A MODEL FOR SIMULATION OF DAYLIGHTING AND OCCUPANCY SENSORS AS AN ENERGY CONTROL STRATEGY FOR OFFICE BUILDINGS

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ABSTRACT

This paper describes a computer simulation model for assessing the potential energy savings in office buildings through the use of daylight and occupancy sensors. Because motion sensors control the lights, special attention is placed on a Monte Carlo approach to establishing lighting schedules for the typical workday. Fixed lighting profiles were shown to generate misleading information regarding electric demand charges and life-cycle costs of the building.

A case-study building containing motion sensors and individual room air conditioners was used to provide essential data for the study and corroborate the model. Illuminance data were measured in daylit and non-daylit spaces of the building in order to validate the energy savings from daylighting that were predicted by the simulation model.

INTRODUCTION

Energy simulation models have evolved for nearly 40 years, and during this period, most of the development efforts have focused on perfecting the model's thermal processes. Ironically, a building's operational characteristics have a much larger impact on the building's energy performance than does the thermal envelope. When the building's operations are reasonably predictable and routine, energy simulation models seem to do a good job of predicting real building performance. Many successful energy model calibration efforts have been reported (Carroll and Hitchcock '93, Manke et al '96, Soebarto '97).

In cases where the building occupant operates environmental conditioning controls, good calibration is much more difficult. While performing several simulations on buildings with individualized units (in contrast to centralized systems), it has been discovered that there can be a wide range of discrepancy between the simulation results and the real building performance. In this study, we consider buildings that have motion and daylight sensors that control individual room lights and ventilation systems. Since this method of control results in lights being on and off at irregular intervals, it presents an especially difficult problem to the user in defining the lighting and occupancy schedules. The method chosen here is a stochastic process that uses a probability function as a means of choosing whether lights are on or off.

The 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 software includes a calculation procedure based on the lumen methodology developed by the Illuminating Engineering Society and utilized in several environmental control textbooks (e.g., Stein and Reynolds 1992). While many daylighting design tools estimate a total distribution of illuminance on the interior workplane, this software predicts the illuminance on a center line in order to calculate the potential amount of electric lighting that can be saved during each occupied hour. Both step dimmers and continuous dimmers can be evaluated. Initial investments in daylighting sensors and lighting dimmers are compared to the life-cycle savings in lighting costs.

Since lighting and space conditioning represent the majority of energy use in office buildings, simulation results have demonstrated potential energy savings of 50% and more.

PROCEDURES

The procedures followed in this study were to:

1. Model a case-study building.
2. Take survey data on building's environmental conditions.
3. Develop a motion sensor control model.
4. Develop dimmer control model.
5. Test simulation methods in two separate climatic regions.

CASE-STUDY BUILDING

The author occupies a building that is ideally suited to the purposes of this study, so the building was chosen as a case study in order to illustrate the modeling approaches. The building is a combination office / laboratory / classroom building on the campus of Nagoya University, identified by the university as Engineering, Building #1. (See Figs. 1 & 2.)

Fig. 1 South face of case study building

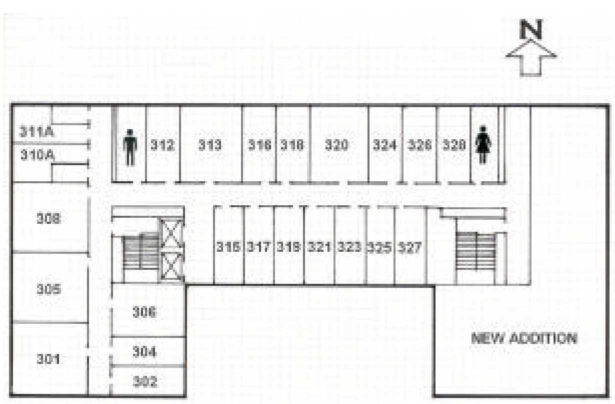

Fig. 2 Typical office floor plan in case study building. There are approximately 268 offices on the 10 floors.

The case study 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.

