lighting load is closely related to the building HVAC and operating schedules. Figure 6.1 illustrates the seasonal variation of the measured daily lighting energy consumption for FY94 for Dunbar Middle School. It can be seen approximately when the school is open and when it is partly or totally shut down.

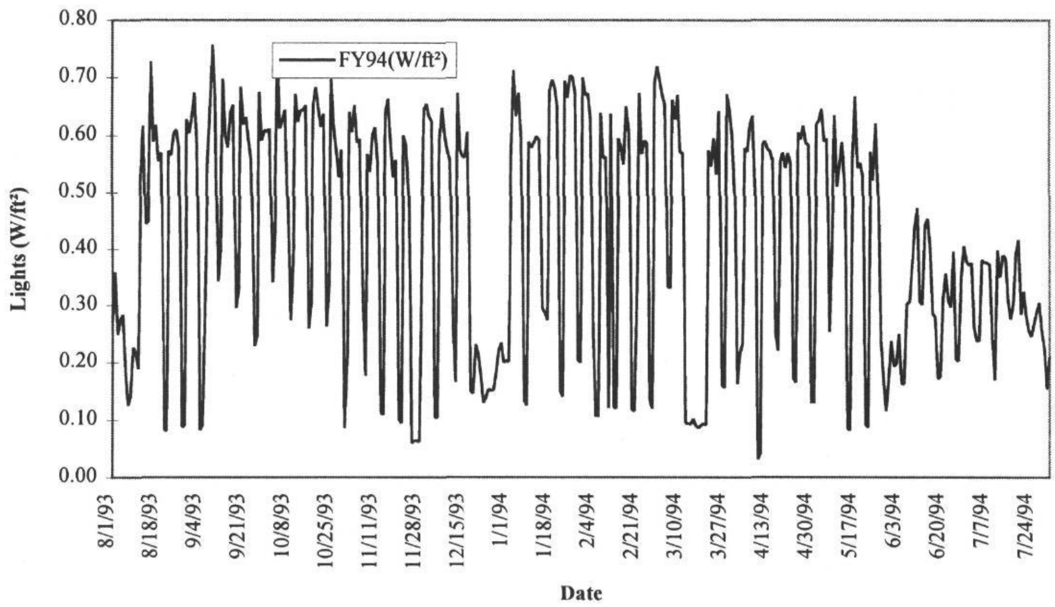


Figure 6.1 Average Daily Lighting Load for Dunbar Middle School FY94

CREATION OF SYNTHETIC UTILITY BILL DATA

The use of the proposed methodology for identifying a monthly baseline model from utility bill data for seasonally scheduled buildings such as schools, has been compared to the 3P-mean methodology as follows. First, evaluation will be performed using "synthetic daily data" predicted by a daily model developed from the baseline year (FY94) to remove random and unknown changes in building operating schedules as well as changes in installed plug-loads from year to year. Instead of picking an arbitrary year for model evaluation, climatic data over the last five years were studied and FY96 and FY95 were selected since they were extreme in that they were hotter in summer and colder in winter than the baseline year of FY94. Thus differences in predictive ability of the proposed methodology versus the 3P-mean method are likely to be accentuated.

The basis for comparing the predictive accuracy of both approaches is the daily model which has been identified from daily data from FY94 subdivided into 2 or 3 day-types (as appropriate) with separate 3-P or 4-P regression models identified for each day-type. This set of base models are then used with FY95 and FY96 T_{db} data (assuming identical day-to-day schedule operation over both FY94, FY95 & FY96) to predict daily energy use values for FY95 and FY96. These daily values are summed into monthly values to mimic utility bill data. Whichever of the two baseline methodologies is able to better predict the Synthetic Utility Bill data can be easily determined, and the predictive errors quantified in terms of APE values.

Figure 6.2 shows both the predicted daily electricity consumption from the 3-P daily models for each day using the different day types and the measured daily electricity consumption for Dunbar Middle school for FY 94, the year used to develop the base line models. Figure 6.3 illustrates the time series residual (predicted value - measured value) of the same two values of Figure 6.2 during the baseline year for Dunbar without any schedule adjustment.

It can be seen clearly that the differences are larger during summer months and September. This appears to be due to multiple factors: total consumption is much higher during this period due to an conditioning requirements. The scheduling of air conditioning on and off then results in large fluctuations in consumption, and these fluctuations occur frequently during the summer due to the more variable summer scheduling. This illustrates the complexity and impact that schedule changes have a large impact on energy use.

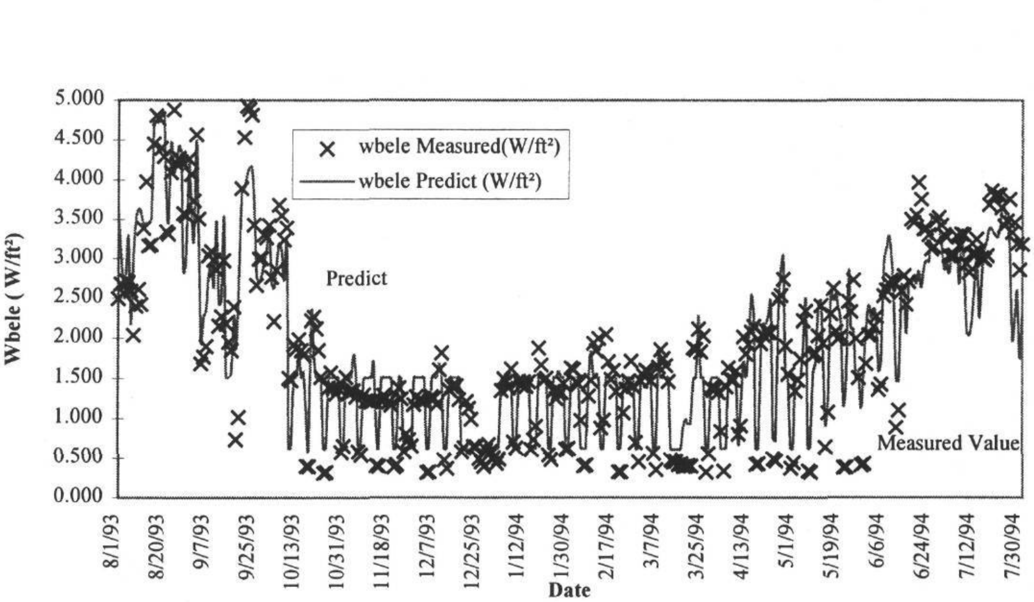


Figure 6.2 Average Daily Electricity Use for Dunbar Middle School (08/93 - 07/94) (Before Schedule Adjustment)

From Figure 6.3 it appears that some special activities occurred during the summer which have not been listed on the school calendar. This suggests that schedule adjustment is needed during the summer. Some schedule adjustment has been made for the summer according to the lighting schedule of the same school as shown in Figure 6.1. This is done by first, choosing the residuals for which the absolute value are greater than 0.5 W/ft^2. Lighting loads at these times are higher than the holiday lighting level (about 0.05 to 0.3W/ft^2) for the negative residuals which means some special activities occurred during the holiday time, hence these periods should not be treated as non-school-day type; the school-day model should be used for these days. Second, use the school-day model to predict the energy consumption, and plot the new residuals. It can be observed from Figure 6.3, about half of the large negative residuals occurred during the summer, and corresponded to this situation.

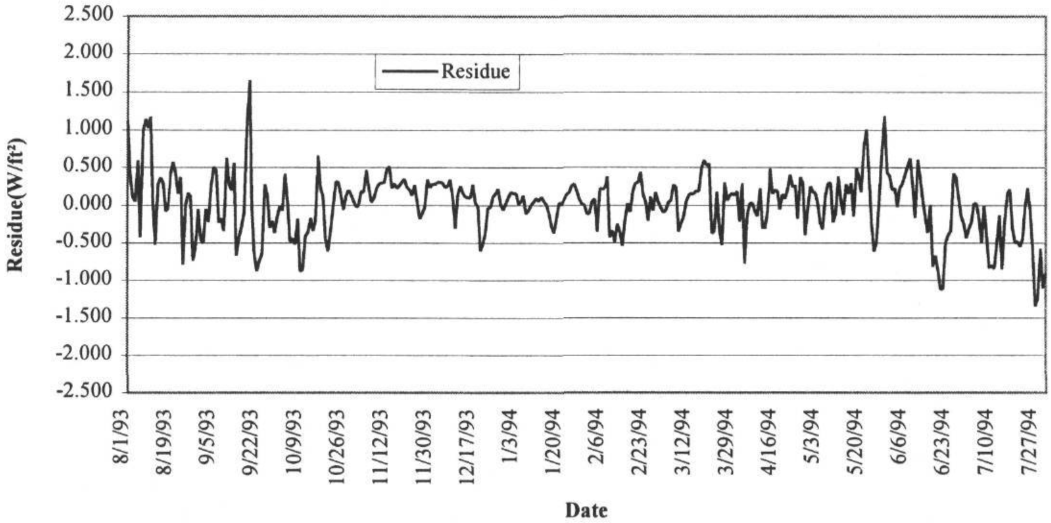


Figure 6.3 Average Daily Electricity Residue Plot for Dunbar Middle School (08/93 - 07/94) (Before Schedule Adjustment)

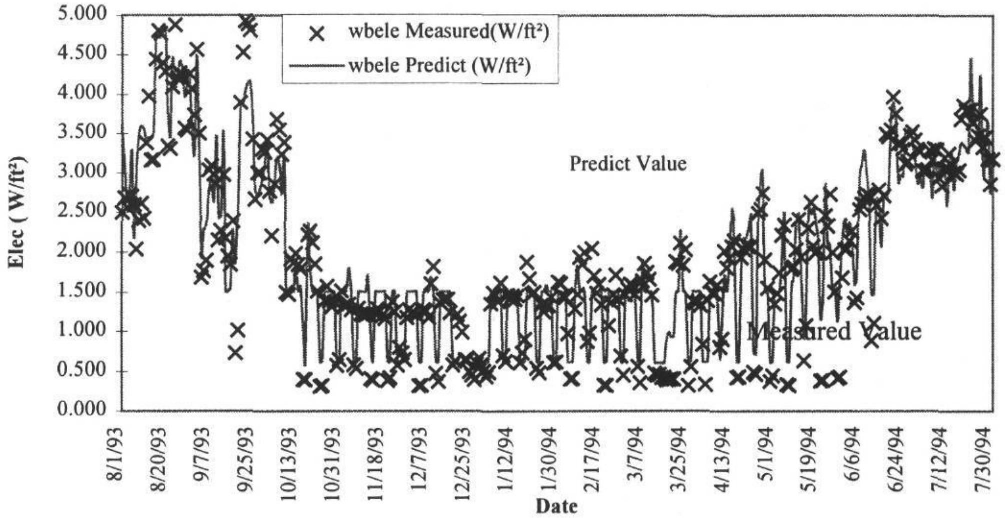


Figure 6.4 Average Daily Electricity Use for Dunbar Middle School
(08/93 - 07/94)
(After Schedule Adjustment)

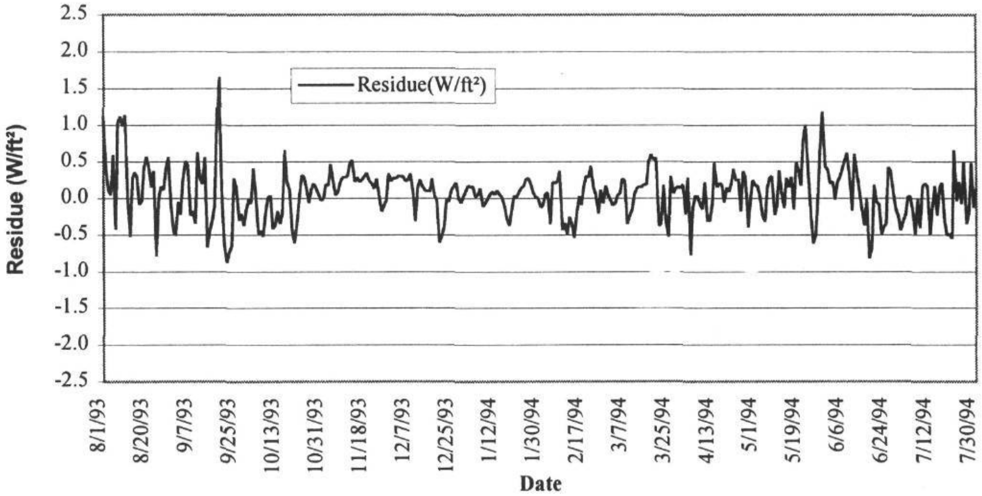


Figure 6.5 Average Daily Electricity Residue Plot for Dunbar Middle School
(08/93 - 07/94)
(After Schedule Adjustment)

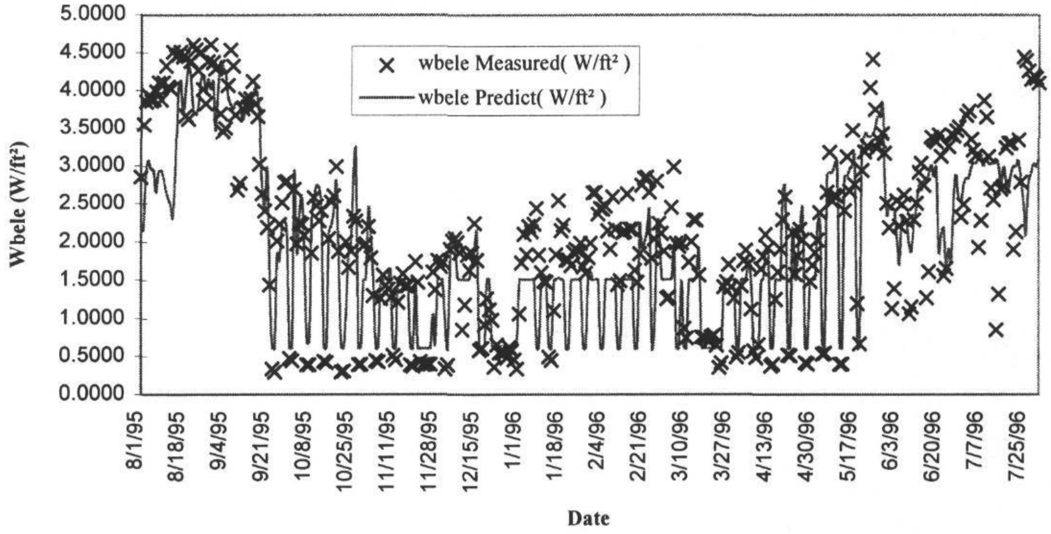


Figure 6.6 Average Daily Electricity Use for Dunbar Middle School (08/95 - 07/96) (Without Schedule Adjustment)

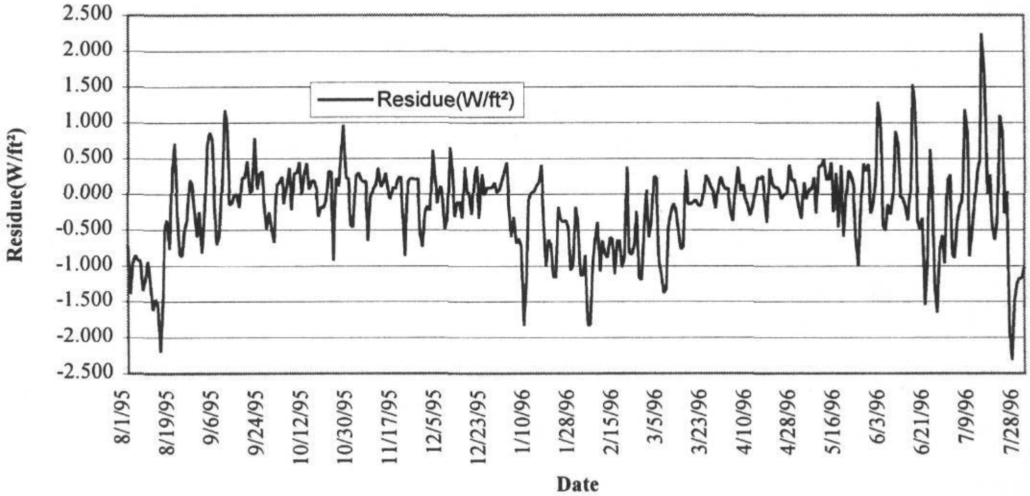


Figure 6.7 Average Daily Electricity Residue Plot for Dunbar Middle School (08/95 - 07/96) (Without Schedule Adjustment)

Figure 6.4 and Figure 6.5 show the same time series daily electricity consumption and residual plots after the above schedule adjustment during the baseline year for Dunbar. By adjusting the schedule for the summer time and September the absolute average residual for the whole year is reduced by 0.03 from 0.30 before the schedule adjustment to 0.27 after the schedule adjustment. The absolute average residual during the days which were adjusted was reduced by 0.53 from 0.90 before the schedule adjustment to 0.37 after the schedule adjustment.

The residuals for several periods such as 8/8/93 - 8/11/93, 9/18/93, and 9/19/93 are still above 1.0 w/ft² after the above adjustment. During those time periods the daily average outside air dry-bulb temperature was above 89°F (for 8/8/93 - 8/11/93) which means the predicted consumption values are high even for the unoccupied period model, and more important, the school was partially or totally shut down during those time. During those periods, the HVAC systems were operated as if school was in session, even through the buildings were not occupied, since the operators felt an extended test of the air conditioning systems was needed. This situation is often obtained by site visiting of the Commissioning group of the Energy Systems Laboratory.

After the schedule adjustment, FY96 one of the extreme years temperature data was used to drive the daily 3-P models for the different day-types. Figure 6.6. illustrates the difference between the predicted and measured daily electricity consumption for Dunbar Middle school for FY 96. Figure 6.7 again shows the residual between the predicted and measured daily electricity consumption. From Figure 6.7 it can be seen that after the schedule adjustment according to the baseline year schedule, the difference between the daily model predicted value and the measured energy consumption for the extreme temperature year is still high for both non-summer periods and summer time. This implies that the schedules for FY94 and FY96 for the same school are quite different, and that much more schedule adjustment is needed.

Comparing the residue plots, this time it is not a surprise to see the difference between them, because the extreme temperature year schedule, including both activity and air-conditioning operation schedule is different from the year used to create the models.

Thus, as stated earlier, it can not be assume the same that the schedule for different years is the same. Hence in order that the evaluation of the proposed methodology for monthly baseline model identification not be confounded by changes in operating schedule from one year to the next, it was decided to use an appropriate model (instead of monitored data) to create synthetic "Utility Bills " for the extreme years

CHAPTER VII

DEVELOPMENT OF REGRESSION MODELS

7.1 Example of the Proposed Methodology

In this section, one of the ten schools, Sims Elementary School will be used as an example to present how both the proposed methodology and the 3P-mean method are used to determine energy savings for seasonally scheduled buildings, and the comparison of the results for these two methods will also be shown.

The following paragraphs numbered to correspond to as described in Chapter III.

1. The selection of baseline year

The hourly energy consumption and weather information are available for Sims Elementary School (site 128) from 9/10/91 to 8/25/97 in the LoanSTAR database. Retrofit construction began on 11/01/91 and was completed on 11/23/91. FY93 which is from 8/92 to 7/93 and during which the weather was not too hot in summer and not too could in winter was selected as the baseline year for the comparison with the 3P-mean method. The average daily energy consumption and the daily average outside air temperature data for the baseline year (FY93) were obtained from the LoanSTAR data base.

2. Group daily data

Duncan's multiple range test which is a mean comparison test for multiple groups of data, (it considers both mean and standard deviation of the groups to be compared) is then performed and the day-groups with statistically insignificant differences in mean energy consumption are aggregated together. The day-types thus achieved are the day-types used to calculate the " synthetic utility bills " for the extreme years.

The results of Duncan's multiple range test are summarized in Table 7.1. These results indicate that the data is most appropriately treated as three day-types.

