# Commercial Building Performance Evaluation System

**Donald J. Frey, P.E., Peter C. Jacobs, P.E.**
*Architectural Energy Corporation*
*2540 Frontier Ave. Suite 201, Boulder, Colorado 80301 USA*

**Karl F. Johnson**
*Electric Power Research Institute*
*P.O. Box 10412, Palo Alto, California 94303 USA*

## ABSTRACT

*Computer simulations play an important role in programs being conducted by electric utility companies in the United States to reduce customers' demand for electricity. These utility program are referred to as demandside management (DSM) programs and are based on the premise* that energy efficiency can be a cost-effective source of new electricity supply. The Electric Power Research Institute (EPRI) and Architectural Energy Corporation (AEC) are developing measurement hardware and computer software to use in planning, implementing, and evaluating DSM programs, targeting healing, ventilating, and air-conditioning (HVAC) equipmenr and lighting equipment in commercial buildings. The hardware and software form a system referred to as the Commercial Building Performance Evaluation System.*

*In the* **planning phase,** *computer simulations are often used to predict the benefits of conventional and energyefficient HVAC and lighting equipment so that an economic analysis of the energy-efficiency measures, including the benefit to the utility, can be performed. In the implementation phase, simulations are used in new construction programs to predict costs and benefits and in some cases as a screening tool to select program participants. In the evaluation phase, simulations are used as a tool to help estimate the performance of energy-efficient measures. In all three of these applications, a major concern is the accuracy of the inputs to the simulations of actual energy use profiles, operating schedules, and control strategies.*

*Two applications of the Commercial Building Performance Evaluation System and its role in deriving accurate information for input to simulations within the context of DSM are discussed in this paper. The first application discussed is a surrogate measurement strategy for establishing lighting and equipment usage profiles. The second is the use of direct measurements to characterize the control strategies used in commercial building HVAC equipment, such as fan schedules, economizer operation, thermostat setpoints, supply air setpoints, and others.*

## INTRODUCTION

Electric utility companies throughout the United States are conducting programs to encourage customers to use electricity more efficiently. These programs are referred to as demand-side management initiatives, or simply DSM programs. They focus on the customer's use of electricity and target inefficiency as the potential source of new electricity supply. Historically, investment in new generating capacity has been the source of additional supply. DSM programs are based on the premise that investment in energy efficiency is a cost-effective source of new electricity supply. Public utility commissions provide the utilities with criteria for determining the cost-effectiveness and prudency of investing in demand-side energy-efficiency versus supply-side generation. The customer, the utility, and the environment all derive benefits under the DSM program scenario.

The utility companies are charged with the responsibilities for planning, implementing, and evaluating their DSM programs. During the planning phase, energy-efficient technologies are identified for various customer segments (residential, commercial, industrial, and agricultural). The potential costs and savings to the customer and utility are calculated and methods for delivering the energy-efficiency programs to customers are developed, including the amount of financial incentive the utility is willing to pay to the customer. During the implementation phase, participants are selected, energy efficiency measures are installed, and incentives are paid. During the evaluation phase, the savings to the customer and to the utility are determined and the process by which the program is delivered is analyzed. The evaluation process provides feedback to program planning to determine what improvements or changes need to be made to the energy efficiency measures offered, the incentives paid, or the process by which the program is presented to customers.

In the planning phase, computer simulations are often used to predict the direct and indirect benefits of conventional and energy-efficient HVAC and lighting equipment. Direct benefits are derived directly from the energy-efficient measure, such as lighting energy savings. Indirect benefits are derived as a byproduct of the technology, such as reduced cooling load created by a reduction in lighting. In the implementation phase, simulations are used in new construction programs to predict costs and benefits and in some cases as a screening tool to select program participants. In the evaluation phase, simulations are used as a tool to help estimate the performance of energy-efficient measures. In all three of these applications, the accuracy of the inputs to the simulations is a major concern.

