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A MODEL FOR EVALUATION OF LIFE-CYCLE ENERGY SAVINGS OF OCCUPANCY SENSORS FOR CONTROL OF LIGHTING AND VENTILATION IN OFFICE BUILDINGS

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ABSTRACT

Lighting and ventilation represent the majority of the air conditioning loads in office buildings in hot humid climates. Use of motion sensors is one way to minimize the energy used for these loads. This paper describes the methods used for simulating a case study building with motion sensors installed and the monitoring of system on-off statistics related to occupant patterns. It also describes the development of the Monte Carlo model used to predict the on-off status of sensors. The building using the motion sensors is compared to a building that controls the lights and ventilators by a conventional pre-programmed schedule. The conventional methods of simulation were shown to generate misleading information regarding electric demand charges and life-cycle costs of the building. When comparing to actual use patterns, the Monte Carlo process was shown to represent an adequate way to represent the on-off patterns. Computer simulations further demonstrate the potential life cycle cost savings from the use of the motion sensors.

INTRODUCTION

[illegible] use by the lighting fixtures themselves represents a large fraction of annual energy use, and in addition the lights add an extra burden to the air conditioning loads. Ventilation air typically has high enthalpy values because of the high outdoor temperatures and humidity, so this represents an extra load for most of the year in what is already a heat-rich environment. Reductions in lighting and ventilation loads would therefore be an asset toward attempts to reduce energy use and utility bills.

The author previously described the computer model calibration difficulties when motion sensors are present to control lights and exhaust fans (Degelman 1999). The previous study reported on a case study building (in Nagoya, Japan) with motion sensors installed to control corridor lights and toilet room lights and exhaust fans. The data from that building were later used in this new study to test the concept in a hot-humid climate.

To describe occupancy and lighting profiles in energy simulation software, we normally use profiles that fix the hourly values to a specific number between 0 and 1 (or 0 to 100%). A profile for typical office lighting is shown in Figure 1. This represents a normalized pattern in which a certain fraction of the lights are presumed to be on for each hour throughout the day. When this curve is used in a simulation model, the electric use for lights follows a rather repetitive and predictable pattern. When motion sensors control the lights, however, a more erratic pattern results with many spikes and valleys. One sample day of measured data from the Nagoya office building is shown in Figure 2. Though the patterns in Figures 1 and 2 resemble each other at a gross level, when viewed from minute to minute, they vary quite significantly. The previous paper demonstrated that when there are high numbers of rooms being controlled by motion sensors, there might be significant reductions in peak power demand because of the randomness of the on-off patterns from room to room. When random on-off patterns for many rooms are summed, they result in a power demand that is much lower than the peak power demand of one room multiplied [illegible] well as reducing total energy consumption in the building.

