CALIBRATION OF HOURLY ENERGY SIMULATIONS USING HOURLY MONITORED DATA AND MONTHLY UTILITY RECORDS FOR TWO CASE STUDY BUILDINGS

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ABSTRACT

This paper presents a calibration methodology using only two to four weeks of hourly monitored and monthly utility records. The methodology was developed and tested using two case study buildings. The building and HVAC systems data were collected from the building drawings and site visits. "On-off " tests were conducted to accurately determine the power densities of the temperature-independent loads. The 24-hour use profiles were derived from the hourly monitored whole-building electricity use.

The results were analyzed statistically, by calculating the CV(RMSE) and total percent difference; and visually, by comparing the hourly and monthly whole-building electricity use, the 24-hour use profiles, and the daily and monthly peak demands. Results from the two case study buildings showed that when the model was calibrated to the short-term hourly monitored data, it compared favorably to long-term monitored data as recorded in the monthly utility records. This confirms that energy use in existing buildings can be predicted with acceptable accurately without requiring long-term hourly monitored data.

INTRODUCTION

In retrofit projects, the energy simulation model of the building needs to be calibrated to measured data so that retrofit strategies can be targeted to solve the building's energy problems. During the last ten years, several calibration methodologies have been developed. Most of these methods require site measurement and monitoring of the building's energy use. Hsieh (1988) focused on calibrating the use schedules of the lights and equipment, HVAC equipment operation, thermostat settings, infiltration rates, and the building envelope. Bou-Saada (1994) proposed a similar approach with additional steps of using a visualization program to verify the positions of the building envelope and several statistical analysis tools to analyze the comparison between the simulation results and measured data. Subbarao et al. (1988) and Manke et al. (1996) focused on calibrating the building heat loss coefficient, internal mass, and effective solar gain area, while Bronson et al. (1992) focused on calibrating the temperature-independent loads only.

The above methods proposed different calibration periods. Hsieh (1988), Bou-Saada (1994), and Bronson et al. (1992) used a long-term hourly energy monitoring from 6 to 12 months to calibrate the hourly simulation results. However, while conducting long-term hourly monitoring will provide sufficient data for calibration, this approach becomes a burden for small scale retrofit projects with a limited budget (Reynolds et al. 1990). Carroll and Hitchcock (1993) proposed using monthly utility records with the assumption that most building owners can easily obtain their utility records. However, while this approach would be appropriate for retrofit projects with a limited budget, calibrating the monthly values only may hinder the daily or hourly discrepancies. Subbarao et al. (1988) and Manke et al. (1996) calibrated the simulation inputs using data from STEM (Short-Term Energy Monitoring) test in three days. Kaplan et al. (1990) used one month of measured data in three to five periods (cold, hot and temperate).

This paper presents a calibration methodology using only two-to-four weeks of hourly monitored data from any period in the year. After the simulation model was calibrated for that period, monthly utility records were used to calibrate long-term simulation results. The focus of the strategy was to calibrate the temperature-independent components (lighting and receptacle) and whole-building electricity use. The two case study buildings, located in College Station, Texas, were simulated using the ENER-WIN hourly simulation program (Degelman 1990, Soebarto and Degelman 1995).

METHODOLOGY

The calibration procedure included the following tasks: (1) data collection of the building, the HVAC systems and operations, weather, and monthly energy consumption; (2) short-term monitoring and development of the 24-hour use profiles; (3)

disaggregation of measured energy use; (4) analyses of the simulation results using graphical and statistical tools; and (5) changes of the input parameters.

Data Collection

The building physical data included the building orientation, surrounding structures, ground surfaces, building envelope, interior, lighting and receptacle types. The data were collected from the architectural drawings and site survey. The HVAC system equipment and operational data were obtained from the mechanical drawings, site observations and interviews. The lighting and receptacle loads were obtained by conducting "on-off tests". In these tests, all electrical loads were turned on and off in a predetermined patterns while the changes in the electricity use were recorded by a data logger. The monitored data in each on period showed the electricity use of the corresponding load. These tests avoided the possibility of underestimating the lighting and receptacle loads without having to go through the building and count all the fixtures. Details of the data collection procedure as well as the on-off tests can be found in previous publications (Soebarto 1996, Soebarto and Degelman 1996).

The hourly data of the outdoor dry bulb temperature, relative humidity, and wind speed were measured by the local weather station. These data had been compiled by the Energy Systems Laboratory at Texas A&M University. The global solar radiation was locally measured by the Energy Systems Laboratory. A weather data processing program which follows a model developed by Liu and Jordan (1960) was then used to split the global solar radiation into direct and diffuse components (Degelman 1991, Soebarto 1996).

Short-term monitoring and 24-hour use profiles

Hourly short-term monitorings were conducted in a two-to-four week period to collect: (a) electricity use data to develop the 24-hour lighting, receptacle and HVAC fan motor use profiles, (b) electricity use and thermal energy use data to calibrate the simulation results, (c) indoor air temperatures to be used as the simulation input and to confirm the HVAC fan operation schedules.

