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Occupancy and Time-Based Lighting Controls in Open Offices

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Occupancy and Time-Based Lighting Controls in Open Offices

Abstract

We present analyses of two years' lighting data in open office areas, controlled by occupant sensors, time scheduling, or wall switches alone. We compare the energy savings using a before-after analysis of time scheduling and a conservative "moving baseline" analysis of both occupant sensing and time scheduling. We found that both techniques saved energy effectively when no occupants were present compared with wall switches alone. Time scheduling saved from 0.7 to 6.6% or an average of about 5%. Occupant sensors in similar areas saved from 9.0 to 14.6%, with an average of about 10%. False triggering of occupant sensors (by passersby) that would have caused energy waste was avoided by the presence of wall switches that positively turned lights off. Variations in occupant schedules and habits affected overall lighting energy use and the appropriateness of different control types. Little savings were found during the normal 8am to 5pm workday from either technology in large offices, but significant savings occurred after hours and on weekends. Our findings contrast with previous results for private offices in which only a single occupant is present, strengthening the evidence that different types of office space can be controlled appropriately with different types of control systems. However, small percentage savings in open areas result in larger actual savings due to the large number of fixtures controlled.

Introduction

Lighting controls are making their way into increasing numbers of U. S. buildings, but the potential for application of these technologies is still far from fully being achieved. A key element for decision makers in choosing lighting control technologies is evidence that these technologies will be effective in reducing rising energy costs. This long-term study adds to the small but growing body of literature describing the potential savings from occupant sensors and time scheduling controls in large open office areas.

Occupancy sensing has been shown to be an effective means of reducing lighting energy use in private offices [1,2,3]. Time scheduling can also save significant energy in similar large spaces [4,5]. In the lighting testbed on the General Services Administration floors of the Phillip Burton Federal Building in San Francisco, we examined lighting energy use in large open spaces with either occupant sensors or time scheduling controls versus wall switching alone. We discuss the operation of both control systems in the context of one working office building, and describe the impacts of user behavior on the potential for energy savings from either.

Description of the Site

Floors 3, 4, and 5 of the Phillip Burton Federal Building are devoted to the Advanced Lighting Testbed, with different technologies being tested on floors 3 and 5, and with floor 4 reserved as the reference or "base case" floor. The testbed encompasses 13 different technologies in three types of office space. This work describes the time-scheduled switching and occupant sensing technologies implemented in non-private open office areas in the testbed.

Figure 1. Floor plan of the testbed showing large open areas.

Overhead lighting consists of 2' X 4' 3-lamp T8 fluorescent troffers with parabolic louvers on an 8' grid over the entire ceiling, with a few 2' X 2' 2-lamp fixtures. Under-shelf task lighting is available in most of the cubicles. After relamping and initial lamp burn-in at the start of the testbed, the average full-light illuminance in open areas was about 700 lux, with a minimum of 231 and a maximum of 992. The wide range reflects the lack of coordination between furniture and lighting layout.

Figure 1 shows the layout of the entire testbed. The unshaded areas are the subject of this paper.

METHODS

Before the installation of controls, the whole testbed area had bi-level switching, with one switch operating the inboard lamp in each 3-lamp fixture and the other switch operating the outboard lamps. In the two floors (3 and 5) where dimming controls were to be installed, the bi-level switches were replaced by a single electronic switch that controlled both loads. This switch appeared identical to a standard wall switch except that it actually controlled a low-voltage relay rather than directly controlling a switch leg. In a few zones this rewiring was done incorrectly, complicating the data and sometimes making it unusable. The new electronic switches allowed all wall switch "on" and "off" events to be recorded. On the fifth floor, occupant sensors were installed in the open areas addressed in this paper. All use ultrasonic technology, and are set with a time delay of 15-20 minutes as in previous work [1]. When the wall switch was in the off position the occupant sensors did not turn the lights on, but every occupant sensor on or off event was recorded regardless of the actual state of the lights. On the third floor during 1998, there was no additional control in the open areas besides the switches. In November/December 1998, a time schedule was added to automatically shut off the lights at two-hour intervals on evenings and weekends.

The testbed was subdivided into zones, each with a separate kWh meter. Load (on or off status of lamps) and "reason" (switch, time schedule, operator, etc.) data were collected at the level of the lighting control panels, and served as a means of checking any anomalies in the switch and occupant sensor data. Energy data were collected in the form of accumulated pulses every 15 minutes.

Although dimming ballasts are installed on the third and fifth floors, in this paper only switching data are analyzed, and any dimming methods that affect energy consumption (see previous work [1]) are ignored. However, on the third floor the zones near windows are smaller and arranged in separately-switched rows, so they are analyzed separately from the larger multi-row interior zones just on the basis of their size. The two types of zones are called "large" and "small" throughout the rest of the paper, where "small" zones have 20 or fewer fixtures and "large" zones have more than 20 fixtures for two reasons. Most of the small zones on the third floor were narrow adjacent rows with very low or shared occupancy (each desk in more than one narrow zone), and so are not entirely independent, although they have separate switches and can be operated separately. In addition, the small zones have a larger proportion of corridor to office space than the large zones, and so are likely to see more casual passersby. Because of the high level of diversity of our data from this "real life" office environment we do not attempt to analyze these differences in this paper, but we noted the size difference for the reader's information.