Table 7.1
Results of Duncan's Multiple Range Test Performed to Identify Day-types for Whole Building Electric Energy Use (in W/ft^2) for SES in FY93

Analysis of Variance Procedure
Duncan's Multiple Range Test for variable: WBELE

Alpha= 0.01 df= 353 MSE= 9643.62
Harmonic Mean of cell sizes= 1.274

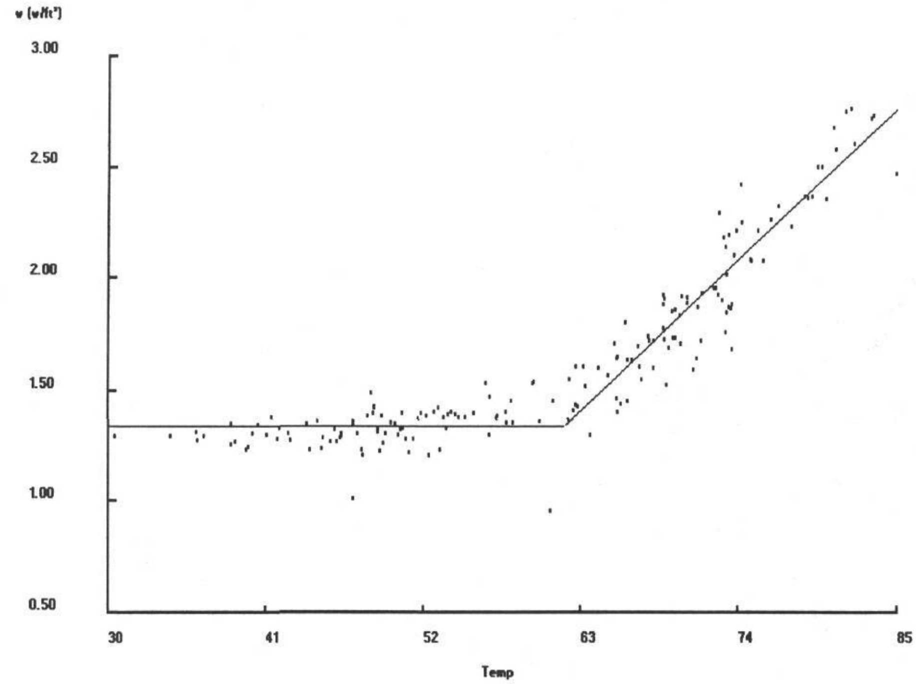
Number of Means 2 3 4
Critical Range 18.92 19.89 20.52
Means with the same letter are not significantly different.

Duncan Grouping	Mean	N		DAYTYPE
A	1.617	174	1	working weekdays
B	1.212	119	2	holidays longer than 3 days
B				
C	0.993	58	3	remaining weekends and one-day holidays

A detailed description of Duncan's multiple range test is presented in Chapter 13 of the third edition of *Introduction to Probability and Statistics: Principles and Applications for Engineering and the Computing Sciences* by Milton and Arnold, (1995).

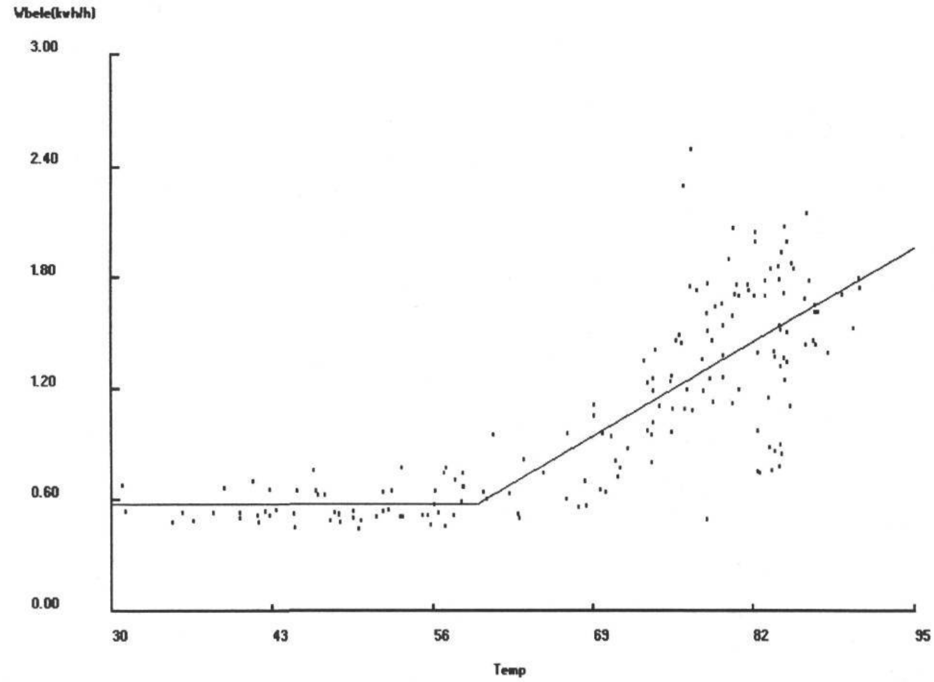
The improvement provided by using these day types can be observed by comparing the 3-P or 4-P daily regression models for different day types as follows:

Get the school calendar for Sims, group the baseline year into 174 days in the school-day group (modeled in Figure 7.1a) and 182 days in the non-school day group (modeled in Figure 7.1b); then further divide the 182 non-school days into a group of 122 holidays longer than 2 days (modeled in Figure 7.1c) and another group composed of the 60 remaining weekend days and one-day holidays, (modeled in Figure 7.1d). Compare the scatter plots of Figure 7.1b with Figure 7.1c and Figure 7.1d. It may be observed that the model of Figure 7.1d shows a relatively good fit to the weekends and one-day holidays group. It also shows a CV of 13.2%. By contrast the groups of Figures 7.1b and 7.1c show CVs of 27.1%, and 27.8%, respectively. Thus one may infer that the combined CV of Figures 7.1c and 7.1d (which should be obtained from RMSE/mean value for all 182 days) will be substantially smaller than the 27.1% of Figure 7.1b. Consequently the three-group day type is used for Sims to generate the "synthetic utility bills " of step 3. The results of Duncan's multiple range test for the other nine schools have been shown in Chapter III.



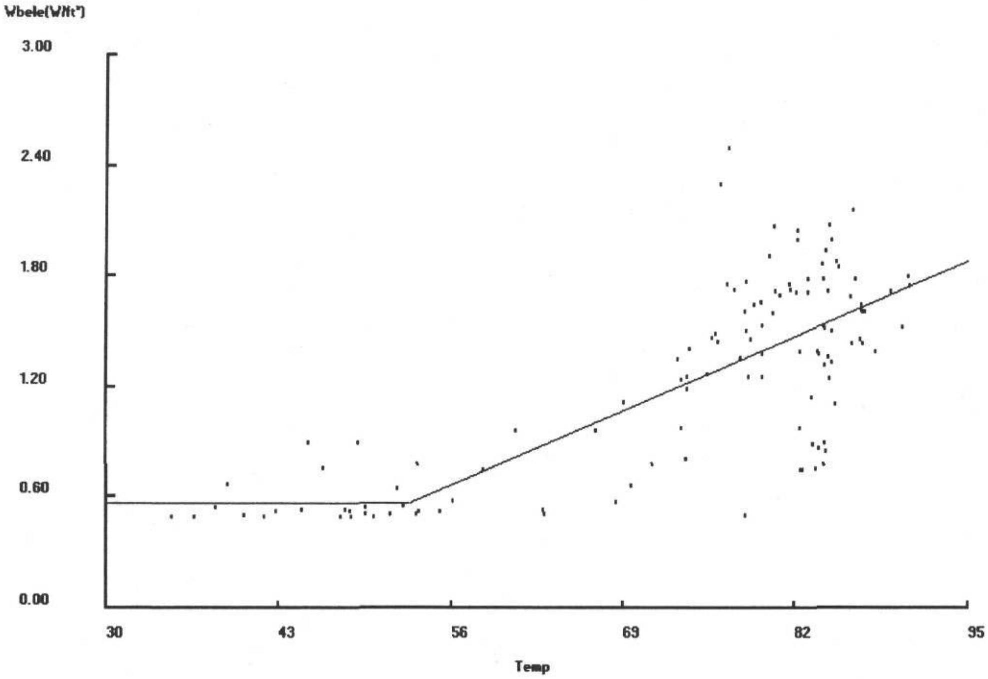
Model: Un-grouped 3P-CP (C). w (w/ft²) vs. TempYcp = 1.3364 (0.0113) LS = 0.0000 (0.0000) RS = 0.0620 (0.0014)
Xcp = 61.9341 N = 174 N1 = 85 N2 = 89 R2 = 0.91 RMSE = 0.12 CV-RMSE = 7.2% p = 0.31 DW = 1.36 (p>0)

Figure7.1a 3-P Daily Model for School Days



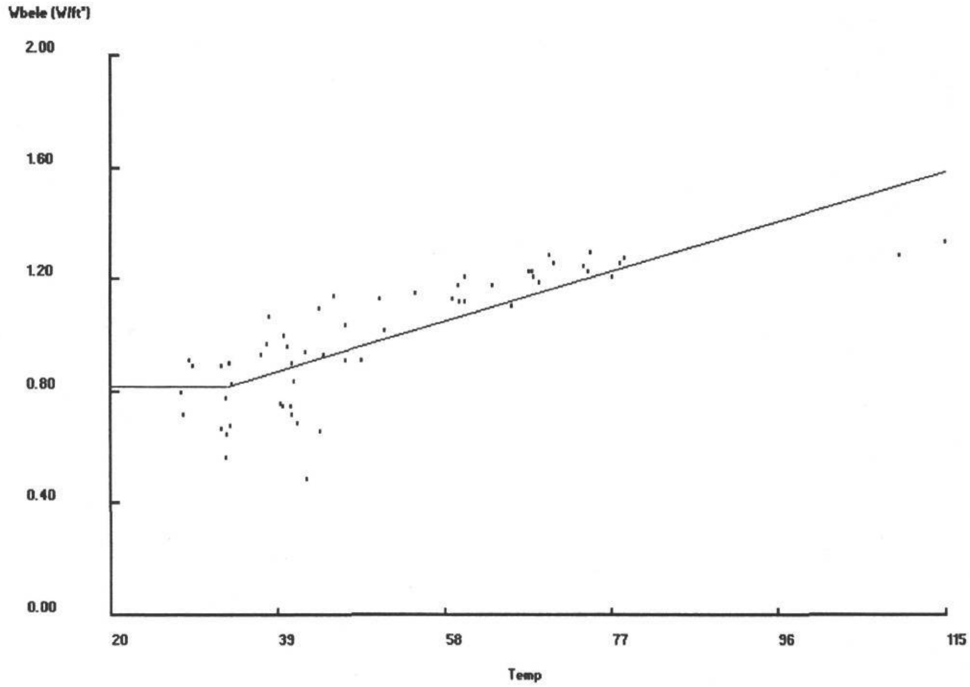
Model: Un-grouped 3P-CP (C). Wbele(kwh/h) vs. TempYcp = 0.5789 (0.0349) LS = 0.0000 (0.0000) RS = 0.0391 (0.0021)
Xcp = 59.5563 N = 182 N1 = 58 N2 = 124 R2 = 0.67 RMSE = 0.29 CV-RMSE = 27.1% p = 0.70 DW = 0.59 (p>0)

Figure7.1b 3-P Daily Model for Non-School Days



Model: Un-grouped 3P-CP (C). Wbele(W/ft²) vs. Temp Ycp = 0.5688 (0.0612) LS = 0.0000 (0.0000) RS = 0.0311 (0.0025) Xcp = 52.8112 N = 122 N1 = 24 N2 = 98 R2 = 0.58 adjR2 = 0.57 RMSE = 0.34 CV-RMSE = 27.8% p = 0.69 DW = 0.63 (p>0)

Figure 7.1c 3-P Daily Model for Holidays Longer than 3 Days



Model: Un-grouped 3P-CP (C). Wbele (W/ft²) vs. Temp Ycp = 0.8188 (0.0244) LS = 0.0000 (0.0000) RS = 0.0094 (0.0009) Xcp = 33.3404 N = 60 N1 = 10 N2 = 50 R2 = 0.65 adjR2 = 0.64 RMSE = 0.13 CV-RMSE = 13.2% p = 0.49 DW = 1.02 (p>0)

Figure 7.1d 3-P Daily Model for the Remaining Weekends and One-Day Holidays

3. Calculate the " synthetic utility bills " for the extreme years

From the outside temperature plot for Fort Worth, (Figure on page 46 in Chapter V) FY95 and FY96 are the years with the highest and second highest daily average temperatures in summer and the lowest and the third lowest daily average temperatures in winter. These two years are chosen as the two years in the available data set with the greatest extremes between average daily summer and winter temperatures. They are then used as the years to check the accuracy of the regression models. Run the three 3-P daily models from step 2 with the extreme years' temperature data as input. Sum up the predicted daily data for each month of the extreme years, divide by the number of days to get the average daily consumption for each month and use these as the " synthetic utility bills " for the extreme years. (Results are shown in Table 7.4).

4. Develop 3-P non-summer month models

Sum up the daily data from the database for each month of the baseline year, and divide by the number of days to get the mean daily average energy use values for each month. Use these values for the 9 non-summer months to develop a monthly 3-P linear regression model according to equation 3.1 in Chapter III. The data for Sims yields the model shown as equation 6.1 below:

$$E = 1.04 + 0.058(T_{db} - 60.08)^{+} \qquad (W/ft^2) \qquad (7.1)$$

where 1.04 is the intercept of E; 0.058 is the temperature slope and 60.08 is the balance temperature in °F. This value will be chosen as the initial value of the balance temperature for the proposed model; i.e. $C_{initial}$ which will be 60.08 °F for Sims.

5. Develop 4-P M.L.R model

Calculate occupancy fraction (k_i) for each month i according to the school calendar for the twelve months of the baseline year. Using the equation below:

$$k_i = \frac{\text{Number of school days}}{\text{Number of school days} + \text{Number of non-school days}} \tag{7.2}$$

Use $C_{initial}$ = 60.08 to determine (T_{db} - C) in equation 7.1, for each of the 12 months of the baseline year. These values are shown in Table 7.1. Develop a monthly multiple linear regression model for this year, which is the "Proposed Model" given as equation 3.5 in Chapter III:

$$E_{tot} = 0.466 + 1.04k + 0.047(T_{db} - 60.08)^{+} \quad (W/ft^2) \tag{7.3}$$

where 0.466 is A_0 which equals to the intercept of energy E for unoccupied period; 1.04 is A_1 which equals to difference of the intercept of energy E for the occupied and unoccupied periods; 0.047 is B_m, the temperature slope and 60.08 is the change point temperature C (initial value obtained from step 4). Change the C value by 1°F increments, get the corresponding CV values, choose the C value which causes the smallest CV. Results are shown in Table 7.2 below. 60.04 °F is chosen for this model. Then the proposed model becomes:

$$E_{tot} = 0.372 + 1.217k + 0.06(T_{db} - 60.04)^{+} \qquad (W/ft^2) \qquad (7.4)$$

Table 7.2
The C Values and Their Corresponding CV Values for Proposed Model for Sims

C	CV-RMSE	C	CV-RMSE	C	CV-RMSE
60.083	4.9396	59.5	5.315	60.08	4.9393
60	4.9397	59	6.219	60.07	4.9384
61	6.0388	58	8.906	60.06	4.9378
62	8.6535	57	12.095	60.05	4.9374
63	11.8172	56	15.479	**60.04**	**4.9373**
				60.03	4.9375
				60.02	4.9380

The coefficient of variation of the root mean square error, CV-RMSE for the M.L.R. model of this example is computed as:

$$CV\text{-}RMSE = 100\left(\frac{1}{Y_{mean}}\right)\left[\frac{MSE}{(24-4)}\right]^{0.5} \qquad (7.5)$$

where $$MSE = (E_{measured} - E_{predict})^2 \qquad (7.6)$$

Determine $E_{predict} = \sum_{i=1}^{12} E_{toti}$ and $E_{measured}$ the corresponding annual predicted and measured consumption. Calculate APE the Annual Prediction Error as below:

$$APE = 100\,\frac{(E_{measured} - E_{predict})}{E_{measured}} \qquad (7.7)$$

Table 7.3 shows the results.

Table 7.3
Monthly Data from Proposed Model for Sims for FY93

Year	Month	Measured Wbele (W/ft²)	Predicted Wbele (W/ft²)	T_{db}	k	1-k	$(T_{db} - C)^+$
92	8	1.674	1.491	78.734	0.194	0.806	14.834
92	9	2.004	1.926	76.134	0.679	0.321	12.234
92	10	1.502	1.589	69.199	0.741	0.259	5.299
92	11	1.028	1.138	52.126	0.630	0.370	0.000
92	12	0.971	0.921	48.708	0.452	0.548	0.000
93	1	1.006	1.078	44.031	0.581	0.419	0.000
93	2	1.117	1.183	48.556	0.667	0.333	0.000
93	3	1.100	1.061	55.771	0.567	0.433	0.000
93	4	1.272	1.211	63.200	0.690	0.310	0.000
93	5	1.642	1.617	70.976	0.677	0.323	7.076
93	6	1.605	1.448	79.915	0.1	0.900	16.015
93	7	1.387	1.675	85.766	0	1.000	21.866
CV-RMSE	11.167 %	**APE**	-0.185 %				

6. Calculate CV-RMSE and APE for the extreme years

Drive the monthly M.L.R model from step 5 with the two extreme years' temperature and k_i data to predict the consumption for the extreme years. Compare the predicted consumption from the M.L.R model with the "synthetic utility bills " from step 3; get CV-RMSE and APE for the extreme years.

For the two years of data, CV-RMSE becomes:

$$CV\text{-}RMSE = 100 \left(\frac{1}{Y_{mean}}\right) \left[\frac{MSE}{(24 - 4)}\right]^{0.5} \tag{7.8}$$

The results are shown below in Table 7.4.

Table 7.4
Monthly Data from Proposed Model for Sims for FY95 & FY96

Year	Month	Measured Wbele (W/ft²) (Synthetic Utility Bills)	Predicted Wbele (W/ft²)	T_{db}	k	1-k	$(T_{db} - C)^+$
94	8	1.660	1.642	81.264	0.194	0.806	17.364
94	9	1.978	2.037	77.983	0.679	0.321	14.083
94	10	1.671	1.752	71.940	0.741	0.259	8.040
94	11	1.378	1.310	66.797	0.630	0.370	2.897
94	12	1.023	0.921	58.683	0.452	0.548	0.000
95	1	1.109	1.078	56.568	0.581	0.419	0.000
95	2	1.194	1.183	60.353	0.667	0.333	0.000
95	3	1.267	1.061	62.696	0.567	0.433	0.000
95	4	1.534	1.532	69.291	0.690	0.310	5.391
95	5	1.936	1.985	77.137	0.677	0.323	13.237
95	6	1.523	1.485	80.540	0.1	0.900	16.640
95	7	1.526	1.548	83.633	0	1.000	19.733
95	8	1.8791	1.934	86.155	0.194	0.806	22.255
95	9	2.0483	1.933	76.239	0.679	0.321	12.339
95	10	1.6505	1.593	69.273	0.741	0.259	5.373
95	11	1.1920	1.138	57.548	0.630	0.370	0.000
95	12	1.0559	0.921	50.291	0.452	0.548	0.000
96	1	1.0447	1.078	48.513	0.581	0.419	0.000
96	2	1.3480	1.183	60.825	0.667	0.333	0.000
96	3	1.1757	1.061	59.558	0.567	0.433	0.000
96	4	1.4933	1.315	65.654	0.690	0.310	1.754
96	5	2.0224	2.114	79.313	0.677	0.323	15.413
96	6	1.5909	1.591	82.323	0.1	0.900	18.423
96	7	1.6098	1.692	86.049	0	1.000	22.149
CV-RMSE	6.720 %	APE	2.290 %				

7. 3P-mean model method

Fit the 3-P model $E = 1.04 + 0.058(T_{db} - 60.08)^{+}$ W/ft^2 Equation (7.1)

to the data for the non-summer months which we have developed in step 4, and use a Mean model for the summer months which is

$$E = 1.56 \ W/ft^2 \tag{7.9}$$

8. Calculate CV-RMSE and APE for the extreme years using 3P-mean method

Use the extreme years' temperature data in the two models to predict the extreme years' consumption. Calculate CV and Annual Prediction Error using the extreme year " synthetic utility bills " from step 3. The results are shown below in Table 7.5.

