PREDICTING ENERGY USAGE IN A SUPERMARKET

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ABSTRACT

Very little is known about the energy using systems in commercial and retail stores, which consume 24.8% of the energy used by all commercial buildings [1]. This paper describes development of a change-point regression model for predicting the hourly and daily electrical use of a supermarket. Operational improvements already identified with the model can save the store over 4% of their electricity cost annually. Further analysis is expected to save the store additional energy costs.

INTRODUCTION

By the early 1980's there were approximately 3,948,000 commercial buildings in the United States. Of these, 1,071,000 (27.1 %) were in the mercantile/services category [2]. The 12.4 billion ft^2 in the mercantile/services group used 1.28 Quadrillion Btu's of fuel, of which 0.65 Quadrillion Btu's represented electricity [3]. Energy use intensity in these commercial buildings continues to grow despite industry efforts to improve efficiency in both new and existing buildings [4,5]. One reason for such an increase in energy use may be due to the fact that "energy efficient technologies, such as clock thermostats and high-efficiency lights, are not used by business managers because of a lack of awareness and a perceived difficulty of control" [6].

Recently, affordable monitoring technologies have improved to the point where data analysts can now apply techniques previously available only to large-scale projects. However, the job of understanding energy use in commercial buildings still remains a daunting task given the "diversity of potential improvements, the diversity of these (commercial) buildings, and the high rate of change in use " [7].

According to MacDonald, et al., there are five main categories of data analysis which can be used to analyze a buildings metered energy data: (1) annual total energy and energy intensity comparison, (2) linear regression and component models, (3) multiple linear regression models, (4) building simulation programs, and (5) dynamic thermal performance models. One method which is rapidly gaining acceptance is regression modeling. This paper presents a variation of the multiple regression modeling, namely, a change-point multiple linear regression model having slopes over both the heating and the cooling regimes.

Results of the application of regression modeling to empirically determine building energy parameters from energy consumption data have been widely consumption data have been widely reported. Two studies of interest include: (1) an energy predicting model using physical variables to account for conduction, solar radiation, lighting and other internal loads [8] and (2) a regression model, with temperature and customer count as variables, to predict the end-use energy usage in restaurants [9].

There has also been specific work accomplished studying the energy usage in supermarkets. One study predicted the energy savings from retrofits in a gas heated grocery store. One retrofit dealt with lights and included switching the exterior mercury vapor fixtures with high pressure sodium fixtures and rewiring the overhead interior lights so that they could be used with an automated control system. A second retrofit involved installing freezer case doors on the upright freezer cases and hanging strip curtains in the walk-in coolers. These measures were estimated to reduce the grocery store's electricity cost by 16% annually [10]. Another study looked at the relationship between the open-display refrigerators and the air conditioning in supermarkets [11].

One approach which has become popular among analysts is to compare actual energy data with the energy use predicted by a model of the building. Models can be constructed using first principles (i.e., DOE2, BLAST, etc.), by using parameters derived from a statistical analysis or a combination of the two. One previous study which motivated the work discussed in this paper reduced energy consumption in a building by comparing actual energy use to energy use predicted by a multiple linear regression model (sensitive to environmental, operational and system parameters) [12]. This paper extends this concept by developing daily and hourly predictors for a grocery store and applying those to actual data to find operation and maintenance problems. The predictors utilize a change-point multiple regression model with different slopes for the heating and the cooling regimes. In order to compare the predicted energy usage with the actual usage it was necessary to look at several methods of data presentation to determine which ones worked best. Although the primary objective of this study was not intended to be a study of the effect of graphical and tabular feedback on the energy usage, it became an important aspect of the study in order to better evaluate the understanding of the energy usage.

WHAT'S AHEAD

In the sections that follow, we describe the case study grocery store, explain how consumption data were gathered, discuss how the stores' equipment and operation data were obtained and how the data were analyzed to construct the predictive models. Results are then presented showing how the predictive models were used to identify operational problems.