On the third floor, we analyzed 7 large and 12 small zones. On the fifth floor we analyzed 2 large and 3 small zones. The two large zones that shared a wall switch had separate occupant sensors that operated the zones differently, so we analyzed them separately. Two of the small zones were adjacent and shared an occupant sensor, but had separate wall switches right next to each other. These were almost always operated simultaneously on weekdays but were often operated separately on weekends. We present data for these zones separately though grouped in the tables, with the caution that their lights are operated by the same occupant sensor or (in one case) that two zones may be operated by one wall switch.

On the fourth floor, no switching data were available, so the switching times were calculated from the available energy data and the known installed wattage in each zone. We used the results to estimate the daily average "on" time, the average morning "on" time, and the average evening "off" time. We were also able to determine the average number of times lights were left on overnight on this floor both on weekdays and weekends, for comparison with the other two floors.

Culling the Data

For the weekday analysis, only days with more than 8 hours of occupied time were considered. This eliminated only a couple of days in two or three zones, mostly days with faulty data collection. Holidays were also omitted. On weekends, there are no normal working hours, so this criterion was not applied.

We had an unusually large number of problems in this testbed due to inexperienced installers and complex data collection needs. In addition to the miswired switches, occasionally a problem occurred in a lighting control panel that necessitated bypassing the control functions until the problem was solved. In bypass mode, the lights are forced on and remain on until the problem is corrected and the bypass is removed. We omitted such days from the analysis, both for weekdays and weekends. The final average count of weekdays included in the analysis in floor 3 was 90 in 1998 and 217 in 1999. For weekends on floor 3 average surviving days were 37 in 1998 and 96 in 1999. For floor 4, the analysis included an average 186 weekdays and 85 weekend days. On floor 5 the data for 1998 and 1999 were analyzed together, for an average of 317 weekdays and 129 weekend days. The data sets for both years contain data from each season, though more data was missing or unusable in 1998.

Several areas were dropped from the data set for two reasons. Some had remained unoccupied during major renovation for long periods, and in a few others the sensors malfunctioned and did not turn out the lights. This left us with valid data on the third floor for all the large zones but only 12 of the original small zones, and on the fifth floor for two of the original six large zones and three of the original four small zones. On the 4th floor, fewer changes occurred and we only lost one small zone that turned out to be a corridor.

Uncontrolled Areas

For uncontrolled areas on the fourth (reference) floor, only energy data was collected. We used the energy data to estimate the on/off switching behavior to determine the number of days the light switches were left on overnight for comparison with switching behavior on other floors. On the third floor in 1998, the time schedule had not been implemented, so we were able to include that data in the anlaysis of uncontrolled areas.

Occupant Sensors

Using wall switch and occupant sensor state data and a computational method based on previous work [1], we determined the total time the lights were in each of four states defined in Table 1 below, for each zone in the 5th floor. For all hours each day, we compared the time the wall switch was on (states 2 + 3) with the time the lights were on (state 3). The total wall switch "on" time between the first and last events of the day serve as a "moving" baseline. The lights are off in all states but State 3. Note that states 1 and 3 include the time of the occupant sensor delay.

Table 1. State Definitions

State	Description	Wall Switch	Occupant Sensor	Overhead Light State
0	Vacant, wall switch off	Off	Off	Off
1	Occupied, wall switch off	Off	On	Off
2	Vacant, wall switch on	On	Off	Off
3	Occupied, wall switch on	On	On	On

Noting that wall switches are regularly turned out in uncontrolled areas of this building, we determined that a reasonable calculation of savings from occupant sensors could only be carried out with the assumption that without them the lights would have been turned out manually as described below.

Calculating savings from occupant sensors

To account for decreased use of wall switches in controlled areas, we split the days into two types, days when the wall switch is turned out by midnight (Day Type 1), and days with lights left on at midnight, either at the end (11:59 pm) or the beginning (0:01) of the day or both (Day Type 2). We performed the following calculations for each day type to determine the boundaries of savings from the occupant sensor in the controlled area. We then applied a factor to the two values based on the 3rd and 4th floor uncontrolled behavior to arrive at a "best" estimated occupant sensor savings based on the wall switch use pattern found in the uncontrolled zones.

The lights are only actually on in State 3. We can simulate the effect of using a wall switch alone, or an occupant sensing alone (without a wall switch):

Lighting hours with wall switch alone = Time in State 2 + Time in State 3

Lighting hours with occupant sensor alone = Time in State 1 + Time in State 3

We define the nominal savings from occupant sensors as the time in state 2. In all other states, the lights are either off due to the state of the wall switch, or on because they are apparently needed[1]. We can calculate the percentage savings as follows:

$$\text{Nominal \% Savings from occupant sensors} = \frac{\text{Time in State 2}}{(\text{Time in State 2} + \text{Time in State 3})}$$

where the denominator is the "moving baseline," or the total wall switch on time each day.

Finally, we calculate the energy that would have been wasted by an occupant sensor alone if the wall switches had not been available or had not been used by examining the occupant sensor intervals of exactly the duration of the time delay versus the total wall switch on time.

Time Scheduling with Telephone Override

Time scheduling is the practice of turning off the lights in a building automatically at specified hours after the normal working day. The time scheduling system used in the testbed is similar to systems used in other buildings. In some time-scheduling systems the lights are also turned on automatically at the beginning of the work day, but in this office this was considered an unnecessary step that had the potential to waste energy (there are no automatic-on schedules anywhere else in the building). Lights are turned on in the morning by the first person who desires them.

[1] This statement ignores the occupant sensor time delay.