Monitoring the electricity use

The hourly electricity use for the 2-to-4 week period was also monitored for calibration purposes. The monitoring was conducted in two ways: (1) by using a multi channel data logger with current transducers (CTs) and potential transformers (PTs) that are connected to the electrical panel to measure the Watt-hour/hour, and (2) by using a data logger connected to the Watt-hour meter that sends a series of on/off pulses of the electrical consumption. The second type was simpler and less expensive because no current transducers and potential transformers were required. The data logger received the pulses and converted them into Watt-hours based on the "pulse factor" (e.g. 1 pulse = 0.864 kWh).

Use profiles

At least two daytype profiles were developed, one for workdays and one for weekends. If necessary, a holiday profile was also developed. For the same daytype, the hourly value of the profiles was calculated by taking the average of the recorded data for that hour. To evaluate how well the average profiles represented the measured data, several statistical tools were used including the root-mean-squared-error (RMSE), coefficient of variance of the root-mean-squared-error (CV(RMSE)), and the percentiles presented in box-whisker-plots.

The equations for the RMSE and CV(RMSE) are as follow:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (\hat{y}_i - y_i)^2}{n}} \qquad (1)$$

where $\hat{y}_i$ is the predicted value at hour *i*, y_i is the recorded value at hour *i*, and n is the number of hours in the comparison period, and

$$\text{CV(RMSE)} = \text{RMSE} / \bar{y} \times 100 \qquad (2)$$

where $\bar{y}$ is the average of the recorded values for all hours in the comparison period, or $\bar{y} = \sum_{i=1}^{n} (y_i / n)$.

The specific percentiles of interests were the 10th, 25th, 50th, 75th and 90th percentiles. For every hour the box-whisker was plotted with the 25th percentile value as the lower end of the box and the 75th percentile value as the upper end of the box. By drawing the box-whisker plots, variability and outliers could be detected; thus data from the "irregular day" could be taken out from the data set and would be assigned for developing profiles for different daytypes.

Monitoring the indoor and outdoor temperatures

To confirm the information on the indoor thermostat settings given by the building operators, the hourly indoor temperatures in different spaces were monitored using a data logger connected to a temperature sensor. The monitored data were then used in the simulation model. Observing the patterns of the hourly indoor and outdoor temperature profiles also helps to confirm the operating schedules of the HVAC fan motors.

Disaggregation of measured energy use

The measured total energy use was disaggregated into the temperature-independent and temperature-dependent components. First, the temperature-

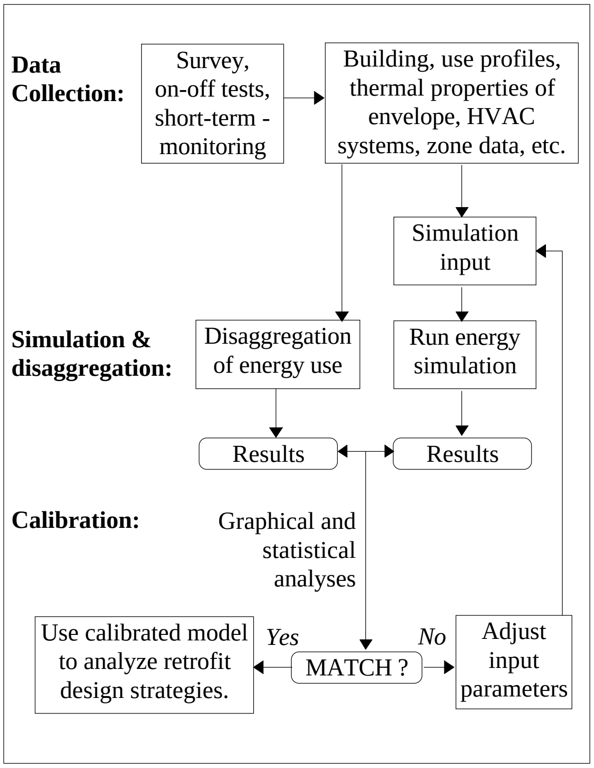

Figure1. Flow chart of the calibration procedure.

independent energy end-uses -- that is the lighting and receptacles -- were calculated using the load density obtained from the on-off tests and the 24-hour use profiles developed from the short-term monitoring. In the two case study buildings, the HVAC fans operated on a regular schedule; thus, the fan energy use could also be calculated. The temperature-dependent energy use could then be calculated by subtracting the energy use for lighting, receptacles and fans from the total energy use. Results from the disaggregation were used to calibrate the simulation.

Analysis of simulation results

The first step was to compare the hourly temperature-independent components and the 24-hour average electricity use profiles for the workdays and weekends during the 2-to-4 week period. The latter was to determine if any discrepancies occurred during certain hours in a day. The next step was to compare the daily electric peak demands.

Graphical presentations were used to analyze these comparisons. The total disaggregated energy use was compared in a bar chart, while the hourly energy end-use and residuals were plotted in a time-series plot. Statistical analyses were also performed by calculating the hourly RMSE, CV(RMSE) for the hourly whole-building electricity use; percent difference for the daily peaks; and percentiles for the 24-hour use profiles. The acceptable limit for the hourly CV(RMSE) was 20% and 15% for the percent difference of the daily peaks.