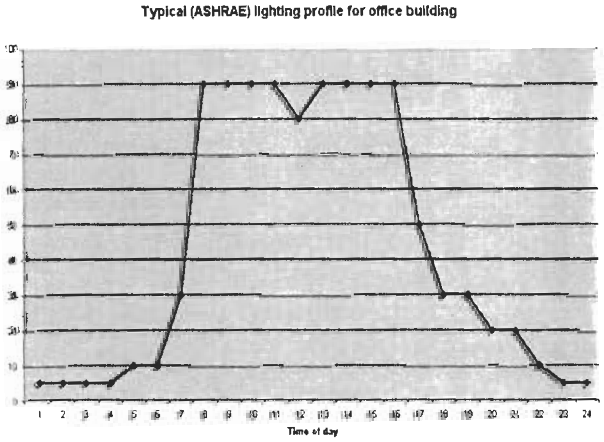

Figure 1. Typical lighting profile for use in computer simulation models

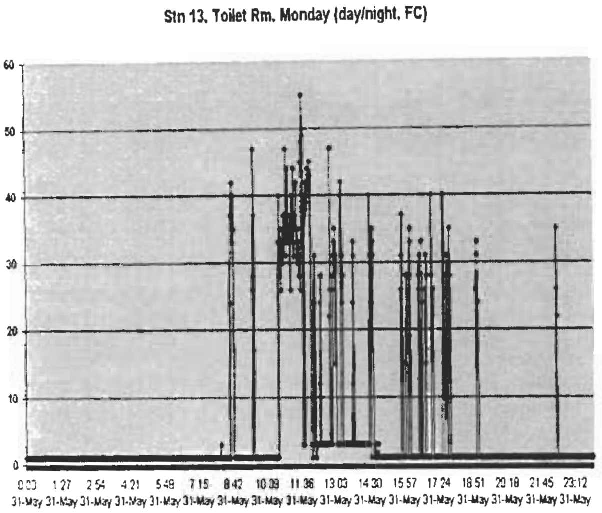

Figure 2. Measured lighting profile when a motion sensor controller is present

CASE-STUDY BUILDING

The case-study building for this project is a U-shaped combination office/laboratory/classroom building on the campus of Nagoya University (See Fig. 3). There are approximately 268 offices on the 10 floors. Occupancy sensors control only the corridor lights and the toilet room lights and exhaust fans.

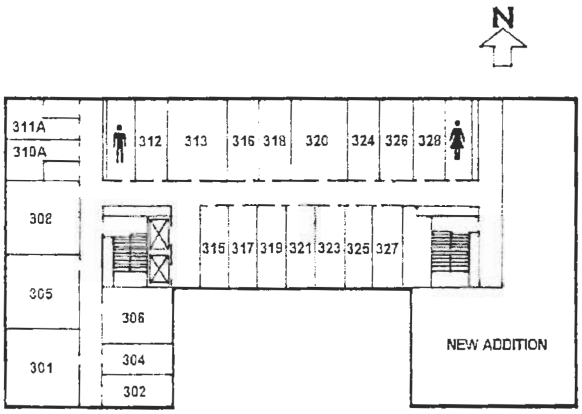

Figure 3. Typical office floor plan in the case study building.

Each office has an individually controlled heating/cooling unit in the ceiling with a wall thermostat in each room. The lighting is provided by six (6) ceiling surface-mounted fluorescent fixtures (2-40w each), totaling 480w for the 26-m^2 room. None of the fixtures have diffuser lenses. There are two light switches – one controls the two fixtures nearest the window, the other controls the four fixtures nearest the corridor side.

Other building characteristics are as follows:

- Size: 10-story, 62m by 30m, U-shaped plan, with entrance on the second floor.
- Gross floor area: 15,980 m^2.
- Wall: 25 cm thick (10 cm brick, 5 cm rigid insulation, 10 cm block); U.F. 0.79 W/m^2K, per Table 4, Chap 24 (ASHRAE 1997).
- Windows: Single pane clear glass w/ aperture ratio of 0.82, aluminum frames, and venetian blinds at 45-deg. open; U.F. of 6.47 W/m^2K, SHGC of 0.476 and visible transmittance of 0.437, per Tables 11 and 25, Chap. 29 (ASHRAE 1997).
- Lighting power densities: 18.2 W/m^2 in offices, labs and classrooms; 1.8 W/m^2 in corridors; 6.2 W/m^2 in elevator lobbies; 12.1 W/m^2 in toilet rooms; 4 W/m^2 in the entry lobby; and 3.3 W/m^2 in stairwells.
- Typical office: 3.57m by 7.4 m, or 26 m^2.

Motion sensors control lights (ON/OFF control) in the entrance lobby and in all corridors and restrooms. Corridors have three zones on separate motion sensors. A typical ceiling-mounted motion sensor in the corridor is shown in Figure 4.

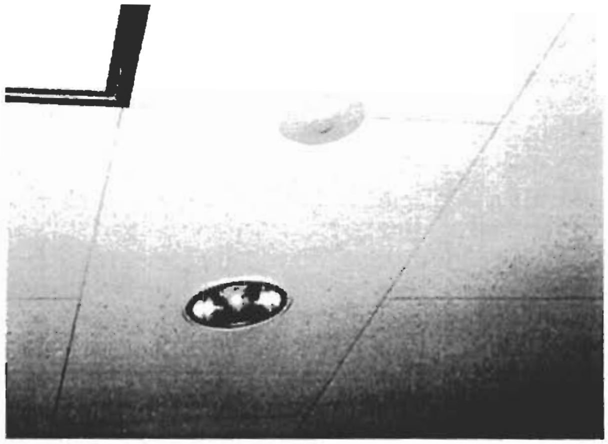

Figure 4. Typical ceiling-mounted motion sensor and recessed compact fluorescent light.