SURVEY DATA

A lighting survey was made of the building in several offices on each floor and in all stairwells, elevator lobbies, restrooms, and corridors. Horizontal illuminances in the offices at typical work height varied from 550 to 800 Lux during nighttime hours (up to 1600 Lux during daylight hours at 1 meter from the window), 10-70 Lux in the corridors, and 50-70 Lux in the stairwells. During daylight hours, the levels were 11-200 Lux in elevator lobbies, 250-4000 Lux in the entry lobby, and 300-1000 Lux in restrooms. Outdoor horizontal illuminance during this period was 19,000 Lux diffuse and 80,000 Lux global direct plus diffuse.

Delay times of the motion sensors were recorded by 19 portable data loggers located throughout the building. Lights switch on instantaneously when motion is sensed and turn off after motion has ceased for 4 minutes and 20 seconds. By casual observation, during working hours, the corridor lights remained on around 75% of the time and restroom lights were on around 30% of the time.

The lighting power density, at 18.2 W/m^2, in offices represents the predominant lighting load in the building. This compares favorably to the accepted ASHRAE/IES Standard 90.1 value of 17 W/m^2 (ASHRAE 1989). Since the remaining areas of the building have very low levels of illumination power, the average for the entire building is significantly below Standard 90.1.

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.

Daylighting information was collected from a third floor office on the north side of the building. The results are shown in Fig. 3. This figure shows lighting levels with no daylight, a mixture of daylight and 4 electric lights, a mixture of daylight and 6 electric lights, and daylight only at three different times of the day (9 a.m., 10 a.m., and 4 p.m.) The electric lights alone provide 580 to 800 Lux throughout the entire space – well above the office level criterion of 500 Lux. When daylight is added, the levels are from 630 to 1350 Lux. The conditions of most interest, however, are daylight combined with 4 lights and daylight with no lights. When the two lights nearest the window are turned off, the levels are from 580 Lux nearest the corridor wall to 820 Lux nearest the window. (See third curve in Fig. 3.) The symbol key to the right of the figure includes a number following each label – this indicates the time of day the measurements were made.

The data in Fig. 3 proved to be useful later in establishing the input parameters for the simulation process. From the data, it immediately became obvious that daylighting alone will not provide adequate levels of illumination throughout the space, revealed by the bottom three curves showing levels of 15 to 50 Lux near the corridor wall. However, it became quite clear that use of the pair of ceiling fixtures near the window is not necessary. Daylight contribution to the outer one-third of the room (2.5-m depth) is quite adequate when supplemented by the spillover from the inner four ceiling lights in the room.

In addition to window visual properties and size, the ENER-WIN model requires the user to input two space parameters -- the depth to which daylighting is to be used and the target Lux level. On an hourly basis, the model then computes the daylight contribution to the depth specified and, using continuous dimmers, only supplements this with electric lighting if the lowest level in that zone falls below the target Lux. By inspecting the 10 a.m. daylight curve in Fig. 3, one can observe that the daylight contribution at 2.5 m is around 350 Lux. When the inner four lights are turned on, the spillover brings this up to around 670 Lux – more than adequate for typical office working conditions. Therefore, the simulation parameters of depth=2.5 m and level=350 Lux were used for the ENER-WIN input. Even the lowest curve (4 p.m.), there would be almost enough daylight to keep the space at 500 Lux.