9. Compare the results of the proposed method with that of the 3P-mean method

Compare the results of the 3P-mean method in step 8 with the results of step 6. By using the proposed method, CV-RMSE and APE values for the two extreme years

Table 7.5
Monthly Data from the 3P-mean Model for Sims for FY95 & FY96

Year	Month	Measured Wbele (W/ft^2) (Synthetic Utility Bills)	Predict Wbele (W/ft^2)	T_{db}
94	8	1.660	1.56	81.264
94	9	1.978	2.069	77.983
94	10	1.671	1.721	71.940
94	11	1.378	1.426	66.797
94	12	1.023	1.040	58.683
95	1	1.109	1.040	56.568
95	2	1.194	1.040	60.353
95	3	1.267	1.190	62.696
95	4	1.534	1.569	69.291
95	5	1.936	2.020	77.137
95	6	1.523	1.56	80.540
95	7	1.526	1.56	83.633
95	8	1.8791	1.56	86.155
95	9	2.0483	1.968	76.239
95	10	1.6505	1.568	69.273
95	11	1.1920	1.040	57.548
95	12	1.0559	1.040	50.291
96	1	1.0447	1.040	48.513
96	2	1.3480	1.082	60.825
96	3	1.1757	1.040	59.558
96	4	1.4933	1.360	65.654
96	5	2.0224	2.145	79.313
96	6	1.5909	1.56	82.323
96	7	1.6098	1.56	86.049
CV-RMSE	8.623 %	**APE**	3.212 %	

are reduced from 8.623% and 3.212% from 3P-mean method to 6.72 % and 2.29% respectively.

In fact when the proposed method is used, only steps 1 and 4 to 6 need to be performed. The other steps are simply needed for the comparison with 3P-mean method.

The remands of Chapter VI will summarize the daily, monthly single linear regression models and the proposed multiple linear regression models for the other nine schools that have been studied.

7.2 Development of Regression Models

Daily and monthly regression models were developed using the measured data for the baseline year from the LoanSTAR database. Daily regression models were developed by regressing the daily average energy consumption versus the daily average outdoor air temperature. The daily data were first grouped according to the three different day-types as discussed in Chapter III. Then models were developed separately for each group. Monthly regression models were developed by regressing the monthly average energy consumption versus the monthly average outdoor air temperature.

7.2.1 Daily Regression Models

Both 3-P and 4-P models were tried for daily models, and the relatively better one or the one with smaller CV % and larger R^2 values were selected.

Table 7.6 summarizes the parameters of the daily electrical regression models for each of the different day types. The scatter plots and regression lines for these models are given in Appendix A. The regression correlation (R^2) of these models varied from 0.06 to 0.91. The coefficient of variance for the models varied from 7.2% to 96.8%. The selection of day types for each school was based on the results of Duncan's Multiple Range Test.

The parameters shown in the table are described below:

A: The energy consumption at the change point temperature T_{cp}, W/ft².

B1: The left side temperature slope for 4-P models.

B: The right side temperature slope.

T_{cp}: The change point temperature, °F.

Table 7.6
Daily Model Development for Ten Primary and Secondary Schools in Texas

		For School days				For Holidays longer than 2 days						For the remaining weekend days				For Non-school days (combination of groups 2 & 3)				
School Name	A	B	T_{cp}	R^2	CV (%)	A	(B1) B	T_{cp}	R^2	CV (%)	A	B	T_{cp}	R^2	CV (%)	A	B	T_{cp}	R^2	CV (%)
SES	1.336	0.062	61.934	0.91	7.2	0.569	0.035	56.142	0.6	28.4	0.617	0.056	66.611	0.81	16.2	0.593	0.041	60.751	0.66	27.1
DMS	1.508	0.143	67.06	0.88	16.7	0.389	(-0.01) 0.137	65.544	0.78	26.8	0.611	0.161	72.035	0.59	63.3	0.607	0.151	69.62	0.78	34.3
SHS	0.832	0.024	57.367	0.66	14.1	0.283	0.019	57.964	0.37	42.9	0.301	0.006	53.185	0.14	40.8	0.337	0.033	71.648	0.39	45
VHS	0.960	0.038	62.325	0.75	13.8	0.389	0.050	74.191	0.46	41.1	0.341	0.008	73.28	0.07	32.4	0.361	0.042	74.191	0.39	44.1
NHS	1.337	0.077	61.513	0.86	12.7	0.559	0.029	60.73	0.24	49	0.476	0.01	48.116	0.17	43.5	0.529	0.028	60.73	0.27	49.8
CMS	1.189	0.119	73.474	0.47	29.4	0.602	0.304	81.31	0.16	61.7	0.206	0.007	56.109	0.2	47	0.435	0.156	79.35	0.21	70.2
OES	1.609	0.016	53.014	0.35	12.2	0.274	0.012	60.295	0.17	74.7	0.393	0.002	44.464	0.01	49.6	0.323	0.025	70.622	0.16	74.7
WMS	2.011	0.031	62.813	0.45	12.2	0.431	0.122	84.703	0.05	86.5	0.421	0.052	76.028	0.24	52.7	0.424	0.134	84.703	0.06	81.4
PES	1.59	0.035	61.835	0.61	12.5	0.453	0.146	83.764	0.11	82.3	0.348	0.001	52.355	0.02	32	0.416	0.154	83.764	0.14	78.1
MES	2.152	0.040	66.723	0.44	12.9	0.474	0.257	83.764	0.16	98	0.342	0.011	72.521	0.06	48.2	0.428	0.266	83.764	0.19	96.8

It appears that the daily models for school days have better goodness of fit than those of non-school days, because of the more regular operation of the HVAC systems and the buildings on school days. And the three day type groups fit better for the fiscal year than the two day type groups for most of the schools according to Duncan's Multiple Range Test.

7.2.2 Monthly Regression Models

Table 7.7 summarizes the monthly electrical regression models for the model year. The scatter plots and regression lines for these models are given in Appendix B. The regression correlation (R^2) of these models varied from 0.55 to 0.97. The coefficient of variance for the models varied from 5.1% to 17.5%.

The parameters shown in the table are described below:

A_{oc}: The energy consumption for occupied days at the change point temperature T_{cp}, W/ft².

B: The temperature slope.

$C_{initial}$: The change point temperature, °F.

Table 7.7
Monthly Model Development for Ten Primary and Secondary Schools in Texas

School Name	A_{oc}(W/ft²)	B	$C_{initial}$(°F)	R^2	CV (%)
SES	1.0395	0.0575	60.083	0.97	5.1
DMS	1.1025	0.0931	61.174	0.85	17.5
SHS	0.6698	0.0247	60.504	0.89	8.4
VHS	0.7442	0.0289	61.008	0.92	7.6
NHS	0.9539	0.0348	50.505	0.55	13.9
CMS	0.9007	0.0635	70.587	0.95	6.5
OES	1.1664	0.029	65.164	0.68	9.8
WMS	1.385	0.0367	63.011	0.73	10.5
PES	1.1329	0.0328	61.935	0.86	7.7
MES	1.4132	0.0336	60.86	0.79	8.9

The non-summer monthly models appears have better goodness of fit than the daily models.

7.2.3 4-P Multiple Linear Regression Models (M.L.R.)

Table 7.8 summarizes the monthly electrical M.L.R. models for the model year. Compare the results with table 7.7; it appears that the change point temperature from C_{inital} to C_{final} and the temperature slope from B to B_m did not change much for the two different kinds of monthly models.

The parameters shown in the table are described below:

A_0: The energy consumption for unoccupied days at the change point temperature T_{cp}, W/ft².

A_1: The energy consumption difference for occupied days and unoccupied days at the change point temperature T_{cp}, W/ft².

B_m: The temperature slope for M.L.R. Models.

C_{final}: The change point temperature, °F.

Table 7.8
Model Development for FY94 (FY93 for Sims) for Ten Primary and Secondary Schools in Texas

School Name	$C_{initial}$(°F)	C_{final}(°F)	A_0(W/ft²)	A_1(W/ft²)	B_m
SES	60.083	60.0	0.372	1.217	0.06
DMS	61.174	61.5	0.6207	0.7737	0.0985
SHS	60.504	65	0.141	0.5516	0.0165
VHS	61.008	61.0	0.2513	0.8108	0.0273
NHS	50.505	56	0.1573	1.416	0.0413
CMS	70.587	74	0.0279	1.4033	0.1156
OES	65.164	67	0.2576	1.5171	0.0227
WMS	63.011	68	-0.1668	2.6091	0.0346
PES	61.935	67	0.0322	1.8722	0.0325
MES	60.86	67	0.165	2.1305	0.0347

CHAPTER VIII

COMPARISON OF THE TWO METHODOLOGIES

8.1 Development of the MLR Models

The multiple variable modeling process is started by selecting the change point value C of the model for the 9 non-summer months. This value is then used as the initial value to determine (T_{db} - C), for each of the 12 months during the baseline year. Then a monthly multiple linear regression model is identified for this year which is called the "Proposed Model", described earlier:

$$E_{tot} = A_0 + A_1 k_i + B_m(T_{db} - C)^+ \qquad (8.1)$$

where A_0, A_1, B_m and C are the multiple linear regression coefficients. $A_0 = A_{un}$; $A_1 = A_{oc} - A_{un}$. The coefficient of variation of the root mean square error (CV-RMSE) is one of the most important statistical indices for the goodness-of-fit of the model to the measured data during the pre-retrofit period. Since the initial value of C is obtained from the 3-P model for the 9 non-summer months and not from the multiple linear regression model itself, we change the C value by small increments, for example 1 °F initially, find how the CV value changes with C, then make the increments smaller such as 0.2°F or 0.1°F between the temperatures where CV is minimum. Finally choose the value which yields the smallest CV. Use this as the final value of C and thereby make the model as accurate as possible. Calculate CV-RMSE and APE (Annual Prediction Error). Plot E - B_m(T_{db} - C) VS k, shown as Figure 8.1 If it shows a linear relationship, it means that the functional form of the model is correct because from equation (8.1):

$$E_{tot} - B_m(T_{db} - C)^+ = A_0 + A_1 k$$

It is noted from Figure 8.1 to Figure 8.10, that a linear relationship indeed exists which lends further credence to our model formulation.