For simulating this building relocated to the U.S., mostly all building physical characteristics were maintained. The lighting power density, at 18.2 W/m^2, in the office spaces represents the predominant lighting load in the building. This is just slightly higher than the Standard 90.1 value of 16 W/m^2 for enclosed offices (ASHRAE/IESNA 1999). The toilet rooms were left at 12 W/m^2. The corridors lighting level at 1.8 W/m^2, however, was far below what would be common in the U.S., so this was reset to the Standard 90.1 value 7.5 W/m^2.

COLLECTING USE STATISTICS

The building use statistics were collected by using Hobo® data loggers. The loggers were set to sense light levels and were fastened to corridor walls in the different lighting zones on each floor and to the toilet room walls so as to avoid daylight from the window but to sense light from the ceiling fixtures. The loggers' time interval was set to one minute. Loggers were left in place for 5.5 days (capturing 7943 data points). Loggers were all set to begin logging at precisely the same instant. Lights switch on instantaneously when motion is sensed and turn off after motion has ceased for 4 minutes and 20 seconds. By analyzing the logged data, it was determined that during working hours the corridor lights remained on around 68% of the time and restroom lights were on around 40% of the time. During non-working hours and nighttime, the corridor lights were on for 28% of the time and the toilet room lights were on for 10% of the time. One of the data loggers is shown attached to a hallway door in Figure 5.

Figure 5. Wall-mounted Hobo data logger.

Samples of the logged data are shown in Figures 6 through 8. The lowest value from the loggers is shown as 1 (off), rather than a zero value.

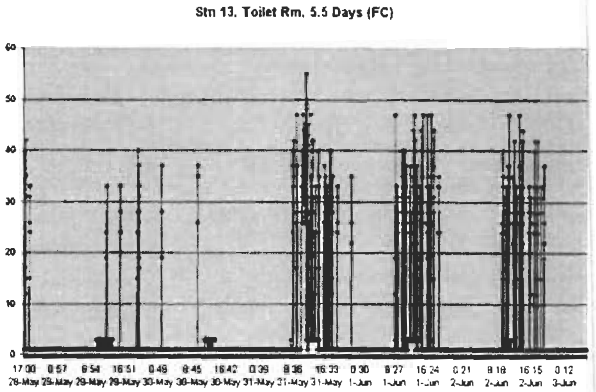

Figure 6. Measured lighting profile for 5.5 day period.

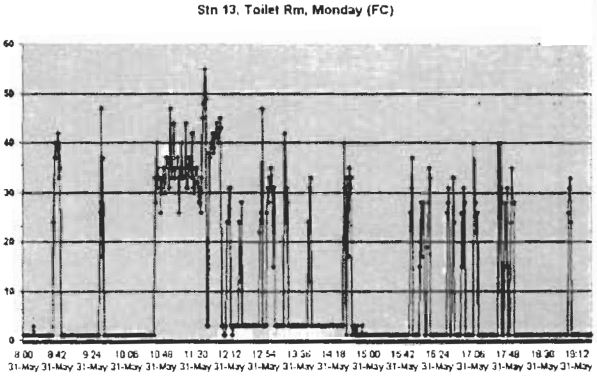

Figure 7. Logged toilet room data for Monday daytime.

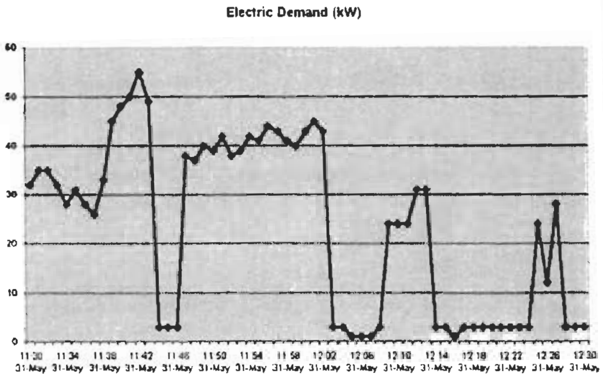

Figure 8. Logged toilet room data for one hour.