CASE STUDY

The case study grocery store is located 100 miles North-Northwest of Houston, Texas. The climate is hot and humid; the 1% mean dry bulb temperature is 98 F and the coincident mean wet bulb temperature is 76 F. The location has 1786 heating degree days and 2806 cooling degree days annually.

The grocery store is located in a small shopping mall which houses eight businesses. Customer parking is available in the front of the mall and deliveries are generally made at the rear. The grocery store shares party walls with other businesses on the northwest and southeast sides. However, the adjacent northwestern space is currently unconditioned. The northeast and southwest walls are 160 feet in length and are constructed of 6 inch poured concrete, 3.5 inches of interior batt insulation and interior drywall. The northeast and southwest walls are 250 feet long and the east wall has a 60 ft by 16 ft foot section of glass. The entrance to the store is an L-shaped vestibule with automatic doors. The roof is constructed of a lightweight metal deck which supports a 1-1/2 inch layer of Styrofoam insulation, a 2 inch concrete slab and a built up roof covered with light colored aggregate.

The building is a single story structure which has 16 foot high ceilings and a total area of 40,000 ft^2 (160 ft x 250 ft). The front 35,000 ft^2 of space is used for display, and the rear 5,000 ft^2 holds the space conditioning equipment, the walk-in coolers and the meat and product preparation areas. The store contains a 500 ft^2 office space above the pharmacy and delicatessen and a 150 ft^2 compressor room located above the restrooms.

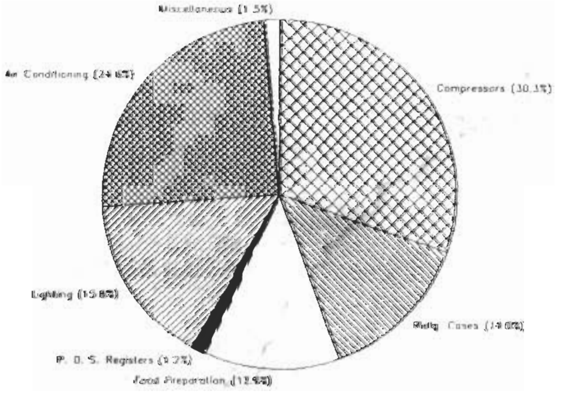

Figure 1. This figure shows the estimated breakdown of the electrical energy using systems in the store. This breakdown is for the peak demand of the store, which occurs during the refrigeration defrost cycles.

Figure 1 shows the estimated contribution of each category during peak operation. The estimated end-use breakdown of the several electrical systems in the store is: refrigeration cases and compressors (44.3%), air conditioning (24.6%), lighting (15.8%), food preparation (12.6%), point-of-sale registers (1.2%), and miscellaneous end uses (1.5%). Clearly, the best candidates for energy savings are the systems which use the most energy in the store. Of the total energy use, 84.7% can be attributed to three system: refrigeration, air conditioning and lighting.

An overview of the electrical energy using systems in the store is presented in Table 1. The energy using systems in the store were located by several walk-through audits, interviews with store managers and maintenance personal and examining the equipment specifications.

The category using the most electricity is the refrigeration system which is comprised of twenty R12 compressors in conjunction with forty-six refrigeration and freezer cases. This refrigeration system preserves fruits and vegetables, dairy products, frozen food and other perishable items. A good feature of this store is that the refrigeration system waste heat is reclaimed to heat the store when the first two stages of heating are needed. The defrost cycle on the cases is controlled by 20 time clocks — one for each compressor. Interestingly, our investigation revealed that many of the time clocks were not calibrated to the proper time, but were off by a couple of hours in either direction. Another large energy using system is the HVAC system which consists of two 50 ton units for cooling, which have an EER of 8.47. Heating is provided through heat reclaim from the refrigeration system supplemented by natural gas duct heaters. The next largest energy using system in the store are the lights. All of the interior lights are on during the day; however, some of the overhead and display case lights are shut off manually at night by the store managers (this practice did not begin until January 1989). The exterior parking lot lights are controlled by photo sensors — turning on at dusk and off at dawn. Other electrical equipment in the store include food processing equipment for preparing and packaging items, a point-of-sales system and other miscellaneous pieces of equipment.