Short-term monitoring of energy systems in buildings has been identified as a method for obtaining important data in a cost-effective manner. Such data can be used to improve inputs to simulations, for performing HVAC system diagnostics and commissioning, and for performing evaluation of system performance. The Electric Power Research Institute (EPRI) and Architectural Energy Corporation (AEC) are developing a Commercial Building Performance Evaluation System which utilizes short-term monitoring of key energy consuming equipment for the purposes of characterizing equipment operation, evaluating DSM impacts, and for HVAC diagnostics and commissioning. The Commercial Building Performance Evaluation System and two of its DSM applications are described in this paper.

## SYSTEM DESCRIPTION

The Commercial Building Performance Evaluation System is an integrated package of software and hardware. A series of small, microprocessor-based, battery-powered data loggers, referred to as MicroDataLoggers™ or MDLs are the central hardware component. Rather than running wire to connect sensors from many points around a building back to a single data logger, the system uses many MDLs deployed throughout a building with sensors connected to each MDL. The MDLs are time synchronized so that they form a wireless network of distributed data loggers. Each MDL is capable of measuring a number of physical quantities, including temperature, humidity, pressure, on-off status, current, voltage, frequency, and electric power, though only four of these can be measured at one time by a single MDL. An instrumentation plan, prescribing the types of measurements to make at specific locations, is created by the software to meet specific needs of the analysis. The appropriate sensors are then connected to each MDL. The MDLs are then connected to a host PC, given operating instructions, and are time synchronized by the software via a serial port. The MDLs are deployed throughout the building for a short period of time to collect data (generally 2 weeks for most applications), then retrieved and reconnected to the serial port to transfer the collected data to the host PC. Data analysis is automatically performed by the software in the host PC. Patent applications have been filed by Architectural Energy Corporation for this system concept. The system has a number of unique features, as explained below.

Standardization - The procedures used to perform HVAC and lighting diagnostics and commissioning are completely standardized. With proper training, they will be implemented in exactly the same way regardless of who performs them. This standardization eliminates the uncertainties associated with different people having different skill levels performing the procedures. The standardization is accomplished by using computer software to direct all aspects of the procedures, including defining the data requirements, establishing the performance monitoring plan, verifying the set-up of the data acquisition equipment, analyzing the data, and specifying reporting formats for results.

Modular Organization - Though not necessarily apparent to the users, the system is organized in hardware and software modules. The system was structured this way for two reasons. The first is flexibility. The user is able to define the characteristics of the HVAC equipment component by component in the software, allowing many combinations of equipment to be analyzed. The second is expandability. It allows new types of systems and equipment to be easily added to the software and to the manual. The capabilities can be easily extended as the needs to handle other types of systems are identified.

Wireless Hardware - MDLs are dispersed throughout a building to collect the data needed by the system. The MDLs communicate with the software for initial programming and for data transfer via the computer's serial port. For data collection, they are disconnected from the computer and operate on battery power. They each have their own clock and form what we refer to as "a distributed wireless data acquisition network." At the completion of data collection, the loggers are retrieved and reconnected to the computer for transferring their data.

Artificial Intelligence - The collected data can either be analyzed manually, or an option is available to use artificial neural networks to analyze the collected data. Fuzzy logic uses the results of the analysis of the collected short-term data to determine the probability of various problems existing with the system. The artificial intelligence is intended to assist the user in data analysis and fault determination, but does not totally replace the human operator.

## LIGHTING LOAD CHARACTERIZATION

The Commercial Building Performance Evaluation System is designed to provide data required for impact evaluation of lighting and HVAC measures. For impact evaluation of lighting systems, the system uses the MDLs to collect information on lighting usage schedules and occupancy. The data loggers do not measure power directly, but rather observe lighting fixture on and off status. This information, combined with one-time measurements of lighting fixture power, is used to estimate energy consumption and savings resulting from energy-efficient lighting measures.

Lighting fixture status is one of several "surrogate" measurements used to estimate energy consumption and energy savings of various DSM measures in buildings. These surrogate measurements have been selected to reduce costs over traditional electricity metering methods, while preserving reasonable accuracy. Cost savings using surrogate measurements can result from:

*Lower hardware costs:* Low cost, battery-powered data loggers cost between $150 US to $250 US per channel, including sensors. This compares favorably with conventional, multi-channel electricity metering equipment which costs $200 US to $1000 US per channel, including sensors.