After the simulation was calibrated to the short-term monitored data, the monthly utility records were used to calibrate the simulation for the long period. Using the same billing periods as shown in the utility records, the simulated monthly energy use (electricity, gas, or other thermal energy) and monthly electric peak demand were compared to the monthly recorded data. The comparisons were presented in bar charts, and the monthly percent differences were also calculated. The allowable maximum percent differences were 10% for each of the monthly temperature-independent energy end-uses, 20% for the temperature-dependent, and 10% for the monthly electric peak demands. Figure 1 shows the flow chart of the calibration procedure.

Changing input parameters

Before simulating the building, two types of input parameters were confirmed. The first one was the "basic data", whose values were definite and could be obtained from the building drawings and site survey, such as the building orientation, areas and dimensions of all envelope surfaces, positions of the windows on the walls, and any shading devices on the walls. Other values that were confirmed from the building drawings and site survey, although through estimation only, included the thermal properties of the building envelope, reflectance of ground surfaces, infiltration rates, and the HVAC system specifications (types, size, efficiency, percentage of outside air). The second type of input parameters to be confirmed was the "measured/ derived data". These were the parameters whose values were obtained from the survey, on-off tests, and short-term monitoring, such as the occupancy levels and schedules, the lighting and receptacle loads and schedules, space temperature settings, and the HVAC fan horsepower and schedules.

The simulation process started with the model containing the basic data and the measured/ derived data. If discrepancies occurred, the first step was to adjust the use profiles and peak values of the temperature-independent loads. The model was simulated again using the new profiles and peak values until the simulated temperature-independent end-uses matched the measured data within the predetermined tolerances. After the temperature-independent components were calibrated, the model was used to simulate the temperature-dependent energy use. Using the known efficiency of the HVAC systems (from the site survey), the simulated space heating and cooling energy were compared to the actual heating and cooling energy. The discrepancy that occurred was assumed to be an indicator of the inefficiency of the actual HVAC systems. In this work, no further steps were taken to calibrate the temperature-dependent energy use.

CASE STUDY BUILDINGS

The procedures above were used to calibrate the simulation models of two case study buildings. The first one was a campus building consisting of offices, laboratories, and classrooms, located in College Station, Texas. The second one was a municipal building, also located in College Station, Texas.

Campus building

The building, built in 1971, has a basement and four stories connected by two elevators and staircases in a large 3-story atrium. Each floor, except the basement, is air-conditioned. The total conditioned area is 251,375 sq.ft. The exterior walls are precast concrete and insulated aluminum panel with gypsum board on the interior surfaces. The windows are single pane tinted glass, shaded on the left and right sides by the fresh air intake shaft. The interior floors are concrete, covered with carpet and tiles. The building uses chilled water for space cooling and hot water for space heating and is mainly served by dual duct variable air volume systems. The building was heavily occupied from 7:00 a.m. to 5:30 p.m. and, to a lesser extent, was occupied for the remaining 24 hours per day. During the weekends and holidays, the building was generally occupied from noon until after midnight. The peak occupancy level was estimated to be 2,000 people.

On-off test results

Since 1991, the Energy Systems Laboratory has been monitoring the whole-building and fan motors electricity use and the thermal energy use for the HVAC systems. The on-off tests were performed in July 1995. The results of the tests, presented in Figure 2, clearly showed the lighting and receptacle loads on each floor. The power density of each electrical load was calculated by dividing the load by the floor area.

Short-term monitoring results

The hourly monitored data of the whole-building electricity use were used to develop the 24-hour profiles for the workdays and weekends. The results showed that the profiles developed from two weeks of monitoring were similar to those from four weeks of monitoring. The box-whisker plots, presented in Figure 3, also show small variability. Thus, in this building where the schedules are similar for the entire month, two weeks of monitoring can provide sufficient data to develop the use profiles.

The RMSE and CV(RMSE) of the workday profile over the 240 hour comparison period were 16.54 kWh and 2.57% respectively. For the weekend profile, the RMSE and CV(RMSE) were 11.72 kWh and 2.08% over 96 hours of comparison period. These show that the average 24-hour use profiles well represented the measured data because the CV(RMSE)s were lower than 10%.

These profiles were also disaggregated into the indoor and outdoor lighting, receptacles and fan motors. Except the fan motor electricity use, which was monitored separately by the data logger, the values for the lighting and receptacles were calculated by using the ratios of the loads obtained from the on-off tests. Figures 4 shows the workday disaggregated use profiles. The use profiles for lighting, receptacles, and fan motors were then developed. The hourly fractions (up to 1.0) in the profiles were calculated by dividing the maximum electricity use in the end-use by the use in each hour.

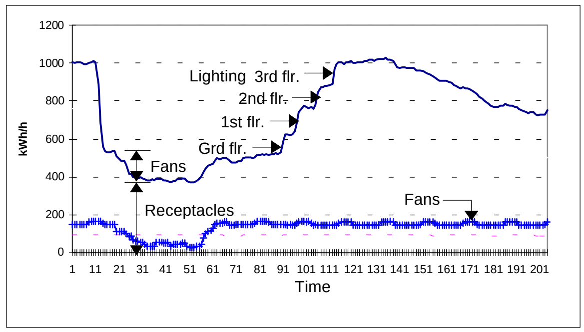

Figure 2. On-off test results in the campus building.