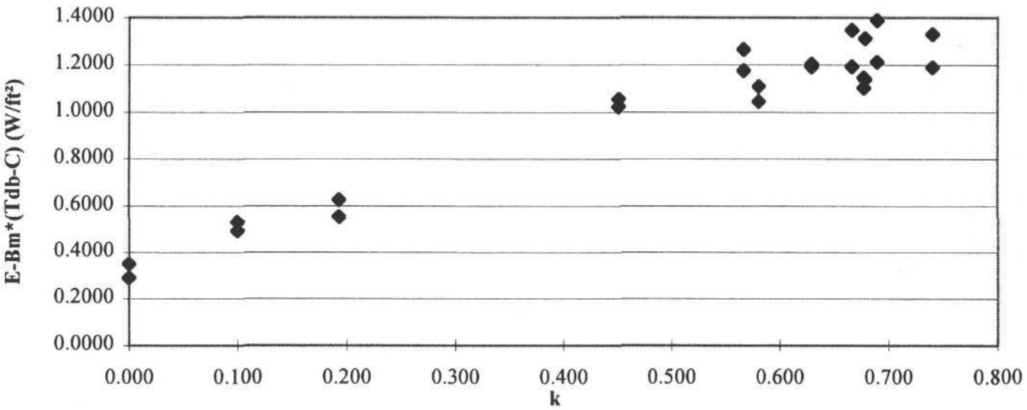


Figure 8.1 k VS E - B_m (T_{db} - C) for SES FY95 & FY96

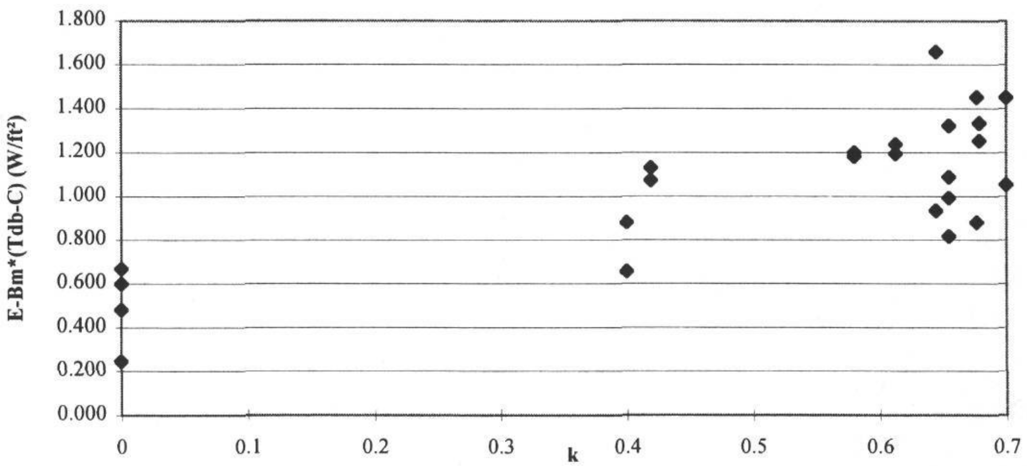


Figure 8.2 k VS E - B_m (T_{db} - C) for DMS FY95 & FY96

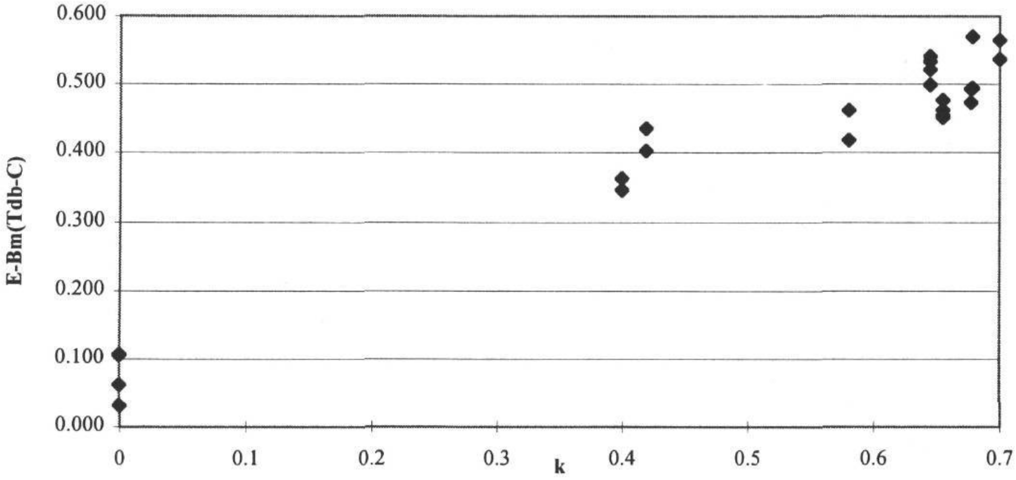


Figure 8.3 k VS E - B_m (T_{db} - C) for SHS FY95 & FY96

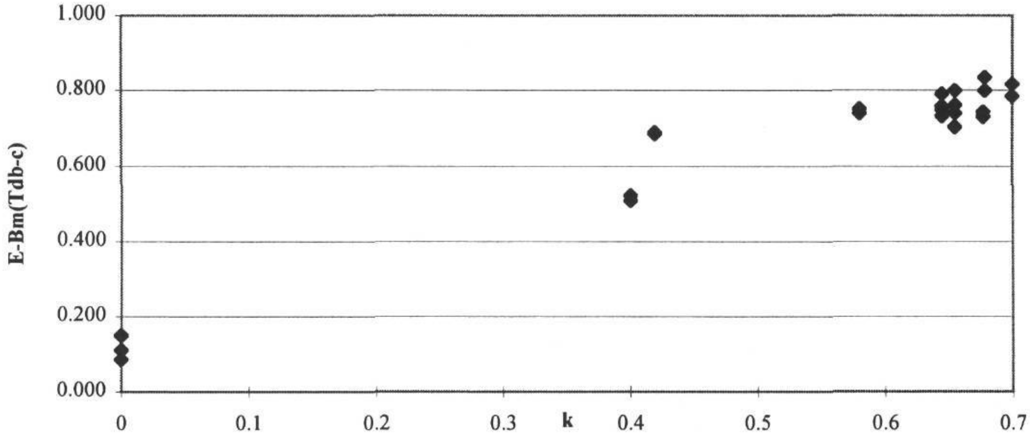


Figure 8.4 k VS E - B_m (T_{db} - C) for VHS FY95 & FY96

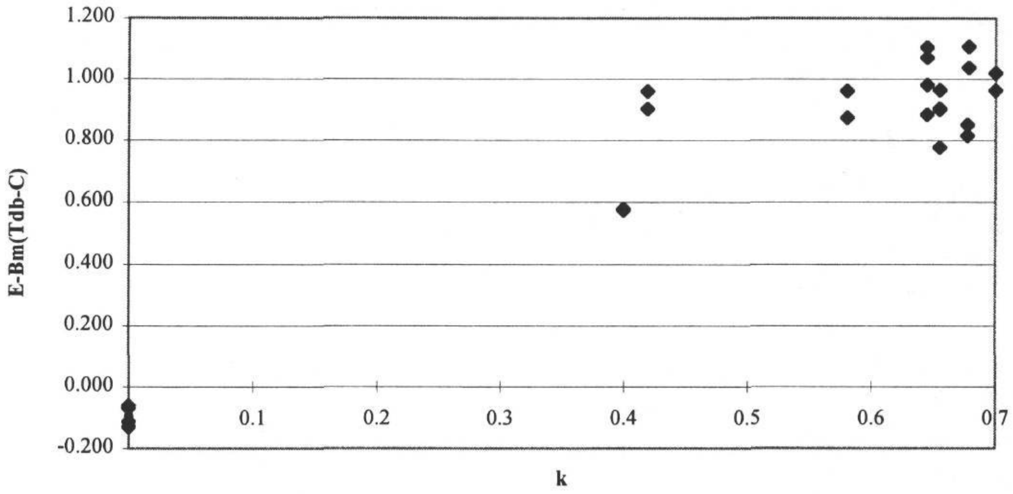


Figure 8.5 k VS E - B_m (T_{db} - C) for NHS FY95 & FY96

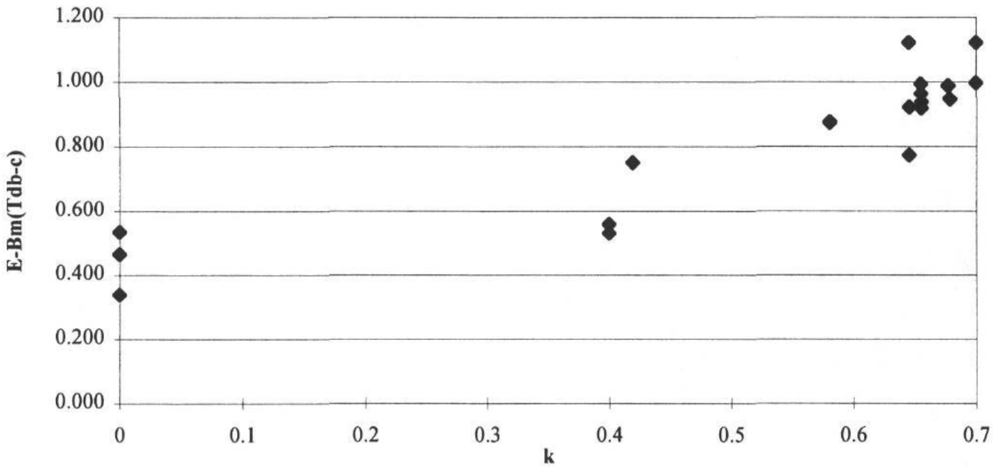


Figure 8.6 k VS E - B_m (T_{db} - C) for CMS FY95 & FY96

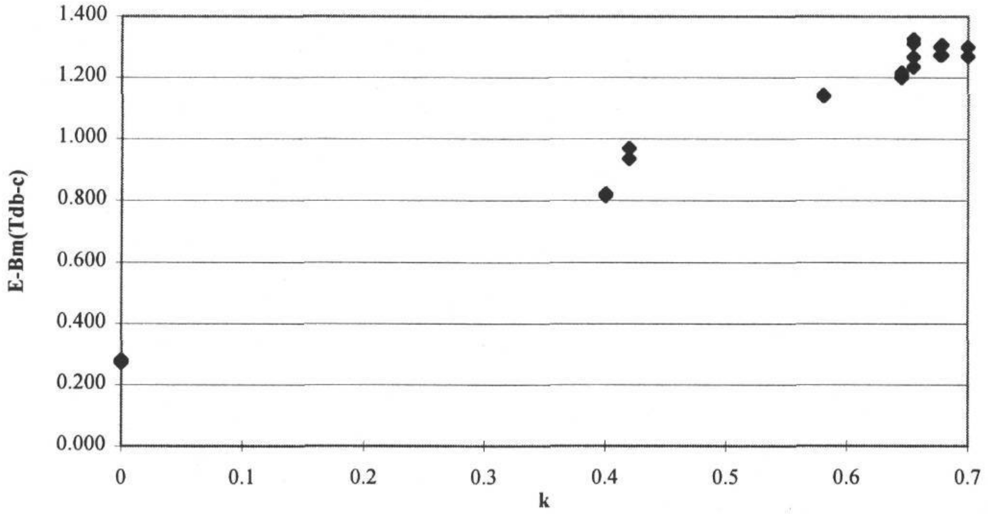


Figure 8.7 k VS E - B_m (T_{db} - C) for OES FY95 & FY96

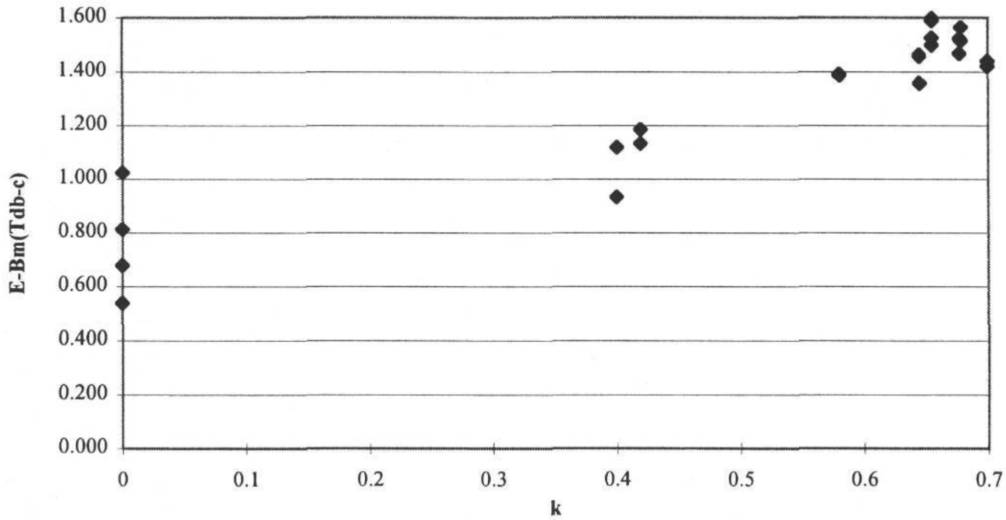


Figure 8.8 k VS E - B_m (T_{db} - C) for WMS FY95 & FY96

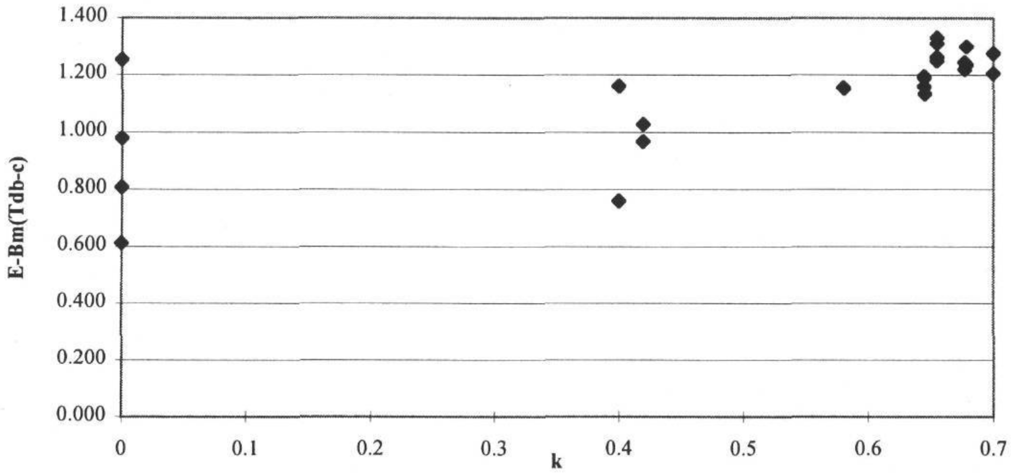


Figure 8.9 k VS E - B_m (T_{db} - C) for PES FY95 & FY96

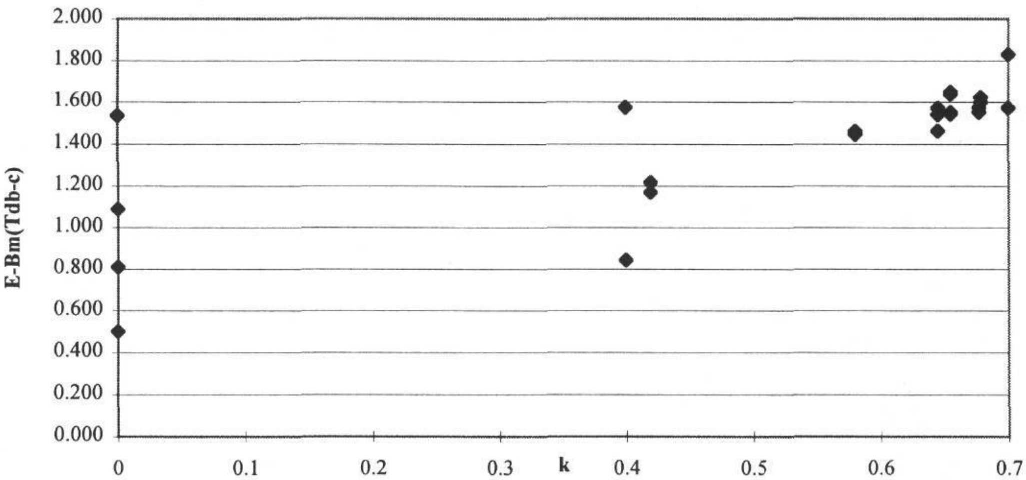


Figure 8.10 k VS E - B_m (T_{db} - C) for MES FY95 & FY96

8.2 Calculation of CV-RMSE and APE for the Extreme Years

We predict the monthly consumption of the two extreme years using the M.L.R. model and the corresponding temperature data. The predictions of M.L.R models are compared with the "synthetic utility bills " and the real measured energy consumption by computing the CV-RMSE and APE for the extreme years. For the two-year data, CV-RMSE becomes:

$$CV\text{-}RMSE = 100\left(\frac{1}{Y_{mean}}\right)\left[\frac{MSE}{(24-4)}\right]^{0.5}$$

The M.L.R. models of the proposed method for the ten schools have been shown in Chapter VII. The coefficient of variation of the root mean square error (CV-RMSE), was calculated. The prediction accuracy was evaluated using the annual prediction error, (APE) which is defined as the ratio of the difference between the annual energy use predicted by the regression model and the synthetic utility bill data for the extreme years using both our proposed models and the 3P-mean method. Table 8.1 and Table 8.2 summarize the monthly model goodness-of-fit indices CV and APE for both modeling approaches for the ten primary and secondary schools in Texas for FY95 & FY96

The APE values for the proposed model varied from 0.199% to 10.043%, while for the 3P-mean method it is from 0.587% to 13.13%. The APE values for seven cases were less (by an average of 4.217%) using the proposed method while the other three cases, APE for the 3P-mean method was less (by an average of 1.697%). The CV was smaller in all 10 cases using the proposed method. The coefficient of variance for the proposed method varied from 3.187% to 25.172%; it is from 8.623% to 28.693% for the 3P-mean method when using the synthetic utility billing data.

When comparing the methods with the real data, the APE values for the proposed model varied from 0.99% to -13.76%, while for the 3P-mean method it is from 2.41% to 14.81%. The coefficient of variance for the proposed method varied from 11.38% to 37.3%, while it is from 18.17% to 45.5% for the 3P-mean method.

Again, the CV was smaller in all 10 cases using the proposed method. However, APE values for seven cases are better using the 3P-mean method (by an average of 2.10%). However, in the other three cases, where the proposed method gives a smaller APE, it is smaller by 11.43%, 10.71% and 0.85% for an average of 7.65%, and the average absolute error of the proposed method is 7.5% compared with 8.3% for the 3P-mean method.

Table 8.1
Results of Comparison of the Two Methodologies
(Using Synthetic Utility Bill Data for FY95 & FY96)

	Proposed Method	3P-mean Method	Proposed Method	3P-mean Method
School Name	**CV(%)**	**CV(%)**	**APE (%)**	**APE (%)**
SES	6.720	8.623	2.290	3.210
DMS	12.215	21.251	1.173	-0.587
SHS	5.858	11.037	-1.347	-2.157
VHS	8.489	15.943	-3.368	-4.466
NHS	7.806	20.974	0.475	-13.13
CMS	8.643	17.827	1.396	-0.817
OES	3.187	24.607	0.199	-10.067
WMS	13.789	20.180	4.077	7.543
PES	17.479	26.980	6.801	-2.914
MES	25.172	28.693	10.043	10.818

Table 8.2
Results of Comparison of the Two Methodologies
(Using Real Measured Data for FY95 & FY96)

	Proposed Method	3P-mean Method	Proposed Method	3P-mean Method
School Name	CV(%)	CV(%)	APE (%)	APE (%)
SES	29.46	31.95	-13.76	-12.69
DMS	24.4	27.98	11.35	9.77
SHS	15.38	18.17	6.31	5.56
VHS	13.64	18.84	9.19	8.22
NHS	19.64	31.94	0.99	-12.42
CMS	26.49	26.59	9.04	6.99
OES	11.38	30.76	-4.1	-14.81
WMS	37.3	45.5	-11.78	-7.74
PES	19.92	32.16	6.96	-2.74
MES	19.26	24.64	1.56	2.41

From the results in Table 8.1 and 8.2, CV and APE values are larger when the predictions for the extreme years are compared with the real measured data. Since the synthetic utility bill data which have been obtained from the 3-P daily model assume the same schedule as the baseline year, these results are not surprising, since the schedules for the extreme years are different from the baseline year. It is also probable that other changes such as addition of PCs have occurred. The proposed method still goes consistently better CVs than the 3P-mean method, but the results for annual predictive ability are only marginally better for the proposed method.

Table 8.3
Results of Comparison of the 3-P Mean Model Method
(for FY95 & FY96)

	Values from Landman's Thesis (Sep. 91 - Dec. 93)	3P-mean Method in this thesis based on models developed from FY94 (Aug. 95 - Jul. 96)
School Name	**CV(%)**	**CV(%)**
SES	11.7	8.623
DMS	18.5	21.251
SHS	11.1	11.037
VHS	14.9	15.943
NHS	19.3	20.974
CMS	29.4	17.827
OES	25.2	24.607
WMS	22.7	20.180
PES	18.8	26.980
MES	14.7	28.693

Table 8.3 shows the CV values for the 3P mean model method from Landman's thesis based on data from September 1991 to December 1993 and the CV values from our study which are taken from the "3P-mean method" column of Table 8.1. We can see that the results are within the same range, between 8 % to 30 %, the average difference is about 1 % and for most of the schools such as SES, DMS, SHS, VHS, NHS, OES and WMS the values are very similar to each other although they came from different time periods. Hence we conclude that the 3P-mean method was accurately applied in this study.

8.3 Development of the 5-P MLR Models

For the 4-P M.L.R. models, we assume that B and C values for the occupied period are the same as values for the unoccupied period. For 5-P model the occupied and unoccupied period do not have the same slope (B value), but are assumed to have the same change point (C value). The 5-P monthly multiple linear regression model for this year is:

$$E_{tot} = A_0 + A_1 k_i + B_{oc}(T_{db} - C)^+ + B_{un}(T_{db} - C)^+$$

From the final results of the 4-P M.L.R. models for the ten schools in Texas, we can see that CV values for some schools for the model-year such as for NHS and CMS are higher than 10%. So 5-P models were tried for these schools and it was found that the standard error of the parameter estimate is larger than the parameter itself; that means the estimation of 5-P models for these schools are not stable. Thus we can not use the 5-P model as a reliable baseline. The parameter and the corresponding standard errors of the parameters are shown below in Table 8.4:

Table 8.4
Parameters and the Corresponding Standard Errors of the 5-P Models for NHS and CMS

School Code	Parameter	Parameter value	Standard error of the value
NHS	k_i(T - C)	0.0341	0.0379
CMS	T - C	0.0470	0.0487
	k_i(T - C)	0.0795	0.0913

The 5-P M.L.R. models were also tried for the schools which have high CV values for the extreme temperature year, for example: WMS and PES. The CV values for the baseline year for WMS decrease from 7.04 to 5.67% using the 5-P model but the CV values for the extreme temperature year increased from 13.78% to 17.94%. For PES, CV values for the baseline year decrease from 6.4% to 5.1% but the CV values for the extreme temperature year increased from 17.48% to 28.15%.

CHAPTER IX

CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

The CV values for the proposed methodology are smaller than those of the 3P-mean method when comparison was made with both Synthetic Utility Bill data and actual data for all 10 cases examined. This implies that the proposed methodology is suitable for developing baseline models for buildings that experience large seasonal changes in occupancy patterns such as schools. The APE values for the two comparisons are not as clear-cut due to the schedule changes for the extreme years, but indicate that the proposed method is superior to the 3P-mean method when good schedule information is available. By adding the occupancy rate, it allows a more intuitive and unified model to be developed than the standard 3-P model.

Daily data from Dunbar Middle School was used to illustrate the effect of schedule on energy use heavily scheduled buildings. It was shown to be comparable to weather depend effects.

The 4-P multiple-linear regression model is recommended. It was found to be more accurate compared with the 5-P model multiple-linear regression model or the 3P-mean model approach.

The proposed method uses one M.L.R. model for the whole fiscal year by considering the occupancy rate as one of the variables in the model. It can be used for elementary and secondary schools which have different operating patterns.

9.2 Future Study

The APE values for the proposed method are slightly larger than for the 3P-mean method for a majority of the cases when compared with the real measured data. It is not known what made this happen, how much was due to schedule changes, and how much was due to other changes, such as the internal loads.

From the final results it can be seen that for some schools for example WMS, PES and MES, the CV and APE values are low for the baseline year, but high for the extreme years. For the other schools, such as SES, DMS and NHS, when CV and APE values are higher for the baseline year, they are lower for the extreme years. The relationship between the CV and APE for the different years is not known.

An investigation of the above relationships may lead to additional model refinements.

REFERENCES

ACR., 1990. Energy cost reduction analysis of Victoria independent school district. Austin, TX: ACR Engineering, Inc.

Bevington, R., and A. Rosenfeld, 1990. Energy for buildings and homes. *Scientific American*, 263 (90): pp. 76-86.

Bou-Saada, E. Tarek, and J.S. Haberl, 1995. An improved procedure for developing calibrated hourly simulation models. *Forth International Conference Proceedings, IBPS,* Madison, WI, August 14-16, pp. 475-484.

Bronson, D. J., S.B. Hinchey, J.S. Haberl, and D.L. O'Neal, 1992. A procedure for calibrating the DOE-2 simulation program to non-weather-dependent measured loads. *ASHRAE Transactions* 98(1).

Carter & Burgess, 1990. An evaluation of RFP #90-040 prepared for: the Fort Worth independent school district. Fort Worth, TX: Carter & Burgess Inc.

Claridge, D. E., J.S. Haberl, J.K. Kissock, D. Ruch, S. Katipamula, L. Chen, and J. Wang, 1990. Improved analysis methods for retrofit savings and energy accounting (ERAP #227). Energy Systems Laboratory, Report No. ESL-PA-90/10. College Station: Texas A&M University.

Claridge , D.E., and J.S. Haberl, 1994. Analysis of the Texas LoanSTAR data. *Proceedings of the Seventh Annual Symposium on Improving Building Systems in Hot and Humid Climates*, pp. 53-60.

Claridge , D.E., 1994. Annual energy consumption report. Energy Systems Laboratory, Report No. ESL-PA-94/05. College Station: Texas A&M University.

Dhar, A., T.A. Reddy, D.E. Claridge, 1994. Improved fourier series approach to modeling hourly energy use in commercial buildings. *Proceeding of the 1994 ASME/JSME/JSES, International Solar Energy Conference.*

EIA, 1992. State energy data report, Consumption estimates 1960 -1990. Report No. DOE/EIA - 0214 (90), U. S. Department of Energy, Energy Information Administration, Washington, DC.

Fels., M., 1986. Special issue devoted to measured energy savings, the Princeton score keeping method (PRISM). *Energy and Buildings* 9(1&2).

Forrest, J. and W. Wepfer. 1984. Formulation of a load prediction algorithm for a large commercial building. *ASHRAE Transactions* 90(1):536-551.

Goldstein, R.J., M.E. Schneider, M.I. Clarke, 1985. Residential energy use: an analysis of factors affecting gas and electricity use in single-family houses. *ASHRAE Technical Bulletin* pp. 219-236.

Haberl, J.S., and P.S. Komor, 1990. Improving energy audits: How annual and monthly consumption data can help. *ASHRAE Journal* 90(8): 26-32.

Hadley, D.L., 1993. Daily variations in HVAC system electrical energy consumption in response to different weather conditions. *Energy and Buildings* pp. 235-247.

Hsieh, E. 1988. Calibrated computer models of commercial buildings and their role in building design and operation. Master's thesis, Princeton University, Princeton, NJ.

Katipamula, S., and D.E. Claridge, 1993. Using of simplified models to measure retrofit energy savings. *Journal of Solar Energy Engineering* 116(2).

Katipamula, S., T.A. Reddy, and D.E. Claridge, 1994. Development and application of regression models to predict cooling consumption in large commercial buildings. *1994 ASME/JSME/JSES, International Solar Energy Conference,* San Francisco, March.

Katipamula, S., T.A. Reddy, and D.E. Claridge, 1995. Effect of time resolution on statistical modeling of cooling energy use in large commercial buildings. *ASHRAE Transactions* 101(2):3895-3908.

Kinsman, 1991. Energy cost reduction analysis of Nacogdoches independent school district, Richardson, TX: Kinsmanand Associates.

Kissock, J.K., T.A. Reddy, and D.E. Claridge., 1992. A methodology for identifying energy savings in commercial buildings. *Proceedings of the Seventh Annual Symposium on Improving Building Systems in Hot and Humid Climates*, Dallas, TX, May 12-13. pp. 234-246.

Kissock, J.K., 1993. A methodology to measure retrofit energy savings in commercial buildings. Ph.D. Dissertation, ESL-TH-93/13/03. Department of Mechanical Engineering, College Station: Texas A&M University.

Knebel, D.E., 1983. Simplified energy analysis using the modified bin method. *American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc*., Atlanta, GA.