*Lower installation costs:* Surrogate measurement techniques rely on easily observed data, such as fixture light output to monitor on/off status. The MDLs can be easily deployed by non-skilled personnel. Traditional electricity metering equipment requires licensed electricians for installation. Removal of traditional metering equipment may require other building trades, such as drywall finishing and painting, to repair damage caused by equipment installation and removal.

*Measure specificity:* Battery-powered data loggers can be deployed to monitor the status of the specific fixtures affected by the DSM program. Electric circuits in buildings provide power to many different types of fixtures and equipment. Frequently, lighting and equipment end-uses are supplied by the same electrical circuit. Monitoring of circuits which include fixtures and equipment not affected by the program adds noise to the measurement.

### Issues Surrounding Surrogate Measurement Techniques

#### *Sampling*

It is clearly not practical to monitor the status of every lighting fixture in a building. It may not be feasible to monitor the status of each lighting control switch in the building. It will be necessary to select a sample of fixtures for status monitoring. A random sample of fixtures can be drawn and MDLs assigned to each of the sampled fixtures. Improvements in accuracy and reduced sample size can be obtained with a stratified sample. Control points in the building can be stratified based on connected load, expected run time, or both. A random sample is drawn from each of the strata, and the results are weighted according to the relative load represented by each strata.

#### *Connected load*

Surrogate measurements require either an estimate of the power consumed by each fixture when in operation or a one-time measurement of this value. Manufacturers' estimates of fixture power are frequently used to estimate this value. However, measurements of actual fixture power have been shown to deviate widely from manufacturers' data (Davis, 1992; Landsberg and Johnson, 1991). Table 1 illustrates this problem. Note that fixtures with magnetic ballasts are more susceptible to this problem than fixtures with electronic ballasts. In most cases, this results in an over-prediction of lighting energy savings. In a study of seven retrofit options (Franconi and Rubenstein, 1992), the use of application-specific data instead of manufacturer's data decreased the estimated savings in all cases studied.

**Table 1**
Manufacturers' Rated Power versus Field Test Results for Various Lighting Fixtures
SOURCE: Davis, 1992

| Fixture Description | Rated Input Power | Measured Input Power | Difference |
|---|---|---|---|
| 4 40W T12 lamps w/ 2 EE magnetic ballasts | 172W | 160W | 12W |
| 4 40W T12 lamps w/ 2 electronic ballasts | 144W | 138W | 6W |
| 4 34W T12 lamps w/2 EE magnetic ballasts | 144W | 138W | 6W |
| 4 32W T8 lamps with 1 electronic ballast | 110W | 105W | 5W |

The variability of the in-situ performance of lighting fixtures can account for a significant discrepancy in the estimated savings, as shown in Table 2.

**Table 2**
Errors in Savings Estimate for Selected Lamp and Ballast Combinations
(SOURCE: Davis, 1992)

| Retrofit Option | Savings Predicted | Savings Measured | Error |
|---|---|---|---|
| 40W T12 to 34W T12, EE magnetic ballast | 28W | 22W | 21% |
| Magnetic to electronic ballast replacement (40W T-12 lamps) | 28W | 22W | 21% |
| 40W T12 w/EE magnetic ballasts to 32W T-8 w/electronic ballast | 62W | 55W | 11% |

### *Temperature effects*

Fixture power varies as a function of lamp wall temperature (Franconi and Rubenstein, 1992). Lamp temperature varies with fixture design (open vs. closed fixture), fixture mounting (recessed vs. suspended fixture), return air path (lamp compartment return vs. ceiling return), and room or ceiling plenum air temperature. Fixture power will also vary as the fixture warms to operating temperature. Manufacturers' data and field measurements are often made at a temperature different from the in-situ fixture temperature. To reduce these problems, one-time measurements of fixture power should be made in-situ.

### *Sensor sensitivity*

Measurements of fixture luminous output as a surrogate for fixture on/off status must be able to discriminate between light levels emanating from an operating fixture and light levels from daylighting, adjacent fixtures, or other background sources. It may be necessary to adjust the sensor sensitivity in the field to account for sensor mounting, fixture luminous output and background illuminance.