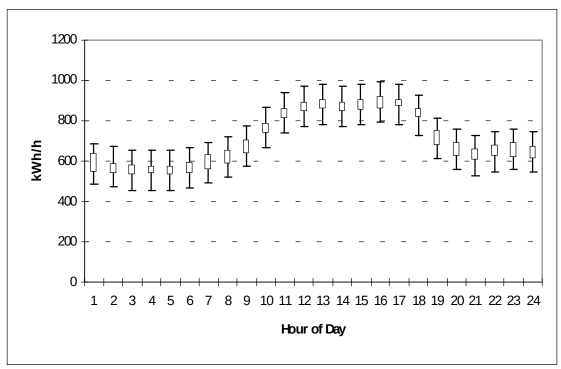

Figure 3. Box-whisker plot of the workday lighting and receptacle profiles.

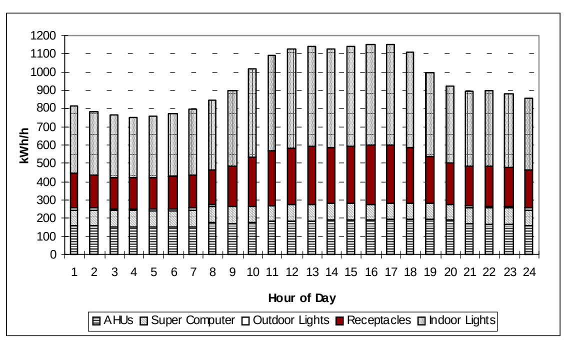

Figure 4. Disaggregation of the 24-hour workday profile in the campus building.

Municipal building

This two-story building consists of mostly offices and one mechanical room. The total floor area is 19,321 sq.ft. The exterior walls are constructed of insulated concrete panel with gypsum board on the interior surfaces. The floor is concrete covered with carpet and tiles. The working hours were from 8:00 a.m. to 5:00 p.m. with a peak occupancy level of 62 people. About 3 people enter the building at 7:00 a.m. and 6 people worked until 7:00 p.m. during working days. On the weekend, up to 3 people worked from 9:00 a.m. to afternoon. This building was served by an air-cooled chiller for space cooling, gas for space and hot water heating, and two air handling units. The air handling units constantly operated from 5:00 a.m. to 9:00 p.m. including on the weekends.

On-off test results

Because of a budget limitation, only the pulses of the hourly whole-building electricity use were monitored. The pulse factor was obtained from the utility company and confirmed by comparing the monitored results (the number of pulses multiplied by the pulse factor) to the meter reading for the same period. Because only the pulses were monitored, the time required to turn the lights on and off was longer than that in the first case study building. This was to allow the data logger to record enough pulses in each step. The on-off tests were conducted during unoccupied period when most of the office equipment was turned off. Therefore, the electricity use for the equipment as well as the chiller obtained from the tests would not be used to calibrate the simulation. The on-off test results are presented in Figure 5 and Table 1.

TABLE 1.
Loads from on-off tests in the municipal building.

Step	Total Pulses	Load (kWh/h)
Lights and HVAC systems off	7 in 20 min	other = 18.14
2nd. flr. lights on	15 in 26 min	other+2nd flr = 29.9 2nd flr. lights = 11.8
1st. flr. lights on	15 in 18 min	other+all lights=43.2 1st flr. lights = 13.3
HVAC systems on	20 in 12 min	all loads = 86.4 HVAC (part) = 43.2

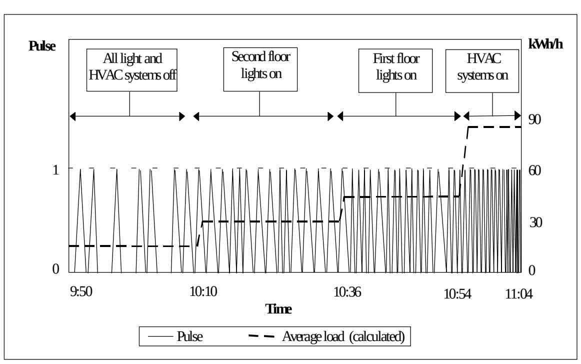

Figure 5. On-off test results in the municipal building.

Short-term monitoring results

The electricity use was monitored in March 1996 when the chiller did not operate continuously. Therefore, to develop the use profiles, all data from the four weeks of monitoring were used. First, the box-whisker plots of the workday and weekend electricity use profiles were developed. Figure 6 shows the workday profile. Next, the CV(RMSE)s were calculated, and they were 9.5% for the workday profile and 15.31% for the weekend profile. These results showed that there was variability in both profiles, which means that the profiles contained the temperature-dependent components. The next step was to plot the hourly electricity use against the outdoor drybulb temperature (Figure 7). This plot shows that the electricity use between 20 to 65 kWh/h was independent from the changes in the temperature. Thus, it was estimated that the peak temperature-independent load was 65 kWh/h and any load beyond that was assigned to space cooling. From the site survey it was learned that the air handling units used 10 kWh/h. The on-off tests showed that the total lighting load was 25.06 kWh/h. Therefore, the peak receptacle load during occupied periods was about 29.94 kWh/h, obtained by subtracting the lighting and fan motor loads from the total temperature-independent load.