Although this study was primarily concerned with the electrical systems in the store, the natural gas systems were also examined. Table 2 lists the natural gas end uses in the facility. There are three pieces of equipment which can use natural gas in the store: a 40 gallon water heater used for domestic water, 2 – 125 MBtu natural gas duct heaters to provide booster heat when the reclaim heat does not provide enough, and a natural gas oven used to bake items in the delicatessen.

In order to perform the analysis three different types of data were required: (1) energy consumption data, (2) operational and maintenance data and (3) weather data. We were fortunate to have access to 15-minute demand data for the store since the local utility

Table 1 – Electrical Equipment Summary

Refrigeration Equipment:

1. 20 – R12 Compressors are used to cool the refrigeration/freezer cases and coolers in the facility and have a total connected load of 157.9 kW during normal operation and a load of 176.53 kW (measured) during defrost cycles. Time clocks control the compressor defrost cycles. The defrost cycle lasts up to 1 hour or until the cooling coils reach 70 F.

2. 46 – Refrigeration/Freezer cases display the food. The cases have a total connected load of 27.1 kW during normal operation and a load of 81.5 kW (nameplate) during defrost periods. The defrost cycle times are controlled by time clocks attached to the compressors.

HVAC Equipment:

1. 2 – 50 ton HVAC units, which have an EER rating of 8.47, are located in the rear of the store to cool the facility. Each unit contains 2 – 25 hp compressors and a 15 hp fan which circulates the air at 21,000 cfm. The maximum load of both air conditioning units is 143.3 kW during second stage cooling. On one of the units, up to 2,000 cfm of outside air is brought into the store through a variable damper. Each AC unit has its own controller which controls the heating or cooling stage based on indoor temperature and humidity sensors.

2. Heat reclaim from the refrigeration system is used to provide heating during the first two stages of heating. A third stage of heating is provided by natural gas duct heaters which have a capacity of 125 MBtu per hour (nameplate). However, the third stage of heating has been rarely used.

Lighting:

1. There are approximately 300 – 80 watt overhead fluorescent fixtures for lighting the main sales area and 150 – 40 watt fluorescent case lights, which are used to display food items in the refrigeration cases. The total connected load of all the lights is 79.9 kW (nameplate). Some of the overhead and case lights are shut off at night by the night manager at the store, this is accomplished by switching the power off at the electrical panels located in the rear of the store. The facility has time clocks to control the lighting but does not currently utilize them.

2. The exterior lights, used to illuminate the parking lot lights nearest the store, consist of 10 1200 W mercury vapor lamps which have a total connected load of 14.6 kW (nameplate). These are controlled by light sensors which turn them on at dusk and shut them off at dawn. Time clocks also exist which can control these lamps. Additional lighting for the parking lot is provided by the shopping mall owners.

Other:

1. There are 20 pieces of food processing equipment used for grilling, frying, slicing meat, packaging meat, preheating baked goods, making ice and other uses. These items have a total connected load of 73.7 kW (nameplate) and are used as needed.

2. The store has 10 point-of-sale registers which are serviced by a main computer that stores the sales data for collection by the store headquarters. The P. O. S. has a total connected load of 7.1 kW (nameplate). During peak periods of the day, all of the registers are operated, but as few as one are operated during the slowest periods in the night.

3. There are other miscellaneous pieces of equipment in the store, the largest of which is the trash bailer used to compress and bail the cardboard cartons that products are shipped in. The total connected load of the trash bailer is 8.8 kW (nameplate).

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has a recording demand meter at the store under study in addition to several other businesses. The meter is capable of storing up to six weeks of consumption data and is polled approximately once per week by the utility's computer. Since this whole-building consumption data was readily available, it was chosen as the predicted, or dependent, variable. The weather data was obtained from the State Climatology Office at Texas A&M University, as measured at a local airport, located three miles from the store, on an hourly basis and recorded on log sheets. The raw data recorded includes dry bulb temperature, dew point temperature, wind speed and direction, atmospheric pressure, total sky cover and opaque sky cover. The solar radiation data was synthesized using total cloud cover data in combination with a method developed by Turner, et al. [13].