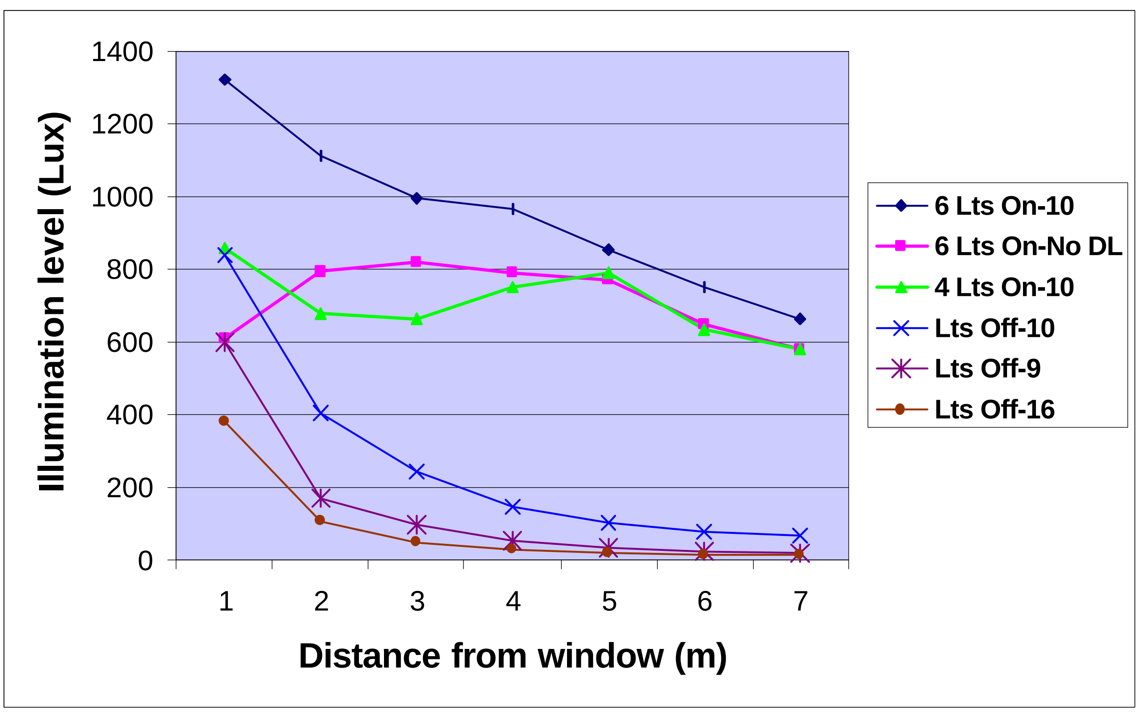

Fig. 3 Measured light levels in north-facing office with and without daylighting (Data in Table 2.)