At the end of 1998, the time scheduling system was implemented. Each zone in the time-scheduled area was given a four-digit code. These codes were supplied to the occupants according to their location, along with the telephone override phone number, in a letter from the building manager's office describing the operation of the scheduling system with instructions for overriding the schedule using their telephone keypad. Stickers on the phone jacks allow occupants who move to a different area to locate the access code in their new space.

Operation. Five minutes before the lights are scheduled to be turned off, the lighting control system causes the lights to blink in the scheduled zone(s). If an occupant wishes to keep the lights on, he or she may either:

1) Pick up the phone and dial the telephone override number and punch in the appropriate 4-digit code and the number of additional hours of light desired (The lights will shut off after the requested time), or

2) Walk over to the wall switch after the lights turn off, turn it off manually and then on again (The lights will stay on until the next scheduled sweep).

The original time schedule flashed the warning lights every hour from 6pm until 11pm, and at 2 hour intervals thereafter until 5am. We changed this schedule once because the occupants of the area thought the custodian was turning out the lights while they were still in their cubicles, whereupon they would begin to call out to her to turn the lights back on. In order to make her life a bit more comfortable, we changed the schedule to shut the lights off at two hour intervals beginning at 7pm. On weekends, the schedule warns the occupants and turns out the lights every two hours over the whole 24-hour period.

Calculating Savings from Time Scheduling

In the open areas on the time-scheduled 3rd floor we were able to use a modified "moving baseline" technique by a careful analysis of the switching events both by the time schedule and by occupants or custodians. Our analysis differentiated the first evening "off" event, because it was the first off event after the normal (8:00 to 5:00) working day. On some days, the lights were turned on one, two or (rarely) three times after hours, either by individual workers or custodians staying late. On other days, the lights stayed on quite late because late-night workers overrode every scheduled event. For each zone-day in the time-scheduled zones we selected all intermediate "off" periods that occurred because of a time-scheduled event, and summed them to obtain the time savings for that day due the schedule. Any "off" periods that occurred because of a manual (wall switch) event were not considered to represent savings, and were not counted. The "moving baseline" for each day was the time between the first "on" and the last "off" event of the day regardless of reason. Final "off" events by the time schedule were not counted as savings. It is likely that a few of the final "off" events by the schedule signaled as much as an entire night's worth of energy saved, but we did not count these savings because lights are rarely left on all night in the uncontrolled areas of this building.

On weekends, the custodians do not clean the offices and therefore do not turn off the lights. The analysis of weekends compares the fraction of the time lights are turned out by the schedule versus by the wall switch. The lights are turned on only rarely on weekends, either by employees putting in overtime or when work is being carried out by the building crew or contractors after hours.

RESULTS

Third and Fourth Floor "No Controls" Results

The data in Table 2 illustrate the switching behavior in areas with no added controls. On the third floor, the time schedule was not implemented until the end of 1998, and the data from 1998 in Table 7 (see Time Scheduling Analysis) are used with the 4th floor data to provide a reference for switching behavior in uncontrolled areas.

On the fourth floor the original bi-level switching caused some uncertainty about the exact time of the lights off events. In general, however, we believe the numbers in Table 2 represent what happened on this floor reasonably accurately. The main point of this table is that the lights are turned off very regularly, and fairly late, practically every weeknight in this floor, probably by the custodian.[2] Each zone was turned off regularly at about the same time every night. Of the total 2234 weekday zone-days on the fourth floor, the lights were left on all night (Day Type 2) only 1.85% of the days overall, and in four of the 12 zones the lights were never left on all night throughout the year. In only one zone was there a significant number of second "on" times. The average first on of the day was 5.58 and the average first off was 21.8 (decimal hours). On this floor, there are only two states: state 0 (off) and state 3 (on).

On weekends, on the contrary, custodians are not on duty. Of the 74 weekend zone-days where workers came in and turned on the lights, the lights were left on quite frequently (about 41% of those days, or 31 times). This number is reasonably consistent with the 28%

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[2] There is one custodian per floor, part of whose job description is to turn off the lights when they finish cleaning.

found on the third floor in 1998. The Day Type 2 percentage of all weekend days is much smaller as seen in the last column of Table 2. Weekends are clearly quite different from weekdays.

Table 2: Fourth Floor Analysis (decimal hours)

Weekdays							**Weekends**			
zone	**total days**	**average total on (hours)**	**average first on time**	**average first off time**	**days with second on**	**Day Type 2 (%)**	**total days**	**Days with any lights on**	**total on hours**	**Day Type 2 (%)**
large										
4-1	195	17.11	5.24	22.35	0	0.0	85	0	n/a	0.00
4-2	195	17.13	5.22	22.35	0	0.0	85	2	40.35	0.00
4-3	183	17.08	5.27	22.34	1	0.0	85	3	1.97	0.00
4-4	183	16.92	5.26	22.26	2	0.0	85	2	0.79	0.00
4-5	189	16.32	5.79	22.27	2	1.1	85	2	2.00	2.35
4-6	187	14.90	5.99	20.65	32	2.1	85	9	6.35	1.18
4-7	185	16.18	5.64	22.16	1	3.8	85	23	19.43	9.41
4-8	184	15.27	5.94	21.30	2	7.1	85	6	5.76	5.88
4-9	181	16.59	5.57	22.17	0	3.3	85	16	13.99	5.88
small										
4-10	180	16.09	5.31	21.40	0	0.6	85	4	12.71	3.53
4-11	189	15.90	5.84	21.74	3	1.1	85	4	3.46	2.35
4-12	183	14.53	5.93	20.69	2	3.3	85	3	2.64	0.00

Occupant Sensors

The control system remained the same in this part of the testbed throughout the analysis period, so no distinction was made between data for 1998 and 1999. The testbed had been in operation for 20 months prior to 1998, so the occupants were fully accustomed to the way the controls operated. Because we collected occupancy data independently of switch data, on the fifth floor we were able to examine occupancy patterns even when the lights were off (States 0 and 1). State 1 includes time when occupants chose to work without overhead lights, as well as time when the occupant sensor was tripped on by a passerby (see False On Analysis below).