FACILITY ENERGY USAGE

Before any statistical analysis was performed on the facility, it was helpful to look at historical energy consumption, which was available from monthly utility billing data. Several interesting features can be seen in Figure 2, which shows the electricity use and electrical demand for the period of April 1988 through July 1989. The first observation one can make about the energy and demand data is that it was fairly flat throughout the year. The percentage of consumption which can be attributed to the base load was 84.4% and the percentage used for cooling the store is 15.6%. Demand varied 128 kW (25%) throughout the year, was at a minimum in February (383 kW), peaked in September (512 kW) and had an monthly average of 445 kW. The consumption had an annual variation of 60,566 kWh (29.4%), was at a minimum during December (217,894 kWh), reached a peak during September (308,461 kWh) and averaged 258,381 kWh per month.

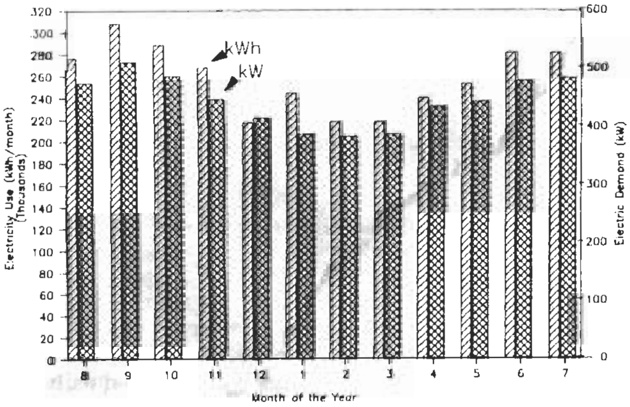

Figure 2. This figure presents the historical energy consumption (kWh) and demand (kW) for the period of August 1988 through July 1989. This data was obtained from monthly utility billing data.

Two possible reasons for the consumption and demand peaking in September were that the students were back in school and the weather was still hot. Their appears to be an unusually high consumption (250,000 kWh) during January 1989; the reason for this has not yet been determined. During this time period, the facility was billed $201,150 for 12 months for an average monthly bill of $16,763. The demand cost was $48,096 (24%) and the consumption cost was the remaining $153,054 (76%) for the 12 month period.

The daily average, hourly electricity consumption was calculated by averaging 24 hours worth of 15-minute demand data (96 data points) for each day, as shown in Figure 3, and displayed against average daily temperature. Several observations can be made about Figure 3. The first noticeable feature is that there are two linear sections of electricity data which meet at 62 F (called the change-point). Above 62 F, the data has a moderate slope and increases with increasing temperature. Below 62 F, the data is basically flat and has a downward trend with decreasing temperature. Therefore, we used a change-point model with varying slopes over these heating and cooling regimes.

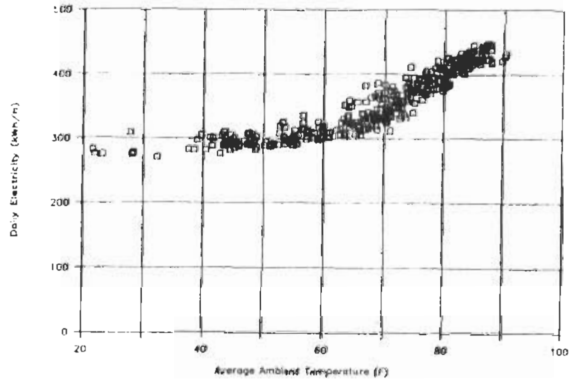

Figure 3. This figure gives the variation of average daily electricity consumption (kWh/h) with average ambient temperature. The most apparent aspect of this figure is that the average daily data consists of two regions which have different slopes and meet at 62 F. This figure is for data gathered from March 1988 through April 1989.