During the unoccupied hours, only emergency, night, and outdoor lights were turned on for a total load of 4 kWh/h. The receptacle and other load for this period was 18.14 kWh/h, obtained from the beginning of the on-off tests. From all of these data, plus the data from the site survey, the workday and weekend profiles could be disaggreggated, and the actual values of the use profiles were determined.

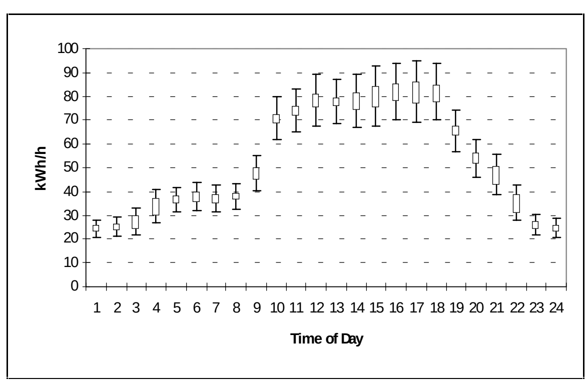

Figure 6. Box-whisker plot of the workday electricity use profile in the municipal building.

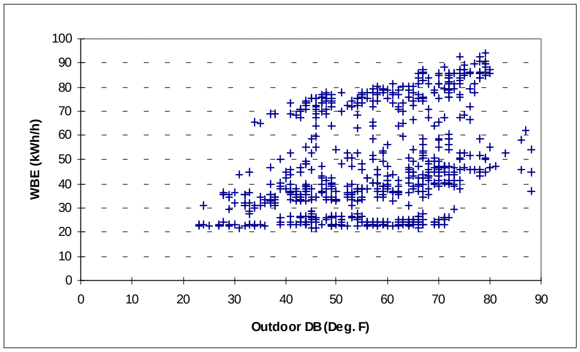

Figure 7. Hourly electricity use in the municipal building vs outdoor temperature.

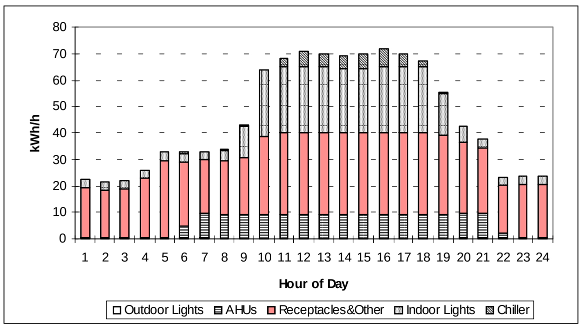

Figure 8. Disaggregation of the 24-hour workday profile on March 8, 1996.

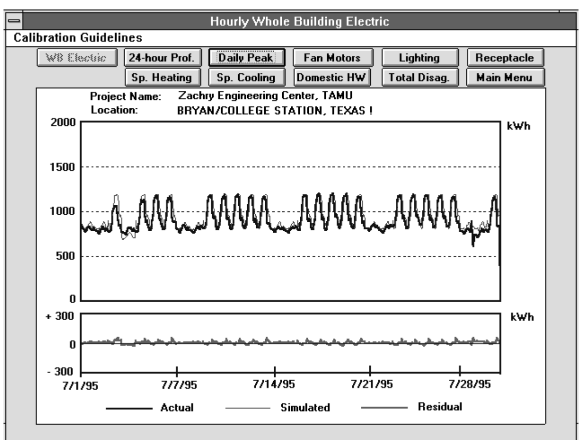

Figure 9. Four weeks calibration of the whole-building electricity use in the campus building.

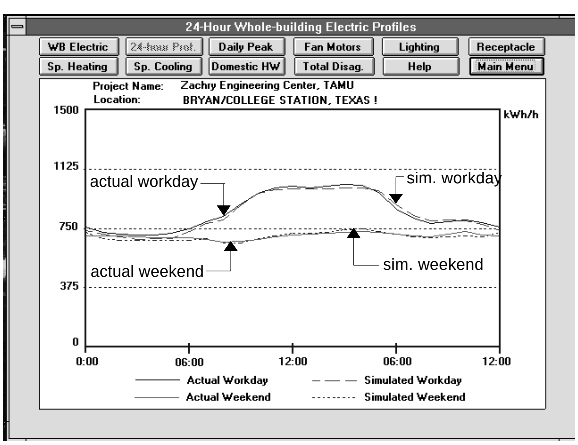

Figure 10. Calibration of the 24-hour average use profiles of the whole-building electricity use

CALIBRATION RESULTS

Results from the campus building

Using all data for the input parameters, the campus building was simulated for the period of July 1 to 28, 1995 when the monitored data were available. Figures 9 and 10 show that the simulated hourly whole building electricity use and the 24-hour electricity use profiles matched the measured data. The end-use electricity use was also calibrated to measured data.