Using the state definition given in Methods, we were able to calculate the average hours in each state for each zone over the entire 24-hour period. The results of these calculations are presented separately for weekdays and weekend days as percentages in Table 3. Weekdays are quite regular with an average standard deviation between 2 and 3, while on weekends the average standard deviation is between 30 and 40. The total number of "on" hours on weekends for days when lights are turned on varies from 0.25 to 24, and the lights are actually on at all on less than half the total days (Days with State 3>0).

The percentage of days when the wall switch was left on in the middle of the night (either at the beginning or the end of the day or both) is shown in the column labeled “Day Type 2.” This number is considerably larger than in the uncontrolled areas, probably because occupants trust the sensors to turn off the lights.

Table 3: State data

WEEKDAYS (Daily Average Hours)												
Zone		Day Type 1					Day Type 2					
		Number of days	State 0	State 1	State 2	State 3	Number of days	State 0	State 1	State 2	State 3	< σ >
large	5-4	282	7.4	1.9	1.1	13.5	43	3.0	0.9	5.8	14.3	2.04
large	5-5	282	7.5	1.9	1.1	13.5	43	2.9	0.9	5.7	14.4	2.14
small	5-1	255	7.5	2.9	1.1	12.5	48	2.8	1.2	5.7	14.4	2.49
small	5-2	254	7.5	2.9	1.1	12.5	49	2.8	1.1	5.7	14.3	2.55
small	5-3	278	8.2	1.2	2.0	12.6	51	3.3	0.6	6.9	13.2	2.59
WEEKENDS (Total Hours)												
large	5-4	97	1936.4	370.6	1.6	19.5	43	3.0	0.9	5.8	14.3	33.9
large	5-5	97	1990.2	316.8	3.7	17.4	43	2.9	0.9	5.7	14.4	34.7
small	5-1	69	1468.3	120.1	27.5	40.0	53	432.0	45.8	600.1	194.0	30.3
small	5-2	65	1392.4	105.7	23.0	38.7	57	489.1	52.4	623.4	203.0	30.8
small	5-3	77	1762.9	84.2	0.5	0.5	41	205.6	3.6	679.3	95.6	40.8

From the state data we calculated the average percentage of hours for weekdays and weekend days for the occupant sensor alone (states 1+3), the wall switch alone (states 2+3), and both wall switch and occupant sensor (state 3, lights actually on) for both day types. Day type 2 constituted 13.2 to 16.2% of the total weekdays, and 31.7 to 46.7% of total weekend days. Table 4 gives the results of the separate analyses. For these zones, the lower bound to the estimate of savings over the period studied is the savings calculation for Day Type 1, when wall switches are used to turn off lights at night. The upper bound is the savings calculation for Day Type 2, where the lights switches are left on for either the late night or early morning hours or both. The actual savings are between these values. Assuming that without occupant sensors the ratio of day type 2 to day type 1 would be as it is in the uncontrolled spaces on floors 3 and 4, the last column of Table 4 shows estimated savings due to occupant sensors, adjusted by this ratio.

There is a dramatic difference between weekday and weekend percentage savings calculated in this way. On weekdays, the occupancy patterns are very regular, while on weekends there may be no occupants, or the room may be occupied for many hours. The small percentage savings on weekdays are over a moderately large estimated baseline use ("Adjusted WS On" column in Table 4), while the large weekend percentage savings are over a much smaller baseline use. Despite the smaller percentage savings on weekdays, the actual weekday and weekend savings are quite similar, because of the larger number of total hours the lights were used on weekdays. The weekend percentage applies only to the wall switch on time on weekend days shown by zone in Table 4. The average actual on time for those days is very small, varying between .02% and 1.37% for Day Type 1 and between 3.38 and 6.93% for day type 2, while the WS On time varies a great deal between Day Type 1 and Day Type 2.

Table 4: Occupant Sensor Results

WEEKDAYS (% of daily hours, averaged over all days)											
		Day Type 1				Day Type 2				Adj. Day	Overall
Zone		OS On (%)	WS On (%)	Actual On (%)	Nominal Savings Lower Bound (%)	OS On (%)	WS On (%)	Actual On (%)	Nominal Savings Upper Bound (%)	Adjusted WS On (%)	Estimated Nominal Savings (%)
large	5-4	64.2	61.1	56.3	7.8	63.3	84.0	59.7	28.9	61.7	8.6
	5-5	64.2	61.0	56.2	7.8	63.8	84.0	60.2	28.4	61.6	8.6
small	5-1	64.1	56.8	52.1	8.3	64.7	83.4	59.9	28.2	57.4	8.9
	5-2	63.9	56.5	51.9	8.2	64.4	83.5	59.6	28.6	57.1	8.8
	5-3	57.4	60.9	52.5	13.8	57.3	83.8	55.0	34.4	61.4	14.4
WEEKENDS (% of total hours, all days)											
large	5-4	11.45	0.62	0.57	7.4	6.59	25.84	5.90	77.2	1.34	46.1
	5-5	9.81	0.62	0.51	17.4	5.58	25.84	5.10	80.3	1.34	52.3
small	5-1	5.47	2.31	1.37	40.7	8.19	27.12	6.63	75.6	2.66	45.8
	5-2	4.93	2.11	1.32	37.3	8.72	28.22	6.93	75.4	2.48	43.5
	5-3	2.99	0.03	0.02	52.6	3.50	27.36	3.38	87.7	0.43	84.9