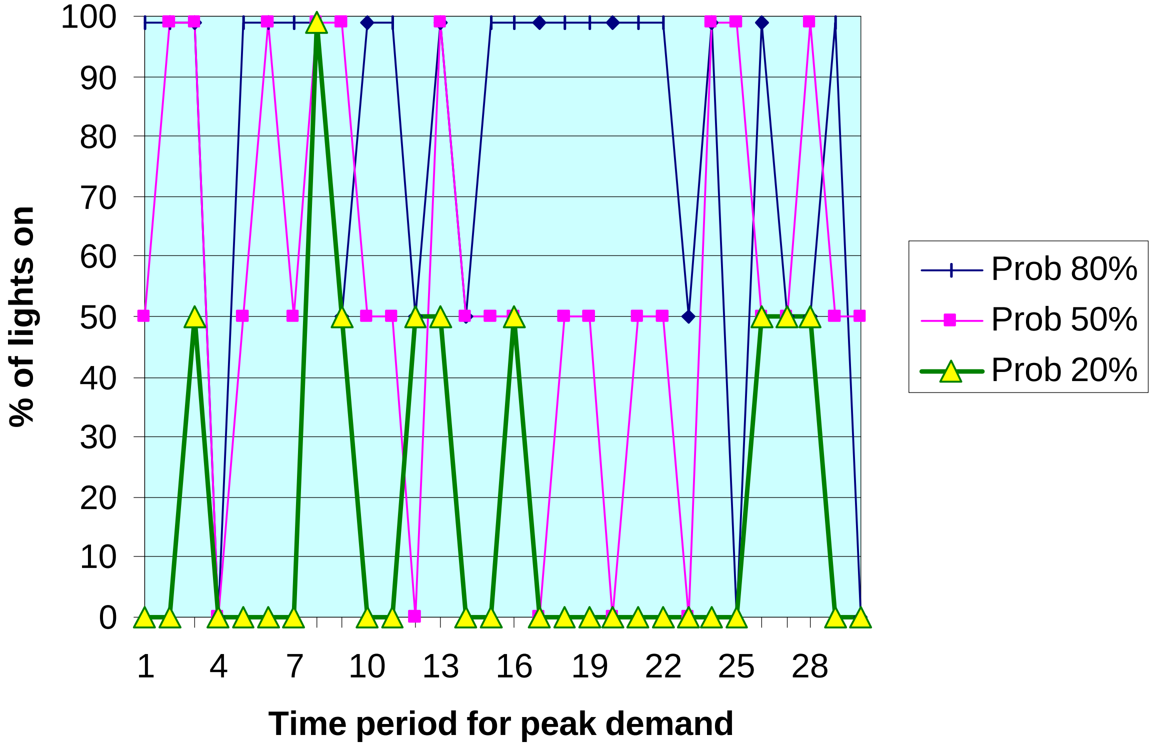

Fig. 4 Peak demand profiles for three sample on-off motion sensors for 30 time steps, or 7.5 hours or operation)

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 is either off or on. The issue here does not have to do with energy; rather, the problem relates to peak load demand. It may be quite a simple task to just observe the average "on time" of the controllers in each of the activity areas and create a load profile that specifies that average. Theory says that when integrated over time, this will result in the correct energy use calculation. However, the peak demand in each of the activity areas could always be 100%, since the controllers will always turn the systems full-on at some time or another. So, a method of representing the impact of the peak lighting load or peak ventilation load has to be re-evaluated.

In the U.S. and a number of other countries, for non-residential customers it is common for the electric utility to levy a "demand charge" for the peak of demand encountered each month of the year. In the U.S., these rates vary from 5 to 12 USD/kW. In Japan, the rate is similar, at around 1500 JPY/kW. In Australia, the rate is also similar, at around 17 AUD/kW. A common way to measure peak demand is to use a 15-minute average time period. Since most energy simulation models (also ENER-WIN) 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 delay 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 (or ventilation fan) turned on, they would be on for 7.33 minutes (or 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 the on time did not fill up the 15-minute interval. If these example motion sensors were on only once during a 15-minute period, the demand would be just 50%. This means that these particular motion sensors would cause the peak demand to have three values rather than just two values. It would be zero, 50% or 100%. Fig. 4 shows a plot of the on/off cycle times in three separate zones in which the probability of being on is 20%, 50% or 80%.