The hourly data was constructed by summing consecutive 15-minute demand readings. Figure 4 shows hourly consumption and the corresponding ambient temperature values for the period of April 1 through April 29, 1989. As can be seen in Figure 4 many days have an hourly electricity variation which exceeds 100 kW. Furthermore, it is noticeable that the electricity trend roughly tracks the ambient temperature. For example, a drop of temperature can be seen on April 8 and the electricity also drops accordingly.

As an next step we evaluated the hourly plots as displayed against hourly temperature. To facilitate the analysis, the data were separated into two bins. The first bin contained daytime data (Figure 5) and the other bin contained nighttime data for the store (Figure 6). At that point, certain operating characteristics became more apparent.

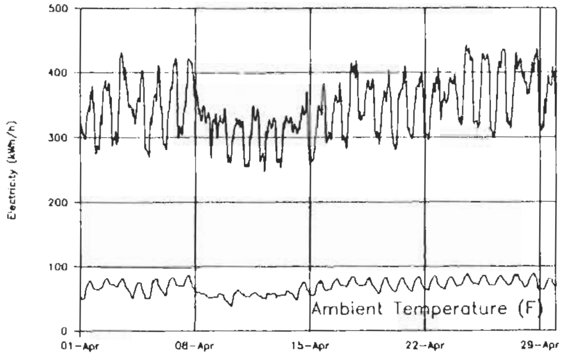

Figure 4. This figure shows the hourly electricity consumption (kWh/h) and the hourly ambient temperature (F) in a time-line from April 1 through April 29, 1989.

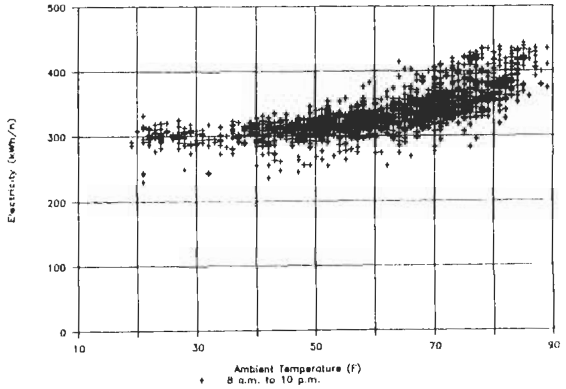

Figure 5. This figure shows the hourly electricity (kWh/h) variation with hourly ambient temperature (F) for the daytime mode of store operation (8 a.m. – 10 p.m.).

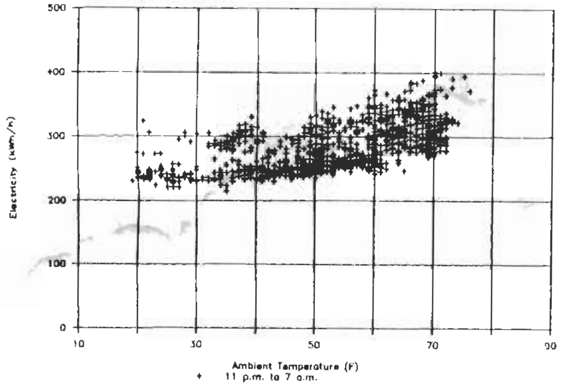

Figure 6. This figure shows the hourly electricity (kWh/h) variation with hourly ambient temperature (F) for the nighttime mode of store operation (11 p.m. – 7 a.m.).

For the daytime data (see Figure 5), we can still see the dependence of demand with temperature and a change-point of 62 F, which appears to be very similar to the observations seen in the daily average, hourly data (see Figure 3). Secondly, the vast majority of the data lies above 300 kW. Further investigation shows that many of the points below this regime are at the transition times of 8 a.m. and 10 p.m. which means that the store does not always follow a rigid schedule.

The nighttime data (see Figure 6) told a different story than the daytime data. When one compares Figure 6 to Figure 5, much of the data set can be seen to shift well below 300 kW, which correlates to when the lights have been turned off according to schedule. Also, many points can be seen which are above 300 kW. These were due to lights being left on at night and was verified through unannounced night walk-through audits. In contrast to Figure 5, the data still shows a similar yet different trend for the temperature dependence below 62 F. However, above 62 F no linear trend can be determined. Unfortunately, due to project constraints, the data above 75 F was not available for analysis.