Respectively, the RMSE and CV(RMSE) of the hourly whole-building electricity use were 61.54 kWh and 6.7% over the 672 hour simulation period. Since the electricity was only used for the lighting, receptacles, fans and HVAC auxiliary equipment, it was concluded that the simulated electrical loads were accurate. The next step was to compare the thermal energy use. The result showed that the difference between the simulated and measured total chilled water use was only 1%.

Because the model matched the measured data for a short-term period, the model was used to simulate the building for a twelve month period. Measured data from 1994 were used because the 1995 measured data were not complete. No changes in the input parameters were made except for the equipment load in the main computer room which was increased based on the actual use in 1994. The results showed that monthly electricity use and peak demands matched the monthly data within the acceptable differences (Figure 11). The simulated monthly space cooling energy during summer months also matched the measured data, but it was lower during winter months (Figure 12). Because the internal loads from lights and receptacles were calibrated, it was assured that the discrepancies were not due to the internal loads. The inputs of the building envelope were also re-checked and adjusted, but no obvious impacts were discovered.

To investigate the cause of the discrepancies, the hourly chilled water uses were plotted against the outdoor temperature (Figure 13). The plot shows that the actual HVAC systems still used the chilled water to cool the building even though the outdoor temperatures were already low. Since the simulation program used in this work did not allow the user to simulate dual duct VAV systems that always operate even if not required (the HVAC systems were simulated with 100% efficiency), the simulated results were always lower than the actual use at the low temperatures. Therefore, no further attempts were made to calibrate the thermal energy use, and the discrepancies were assumed to indicate the “inefficiency” of the actual HVAC systems.

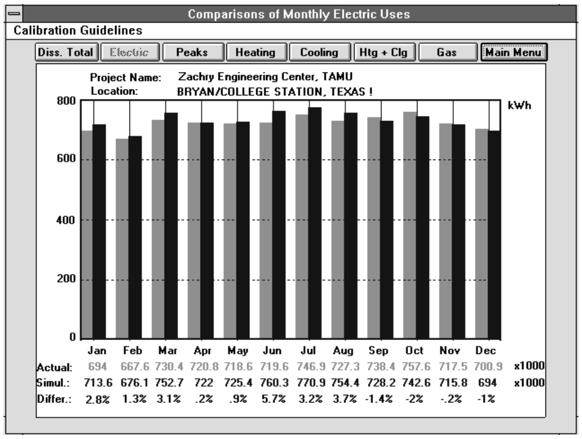

Figure 11. Calibration of monthly electricity use in the campus building in 1994.

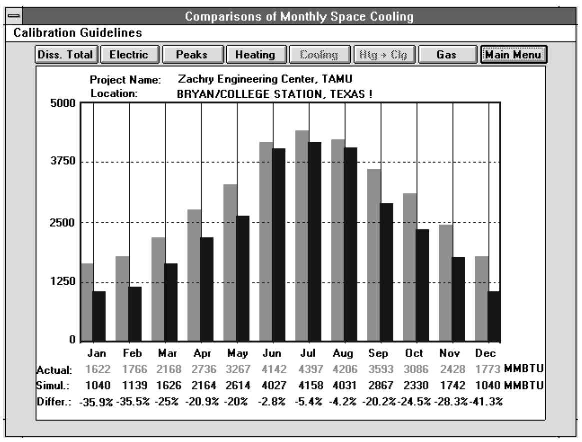

Figure 12. Calibration of monthly chilled water use in the campus building in 1994.

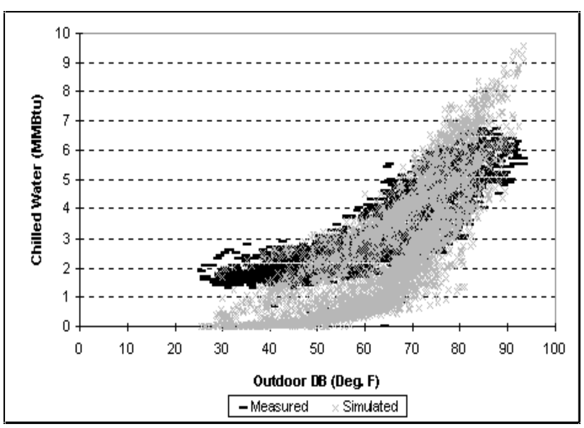

Figure 13. Hourly measured and simulated chilled water use from January to July 1994.

Results from the municipal building

Since the building was monitored during the period of March 4 to 31, 1996, the simulation was conducted for the same period. However, since hourly gas and energy end-use data were unavailable, only hourly electricity use and the 24-hour average profiles were compared. Thus, the simulated lighting, receptacle, and fan motor loads were the same as in the actual building.