Landman, D.S., 1996a. A study of diagnostic pre-screening methods for analyzing energy use of K-12 public schools. Report No. ESL-TR-96/11-02, Energy System Laboratory, College Station: Texas A&M University.

Landman, D.S., 1996b. Development of pre-screening indices to improve energy analysis of public K-12 schools. Masters Thesis, Department of Mechanical Engineering, College Station: Texas A&M University.

Liu, M., D. E. Claridge, 1995. Heat flux error of steady-state method for building components under dynamic conditions. *Solar Engineering* 1995: *The 1995 ASME/JSME/JSES International Solar Energy Conference*, Maui, Hawaii, March 95(1): pp. 219 - 227.

Meier, A., L. Rainer, and S. Greenberg, 1992. Miscellaneous electrical energy use in homes. *Energy* 92(17): pp. 509-518.

Milton, J.S., and J.C. Arnold, 1995. *Introduction to probability and statistics: principles and applications for engineering and the computing sciences*. 3rd ed. New York: McGraw Hill, Inc. pp. 552-555.

Pertersen, T. D., 1994. Variation of energy consumption in dwellings due to climate, building and inhabitants. *Energy and Buildings* 94(21): pp 209-218.

Rabl, A. and A. Rialhe, 1992. Energy signature models for commercial buildings: test with measured data and interpretation. *Energy and buildings* 92(17).

Reddy, T.A., J.K. Kissock, S. Katipamula, and D.E. Claridge, 1994. An overview of measured energy retrofit savings methodologies developed in the LoanSTAR program. Report No. ESL-TR-94/03/04. College Station: Texas A&M University.

Ruch, D. and D.E. Claridge, 1992. A four parameter change point model for predicting energy consumption in commercial buildings. *ASME Journal of Solar Energy Engineering* 114(2): 77-83.

Ruch, D., L. Chen, J.S. Haberl, and D.E. Claridge, 1993. A change-point principle-component analysis (CP/PCA) method for predicting energy usage in commercial buildings: the PCA model. *Journal of Solar Energy Engineering* 115(3): 77-84.

Verdict, M., J. Haberl, D. Claridge, D. O'Neal, W. Heffington, D. Turner, 1990. Monitoring $98 million energy efficiency retrofits: the Texas LoanSTAR program. *ACEEE 1990 Summer Study on Energy Efficiency* pp. 7.261-2.272.

Wang, J.,1996. Comparison of the prediction accuracy of daily and monthly regression models for energy consumption in commercial buildings. Master's thesis, Department of Mechanical Engineering, College Station: Texas A&M University, pp. 2-4.

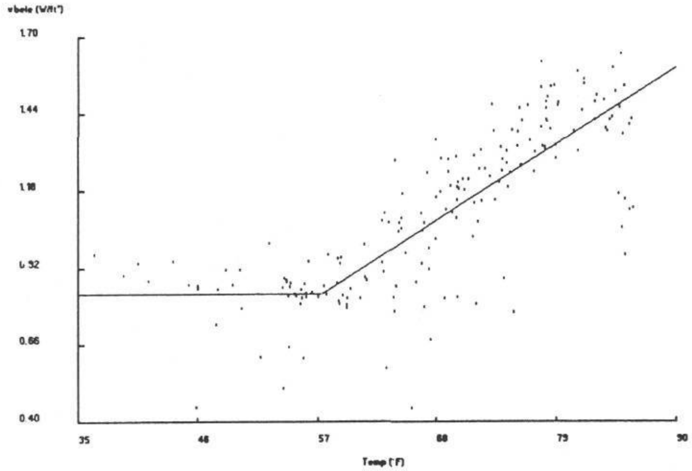
Yandell & Hiller, 1992. Energy cost reduction analysis of Nacogdoches independent school district. Fort Worth, TX: Yandell & Hiller, Inc.

APPENDIX A

DAILY REGRESSION MODELS

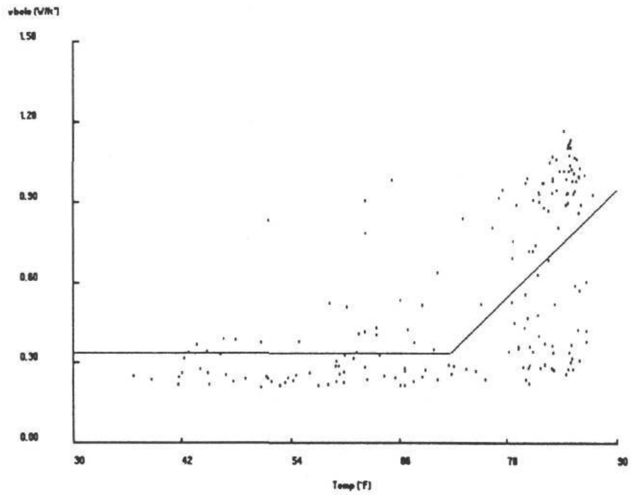
Figures A.1 through A.10 present the scatter plots and the 3-P (4-P) regression models for the simulated daily energy consumption as functions of the outdoor average temperature during operating periods for the 10 elementary and secondary schools.

The information below each plot presents the statistical parameters for the regression model. X_{cp} is the change point temperature and Y_{cp} is the energy consumption at the change point temperature X_{cp}. LS is the slope below X_{cp} and RS is the slope above X_{cp}. N is the number of total data points. R^2 is the coefficient of correlation, RMSE is the root mean square error, p is the autocorrelation coefficient, and DW is the Durbin Watson statistic of the regression model.



Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 0.8321 (0.0188) LS = 0.0000 (0.0000) RS = 0.0235 (0.0012) Xcp = 57.3667
N = 183 N1 = 38 N2 = 145 R2 = 0.66 adjR2 = 0.66 CV-RMSE = 14.1% p = 0.41
DW = 1.14 (p>0)

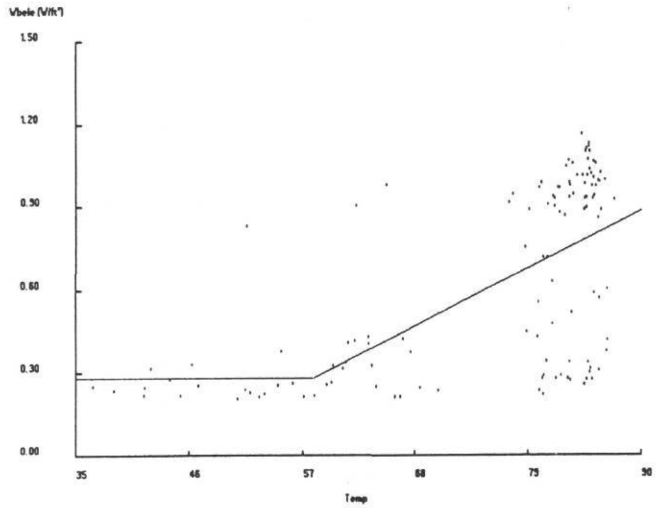
Figure A.1a 3-P Daily Model for School Days



Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 0.3365 (0.0271) LS = 0.0000 (0.0000) RS = 0.0334 (0.0031) Xcp = 71.6475
N = 182 N1 = 73 N2 = 109 R2 = 0.39 RMSE = 0.25 CV-RMSE = 45.0% p = 0.26
DW = 1.47 (p>0)

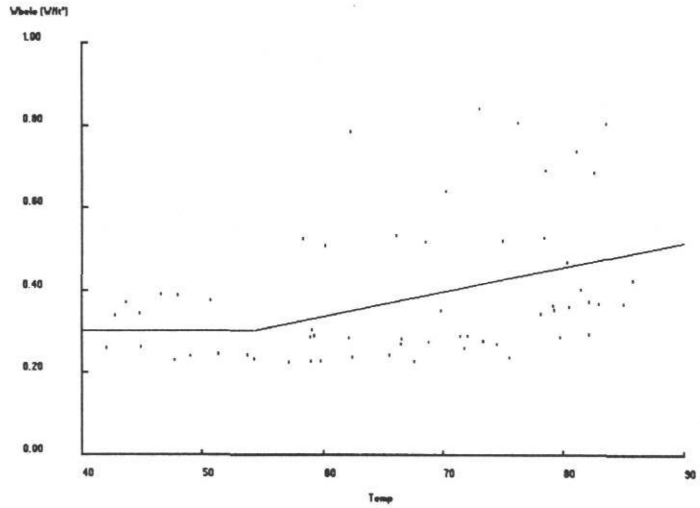
Figure A.1b 3-P Daily Model for Non-School Days

Figure A.1 3-P Daily Models for SHS FY94



Model: Un-grouped 3P-CP (C). Wbele (W/ft²) vs. Temp
Ycp = 0.2835 (0.0475) LS = 0.0000 (0.0000) RS = 0.0189 (0.0022) Xcp = 57.9682
N = 122 N1 = 19 N2 = 103 R2 = 0.37 adjR2 = 0.37 RMSE = 0.27 CV-RMSE = 42.9%
p = 0.29 DW = 1.40 (p>0)

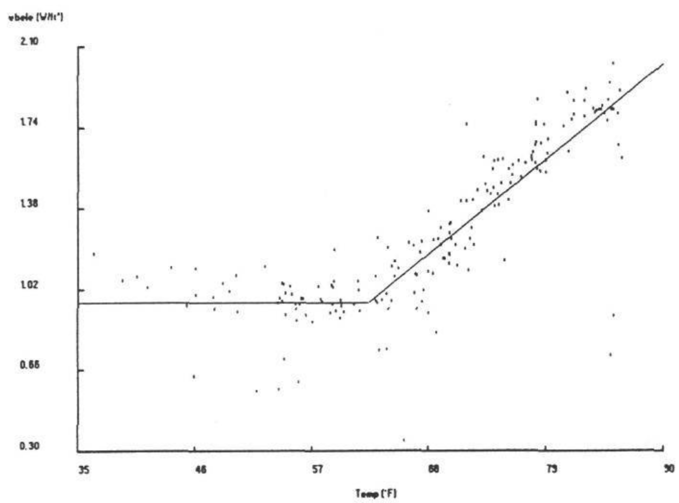
Figure A.1c 3-P Daily Model for Holidays Longer than 3 Days



Model: Un-grouped 3P-CP (C). Wbele (W/ft²) vs. Temp
Ycp = 0.3033 (0.0339) LS = 0.0000 (0.0000) RS = 0.0060 (0.0019) Xcp = 54.2872
N = 60 N1 = 12 N2 = 48 R2 = 0.14 adjR2 = 0.13 RMSE = 0.16 CV-RMSE = 40.9%
p = -0.17 DW = 2.32 (i%)

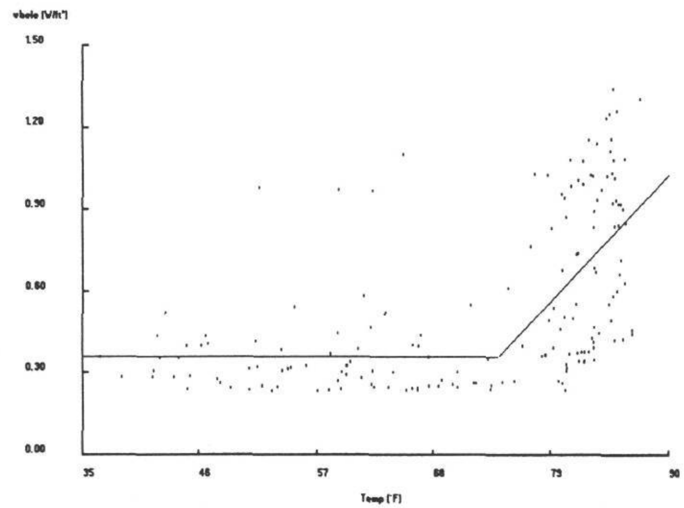
Figure A.1d 3-P Daily Model for the Remaining Weekends and One-Day Holidays

Figure A.1 3-P Daily Models for SHS FY94



Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 0.9602 (0.0188) LS = 0.0000 (0.0000) RS = 0.0384 (0.0017) Xcp = 62.3252
N = 183 N1 = 56 N2 = 127 R2 = 0.75 RMSE = 0.18 CV-RMSE = 13.8% p = 0.43
DW = 1.12 (p>0)

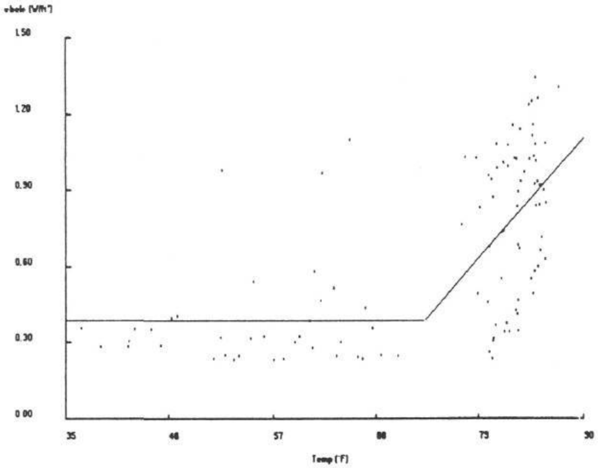
Figure A.2a 3-P Daily Model for School Days



Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 0.3613 (0.0258) LS = 0.0000 (0.0000) RS = 0.0423 (0.0041) Xcp = 74.1909
N = 169 N1 = 78 N2 = 91 R2 = 0.39 RMSE = 0.24 CV-RMSE = 44.1% p = 0.35
DW = 1.29 (p>0)

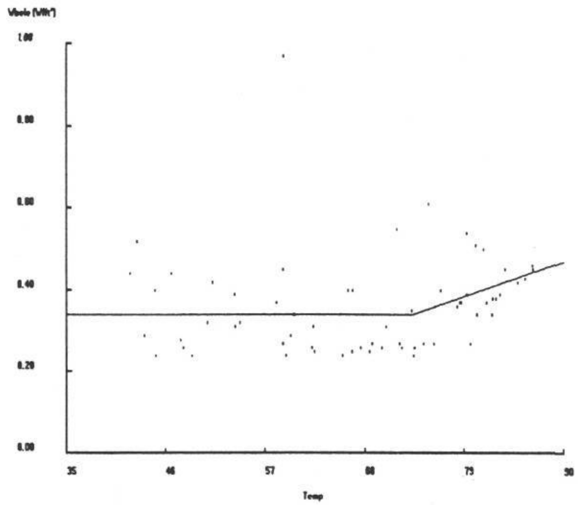
Figure A.2b 3-P Daily Model for Non-School Days

Figure A.2 3-P Daily Models for VSH FY94



Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 0.3893 (0.0390) LS = 0.0000 (0.0000) RS = 0.0428 (0.0049) Xcp = 73.1768
N = 107 N1 = 39 N2 = 68 R2 = 0.42 adjR2 = 0.42 RMSE = 0.25 CV-RMSE = 38.9%
p = 0.35 DW = 1.27 (p>0)

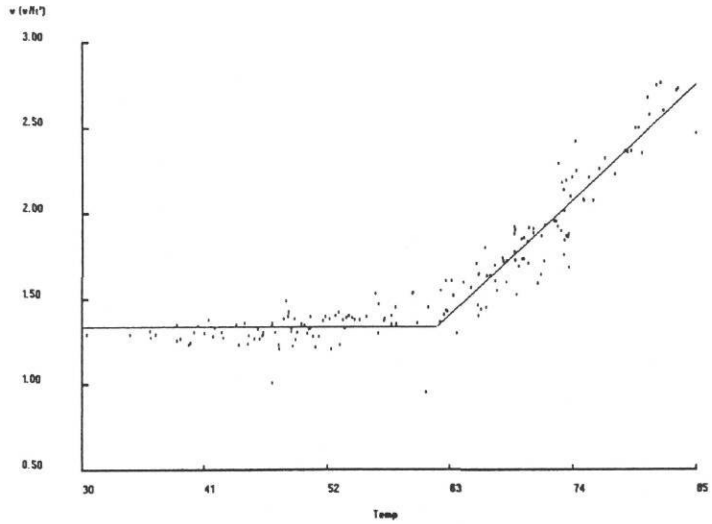
Figure A.2c 3-P Daily Model for Holidays Longer than 3 Days



Model: Un-grouped 3P-CP (C). Wbele (W/ft²) vs. Temp
Ycp = 0.3410 (0.0178) LS = 0.0000 (0.0000) RS = 0.0077 (0.0036) Xcp = 73.2810
N = 62 N1 = 37 N2 = 25 R2 = 0.07 adjR2 = 0.06 RMSE = 0.12 CV-RMSE = 32.3%
p = -0.19 DW = 2.36 (i%)

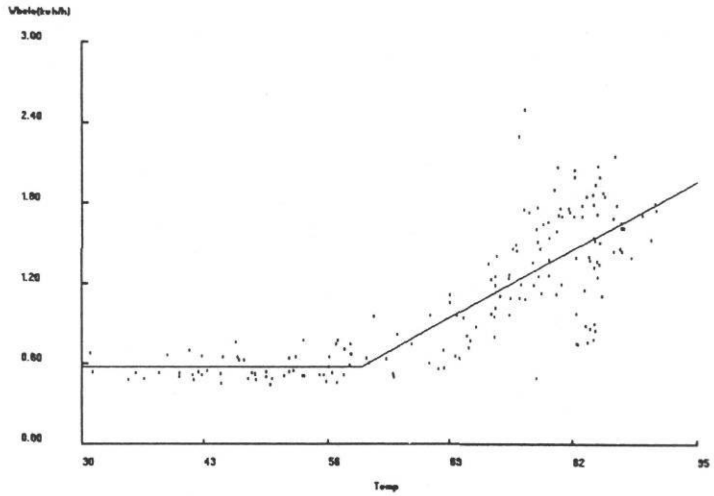
Figure A.2d 3-P Daily Model for the Remaining Weekends and One-Day Holidays

Figure A.2 3-P Daily Models for VSH FY94



Model: Un-grouped 3P-CP (C). w (w/ft²) vs. Temp
Ycp = 1.3364 (0.0113) LS = 0.0000 (0.0000) RS = 0.0620 (0.0014) Xcp = 61.9341
N = 174 N1 = 85 N2 = 89 R2 = 0.91 RMSE = 0.12 CV-RMSE = 7.2% p = 0.31
DW = 1.36 (p>0)

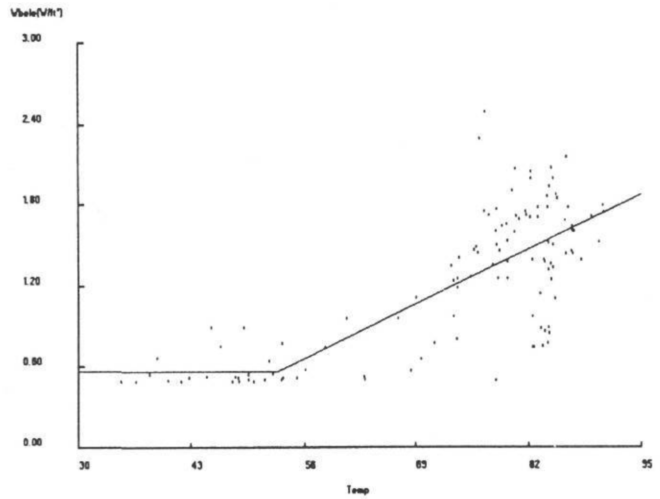
Figure A.3a 3-P Daily Model for School Days



Model: Un-grouped 3P-CP (C). Wbele(kwh/h) vs. Temp
Ycp = 0.5789 (0.0349) LS = 0.0000 (0.0000) RS = 0.0391 (0.0021) Xcp = 59.5563
N = 178 N1 = 56 N2 = 122 R2 = 0.67 RMSE = 0.29 CV-RMSE = 27.1% p = 0.70
DW = 0.59 (p>0)