MOTION SENSOR MODEL

In the case study building, motion sensors control all the lights in the corridors, lobbies, and restrooms. They also control the ventilation system (exhaust fans) in the restrooms. Representing an accurate hourly load profile for the lighting and/or ventilation loads from this sort of control presents an interesting challenge, since the system may be on and off numerous times during each hour. The issue here does not have to do with energy; rather, the problem relates to peak load demand. It was a simple task to measure the average "on time" of the controllers in each of the activity areas. Using this information to create a load profile would be a simple task if all we had to do was calculate the total energy consumption. However, the peak demand in each of the activity areas could easily be 100%, since the controllers will always turn the systems full-on at some time or another. So, a new method of representing the peak lighting load or peak ventilation load had to be developed.

It's common for the electric utility company to levy a "demand charge" for the peak electric demand encountered each month of the year. A common way to measure this is to use the average demand over a 15-minute period. Since most energy simulation models use a time step of one hour, this means that systems cycling on and off in very short periods of time create an additional problem for the simulation process. For example, the on time for the motion sensors in the case study building was measured at 4.33 minutes. The average stay-time of an occupant in the area was 3 minutes. This meant that when the lights and ventilation fan turned on, they would be on for 7.33 minutes (or about one-half of a 15-minute demand charge interval). So, even though the systems might be completely on at any instant in time, the demand charge might be assessed at 50% of total if a second person did not arrive during the 15-minute interval. So, if the motion sensors turn on only once during a 15-minute period, the demand would be just 50%. In general, depending on the arrival frequency of occupants, the demand in any 15-minute period could be anywhere between 0 and 100%.

When looking at the whole building, rather than just one zone, we find that the randomness of occupant arrivals in the various spaces affords us the advantages of statistical diversity. While each zone might reach its full connected load several times in one day, a large number of independently controlled zones will be much less likely to ever reach the building's full connected capacity. The electric codes recognize this fact by allowing a "diversity factor" to be applied when sizing the electric service panel for a building. A Monte Carlo scheme was applied to the simulation model in which random numbers were chosen for each minute throughout the day to determine if an occupant arrived in the space. If an occupant arrived, then the lights switched on and stayed on 5 to 7.5 minutes from the arrival time. An empirical model was developed from the recorded data from the loggers. The independent variables in the model are the overall fraction of time the lights are on (P_A) and the stay-on time of the sensor (Tstay). The dependent variable is the probability that an occupant has arrived during the last 1-minute period (P_M). If an occupant has arrived, then the lights remain on for the next "stay-on" minutes. Figure 9 outlines the methodology.

$$P_M = P_A / [(\text{Tstay}-1) * \text{Sqrt}(1 - P_A)]$$

Where, P_A = On time fraction for long period.
Tstay = Sensor stay-on time (minutes)
P_M = Prob. of sensor turning on at minute, M.

```
If RND(1) < P_M then
    LightOn = True
    Set RemainOn = Tstay
    Else
    Subtract 1 minute from RemainOn.
    If RemainOn <= 0 then LightOn = False
End if
```

Where, RND(1) = random number between 0 and 1

RND(1) is derived every minute and accumulated for 60 minutes. Demand charge is based on the maximum 15-minute total load.

Figure 9. The Monte Carlo "On-Off" motion sensor model.

The Monte Carlo technique was programmed into the simulation model and was run using the parameters that were derived from the case study building. Several of the resulting On-Off patterns are shown in Figures 10 through 13. The "Off" condition was assigned the value of 1 and the "On" condition was assigned the value of 5. If the lights were on for a fraction of a minute, an intermediate value (2, 3, or 4) was assigned. In this example, the stay-on time was entered as 7.5 and 5 minutes, so the intermediate value was always halfway between the 1 and 5; i.e., the value of 3.

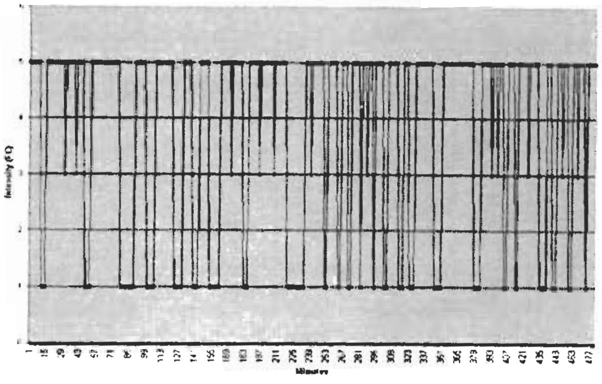

Figure 10. Simulated On-Off pattern for corridor 8-hour daytime period, 68% on time.