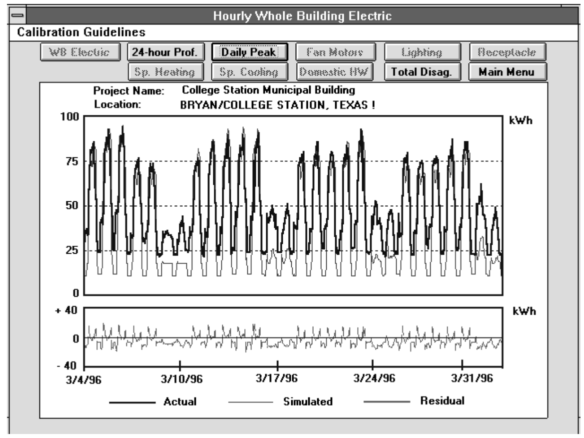

Figure 14. First calibration results of the hourly electricity use in the municipal building.

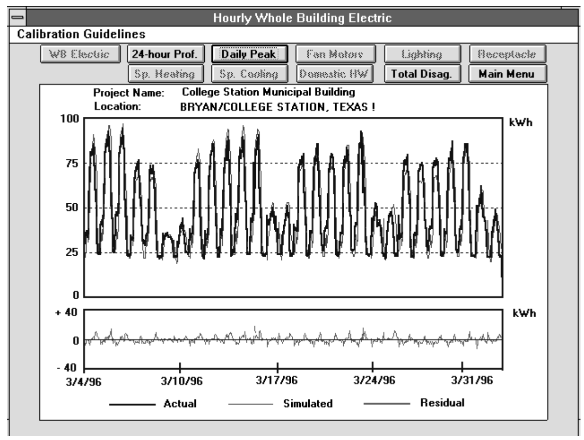

Figure 15. Final calibration results of the hourly electricity use in the municipal building.

The building was first simulated using the data from the interviews and site surveys. The comparisons of the hourly whole-building electricity use are shown in Figure 14. The results showed that there were discrepancies in the use profiles, and these discrepancies caused the hourly CV(RMSE) over 672 hours to be 20.2%. Using the data from the short-term monitoring, the electrical loads and the use profiles were adjusted and the building was simulated again. The new simulation significantly reduced the discrepancies as shown in Figures 15 and 16. The final CV(RMSE) of the hourly electricity use was 16.3%, which was within the acceptable range of error.

The calibrated model was used to simulate the building for a longer period without any changes in the input parameters. Monthly utility records from May 1995 to March 1996 were used and the building was simulated month-by-month based on the billing periods in the utility records. The comparisons of the monthly electricity use, peak demands, and gas use are presented in Figures 17, 18, and 19. These results showed that the monthly simulated results compared favorably with the monthly utility records.

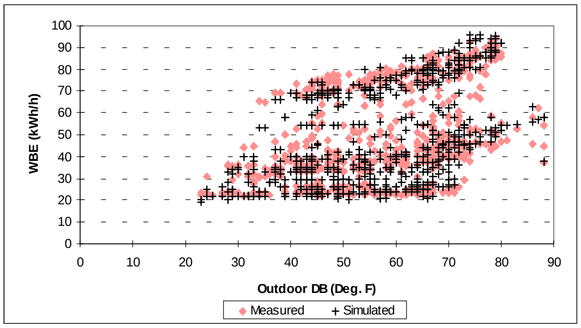

Figure 16. Hourly measured and simulated electricity use vs outdoor temperature.

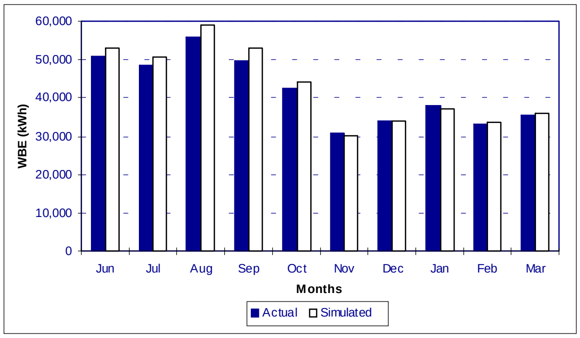

Figure 17. Comparison of monthly whole-building electricity use (May 25, 1995 to March 24, 1996).

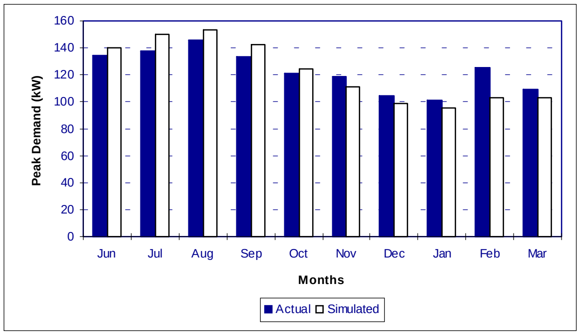

Figure 18. Comparison of monthly peak demands (May 25, 1995 to March 24, 1996).

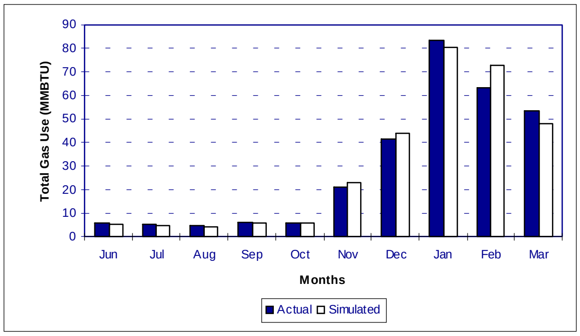

Figure 19. Comparison of monthly gas use (May 22, 1995 to March 19, 1996).