PREDICTING THE ENERGY USE

Many studies have been performed on predicting the energy usage in commercial buildings using regression models. One study simply looked at the relationship between ambient temperature and average daily demand in two buildings, one of which was a grocery store with electric resistance heating [14]. Unfortunately, this paper did not fully explain the parameters or method used to fit the data. A second study attempted to determine the weather and time-related factors which contribute to the total energy use in a group of manufacturing facilities. They applied a multiple linear regression model on 28 U.S. Army armament, munitions and chemical plants using such variables as gas and electric fuel consumption in MBtu, heating and cooling degree days and the total weight and number of items produced at the plants [15]. Another study reduced energy consumption in a building by comparing actual energy use to energy use predicted by a multiple linear regression model which was sensitive to environmental, operational and system parameters [16].

The models used in this paper, which are different from previous studies, are change-point multiple regression models with varying slopes over the heating and cooling regimes and take several parameters into account including weather, operational variations and other system parameters such as the number of customer's in the store.

The purpose of this paper was to extend daily comparison models to hourly comparison models. However, our early attempts discovered that a 100 kW variation (19.5% of total kW) and other unexplained noise, such as the compressors and refrigeration defrost cycles, existed in the data. In order to reduce this variation and simplify the data manipulation, we followed a three step process. First, the hours were totaled for a day and divided by twenty-four in order to get average hourly values for each day. Secondly, we divided the data into the heating and cooling regimes. Thirdly, the data was regressed against average daily ambient temperature in order to find a unique slope and intercept for each regime. This analysis yielded a five parameter model for estimating the hourly energy use: (1) slope for the heating regime, (2) intercept for the heating regime, (3) slope for the cooling regime, (4) intercept for the cooling regime and (5) a change-point.

After numerous site visits, it was decided that there were two primary modes of store operation: (1) daytime operation, which was denoted by the hours of 8 a.m. to 10 p.m. and (2) nighttime operation, which lasted from 11 p.m. to 7 in the morning. An adjustment was calculated based on the difference observed between the nighttime and daytime modes of operation. This added another possible variable to the model, which gives a six parameter model when added to the other parameters. However, for our analysis we used the following equations for the five parameter model:

$$\text{Heating: Electricity} = \beta_{0,h} + \beta_{1,h}*(\text{Temp}) \quad (\text{Temp} <= 62\text{ F})$$

$$\text{Cooling: Electricity} = \beta_{0,c} + \beta_{1,c}*(\text{Temp}) \quad (\text{Temp} > 62\text{ F})$$

In summary, daily values were regressed against temperature for the heating and cooling regimes. It is also possible to include the daytime/nighttime modes of operation. The results of the daily prediction equations are shown in Table 3.

Region	R^2	β_0	β_1
Heating	0.370	256.878	0.868
Cooling	0.755	1.2449	4.976
Daytime Adjustment		+ 0 kW	
Nighttime Adjustment		– 30 kW	

Table 3. This table gives regression results for the prediction of average daily electricity variation with ambient temperature for both the heating and cooling regimes in the store. The daytime and nighttime adjustments may be added into the hourly model to obtain a more accurate predictor.

The ability of the daily predictor models to estimate the daily electricity consumption can best be seen in a plot which depicts the actual daily energy use, the predicted daily energy use and the residual daily energy use (see Figure 7). Looking at Figure 7, it is apparent that the daily predictor model does a fairly good job of tracking the daily consumption. However, anomalies can be seen on April 4th, 8th and 9th. The average residual variation, minus the three chosen anomalies, is 8.6 kWh per day, which is only 1.7% of the the total. We speculate that on the three days in question, the residual may be an effect of a one to two day thermal lag.