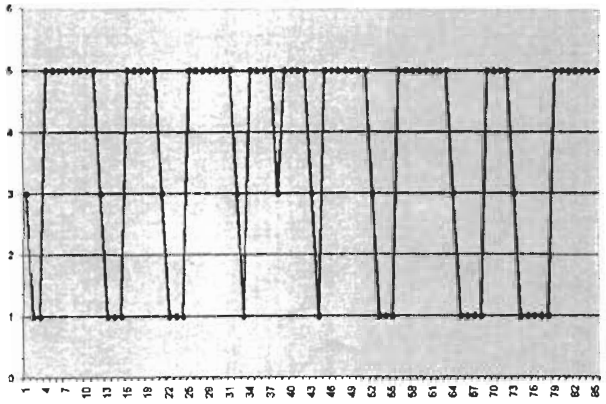

Figure 11. Simulated On-Off pattern for corridor 90-minute daytime period, on 68% on time.

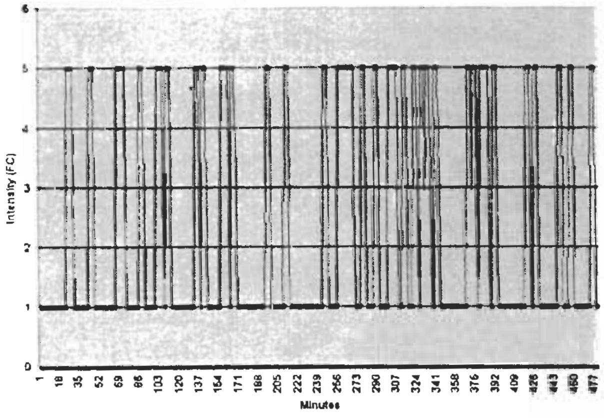

Figure 12. Simulated On-Off pattern for toilet room 8-hour daytime period, 40% on time.

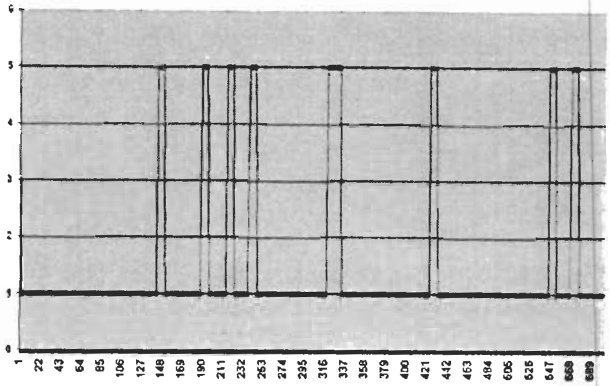

Figure 13. Simulated On-Off pattern for toilet room nighttime period, 10% on time

The model was run for 720 hours times 60 minutes per hour per one month period and loads were summed after each 15-minute period – i.e., four times each hour. The peak demand for any 15-minute period was observed and tabulated in Figure 14. This figure shows plots for three on-time fractions – 68%, 40% and 10% to replicate the case study building statistics. These plots demonstrate that the peak demand is almost always 100% when the number of zones is small (say one or two). However, the case study building had at least 50 separate lighting zones on the ten floors that were independently controlled. The results show that the peak demands in a building with a large number of zones will reach only a fraction of the total of all connected loads. The values of peak demand reach about 80% for a 68% on-time sensor, 55% for a 40% on-time sensor, and 20% for a 10% on-time sensor. (See Figure 14.)