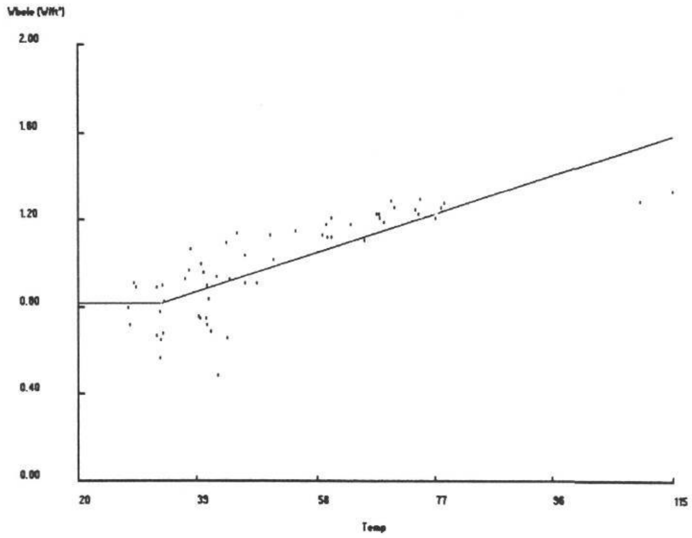
Figure A.3b 3-P Daily Model for Non-School Days

Figure A.3 3-P Daily Models for SES FY93



Model: Un-grouped 3P-CP (C). Wbele(W/ft²) vs. Temp
Ycp = 0.5688 (0.0612) LS = 0.0000 (0.0000) RS = 0.0311 (0.0025) Xcp = 52.8112
N = 119 N1 = 22 N2 = 97 R2 = 0.58 adjR2 = 0.57 RMSE = 0.34 CV-RMSE = 27.8%
p = 0.69 DW = 0.63 (p>0)

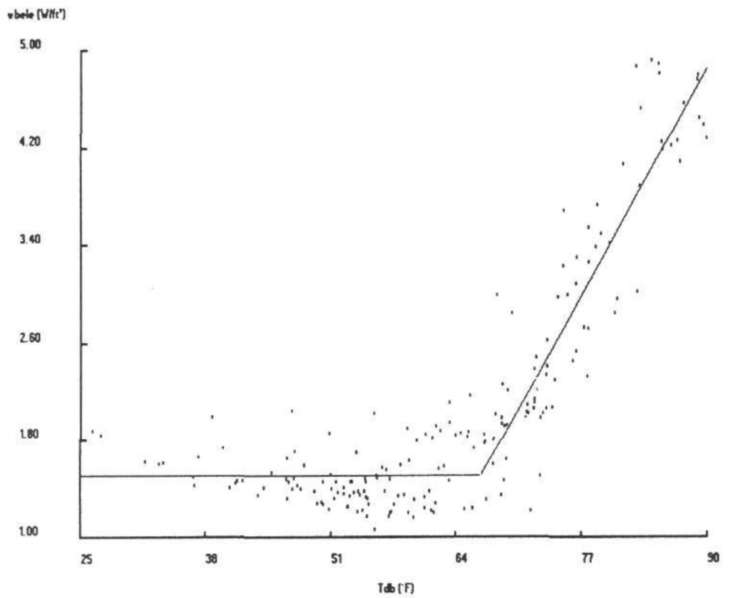
Figure A.3c 3-P Daily Model for Holidays Longer than 3 Days



Model: Un-grouped 3P-CP (C). Wbele (W/ft²) vs. Temp
Ycp = 0.8188 (0.0244) LS = 0.0000 (0.0000) RS = 0.0094 (0.0009) Xcp = 33.3404
N = 58 N1 = 9 N2 = 49 R2 = 0.65 adjR2 = 0.64 RMSE = 0.13 CV-RMSE = 13.2%
p = 0.49 DW = 1.02 (p>0)

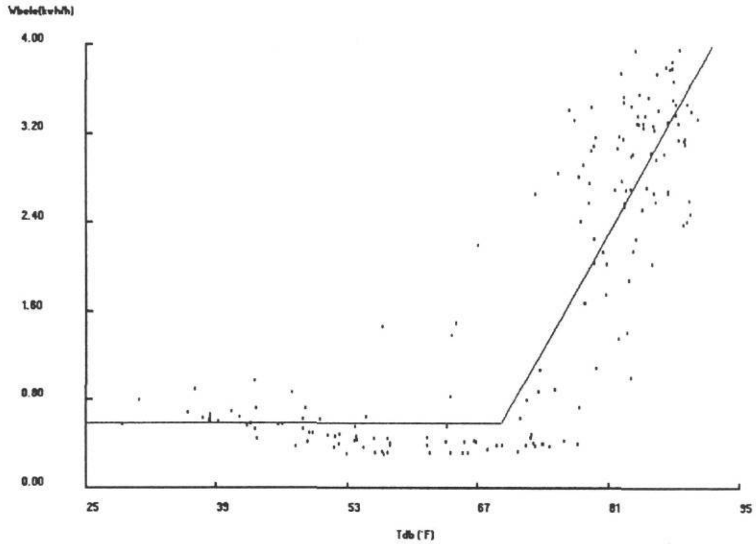
Figure A.3d 3-P Daily Model for the Remaining Weekends and One-Day Holidays

Figure A.3 3-P Daily Models for SES FY93



Model: Un-grouped 3P-CP (C). w (w/ft²) vs. Temp
Ycp = 1.5077 (0.0349) LS = 0.0000 (0.0000) RS = 0.0391 (0.0021) Xcp = 59.5563
N = 178 N1 = 56 N2 = 122 R2 = 0.67 RMSE = 0.29 CV-RMSE = 27.1% p = 0.70
DW = 0.59 (p>0)

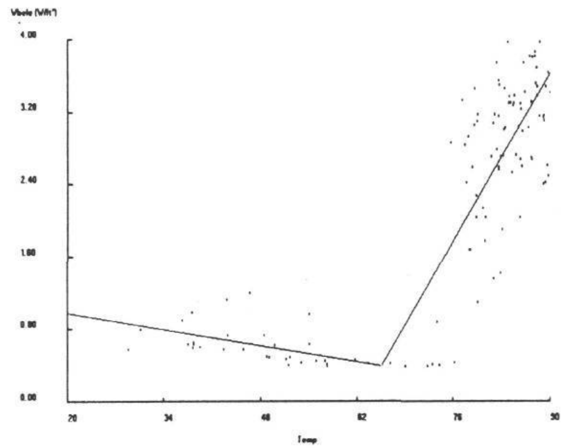
Figure A.4a 3-P Daily Model for School Days



Model: Un-grouped 3P-CP (C). Wbele(kwh/h) vs. Temp
Ycp = 0.5851 (0.0654) LS = 0.0000 (0.0000) RS = 0.1523 (0.0061) Xcp = 69.6195
N = 176 N1 = 68 N2 = 108 R2 = 0.78 RMSE = 0.6 CV-RMSE = 34.1% p = 0.58
DW = 0.82 (p>0)

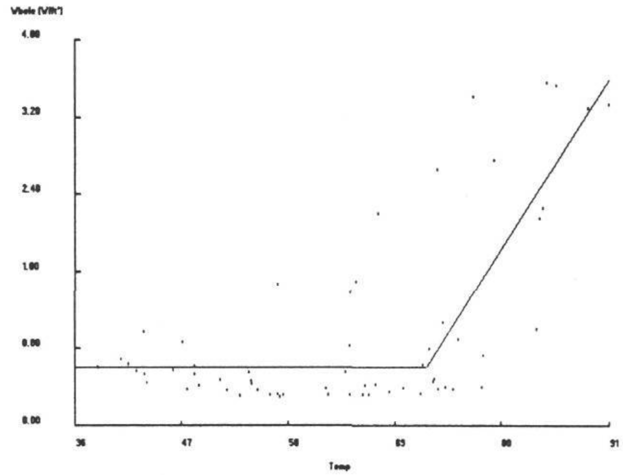
Figure A.4b 3-P Daily Model for Non-School Days

Figure A.4 3-P Daily Models for DMS FY94



Model: Un-grouped 4P-CP. Wbele (W/ft²) vs. Temp
Ycp = 0.3895 (0.4688) LS = -0.0129 (0.0091) RS = 0.1323 (0.0196) Xcp = 65.5440
N = 117 N1 = 30 N2 = 87 R2 = 0.78 RMSE = 0.5843 CV-RMSE = 26.8%
p = 0.72 DW = 0.54 (p>0)

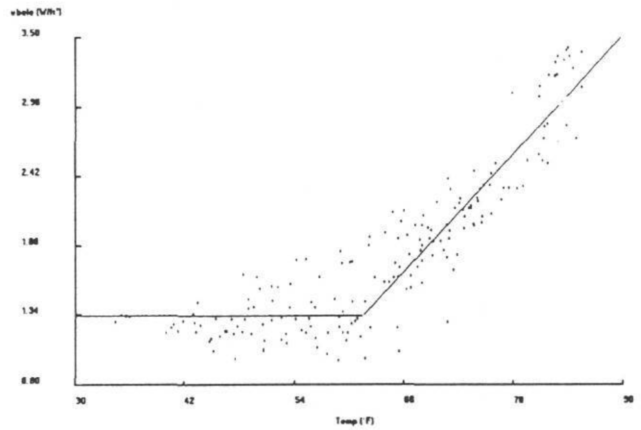
Figure A.4c 4-P Daily Model for Holidays Longer than 3 Days



Model: Un-grouped 3P-CP (C). Wbele (W/ft²) vs. Temp
Ycp = 0.6106 (0.0837) LS = 0.0000 (0.0000) RS = 0.1607 (0.0171) Xcp = 72.0326
N = 63 N1 = 43 N2 = 20 R2 = 0.59 adjR2 = 0.59 RMSE = 0.60 CV-RMSE = 63.3%
p = 0.43 DW = 1.14 (p>0)

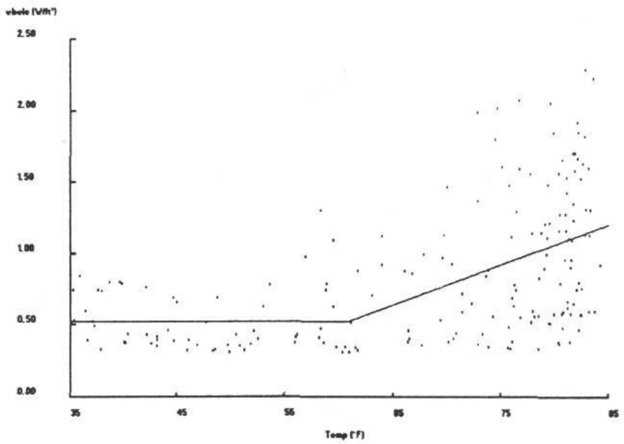
Figure A.4d 3-P Daily Model for the Remaining Weekends and One-Day Holidays

Figure A.4 3-P Daily Models for DMS FY94



Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 1.3374 (0.0223) LS = 0.0000 (0.0000) RS = 0.0768 (0.0023) Xcp = 61.5132
N = 183 N1 = 81 N2 = 102 R2 = 0.86 RMSE = 0.23 CV-RMSE = 12.7% p = 0.45
DW = 1.09 (p>0)

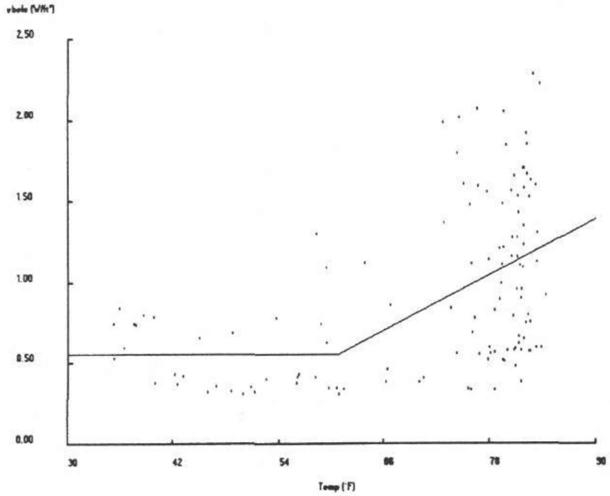
Figure A.5a 3-P Daily Model for School Days



Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 0.5286 (0.0481) LS = 0.0000 (0.0000) RS = 0.0279 (0.0034) Xcp = 60.7300
N = 182 N1 = 59 N2 = 123 R2 = 0.27 RMSE = 0.41 CV-RMSE = 49.8% p = 0.40
DW = 1.19 (p>0)

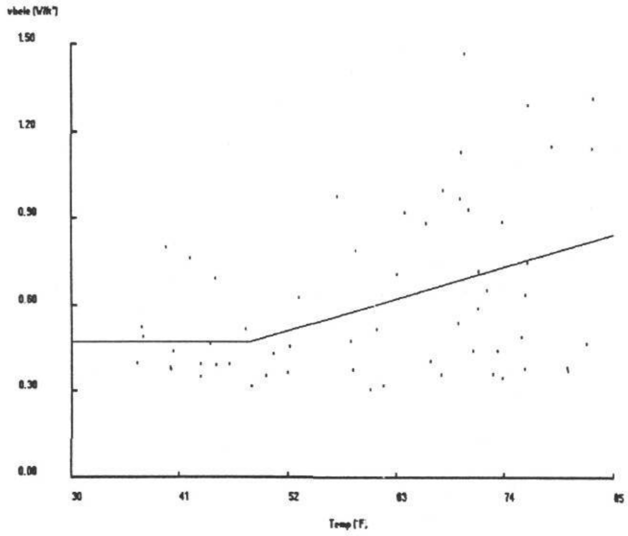
Figure A.5b 3-P Daily Model for Non-School Days

Figure A.5 3-P Daily Models for NHS FY94



Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 0.5599 (0.0742) LS = 0.0000 (0.0000) RS = 0.0286 (0.0047) Xcp = 60.7300
N = 122 N1 = 32 N2 = 90 R2 = 0.24 adjR2 = 0.23 RMSE = 0.46 CV-RMSE = 49.0%
p = 0.50 DW = 0.99 (p>0)

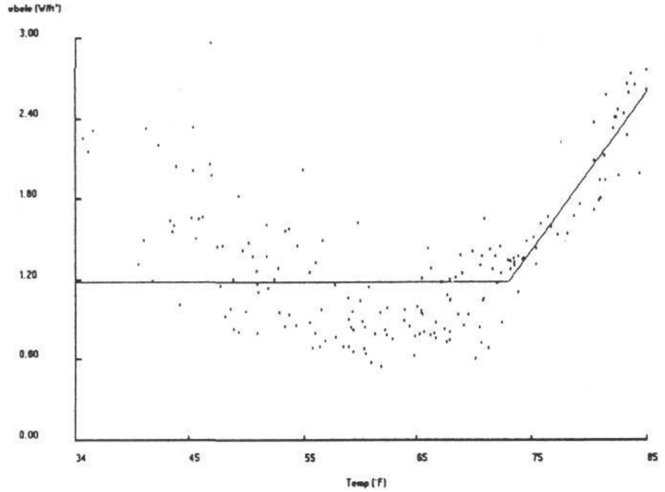
Figure A.5c 3-P Daily Model for Holidays Longer than 3 Days



Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 0.4757 (0.0545) LS = 0.0000 (0.0000) RS = 0.0100 (0.0029) Xcp = 48.1156
N = 60 N1 = 16 N2 = 44 R2 = 0.17 adjR2 = 0.15 RMSE = 0.27 CV-RMSE = 43.5%
p = -0.24 DW = 2.44 (i%)

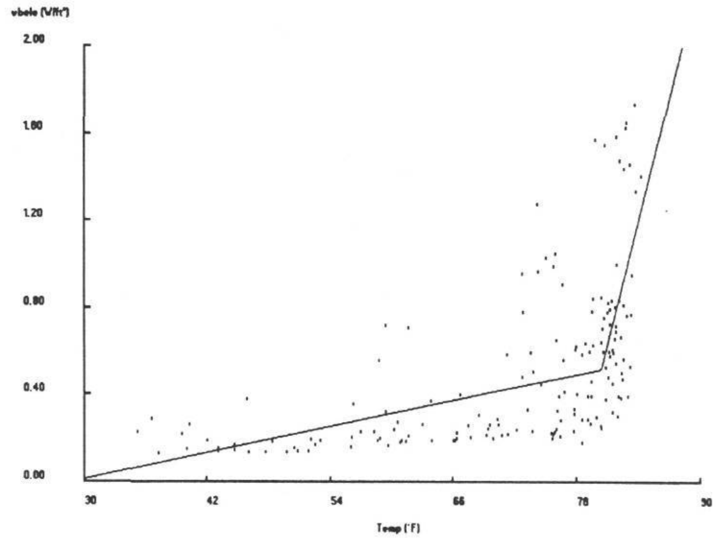
Figure A.5d 3-P Daily Model for the Remaining Weekends and One-Day Holidays

Figure A.5 3-P Daily Models for NHS FY94



Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 1.1860 (0.0325) LS = 0.0000 (0.0000) RS = 0.1155 (0.0090) Xcp = 73.1660
N = 183 N1 = 137 N2 = 46 R2 = 0.47 adjR2 = 0.47 RMSE = 0.40 CV-RMSE = 29.4%
p = 0.55 DW = 0.89 (p>0)

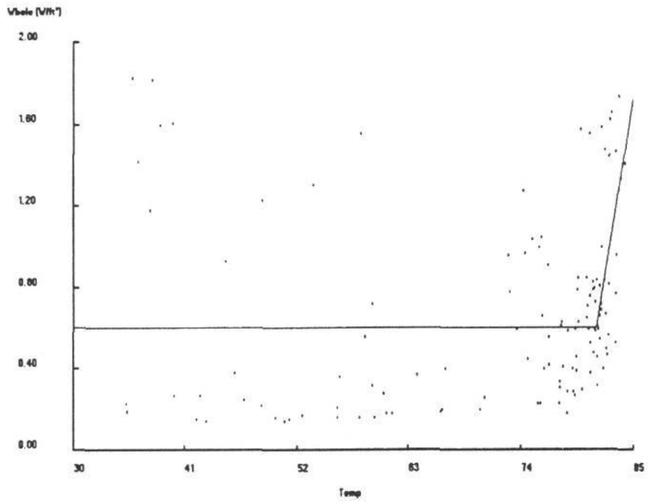
Figure A.6a 3-P Daily Model for School Days



Model: Un-grouped 4P-CP. wbele (W/ft²) vs. Temp (°F)
Ycp = 0.5197 (0.1418) LS = 0.0101 (0.0021) RS = 0.1883 (0.0288) Xcp = 80.3300
N = 160 N1 = 108 N2 = 52 R2 = 0.44 RMSE = 0.2892 CV-RMSE = 56.0%
p = 0.40 DW = 1.18 (p>0)

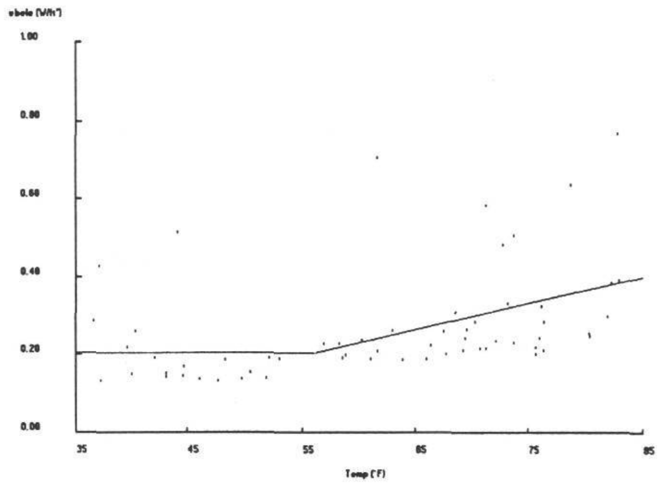
Figure A.6b 3-P Daily Model for Non-School Days

Figure A.6 3-P Daily Models for CMS FY94



Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 0.6022 (0.0421) LS = 0.0000 (0.0000) RS = 0.3039 (0.0632) Xcp = 81.3100
N = 122 N1 = 91 N2 = 31 R2 = 0.16 adjR2 = 0.15 RMSE = 0.42 CV-RMSE = 61.7%
p = 0.40 DW = 1.19 (p>0)