Applying the appropriate estimated nominal savings to the % wall switch on for all weekends and weekdays, we can calculate a total savings. The results of this calculation are given in Table 4.1.

Table 4.1

Zone	Savings for all days (%)
Large	
5-4	9.0
5-5	9.0
Small	
5-1	9.6
5-2	9.4
5-3	14.6

The savings in the upper and lower bound columns in Table 4 illustrate the importance of using wall switches in conjunction with occupant sensors. With no wall switches at all, the lights would have been on for the OS On time on average each day. When the occupant sensor alone showed more on time than the wall switch alone, either there were enough passersby to account for the extra hours, or there were occupants working with the lights out after hours. The occupant sensor delay time affects the numbers in each of these calculations.

"False ON" Analysis

If wall switches are left on, occupant sensors will turn the lights on whenever a person passes through their field of view, whether or not they need the lights. Events triggered by passersby ("false ons") will cause the occupant sensor to be on for almost exactly its delay time. If the wall switch were not present, all of these false ons would represent time the lights were on unnecessarily. To determine how much energy would have been wasted in the absence of a wall switch by these false ons, we can compare the total occupant sensor 15-20 minute periods to the total wall switch 15-20 minute periods. The difference is an indication of the energy that would have been wasted if there had been no wall switches.

A number of 15-20 minute occupant sensor "on" periods can also be seen in the middle traces in Figure 3[3]. Longer periods indicate that someone might have actually been doing something in the zone, and presumably wanted the lights on, so those periods can't be counted as waste except that from the programmed occupant sensor delay time. Most of the time the wall switch was turned off at night, so false triggering did not occur. There are also "false ons" when the light switches are on, and these are included in State 3. In large office areas with multiple occupants, false ons in State 3 are rare during normal office hours, but common after hours until the wall switch is turned off, or on Day Type 2.On weekends, the OS On value in Table 4 is quite large in comparison to the Actual On time for Day Type 1. This includes false ons, but is also an indication that some occupants work for significant periods on weekends using only their task lights, or perhaps only the light from their computer monitors. State 1 in Table 3 represents the energy that would have been wasted in the absence of wall switches. To determine how much energy would have been wasted in the absence of a wall switch by false ons, we can simply add up the number of individual 15-20 minute periods over the day when the occupant sensor was on while the wall switch was off. These "false ons" are analysed in Table 5 for Day Type 1. Subtracting these false ons from State 1 gives the time when occupants are working in the area but have chosen not to turn on the lights (last column of Table 5). The time in this condition would also contribute to wasted energy if wall switches had been omitted or were difficult to find.

The occupant sensor delay time affects the numbers in each of these calculations. In the testbed at 450 Golden Gate, the sensor delays were chosen to minimize occupant complaints and to give the sensors the best chance of seeing the occupants. Figure 3 illustrates an example switching profile for two large adjacent zones. In each, the upper trace shows the state of the wall switch (on or off), and the middle trace shows the state of the occupant sensor. The lower trace shows the actual measured energy data for the zone. The periods when the wall switch is on but the occupant sensor is off represent the savings attributable to