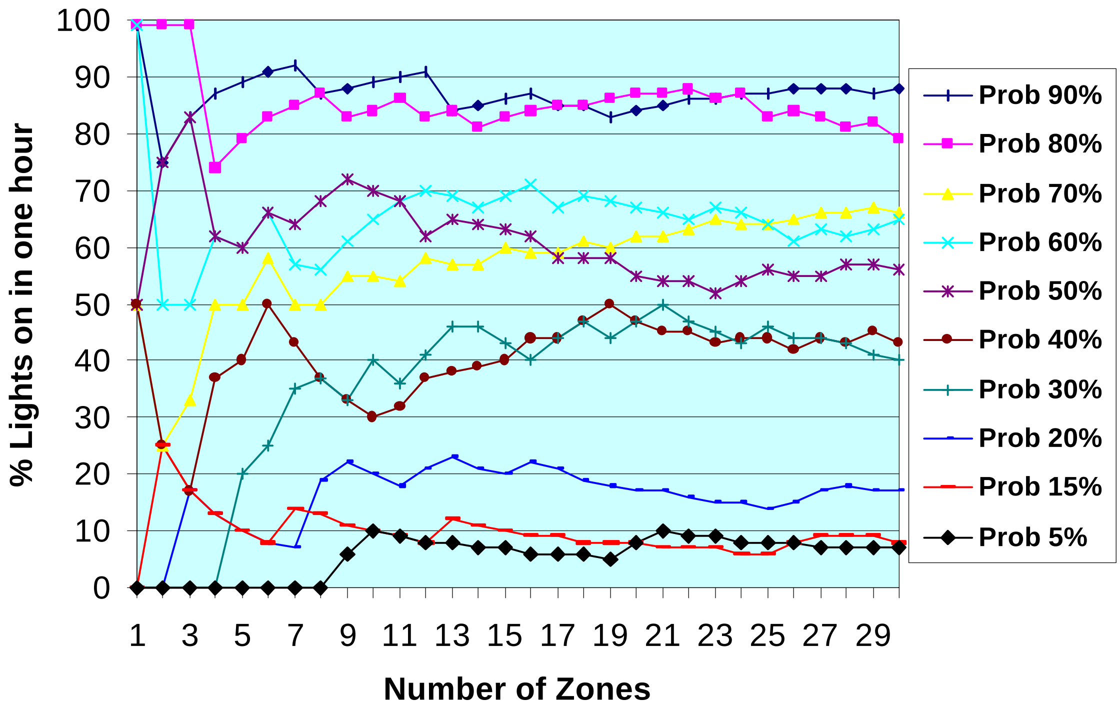

Fig. 5 Results of Monte Carlo simulations of motion sensors in a variable number of zones

In this example, it can be seen that when the probability of being on is 80%, the controller encountered an instance where it was at full peak for a period of 8 steps (2 hours). This is not surprising, but what is more interesting is that a controller with only 20% probability of being on still reached 100% of demand at least once during the 7.5-hour time period (close to a typical work day). Since demand charges are based on the peak demand being encountered only once for the entire month, it is easy to see that controllers with very low probability of being on can easily contribute to the full peak demand. That is the situation for a motion sensor.

The next interesting question is what happens when the building's multiple motion sensors are aggregated into one value. In this situation, statistical probabilities work in our favor. Even though one motion sensor will cause its zone to reach the full connected load, a large number of these (independently controlled) 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 calculating the electric service panel size for a building.) To test the sensitivity to the number of zones in the building, a Monte Carlo scheme was applied to the simulation model in which random numbers (even chances from 0 to 1) were chosen for each 7.5-minute period throughout the day. If the random number chosen was less than the probability of being on, then the controller was turned on – if the random number exceeded the probability, then the controller was turned off. A simulation was performed with the number of zones (number of motion sensor controllers) as the independent variable. Results of this simulation are shown in Fig. 5.

In Fig. 5, the "on" probabilities of the 10 controllers were first determined by observing the total on-time for each zone and dividing this value by the total time period covered. To improve accuracy, this probability should be done for each hour of the day, since that is the time step that is required in the lighting and occupancy profiles in the computer program. This can easily be done by a simple data logger that records light levels in very small time steps for a period of several days. By analyzing the logger data, one can determine the average on-time for each zone and thereby the probability of being on at any time. These probabilities are entered at the right-hand side of the graph in Fig. 5.

The results in Fig. 5 show that if a building has very few zones (say less than 5), the peak loads are very unpredictable. Therefore, in buildings with only a few zones, the lighting profiles should be entered with conservative values – i.e., values that are above the known probability of being on. It is not until around 30 zones, that it becomes safe to enter the lighting profiles with numbers that are approximately equal to the known probability of the on times.

By placing the Monte Carlo simulator inside the energy simulation software, the user does not need to determine when to provide conservative estimates and when to enter the actual known probability values. In the simulations performed in this study, two methods of estimating the hourly lighting loads were tested. The one method tested was to enter some conservatively high values for hourly profile values, so as to guarantee that peaks loads would be encountered in the building's total load estimate. To assure that the total energy consumption would also be realistic, an erratic profile was created with zero load values along side full load values so the integrated daily total would reasonably represent the correct energy consumption. The second method was to just enter the known probabilities and let the Monte Carlo simulator determine the overall values by random choice. This still assures that the total energy consumption will remain the same but with possibly different peak demand charges. The two different simulations did indeed result in different peak demand charges as will be indicated in the results section.