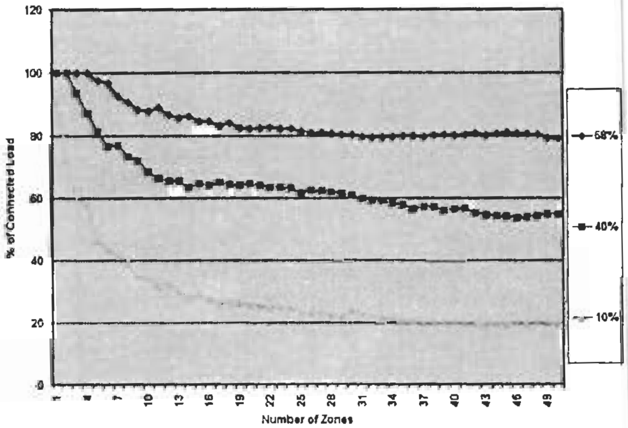

Figure 14. Monthly peak demand vs. number of lighting zones

SIMULATION TEST RESULTS

Computer simulations were performed to predict life-cycle energy consumption and cost implication in the San Antonio climate. Three alternative designs were simulated: (1) a base case using the actual building characteristics except that the occupancy and lighting profiles followed ASHRAE Standard 90.1 (ASHRAE 1989), (2) using the motion sensors in all corridors and toilet rooms with the profiles defined by on-time probabilities and the Monte Carlo method applied, and (3) the motion sensor case with daylighting dimmers added.

Motion sensors were not simulated in the offices, thus replicating the actual situation that existed in the case study building. The occupants manually turn lights on and off in concert with their stay times in the office. Lights were always turned off when the room was vacated. Occupants tend to assume ownership responsibility for their office spaces, but such is not the case for the community spaces like corridors and toilet rooms, so in these the motion sensors are regarded to be essential. Daylight-activated light dimmers, however, were considered to have potential value within the private offices. Light dimmers were therefore assumed to control the outer row of lights in each office, covering an effective perimeter region of 3 meters (10 feet).

The simulation also included the turning on and off the toilet room exhaust fans as well as the lights. Life-cycle costs (LCC) are computed by adding first costs to the present value of annual operating and maintenance costs for a 20-year economic life. An annual discount rate of 7% and an annual fuel price escalation rate of 5% were used in the present value model. Results of the simulations are shown in Table 1 and in Figure 15.

Table 1. Energy and cost comparisons for three alternatives of the case study building for San Antonio

Case	Daylight Savings	1st Cost *	Htg En	Clg En	Peak a.c. load	Ave. Mon. Dem.	Ltg En	LCC *	EUF
Units	MWh	$/sq.m.	MWh	MWh	tons	kW	MWh	$/sq.m	MJ/sq.m
Base Case	0	146	620	576	375	621	906	320	1452
Motion sensors	0	144	506	526	352	561	647	299	1175
Daylight dimmers	110	145	513	520	345	542	627	296	1154
Units	MWh	$/sq.ft.	MBtu	MBtu	tons	kW	MWh	$/sq.ft.	KBtu/s.f.
Base Case	0	13.56	2115	1966	375	621	906	29.73	128
Motion sensors	0	13.38	1726	1795	352	561	647	27.77	103
Daylight dimmers	110	13.47	1750	1774	343	542	627	27.50	102
Percent savings by motion sensors	---	1	18	9	6	10	29	7	19

* Costs include only the HVAC, lighting and the thermal envelope. LCC includes HVAC maintenance.