### Results

An experiment was performed to compare direct measurements of the power consumed by a single lighting circuit over a short period of time with estimates of power consumption based on surrogate measurements of lighting fixture on time. For one of the surrogate estimates total power was calculated by multiplying fixture on time by the manufacturer's specified power draw per fixture and the number of fixtures. For the other, the estimate was obtained by multiplying on time by a one time measurement of fixture power draw times the number of fixtures. Results of this short-term test are shown in Table 3.

**Table 3**
Results of Surrogate Measurement of Lighting Power

| Measurement Technique | Results | Error |
|---|---|---|
| Electricity Metering | 76.1 kWh | |
| Surrogate Measurements Using Manufacturer's Data | 71.8 kWh | 5.7 % |
| Surrogate Measurements Using Measured Data | 74.7 kWh | 1.8 % |

The surrogate measurement using manufacturer's data predicted the metered lighting load within 6 percent. When actual fixture power was substituted for manufacturer's data, the estimate improved to within 2 percent. Graphical representations of the measured power draw over time and the estimated power draw over time are shown in Figures 1 and 2, respectively. Note the variability in the metered data presented in Figure 1. This is due to fixture power changing with changes in lamp temperature.

**Figure 1**
Measured Load Profiles

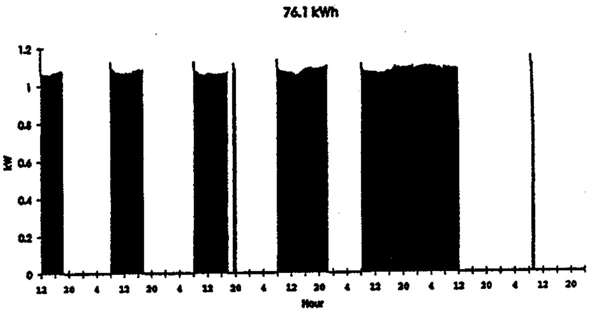
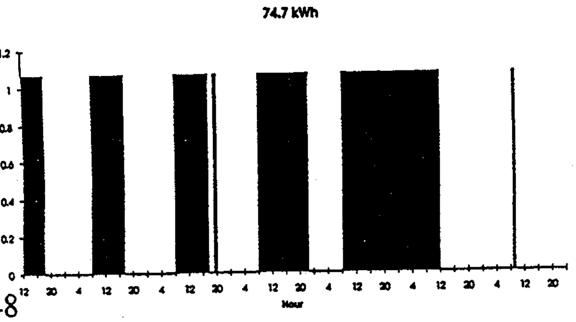


**Figure 2**
Surrogate Load Profiles

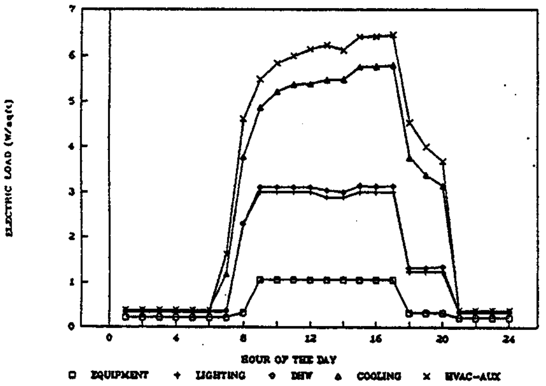


## Applications to Model Calibration

Accurate characterization of lighting and equipment (plug) loads in commercial office buildings is extremely important for an accurate prediction of annual energy consumption and peak demand. The Commercial Building Performance Evaluation System can play a major role in characterizing the lighting and equipment load schedules for inputs to a building energy simulation program. Consider the peak day load shape of a small commercial office building shown in Figure 3. This load shape was calculated using the DOE-2 building energy simulation program (LBL, 1989) and weather data for Denver, Colorado. The hourly energy consumption is broken out according to the following end-uses:

1. Lighting: all internal lighting loads.
2. Equipment: all plug loads (mostly computers and office equipment).
3. Cooling: air conditioning system compressors and condenser fans.
4. HVAC auxiliary: air conditioning system supply and return air fans.
5. DHW: service hot water.