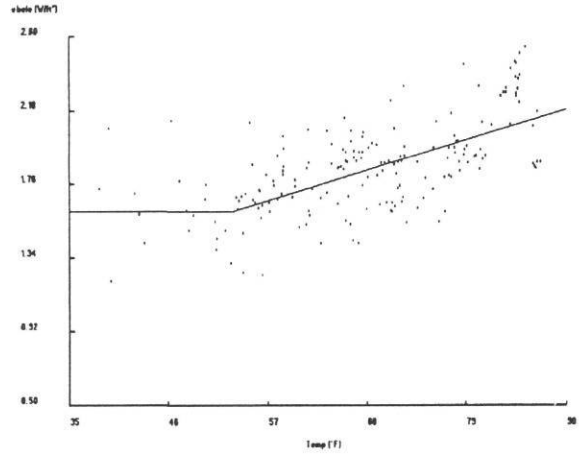
Figure A.6c 3-P Daily Model for Holidays Longer than 3 Days



Model: Un-grouped 3P-CP (C). Wbele (W/ft²) vs. Temp
Ycp = 0.2055 (0.0240) LS = 0.0000 (0.0000) RS = 0.0068 (0.0018) Xcp = 56.1092
N = 60 N1 = 20 N2 = 40 R2 = 0.20 adjR2 = 0.18 RMSE = 0.13 CV-RMSE = 47.0%
p = -0.03 DW = 2.06 (I%)

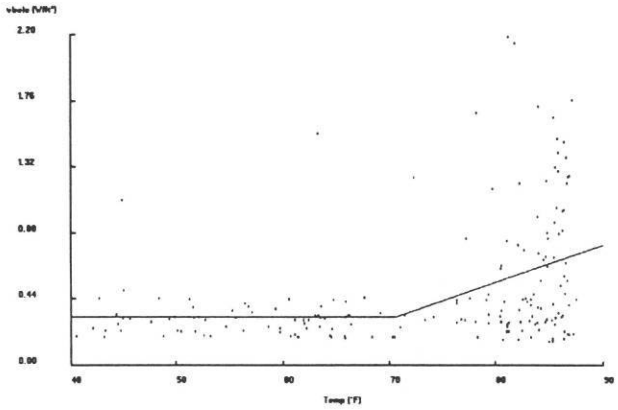
Figure A.6d 3-P Daily Model for the Remaining Weekends and One-Day Holidays

Figure A.6 3-P Daily Models for CMS FY94



Model: Un-grouped 3P-CP (C). wbele (W/ft^2) vs. Temp (°F)
Ycp = 1.6086 (0.0298) LS = 0.0000 (0.0000) RS = 0.0156 (0.0016) Xcp = 53.0410
N = 183 N1 = 18 N2 = 165 R2 = 0.35 RMSE = 0.23 CV-RMSE = 12.2% p = 0.39
DW = 1.22 (p>0)

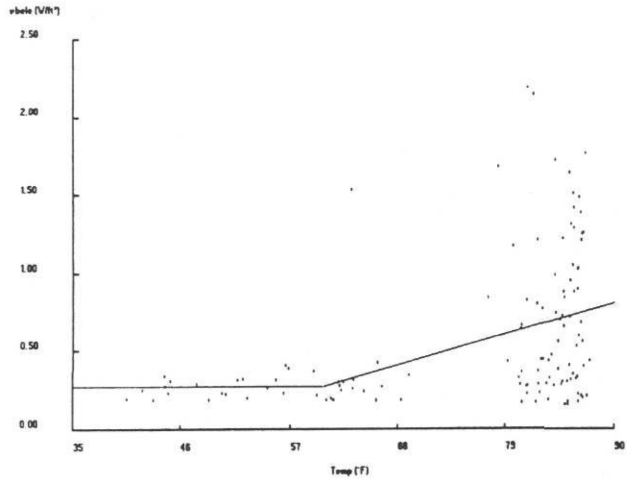
Figure A.7a 3-P Daily Model for School Days



Model: Un-grouped 3P-CP (C). wbele (W/ft^2) vs. Temp (°F)
Ycp = 0.3226 (0.0415) LS = 0.0000 (0.0000) RS = 0.0247 (0.0042) Xcp = 70.6216
N = 182 N1 = 73 N2 = 109 R2 = 0.16 RMSE = 0.38 CV-RMSE = 74.7% p = 0.50
DW = 1.00 (p>0)

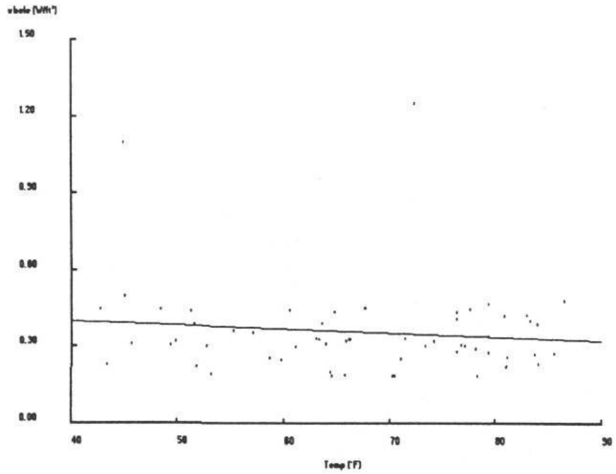
Figure A.7b 3-P Daily Model for Non-School Days

Figure A.7 3-P Daily Models for OES FY94



Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 0.2748 (0.0727) LS = 0.0000 (0.0000) RS = 0.0180 (0.0037) Xcp = 60.2948
N = 122 N1 = 21 N2 = 101 R2 = 0.17 adjR2 = 0.16 RMSE = 0.43 CV-RMSE = 74.7%
p = 0.48 DW = 1.03 (p>0)

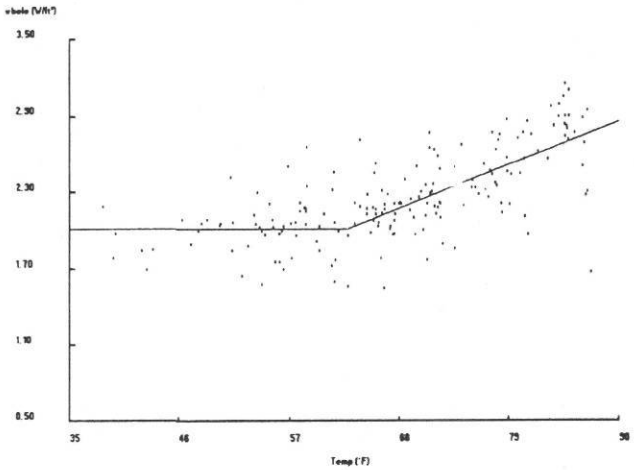
Figure A.7c 3-P Daily Model for Holidays Longer than 3 Days



Model: Un-grouped SLR. wbele (W/ft²) vs. Temp (°F)
Yint = 0.4597 (0.1254) Temp (°F) = -0.0015 (0.0018)
N = 60 R2 = 0.01 adjR2 = -0.01 RMSE = 0.18 CV-RMSE = 49.6%
p = -0.11 DW = 2.22 (p=0)

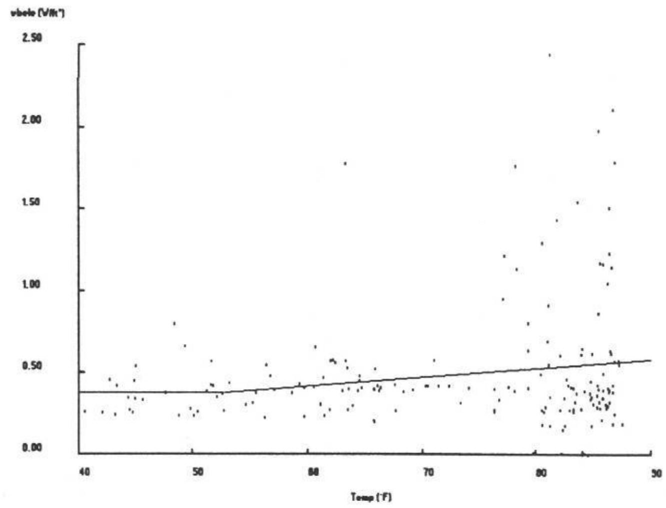
Figure A.7d 3-P Daily Model for the Remaining Weekends and One-Day Holidays

FigureA.7 3-P Daily Models for OES FY94



Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 2.0112 (0.0284) LS = 0.0000 (0.0000) RS = 0.0312 (0.0026) Xcp = 62.8125
N = 183 N1 = 59 N2 = 124 R2 = 0.45 RMSE = 0.28 CV-RMSE = 12.2%
p = 0.31 DW = 1.28 (p>0)

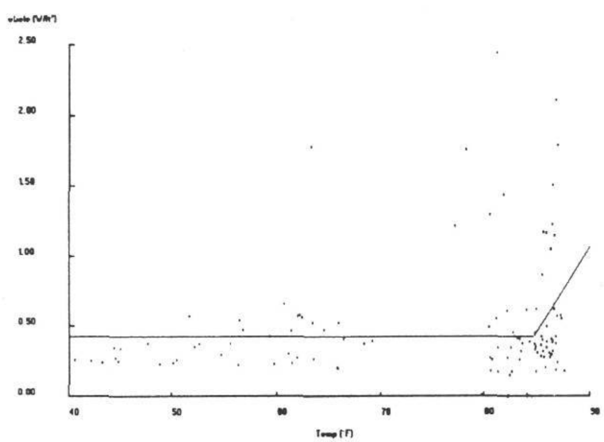
Figure A.8a 3-P Daily Model For School days



Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 0.3805 (0.0551) LS = 0.0000 (0.0000) RS = 0.0056 (0.0023) Xcp = 52.7807
N = 175 N1 = 26 N2 = 149 R2 = 0.03 adjR2 = 0.03 RMSE = 0.39 CV-RMSE = 78.2%
p = 0.50 DW = 0.93 (p>0)

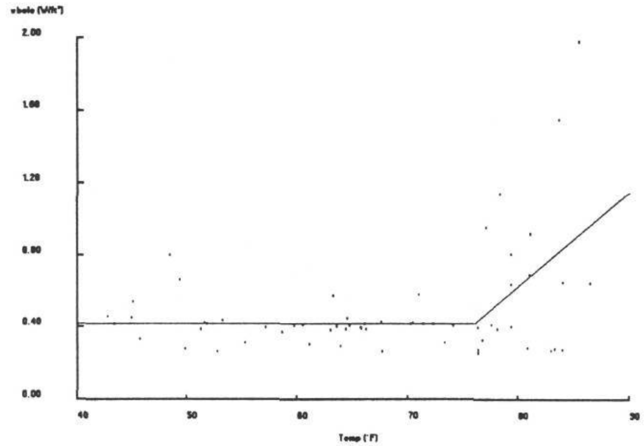
Figure A.8b 3-P Daily Model For Non-School days

Figure A.8 3-P Daily Models For WMS FY94



Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 0.4308 (0.0469) LS = 0.0000 (0.0000) RS = 0.1218 (0.0503) Xcp = 84.7033
N = 115 N1 = 72 N2 = 43 R2 = 0.05 RMSE = 0.43 CV-RMSE = 86.5% p = 0.60
DW = 0.79 (p>0)

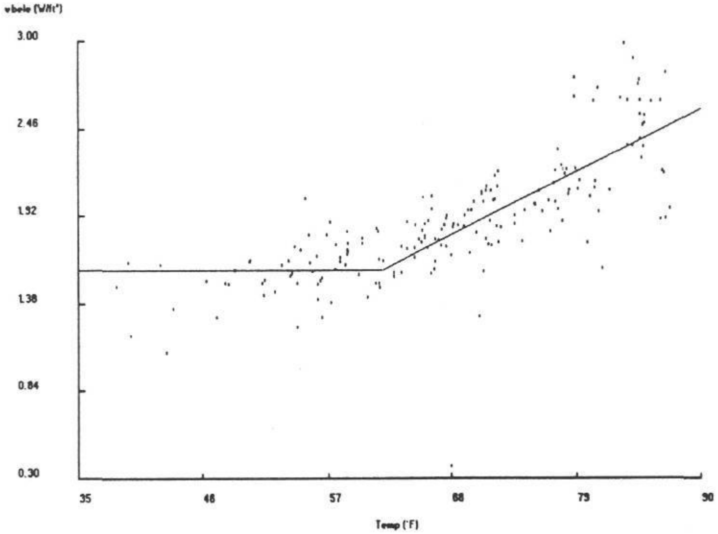
Figure A.8c 3-P Daily Model for Holiday Days Longer than 3 Days



Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 0.4205 (0.0388) LS = 0.0000 (0.0000) RS = 0.0523 (0.0121) Xcp = 76.0284
N = 60 N1 = 39 N2 = 21 R2 = 0.24 RMSE = 0.26 CV-RMSE = 52.7% p = -0.25
DW = 2.21 (i%)

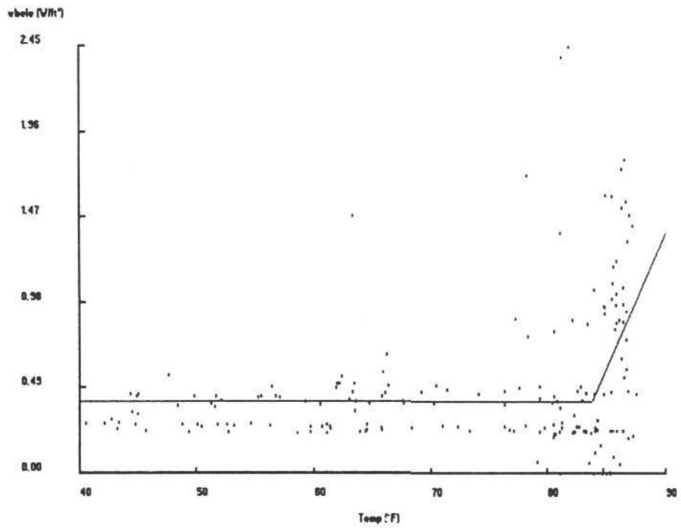
Figure A.8d 3-P Daily Model for the Remaining Weekend and One-Day Holiday

Figure A.8 3-P Daily Models For WMS FY94



Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 1.5900 (0.0249) LS = 0.0000 (0.0000) RS = 0.0354 (0.0021) Xcp = 61.8350
N = 183 N1 = 58 N2 = 125 $R2 = 0.61$ RMSE = 0.24 CV-RMSE = 12.5% p = 0.31
DW = 1.35 (p>0)

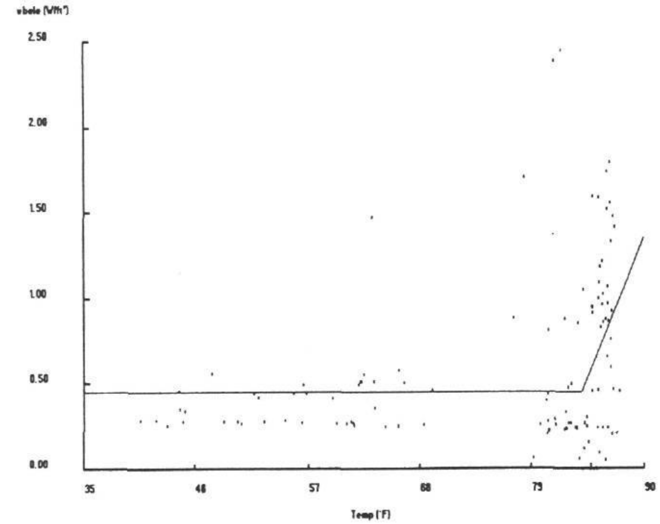
Figure A.9a 3-P Daily Model For School days



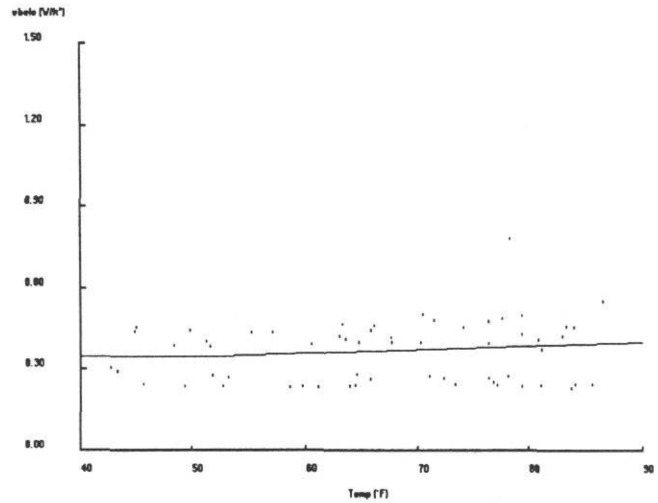
Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 0.4164 (0.0339) LS = 0.0000 (0.0000) RS = 0.1544 (0.0283) Xcp = 83.7644
N = 182 N1 = 126 N2 = 56 R2 = 0.14 RMSE = 0.40 CV-RMSE = 78.1% p = 0.53
DW = 0.94 (p>0)

Figure A.9b 3-P Daily Model For Non-School days

Figure A.9 3-P Daily Models For PES FY94



Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 0.4533 (0.0532) LS = 0.0000 (0.0000) RS = 0.1459 (0.0371) Xcp = 83.7644
N = 122 N1 = 70 N2 = 52 R2 = 0.11 adjR2 = 0.11 RMSE = 0.47 CV-RMSE = 82.3%
p = 0.54 DW = 0.91 (p>0)

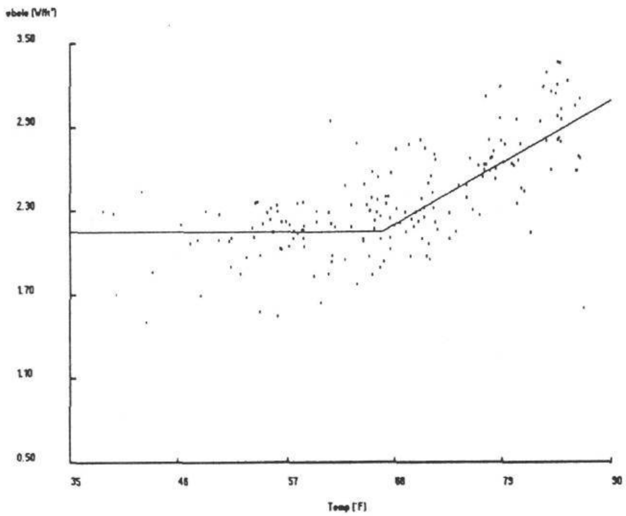


Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 0.3477 (0.0262) LS = 0.0000 (0.0000) RS = 0.0014 (0.0014) Xcp = 52.3548
N = 60 N1 = 11 N2 = 49 R2 = 0.02 adjR2 = 0.00 RMSE = 0.12 CV-RMSE = 32.0%
p = -0.29 DW = 2.54 (i%)

Figure A.9c 3-P Daily Model for Holidays Longer than 3 Days

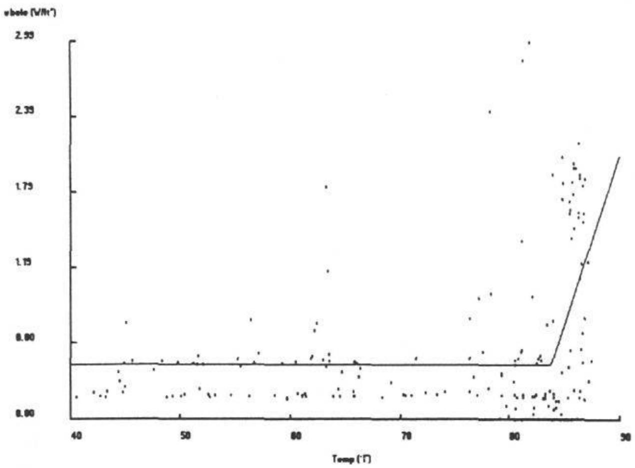
Figure A.9d 3-P Daily Model for the Remaining Weekends and One-Day Holidays