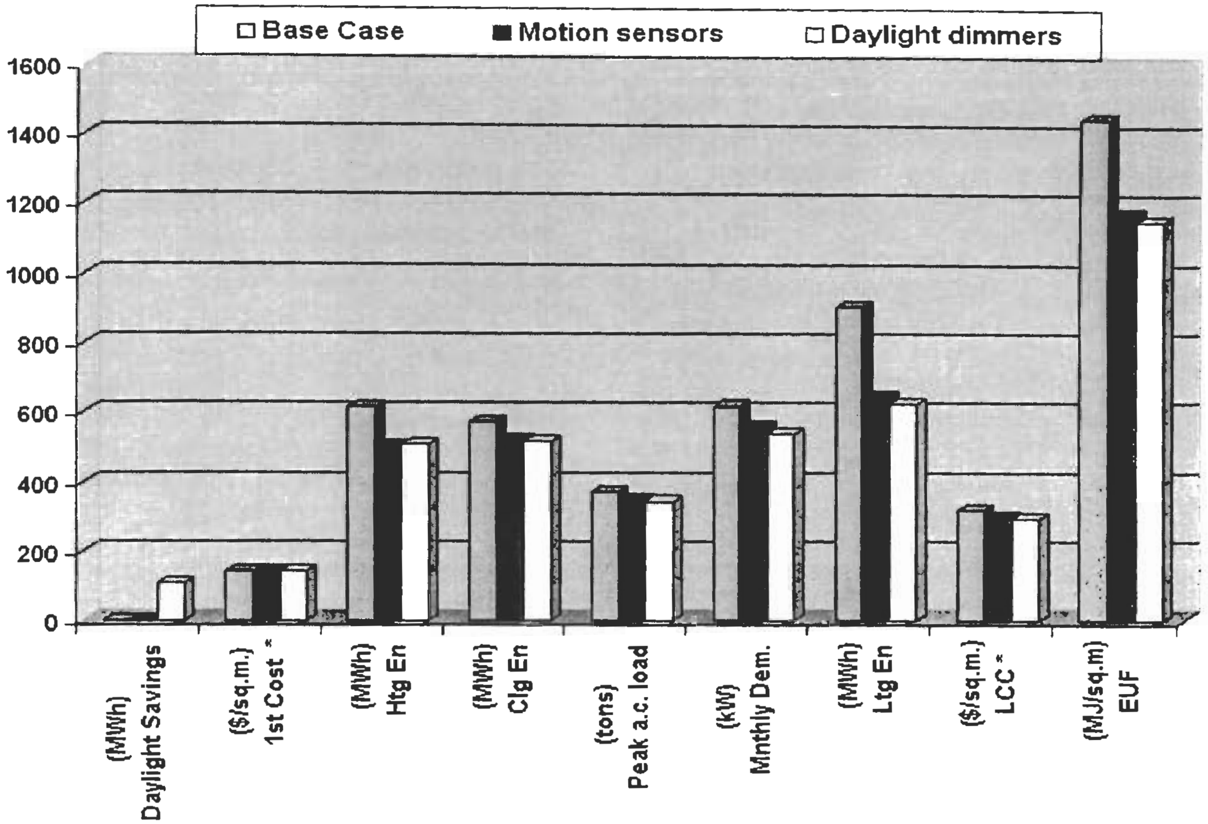

Figure 15. Comparisons of various energy and cost parameters between the base case design, motion sensors and light dimmers for San Antonio.

RESULTS DISCUSSION

Results show the motion sensor controls produce significant energy reductions in almost every category of end use. Lighting reduction is the greatest with annual savings of 29%. The total whole-building energy savings are 19%. The reductions in lighting energy are in direct proportion to the on-time of the lighting systems controlled by the motion sensors. There is even an annual saving of 18% in space heating. In most cases, when lighting energy is reduced, the heating energy will increase. In this example, the heating energy is saved by a 34% reduction in annual ventilation loads. The 9% annual saving in cooling energy is a result of lower lighting loads and the reduced amount of ventilation air introduced to the spaces. Peak demand charges are reduced by 10%

CONCLUSIONS

This study has demonstrated that there is high potential for significant energy savings when occupancy sensors are used in the public use areas of an office building in the hot humid climate examined. It has also been demonstrated that the method of describing occupancy and lighting profiles will make a difference in predicted demand charges when occupancy sensors are used as the lighting control mechanism. The Monte Carlo modeling method affords the opportunity of performing realistic simulations of the behavior of motion sensors when brief statistics of the performance are collected in advance.

Annual savings from daylighting dimmers are rather modest because the dimmers only dim the outer 1/3 of each office's lights. In normal use, the occupants tended to leave the outer bank of lights turned off, so dimming showed little improvement over this already existing procedure.

This study brings to surface questions related to the choice between individualized room controls versus centralized control systems. In cases where the presence of the building occupant affects environmental conditioning, centralized controls are possibly at a disadvantage. While performing several simulations on buildings with individualized units (in contrast to centralized systems using timed schedules), it was discovered that there could be a wide difference in the two results.

The Monte Carlo motion sensor model is implemented in a previously written hourly energy simulation program that was developed at Texas A&M University (Degelman and Soebarto 1995). It is a Windows-based package that evaluates the effectiveness of design strategies through life-cycle cost and comfort analyses.

The next step in the validation of this modeling approach is to calibrate simulation runs to a larger number of actual buildings that use motion sensors for lighting and ventilation control.

ACKNOWLEDGMENTS

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