The monthly percent difference was between -2.4% to 6.2% for the electricity use, -17% to 8.7% for the peak demand, and -9.8% to 15% for the gas use. The largest difference of the peak demand occurred in February 1996; however, no adjustment was made because the discrepancy may have been caused by a construction that occurred during that period.

SUMMARY

Results from the two case study buildings showed that when the model of buildings whose use profiles can be derived from monitored data was calibarted to the short-term hourly monitored, it would compare favorably to long-term monitored data. This confirms that energy use in existing buildings can be predicted with acceptable accurately without requiring long-term monitoring. However, this is only possible if the input to the simulation model is derived from prescribed procedures.

Several statistical as well as graphical tools were used to analyze the calibration results. Bar charts, time series, and scatter plots helped visualize when the discrepancies occurred. CV(RMSE) was used to analyze the hourly calibration while percent difference was used for monthly calibration. Results from both case study buildings showed the CV(RMSE) to be between 10 to 20 percent. The CV(RMSE) of the second case study building was higher than the first one mainly because no electrical end-use metering was conducted. However, acceptable results could still be achieved because the temperature-independent electrical loads were well calibrated.

ACKNOWLEDGEMENTS

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REFERENCES

Bou-saada, T. E. “An improved procedure for developing a calibrated hourly simulation model of an electrically heated and cooled commercial building”, M.S. Thesis, Texas A&M University, College Station, TX, 1994.

Bronson, D.J., S.B. Hinchey, J.S. Haberl and D.L. O’Neal, “A procedure for calibrating the DOE-2 simulation program to non-weather-dependent measured loads”, ASHRAE Transaction 98(1):636-652, 1992.

Carroll, W.L. and R. J. Hitchcock, “Tuning simulated building descriptions to match actual utility data: methods and implementation”, ASHRAE Transactions 99(2):928-934, 1993.

Degelman, L. O. "ENERCALC: A weather and building energy simulation model using fast hour-by-hour algorithms", Proc. of the 4th National Conference on Micro-computer Application in Energy, pp. 15-22, Tuscon, AZ, May, 1990.

Degelman, L. O. "A statistically-based hourly weather data generator for driving energy simulation and equipment design software for buildings", Proc. of the 2nd World Congress on Technology for Improving the Energy Use, Comfort, and Economics of Buildings Worldwide, pp. 592-599, International Building Performance Simulation Association, Nice, Sophia-Antipolis, France, Aug., 1991.

Hsieh, E. S. "Calibrated computer models of commercial buildings and their role in building design and operation", PU/CEES Report No. 230, M.S. Thesis, Princeton University, Princeton, NJ, 1988.

Kaplan, M.B., B. Jones and J. Jansen. "DOE-2.1C model calibration with monitored end-use data", Proc. of ACEEE 1990 Summer Study on Energy Efficient Buildings, pp. 10:10.115-10.115, American Council for an Energy-Efficient Economy, Washington, DC, 1990.

Manke, J. M, D. C. Hittle and C. E. Hancock. "Calibrating building energy analysis models using short-term test data", Proc. Of the 1996 International Solar Energy Conference, pp. 369-378, American Society of Mechanical Engineers, San Antonio, TX, 1996.

Liu, B. Y. H. And R. C. Jordan. "The inter-relationship and characteristic distribution of direct, diffuse and total solar radiation", Solar Energy IV(3): 1-19, 1960.

Reynolds, C, P. Komor and M. Fels. "Using monthly billing data to find energy efficiency opportunities in small commercial buildings, Proc. of ACEEE 1990 Summer Study on Energy Efficient Buildings, pp. 10:10.221-10.231, American Council for an Energy-Efficient Economy, Washington, DC, for an Energy-Efficient Economy, Washington, DC, 1990.

Soebarto, V.I. "Development of a calibration methodology for hourly building energy simulation models using disaggregated energy use data from existing buildings", Ph.D. Dissertation, Texas A&M University, College Station, Texas, 1996.

Soebarto, V. I. and L. O. Degelman. "Short-term monitoring for disaggregation of energy use data and calibration of simulation models in retrofit projects", Proc. of the 21st National Passive Solar Conference, pp. 321-326, American Solar Energy Society, Asheville, NC, 1996.

Soebarto, V. I. and L. O. Degelman. "An interactive energy design and simulation tool for building designers", Proc. of Building Simulation '95 Fourth International Conference, pp. 431-436, International Building Performance Simulation Association. Madison, WI, Aug., 1995.

Subbarao, K, J.D. Burch, C.E. Hancock, A. Lekov and J.D. Balcomb, "Short-term energy monitoring (STEM): Application of the PSTAR method to a residence in Fredericksburg, Virginia, SERI/TR-254-3356, Solar Energy Research Institute, Golden, CO, 1988.