DIMMER CONTROL MODEL

The lighting dimmer model follows a rather simple concept. Initially, the program evaluates the depth of the daylighting zone (a parameter input by the user). If that depth is greater than 4 meters, it is broken into two or more zones, such that each consecutive zone dimension is within the range of 2 to 4 meters. On an hourly basis, the program computes the daylight contribution at the rear edge of each of the room's daylighting zones. It does this by use of a daylight efficacy equation and then applies the IES daylight calculation procedures. The model results match the bottom three daylight curves in Fig. 3, but, of course, vary hourly depending on sun angle, cloud cover and atmospheric clearness. If the calculated illuminance at the rear edge of any daylight zone is at or above the target illuminance value (also input by the user), then the lights for that zone are turned off. If the derived value is below the criterion, then the lights in that zone are dimmed by the same fraction as the available light – the remaining fraction to be provided by the electric lights. One photocell sensor and proportional continuous dimmer were assumed to exist in each daylighting zone segment of the daylit space.

Following the dimmer calculations, the model sums all the electric power used and the resultant air conditioning loads in the space. Monthly and annual outputs reveal the overall energy consumption for heating, cooling and lighting. Because dimmers cause the lights to contribute less internal heat, the demand for space heating energy always increases and lighting and cooling energies always decrease. The resultant savings are included in a life-cycle cost (LCC) model to help the designer know if the investment in dimmer controls was cost-effective.

In the case study building, the measured daylight levels suggested that daylight dimmers used at the rear edge (corridor side) of the room would be a wasted resource. However, dimmers installed in the 2.5-meter space adjacent to the window appeared to make a lot of sense. Simulations were therefore run with the daylighting depth set at 2.5 meters. A follow-up check setting the daylight depth set at 7.4 meters (full depth of the room) showed negligible extra savings in annual lighting energy, confirming that the original assumption of using dimmers in only the outer one-third of the space was correct.

SIMULATION TEST RESULTS

Computer simulations were performed on the case study building to predict life-cycle energy consumption and cost implication in two different climates – hot-humid (Houston, USA), and temperate (Nagoya, Japan). Local energy cost rates were used in order to determine if the energy-saving investments would have different preferences in two different economies. Four alternative designs were simulated in each location: (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 in the offices with a fixed daily profile, (3) same conditions as number 2 except that the profiles were entered as a probability value and the Monte Carlo method applied, and (4) same as case 3 with the addition of daylighting sensors in each space with windows.

In the author's estimation, alternative 4 comes closest to the actual operating conditions of the existing building. Though motion sensors and daylight dimmers do not exist in the offices, the occupants themselves tend to manually control the spaces in accordance with the conditions that exist in option 4. Lights are usually turned off when the room is vacated. (This simulates an occupancy sensor.) Some, but not all, the occupants turn on only the four ceiling lights nearest the hallway and leave the pair nearest the window turned off. (This simulates a daylight-activated dimmer.) This seemed to be dependent on whether they had their venetian blinds closed or open. Many leave them closed.

One additional simulation was performed (not shown in the results here), using the existing motion sensors in just the corridors. Though there were some annual savings, they were almost negligible because of the extremely low lighting power densities in the corridors (only 1.8 W/m^2). This did not demonstrate any value in the motion sensor investment when used in areas with such low lighting levels. The motion sensors in the restrooms did demonstrate adequate savings, because they control the ventilation exhaust fans as well as the lights. Results of the eight simulations are shown in Table 1 and in Figs. 6 and 7. Table 2 shows the measured values of light levels in the case-study office building. These were previously plotted in Fig. 3.

Table 1. Simulation results for four case-study alternatives in two locations

Case	Daylight Savings	1st Cost	Htg En	Clg En	Peak a.c. load	Ave. Mnthly Dem.	Ltg En	LCC
	(MWh)	($/sq.m.)	(MWh)	(MWh)	(tons)	(kW)	(MWh)	($/sq.m.)
Nagoya								
Base Design	0	110	1013	210	404	437	716	641
MS-Fixed Sch	0	116	1167	160	386	401	369	635
MS-Random	0	116	1169	160	383	324	369	624
w/ Daylight Ctrl	39	118	1195	155	381	306	330	623
Houston								
Base Design	0	111	397	376	484	532	716	557
MS-Fixed Sch	0	117	490	291	470	485	367	543
MS-Random	0	117	490	291	468	412	369	535
w/ Daylight Ctrl	44	120	507	280	463	390	325	532