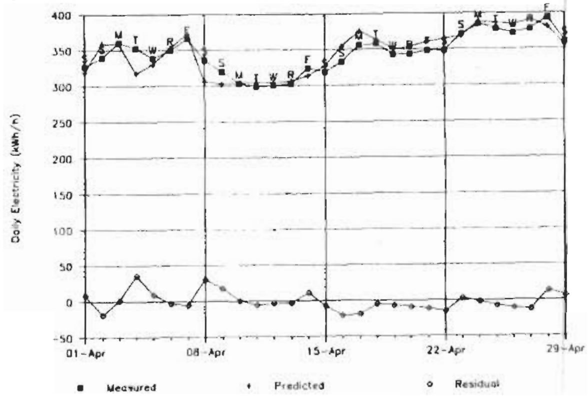

Figure 7. This figure gives a time-line plot of the actual, predicted and residual hourly energy consumption (kWh/h) obtained from a change-point multiple regression model with varying slopes over the heating and cooling regimes. This is for the period of April 1 through April 29, 1989.

The next step in the process was to examine the hourly electricity usage variation with temperature. To reduce the cycling effects inherent in the hourly data, we used the daily predictor model equation with hourly temperature data. Figure 8 is a 3-dimensional plot showing actual electricity variation with hour-of-the-day and day-of-the-year for April 1 through April 29, 1989 — which was the data we attempted to predict on an hourly basis. Upon examining this figure, it is obvious that the store always has equipment running. Another noticeable aspect of the energy consumption is that it never dropped below 250 kW for the month of April 1989. In fact, if one investigates the energy consumption over the entire year, it can be determined that the store demand never dropped below 200 kW, which implies that this was the base load of the building. The hourly energy use was predicted using the five parameter, change-point regression equations originally developed for the daily average model.

The results of the hourly prediction model are shown in Figure 9 as another 3-Dimensional graph. One way to view how effectively the model predicted the actual energy use is to compare Figures 8 and 9. Another way is to let the computer do this and plot it as a positive residual (see Figure 10). As can be seen in Figure 10, most of the residuals are around 0 kW, which means that the model did an excellent job of predicting the energy usage in these sections. However, some areas can seen where the residual energy use is around 50 kW, especially in the hours of 10 p.m. through midnight (hours 20 – 24). In this region a model that is only sensitive to five-parameters cannot account for defrost schedules the hourly energy use in the store. This is due in part to the fact that several of the freezer cases are defrosting during this time period, which lead to an increase in the store's energy usage.

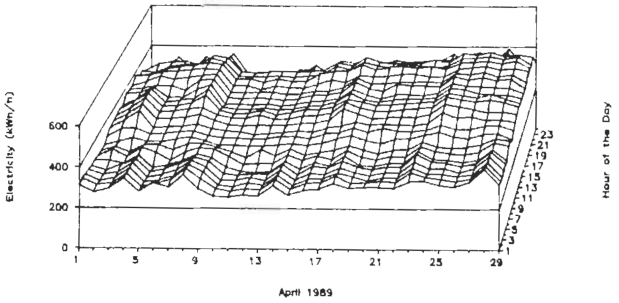

Figure 8. This figure is a 3-dimensional plot of the actual whole-building energy consumption with hour-of-the-day and day-of-the-year for the period of April 1 through April 30, 1989.

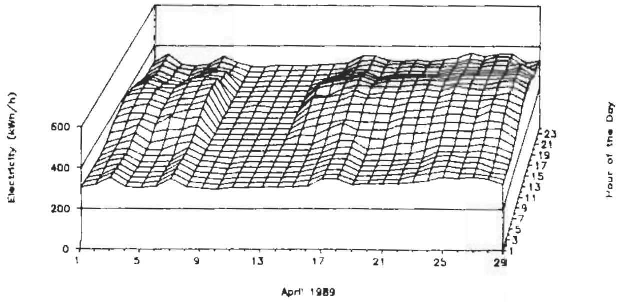

Figure 9. This figure is a 3-dimensional plot of the predicted energy consumption, obtained from the daily change-point multiple regression model, with hour-of-the-day and day-of-the-year for the period of April 1 through April 30, 1989.

DISCUSSION

This study investigated whether or not operational problems could be identified by comparing whole-building hourly electricity consumption in a grocery store to that predicted by a five parameter model. We have found that certain operational problems could be identified. For example, the time clocks that control the defrost cycles on the refrigeration cases are out of synchronization.