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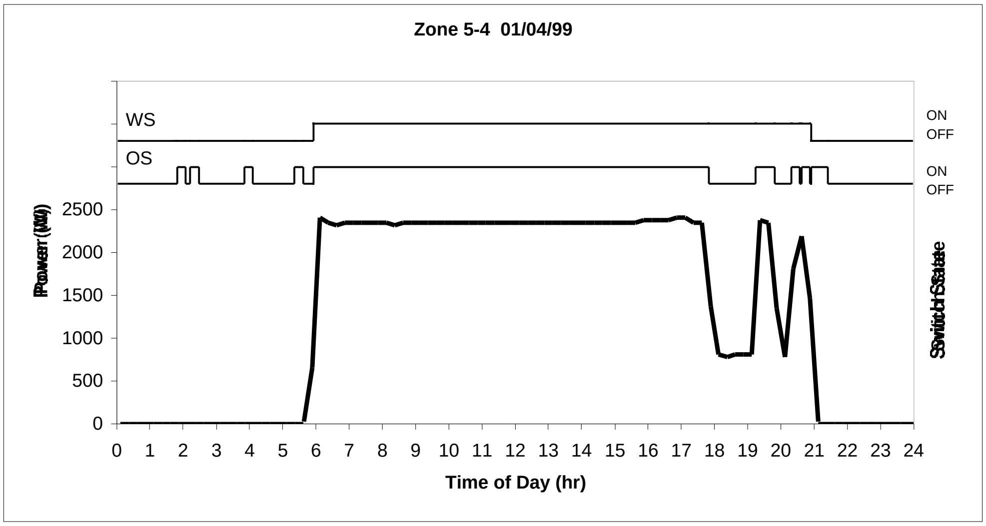
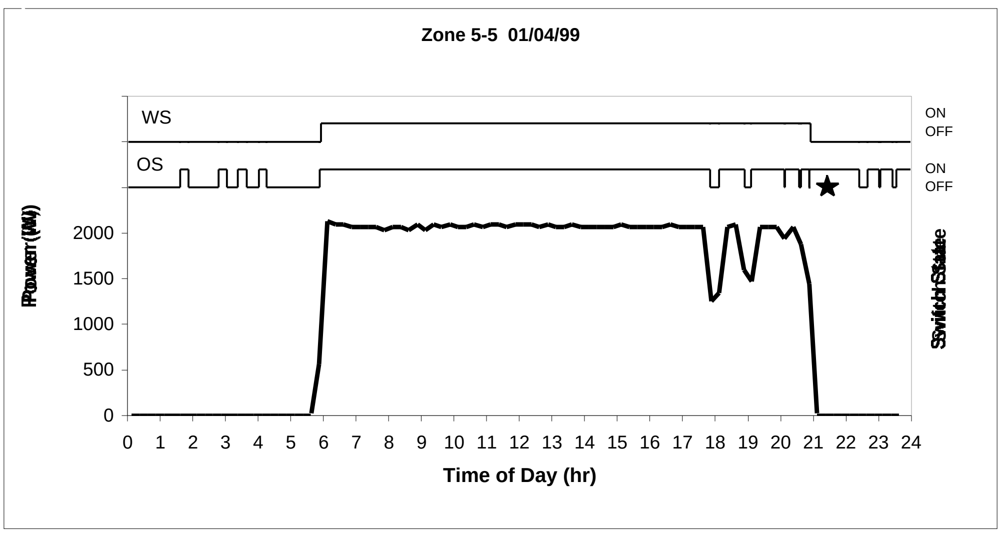
[3] The precision of our graphics program makes the 15-minute intervals appear more variable in width than they actually are.

occupant sensors. Notice also in this figure that there appears to be a period after hours when





an occupant worked without overhead lights, probably using task lights (see Figure 3, at ★).

Figure 3. Three-trace graph for zones 2 and 3

Table 5. Occupant Sensor "False On" Analysis (Daily Average Hours)

Day Type 1				
Zone	15-20 min OS interval	15-20 min OS+WS ON interval	Time wasted if no wall SW	Time occupant worked w/o lights
Large				
504	1.35	0.27	1.08	0.82
505	1.29	0.26	1.03	0.87
Small				
537	0.81	0.25	0.56	2.31
538	0.80	0.25	0.55	2.32
502	0.85	0.38	0.47	0.69

Time Scheduling Results

We did an initial data analysis to test the intended before/after analysis of time scheduling by comparing average daily on hours from a month (August 98) before and a month (August 99) after the application of the control technique in the same experimental areas. The averages for these months are presented in Table 6. We noted that in August 1999 there were 8.6% fewer "on" hours than in August 1998, for both large and small zones. At first glance, this seemed a reasonable estimate of savings.

Table 6. Preliminary comparison: August 1999-1999

	Aug-98	Aug-99	difference
average of large zones	14.32	13.08	8.6%
average of small zones	13.95	12.75	8.6%

Next, we did the same simple analysis for the entire year in 1998 and 1999. Figure 5 and Table 7 indicate that the differences in average "on" hours are much higher in some zones in 1999 than in 1998, and vice-versa in others, which we guessed might be caused by something other than the implementation of time scheduling. The results caused us to delve deeper into the occupants' switching behavior to enable us to evaluate the effects of both time scheduling and other influences in the different zones. This close examination of the data led us to conclude that differences in occupants' schedules over time swamped the differences caused by the control treatment in several zones, perhaps due to a project over a period of months in a section of this floor. This resulted in the development of a "moving baseline" method for this control technique (see Methods).

Figure 6 illustrates four example days of switching data in 1999 for a zone with time scheduling. On 1/5/99, the lights were turned off by the time schedule at the first scheduled "off" time (19:00). On 4/27/99, the lights were turned off at the wall switch by either the occupants or the custodian before 19:00. On 12/6/99, the time schedule tried to turn the lights off twice but an occupant overrode the schedule and kept the lights on. Upon leaving, the occupant turned the lights off again at about a quarter past 10 PM. For these first three examples, no savings were attributed to the time scheduling system because all persistent switching was done either by occupants or custodians. On 12/17/99, the lights were turned off by the time schedule at 7 PM, and then turned on again by an occupant coming in to work after hours at about 7:20. This time the occupant left the lights on, and the schedule turned them off again at 9 PM. In the last example, the time schedule saved energy in the period between the first off event and the arrival of the late-evening worker (the second "on" event).