Table 2. Measured daylight levels (Lux) in 3rd floor north-facing office in Nagoya

Depth (meters)	1	2	3	4	5	6	7
6 Lts On-10 a.m.	1320	1110	995	965	855	750	663
6 Lts On-Night	610	795	820	792	770	650	580
4 Lts On-10 a.m.	860	680	665	750	790	636	580
Lts Off-10 a.m.	840	406	245	148	104	80	70
Lts Off-9 a.m.	600	170	100	55	35	25	20
Lts Off-4 p.m.	380	109	50	30	19	15	13

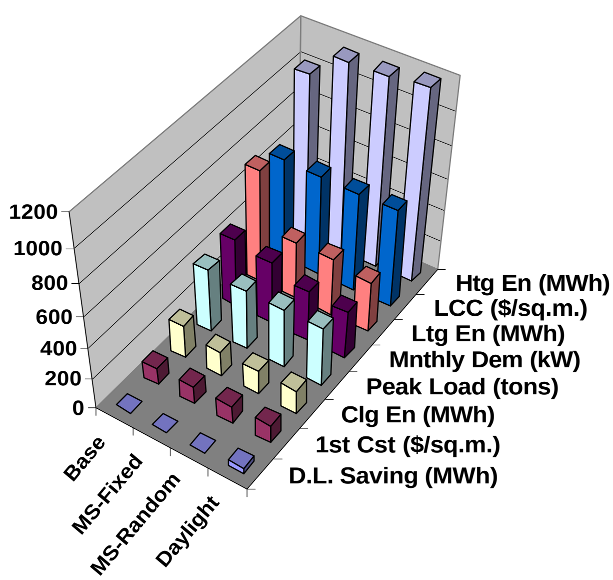

Fig. 6 Simulation results for Nagoya

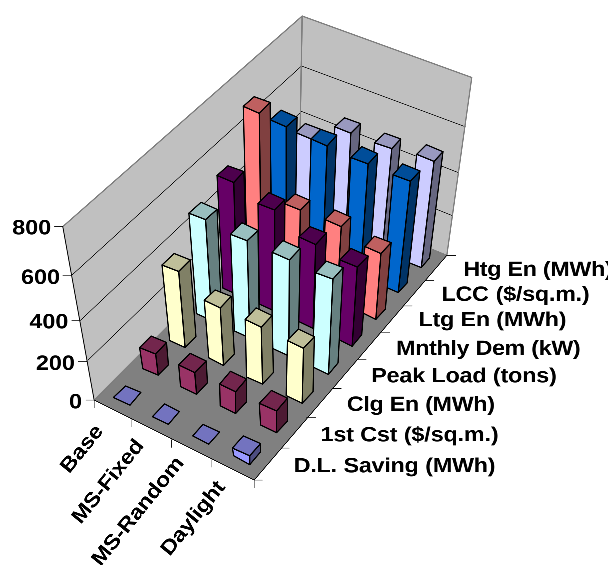

Fig. 7 Simulation results for Houston

RESULTS DISCUSSION

The conventional design in two climates. The base case building, as described here, could be referred to as the "conventional" design – i.e., an office building with no motion sensors or daylight-activated dimmers. In that condition, and without changing any of the connected lighting power density, the lighting energy shown is almost twice that shown for the real building with motion sensors. The peak air conditioning load of 484 tons in Houston represents a cooling load factor of 33 m^2 per ton, or 355 ft^2 per ton, which closely approximates the rule-of-thumb in the U.S. of 300 ft^2 per ton for office buildings. Nagoya pays a slightly lower cooling penalty, resulting in a peak load of 404 tons, or about 40 m^2 per ton. The bigger contrast in the two climates can be seen in the annual cooling energies (376 MWh in Houston and 210 MWh in Nagoya). A reversal of this is true for heating, with Houston requiring between 1/3 to 1/2 of the heating required in Nagoya.