**Figure 3**
Peak Day Load Shape



The contribution of each end-use to the building peak demand is shown in Table 4.

**Table 4**
End-Use Contribution to Building Peak Demand

| End-Use | Load at Peak Hour | Contribution to Building Peak |
|---|---|---|
| Lighting | 2 W/SF | 31 % |
| Equipment | 1 W/SF | 15 % |
| Cooling | 2.9 W/SF | 45% |
| HVAC Aux | 0.4 W/SF | 6 % |
| DHW | 0.2 W/SF | 3 % |

Lighting and cooling are the two largest loads, accounting for 76% or the total. The cooling and HVAC auxiliary end-use demands were decomposed into their component parts using an elimination parametric technique (Ternoey, et. al, 1985). The influence on cooling and HVAC auxiliary end-uses of internal loads resulting from heat gains from lighting, equipment, and people; and shell loads resulting from solar gains, shell conductance, infiltration, and ventilation are shown in Figures 4 and 5. The results are summarized in Table 5.

**Figure 4**
Cooling Load Profile

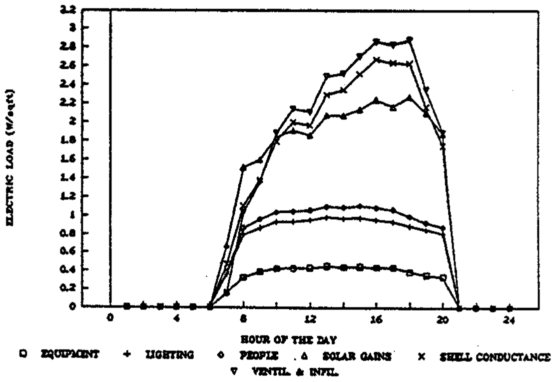


**Figure 5**
HVAC Auxiliary Equipment Load Profile

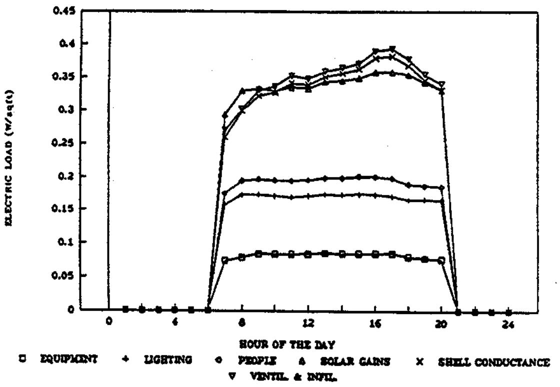
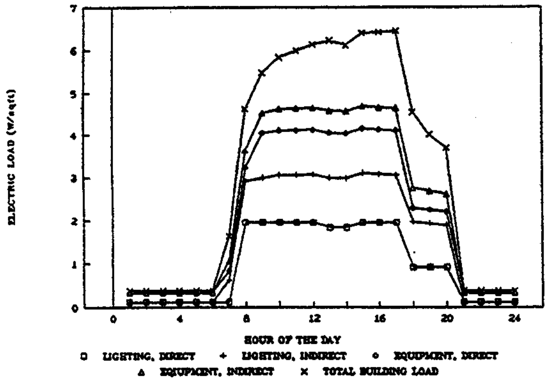


**Table 5**
Components of Cooling and HVAC Auxiliary Peak Demand

| Component | Contribution to Cooling Demand | Contribution to HVAC Auxiliary Demand |
|---|---|---|
| Lighting | 0.5 W/SF | .1 W/SF |
| Equipment | 0.4 W/SF | .08 W/SF |
| People | 0.1 W/SF | .03 W/SF |
| Solar Gains | 1.3 W/SF | .16 W/SF |
| Shell Conductance | 0.3 W/SF | .02 W/SF |
| Ventilation and Infiltration | 0.3 W/SF | .01 W/SF |

Note, the lighting and equipment loads, while representing 46 percent of the building peak demand, also account for 31 percent of the cooling demand and 45 percent of the HVAC auxiliary demand. Considering both the ***direct*** contribution of lighting and equipment loads on building peak demand and the ***indirect*** (cooling and HVAC auxiliary related) contribution of lighting and equipment on building peak demand, lighting and equipment loads account for over 70 percent of the building peak demand, as shown in Figure 6. It is therefore extremely important to accurately characterize the lighting and equipment load schedules, since these schedules influence the majority of the energy consumption and demand of the building. The Commercial Building Performance Evaluation System can do this and is an important tool for generating lighting and equipment load schedules for input into building energy simulation programs.