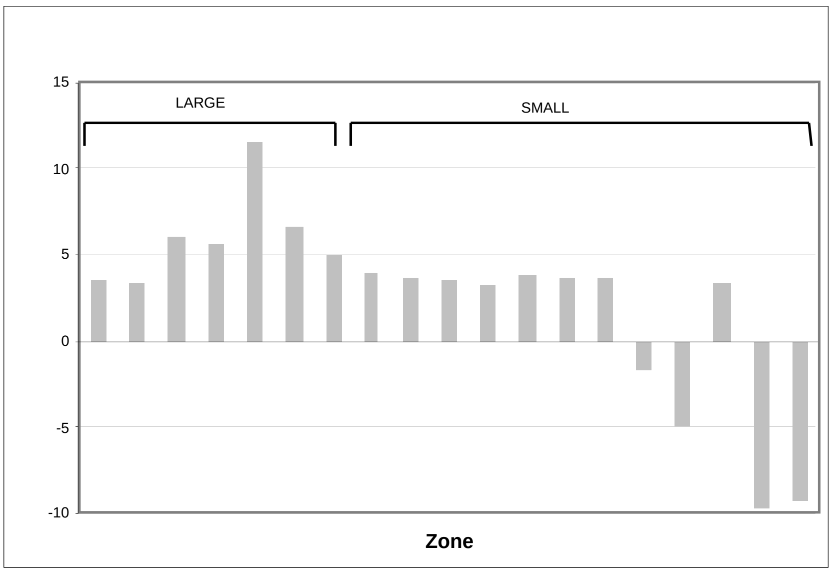


Figure 5. Percent Difference in Total “On” Time for Scheduled Zones, 1998-1999

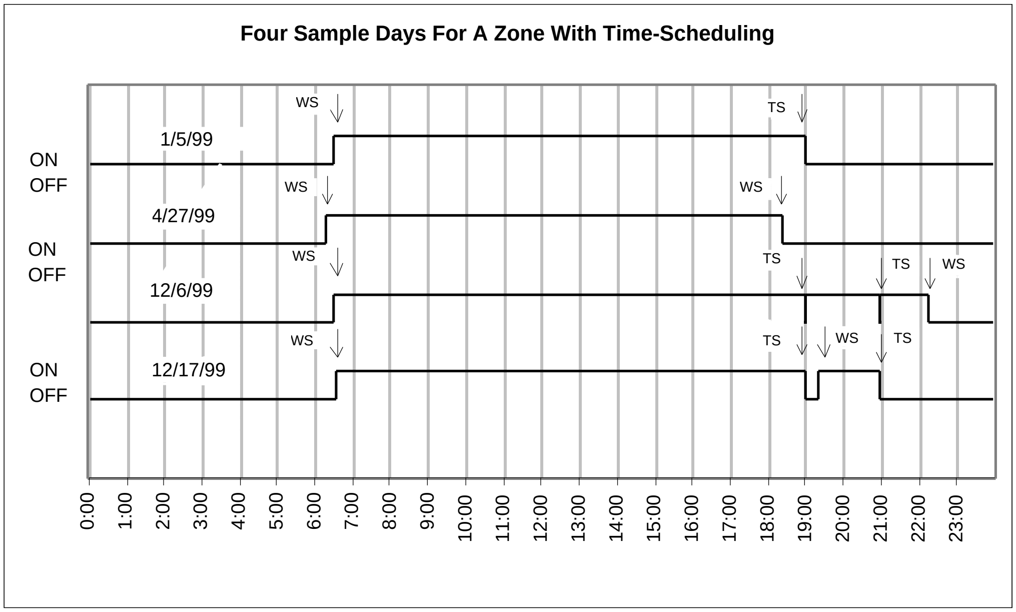


Figure 6. Four sample days for a zone with time scheduling

During most normal weekdays in uncontrolled open areas the lights are turned on once in the morning (the "first on" event) and off once in the evening (the "first off" event). Under the time schedule, workers who need to stay late or who return after a break and find the lights off may use the telephone override to keep the lights on longer or switch them back on at the wall.[4]

An analysis of switching patterns is presented in Table 7. As an example, in zone 3-4 in 1998, there were few "on" events after the lights were first turned off, usually at about 20.3 hours (8:15 pm). However, in 1999 occupants came in a second time 136 out of 233 total days in 1999, at about 20.2 (8:12 pm) on average, and yet a third time on 13 of those days[5]. The average last off time (by any means) is 20.4 hours (8:24 pm).

The nominal savings from time scheduling for this example are calculated as described in Methods. The first "off" event was due to the time schedule 97% of the time. For the second "off" periods, 60% of the 136 "off" events were due to the schedule, and for the third "off" periods, 8% (one) of the 13 off events were due to the schedule. Savings are only counted when a time-scheduled "off" event is followed by an "on" event, as described in Methods. The total average savings for this zone were .73 hours per day, or 170 hours over the 233

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[4] In the time-scheduled zones we have no occupancy data and cannot tell whether people were present and working without lights.

[5] There were even a very few fourth ON events in some of these zones that we did not include due to space.

days studied, for a nominal average savings of 5.1% shown in Table 8. Keeping in mind that most of the small zones are not strictly independent, the average nominal savings calculated in this way for all the zones is 4.8% in both large and small zones, with a range from 0.7% to 6.3%.

The average first off value in Table 6 is later than on floor 3 in 1998. There is one custodian per floor in this building, and it appears that they do not turn the lights off all at the same time. This first off time could have a very significant effect on the baseline against which savings are calculated.

In the example zone (3-4) calculation above, there were 97 days with no second "on" time of which 85 were at 19.00 (7:00 pm), and 8 were at 21.00 (9:00 pm). The remaining 4 were due to wall switches, and were between 22.3 and 22.42 (10:18 and 10:25 pm), indicating that the schedule had been overridden twice before being turned off at the switch.