Differences due to different motion sensor models. One of the original hypotheses of this study was that the use of a Monte Carlo probability simulation approach would made a difference in the way the peak load demands were predicted, while still maintaining the same prediction for energy consumption. The results confirm this clearly – as shown in lines two and three for both cities in Table 1. The differences can be seen more clearly in Figs. 6 and 7 in the third from last set of columns. For Nagoya, both lines show the same cooling energy (160 MWh), but the average monthly peak demand moves from 401 kW to 324 kW (a drop of 77 kW). In Houston, it results in a similar difference, moving from 485 kW to 412 kW (a drop of 73 kW). Though these two methods of simulation produce the same annual energy use, the reductions in average peak demand result in significant savings in the annual utility bills. In Nagoya the annual electric bill was reduced by 10,328 USD and in Houston, it was reduced by 7,373 USD. That represents a 13% reduction in Nagoya and a 9% reduction in Houston. This resulted in LCC savings of 11 USD/m^2 and 8 USD/m^2, respectively in the two cities. [Note that even though all costs are shown in USD, the costs reflect actual utility rates in the two countries. The reason for the higher savings in Nagoya is that the fuel prices are higher than those in Houston.]

In regard to first costs, the National Construction Estimator (NCE 1995) shows the installed cost of a combination motion sensor/switch at about 183 USD (21,960 JPY). The list price of a motion sensor alone in Japan is 8,700 JPY, so the total combination was estimated to be comparable to the U.S. price. Using one sensor per office, this results in an incremental investment of 7 USD/m^2 in the office areas only, which was added to the installed price of the lighting system.

Daylighting benefits. The lowest overall energy use was shown by the daylighting option in both cities. The cost of dimmer switches increased the first cost slightly, but only by about 2 USD/m^2 when considering the building's gross floor area. The 20-year LCC, however, was still reduced by 1 to 3 USD/m^2.

The use of daylight-activated dimmers could result in a reduction in the size of the installed cooling plant. Simulations show this reduction to be 5 tons in Nagoya and 9 tons in Houston. If this option were proposed during the design phase, a credit for the cost reduction in the cooling plant would help pay for part of the cost of the lighting dimmers. Because this study used an existing building, however, the first cost of the cooling plant was held as a constant, so the daylight controls show up as an added cost.

Life cycle costs. Life-cycle costs are computed by a Present Worth (P.W.) model using a 20-year economic life and an annual discount rate of 8%. The LCC is the sum of the first costs of construction (initial investment) and the present worth of the future annual owning and operating costs of the building. Electric and gas tariffs (energy and demand rates) were based on normative local prices for each city analyzed.

In Nagoya, the annual utility bill was estimated to be 172,000 USD for the most energy-efficient design, and in Houston this same design had an annual utility bill of 89,000 USD. Because of the higher price of energy in Japan, it was expected that the LCC benefits of the energy saving approaches would be more dramatic in Nagoya than in Houston. However, this was not the case, as the lower energy costs in Houston were counteracted somewhat by the higher amounts of cooling energy required. The result was that LCC savings were about the same in both cities. The overall annual utility bills were reduced by around 5% in Nagoya and by 16% in Houston. The conclusion here is simply that any energy saving devices that lower internal loads will most likely have greater impact in the climate that imposes the larger cooling loads.

The most dramatic reductions are in annual demand charges – these drop by 30% in Nagoya and 27% in Houston when going from the conventional design to the daylighting design with motion sensors.

CONCLUSIONS

This study has demonstrated that there is high potential for significant energy and LCC savings when occupancy sensors and daylight-activated dimmers are used throughout an office building in locations 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 approach is possibly the preferred method of establishing a realistic simulation of how the spaces are actually used. This method requires some survey statistics on how people use office spaces.

There was not an opportunity to collect real utility records for the case study building used in this project; however, this would be a logical next-step in furthering the work. Work is now underway in monitoring more detailed use patterns, and we plan to obtain energy use records for the building's past operations. This will also make it possible to calibrate the software model.

ACKNOWLEDGMENTS

The author wishes to acknowledge the financial support for this study from the Center for Integrated Research in Science and Engineering (CIRSE) at Nagoya University.

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