Figure A.9 3-P Daily Models for PES FY94



Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 2.1524 (0.0288) LS = 0.0000 (0.0000) RS = 0.0403 (0.0034) Xcp = 66.7225
N = 183 N1 = 83 N2 = 100 R2 = 0.44 adjR2 = 0.44 RMSE = 0.30 CV-RMSE = 12.9% p = 0.25
DW = 1.38 (p>0)

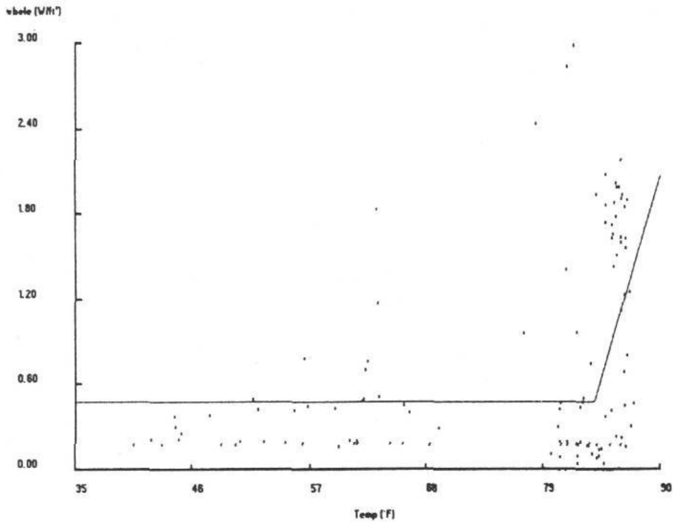
Figure A.10a 3-P Daily Model For School days



Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 0.4277 (0.0484) LS = 0.0000 (0.0000) RS = 0.2665 (0.0404) Xcp = 83.7644
N = 182 N1 = 126 N2 = 56 R2 = 0.19 RMSE = 0.57 CV-RMSE = 96.8% p = 0.54
DW = 0.91 (p>0)

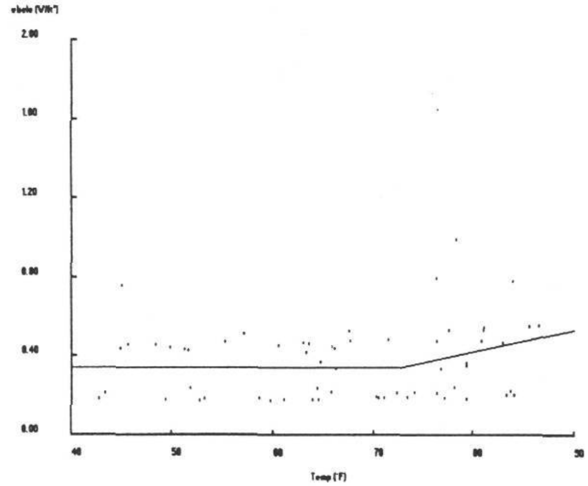
Figure A.10b 3-P Daily Model For Non-School days

Figure A.10 3-P Daily Models For MES FY94



Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 0.4739 (0.0760) LS = 0.0000 (0.0000) RS = 0.2568 (0.0530) Xcp = 83.7644
N = 122 N1 = 70 N2 = 52 R2 = 0.16 adjR2 = 0.16 RMSE = 0.68 CV-RMSE = 98.0%
p = 0.56 DW = 0.86 (p>0)

Figure A.10c 3-P Daily Model for Holidays Longer than 3 Days



Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 0.3424 (0.0279) LS = 0.0000 (0 0000) RS = 0.0108 (0.0056) Xcp = 72.5212
N = 60 N1 = 37 N2 = 23 R2 = 0.06 adjR2 = 0.05 RMSE = 0.18 CV-RMSE = 48.2%
p = -0.27 DW = 2.54 (I%)

Figure A.10d 3-P Daily Model for the Remaining Weekends and One-Day Holidays

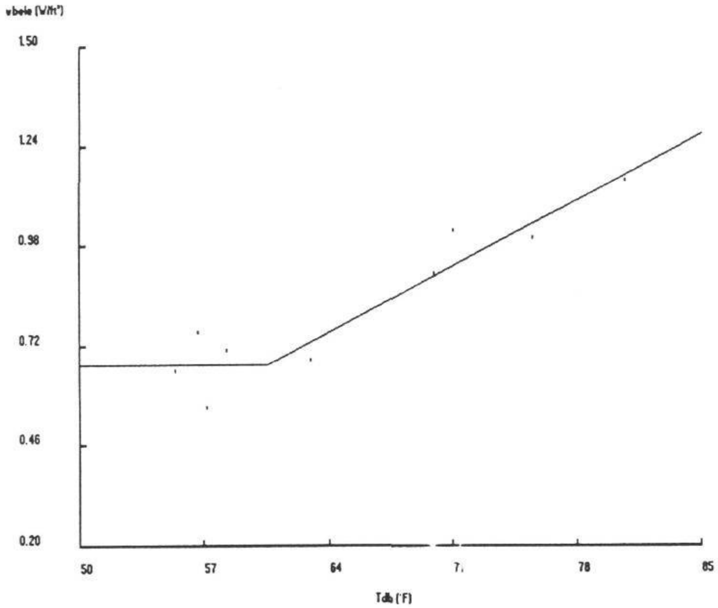
Figure A.10 3-P Daily Models for MES FY94

APPENDIX B

MONTHLY REGRESSION MODELS

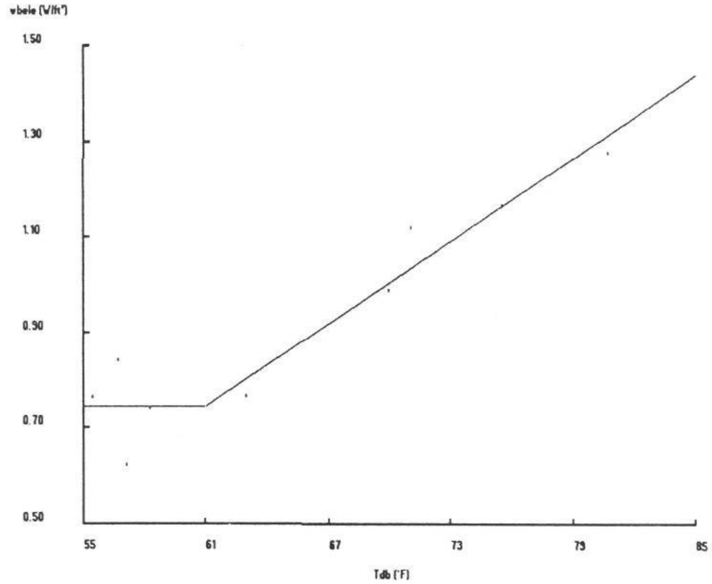
Figures B.1 through B.10 present the scatter plots and the 3-P regression models for the simulated monthly energy consumption as functions of against the outdoor average temperature during operating periods for the 10 elementary and secondary schools.

The information below each plot presents the statistical parameters for the regression model. X_{cp} is the change point temperature and Y_{cp} is the energy consumption at the change point temperature X_{cp}. LS is the slope below X_{cp} and RS is the slope above X_{cp}. N is the number of total data points. R^2 is the coefficient of correlation, RMSE is the root mean square error, p is the autocorrelation coefficient, and DW is the Durbin Watson statistic of the regression model.



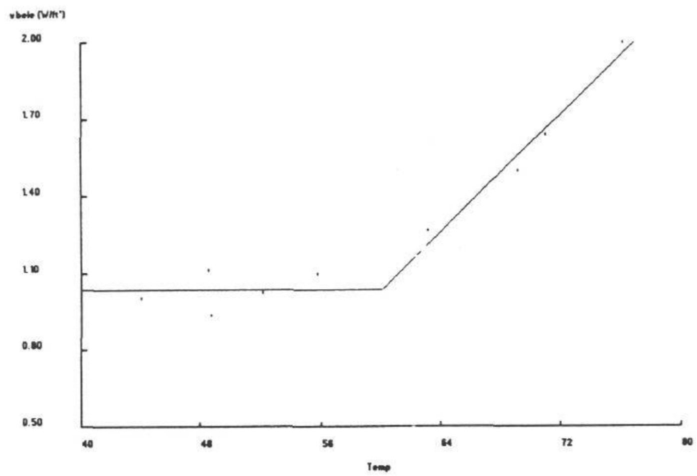
Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Tdb (°F)
Ycp = 0.6698 (0.0312) LS = 0.0000 (0.0000) RS = 0.0247 (0.0032) Xcp = 60.5040
N = 9 N1 = 4 N2 = 5 R2 = 0.89 RMSE = 0.07 CV-RMSE = 8.4% p = -0.21
DW = 2.35 (I%)

Figure B.1 3-P Monthly Model for School Months for SHS FY94



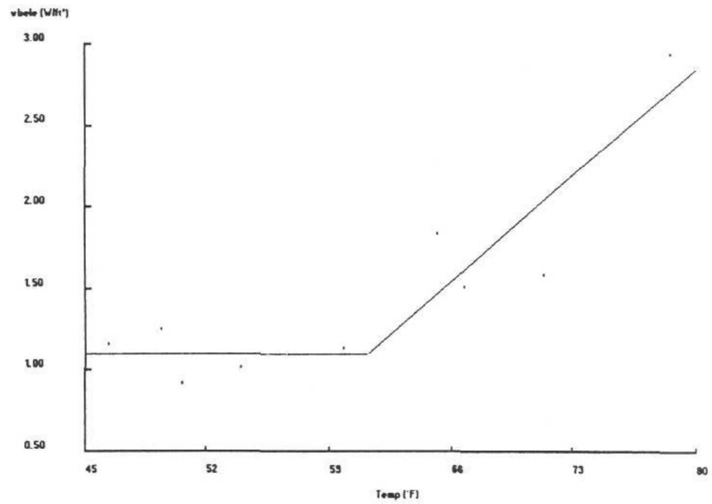
Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Tdb (°F)
Ycp = 0.7442 (0.0308) LS = 0.0000 (0.0000) RS = 0.0289 (0.0033) Xcp = 61.0081
N = 9 N1 = 4 N2 = 5 R2 = 0.92 RMSE = 0.07 CV-RMSE = 7.6% p = -0.18
DW = 2.33 (I%)

Figure B.2 3-P Monthly Model for School Months for VHS FY94



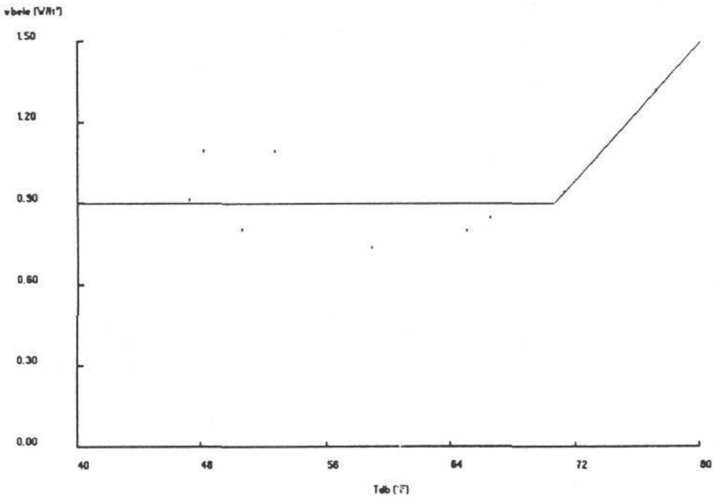
Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp
Ycp = 1.0395 (0.0273) LS = 0.0000 (0.0000) RS = 0.0575 (0.0038) Xcp = 60.0825
N = 9 N1 = 5 N2 = 4 R2 = 0.97 RMSE = 0.07 CV-RMSE = 5.1% p = 0.23
DW = 1.47 (i%)

Figure B.3 3-P Monthly Model for School Months for SES FY94

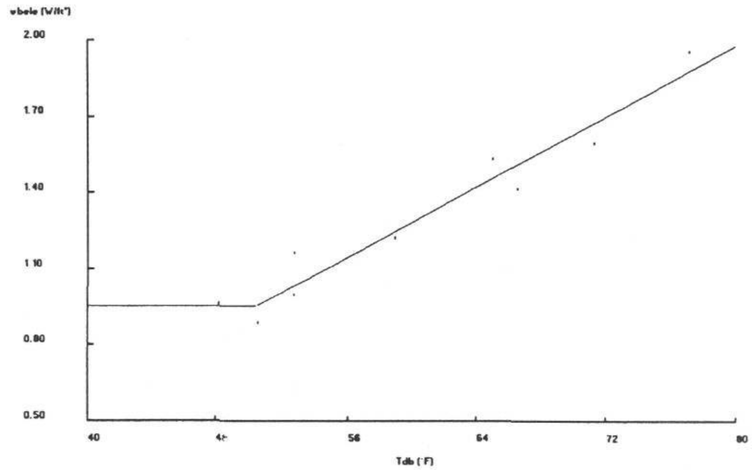


Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 1.1025 (0.1067) LS = 0.0000 (0.0000) RS = 0.0931 (0.0150) Xcp = 61.1741
N = 9 N1 = 5 N2 = 4 R2 = 0.85 RMSE = 0.26 CV-RMSE = 17.5% p = 0.43
DW = 0.97 (i%)

Figure B.4 3-P Monthly Model for School Months for DMS FY94



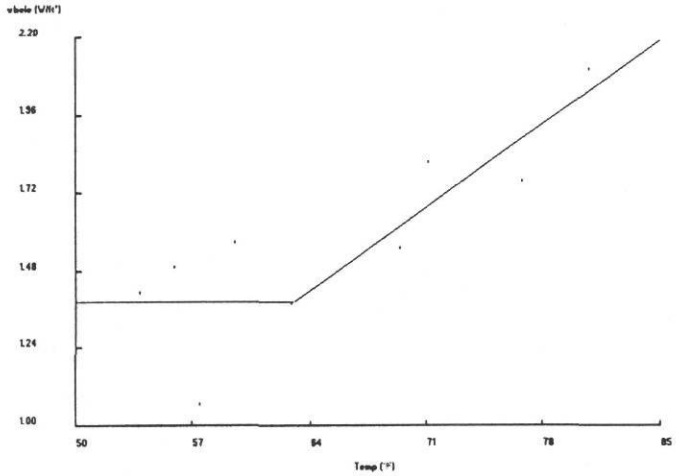
Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Tdb (°F)
Ycp = 0.9539 (0.0420) LS = 0.0000 (0.0000) RS = 0.0348 (0.0031) Xcp = 50.5046
N = 9 N1 = 1 N2 = 8 R2 = 0.95 RMSE = 0.09 CV-RMSE = 6.5% p = 0.29
DW = 1.26 (I%)



Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Tdb (°F)
Ycp = 0.9007 (0.0475) LS = 0.0000 (0.0000) RS = 0.0635 (0.0215) Xcp = 70.5871
N = 9 N1 = 7 N2 = 2 R2 = 0.55 RMSE = 0.13 CV-RMSE = 13.9% p = -0.06
DW = 2.12 (I%)

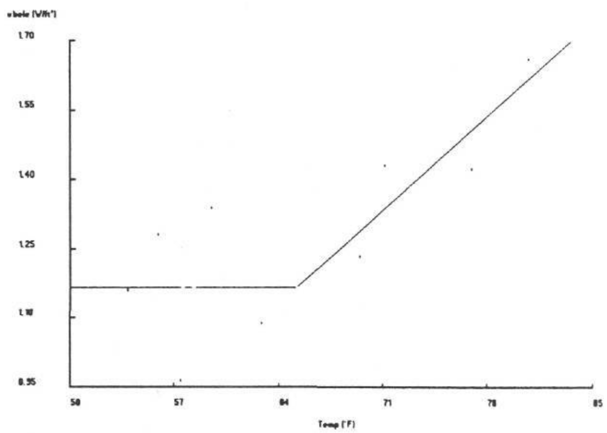
Figure B.5 3-P Monthly Model for School Months for CMS FY94

Figure B.6 3-P Monthly Model for School Months for NHS FY94



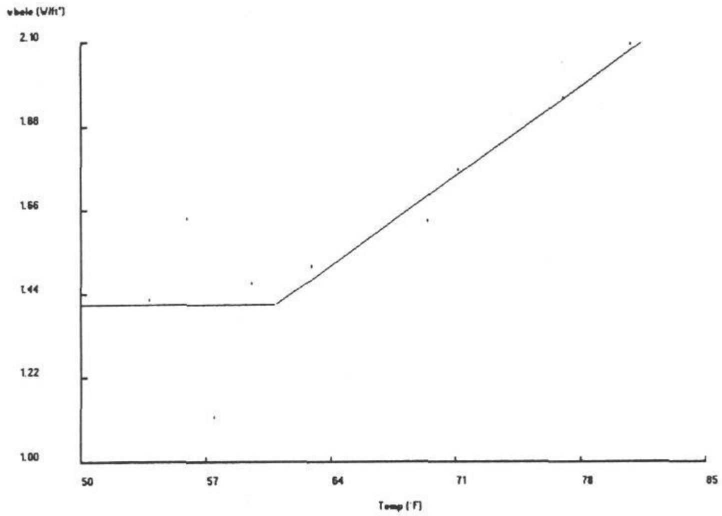
Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 1.3850 (0.0705) LS = 0.0000 (0.0000) RS = 0.0367 (0.0085) Xcp = 63.0106
N = 9 N1 = 5 N2 = 4 R2 = 0.73 RMSE = 0.17 CV-RMSE = 10.5% p = -0.13
DW = 2.12 (I%)

Figure B.7 3-P Monthly Model for School Months for WMS FY94



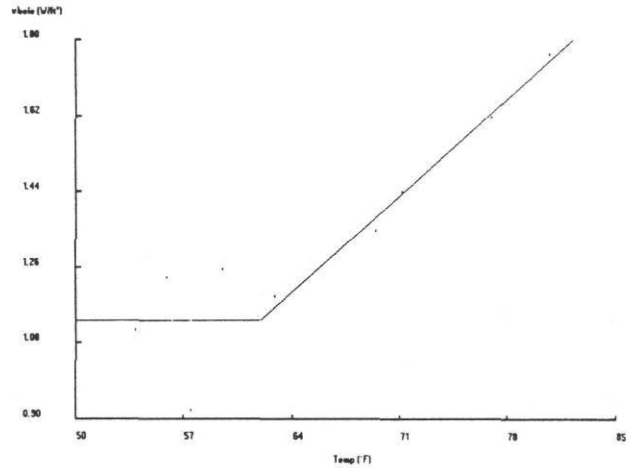
Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 1.1664 (0.0524) LS = 0.0000 (0.0000) RS = 0.0290 (0.0075) Xcp = 65.1637
N = 9 N1 = 5 N2 = 4 R2 = 0.68 RMSE = 0.13 CV-RMSE = 9.8% p = -0.14
DW = 2.18 (i%)

Figure B.8 3-P Monthly Model for School Months for OES FY94



Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 1.4132 (0.0639) LS = 0.0000 (0.0000) RS = 0.0336 (0.0066) Xcp = 60.8598
N = 9 N1 = 4 N2 = 5 R2 = 0.79 RMSE = 0.14 CV-RMSE = 8.9% p = -0.08
DW = 2.15 (i%)

Figure B.9 3-P Monthly Model for School Months for MES FY94



Model: Un-grouped 3P-CP (C). wbele (W/ft²) vs. Temp (°F)
Ycp = 1.1329 (0.0441) LS = 0.0000 (0.0000) RS = 0.0328 (0.0049) Xcp = 61.9352
N = 9 N1 = 4 N2 = 5 R2 = 0.86 RMSE = 0.10 CV-RMSE = 7.7% p = -0.28
DW = 2.56 (i%)

Figure B.10 3-P Monthly Model for School Months for PES FY94

VITA

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