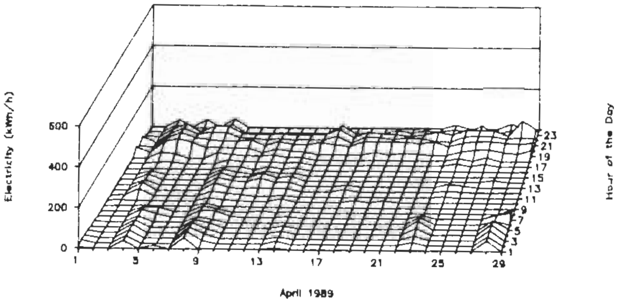

Figure 10. This figure is a 3-dimensional plot of the residual energy consumption (actual consumption minus the predicted consumption) with hour-of-the-day and day-of-the-year for the period of April 1 through April 30, 1989.

This could potentially cause all of the defrost cycles to operate at the same time which would raise the normal store demand by 73 kW. At the latest demand charge, of $9.75/kW, this could potentially cost the store $712 per month. This problem has occurred because the maintenance personal were not aware of the cost of changing the time clock setting and the management were not aware that the clocks had been changed at all. One other problem, which was found during unannounced night walk-through audits of the facility, is that the management did not always shut off selected overhead and case lights during the nighttime period. Correcting this operational problem will lead to additional energy savings for the store.

We are optimistic about this approach since we feel that there is a class of problems which can be identified by analyzing whole-building data. These problems include: (1) a significant portion of lights not being turned off at night, (2) defrost cycles not occurring according to schedule and (3) failures of large pieces of equipment. However, one shortfall of whole-building data analysis is that operational problems in small pieces of equipment cannot be identified. Another drawback inherent in the present system is that the data processing is very labor-intensive.

Several unanswered questions arose during this study. These are excellent starting points for future research and include:

1. Altering the recording demand meter so that it could record additional data (such as sub-metered equipment, store temperature, etc.) along with the electricity data. The meter has four channels available for reading data, but it is currently utilizing only one channel for the consumption data.

2. Examining and correcting the power factor in the store. Lights and compressors are inductive loads and make up 52% of the total store load. There is a large potential for savings in this area.

3. Developing a rule-base system which would automatically log abnormal usage patterns in the store and give the probable causes. In order to complete this system, more diagnostic problems need to be discovered.

4. Sub-cooling the freezers during the night hours by lowering the case temperature and using the frozen food as thermal mass in an effort to prevent the freezer cases form having to defrost during the day.

5. Perform an extensive energy audit analysis on the facility using the data gathered in this study as a starting point.

6. Posted feedback studies to determine how the store managers react to the various graphical and tabular data [17].

SUMMARY

A method for modeling the daily and hourly electricity usage, to identify operational and maintenance problems in a supermarket, has been described. The models predict the daily and hourly values with a high degree of accuracy. Operational problems have already been diagnosed which could save the facility $712 per month, which is 4.2% of the average monthly electricity cost. Further investigation of this store can identify additional operational and maintenance problems.

ACKNOWLEDGMENTS

This work was funded through the Energy Systems Laboratory (ESL) at Texas A&M University. ESL sponsors include The Trane Company, Central Power & Light, Texas Instruments, Texas Utilities Electric Company and Lennox. We would like to thank the store headquarters, managers and maintenance personal for assisting us with this project. We would also like to thank Jeff Haberl for his help with energy consumption analysis and presentation.

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Table 2 – Natural Gas Equipment Summary

Hot Water:

The facility has a 40 gallon hot water heater for domestic water as needed. This unit has an estimated temperature set-point of 140 F and is run continuously.

HVAC Equipment:

Third stage heat is provided by 1 natural gas duct heater per air handling unit. Each of these units are capable of providing 125 MBtu per hour of heat to the store. However, these heaters have rarely been required in the life of the store. These are controlled by temperature sensors in the store.

Delicatessen:

The store uses a natural gas oven to cook their baked goods.