**Figure 6**
Building Load Profile



## HVAC SYSTEM OPERATION

The Commercial Building Performance Evaluation System was originally developed for performing HVAC system diagnostics and commissioning. The data sets needed for performing diagnostics and commissioning also yield information that can be used to improve inputs to building simulations. Among these are:

- room thermostat setpoint temperatures;
- fan operating schedules;
- supply air temperature and temperature reset strategies;
- supply water temperatures and temperature reset strategies;
- pump operating schedules and control strategy;
- supply air volume;
- fan power as a function of flowrate;
- economizer control strategy;
- condenser water temperature;
- cooling tower control strategy; and
- in-situ cooling system C.O.P.

Significant differences can exist between the values assumed for these parameters in simulations and their actual values in real buildings. The actual error in the result will depend on the sensitivity of the result to a change in the input parameter. Influence coefficients can be derived to express this dependency and prioritize data collection activities. An influence coefficient is the partial derivative of a simulation result with respect to an input parameter. (Spitler,et al). Influence coefficients are not set values, but depend on the physical properties of a building and its type of HVAC system, the climate, and usage of the building. Achieving the best estimate of input parameters is extremely important for properly predicting energy performance before and after energy efficient measures are installed. Measured data obtained using the Commercial Building Performance Evaluation System is one way of improving these estimates, reducing input error, and improving simulation results.

## CONCLUSIONS

The accuracy of building energy simulation models are extremely dependent on the input assumptions used. Input assumptions regarding lighting schedules, plug load schedules, fan schedules, and HVAC system control exert a major influence on the results of building energy simulations. The Commercial Building Performance Evaluation System can play a major role in providing these inputs and improving the results obtained from building energy simulations.

## ACKNOWLEDGMENTS

The original work to develop a whole building energy diagnostic system on which the Commercial Building Performance Evaluation System is based was funded under the U.S. Army's Small Business Innovation Research Program (SBIR). Continuing system development is being funded by the Electric Power Research Institute (EPRI).

## REFERENCES

Davis, R. G. 1992. "Explaining the Differences Between DSM Predictions and Actual Savings for Fluorescent Lighting Systems." Proc. 1992 ACEEE Summer Study, American Council for an Energy-Efficient Economy, Washington D.C. pp 1.43 - 1.44.

Franconi, E., and F. Rubenstein. 1992. "Considering Lighting System Performance and HVAC Interactions in Lighting System Retrofit Analysis." Proc. 1992 IEEE Industry Applications Society Annual Meeting, Institute of Electrical and Electronic Engineers.

Landsberg, D. R., and R. K. Johnson. 1991. "Field Verification of the kW Reductions Produced by Common Lighting Conservation Measures in Commercial Buildings." Proc. 5th National Demand-Side Management Conference, EPRI CU 7394, Electric Power Research Institute, Palo Alto CA. pp 109 - 114.

LBL, DOE-2 Reference Manual (Version 2.1D). LBL-8706 Rev. 5, Lawrence Berkeley Laboratory, Berkeley, CA, USA, June 1989.

Spitler, J., D. Fisher and D. Zietlow. 1989. "A Primer On The Use Of Influence Coefficients In Building Energy Analysis." Proc. Building Simulation '89 Conference, Vancouver, pp 299 - 304.

Ternoey, S., L. Bickle, C. Robbins, R. Busch, and K. McCord. 1985. *The Design of Energy-Responsive Commercial Buildings.* ISBN 0-471-80463-0. John Wiley and Sons, New York, NY.