We have assumed that on days with at least a second "on" time, the occupants would not have turned out the lights since they were intending to come back, based on the large fraction of first "off" events due to time schedule in this example zone and the scant number of second "on" events in 1998. First "off" appears to be different from subsequent "off" events. Considering all large zones, we found that although 92% of first "off" events were due to the time schedule, only 52% of all subsequent "off" events (including those that are the last "off" of the day) are due to the schedule. It appears that people who stay late are more inclined to take the initiative to turn off lights, probably because they are likely to know that they are the last person in the space. Overall, the time schedule was responsible for 76% of all "off" events in the time-scheduled zones.

Note also that there is a trend toward more late night activity in the zones toward the bottom of the table. The larger zone numbers are on the east end of the building, where we noticed that people seemed to stay late during a certain period of 1999, possibly due to a group in that area working on a big project deadline. On the west end of the building there were fewer late night events.

Although no savings are claimed for off events by the time schedule that are not followed by another "on" event, though it is probable that some savings are due to these events, and even likely that on a few of these nights the lights would otherwise have been left on all night (see Results,Third and Fourth Floor "No Controls" Results). An estimate of the potential savings is about 10 additional hours for each night the lights are left on. On the 4th floor the lights were left on overnight an average of 1.9% of the days.

Table 7: Time Scheduling Analysis

Weekdays (decimal time)

Zone	Total days		Day Type 2	Average 1st ON time		Average 1st OFF time		Average Last OFF time		Average Total ON hours		Days with 2 or more ON events		Days with 3rd ON event	1st off by TS (%)	2nd off by TS (%)	3rd off by TS (%)
Year	98	99	98	98	99	98	99	98	99	98	99	98	99	99	99	99	99
Large																	
3-1	96	235	4	6.23	6.15	19.3	19.0	19.3	19.2	13.4	12.9	1	28	2	87%	54%	0%
3-2	88	184	0	6.40	6.34	19.8	19.1	19.9	20.0	13.5	13.1	3	80	6	96%	70%	0%
3-3	87	233	10	5.96	6.36	20.3	19.1	20.4	20.4	14.5	13.7	6	137	12	97%	61%	8%
3-4	88	233	5	5.96	6.36	20.3	19.1	20.3	20.4	14.4	13.7	5	136	13	97%	60%	8%
3-5	94	225	8	5.99	6.14	22.2	19.3	22.4	21.7	16.5	14.6	4	189	77	86%	43%	6%
3-6	95	225	6	6.00	6.08	21.2	19.3	21.3	21.5	15.5	14.5	3	181	61	92%	67%	7%
3-7	91	215	0	6.49	6.45	21.4	19.5	21.4	21.7	14.9	14.2	2	170	67	92%	71%	7%
Small																	
3-8	96	233	4	6.34	6.19	19.3	19.0	19.3	19.2	13.3	12.8	1	28	2	85%	61%	0%
3-9	88	183	0	6.38	6.34	19.8	19.1	19.9	19.9	13.5	13.1	3	84	6	95%	71%	0%
3-10	88	184	0	6.40	6.34	19.8	19.1	19.9	20.0	13.5	13.1	3	85	8	95%	72%	0%
3-11	88	183	0	6.40	6.34	19.8	19.0	19.8	20.0	13.5	13.0	3	84	7	95%	70%	0%
3-12	87	233	4	5.96	6.36	20.3	19.1	20.3	20.3	14.2	13.6	2	128	11	97%	59%	18%
3-13	87	233	4	5.96	6.36	20.3	19.1	20.3	20.3	14.2	13.7	2	135	14	97%	59%	29%
3-14	87	233	4	5.96	6.36	20.3	19.1	20.3	20.3	14.2	13.7	2	135	12	97%	60%	17%
3-15	94	225	3	6.01	6.07	20.1	19.3	20.2	21.3	14.1	14.4	5	175	53	87%	59%	8%
3-16	94	225	3	6.02	6.14	19.8	19.3	20.0	21.6	13.9	14.6	5	191	71	88%	66%	8%
3-17	90	219	0	6.50	6.45	20.9	19.3	21.1	21.5	14.5	14.0	4	179	64	91%	66%	6%
3-18	91	216	0	6.49	6.45	19.5	19.5	19.7	21.9	13.1	14.3	6	178	84	90%	69%	10%
3-19	91	215	0	6.50	6.45	19.5	19.5	19.7	21.8	13.1	14.3	4	175	82	91%	65%	12%

Weekends (decimal time)

	Total weekend days		Days with any lights on		total ON hours		0n at midnight		midnight on/days on	
zone	1998	1999	1998	1999	1998	1999	1998	1999	1998	1999
Large										
3-1	37	96	n/a	2	n/a	0.59	n/a	0	n/a	0%
3-2	37	96	3	18	0.76	2.18	0	0	0%	0%
3-3	37	96	7	1	20.76	2.88	6	0	86%	0%
3-4	37	96	5	1	19.48	2.88	4	0	80%	0%
3-5	37	96	6	21	8.94	4.05	2	0	33%	0%
3-6	37	96	4	21	1.42	3.82	0	0	0%	0%
3-7	37	94	4	14	2.15	2.56	0	0	0%	0%
Lg. totals			29	78			12	0		
Small										
3-8	37	96	n/a	2	n/a	0.59	n/a	0	n/a	0%
3-9	37	96	3	16	0.91	10.14	0	0	0%	0%
3-10	37	96	3	17	0.91	4.18	0	0	0%	0%
3-11	37	96	3	18	0.89	2.18	0	0	0%	0%
3-12	37	96	3	1	16.49	1.40	2	0	67%	0%
3-13	37	96	3	1	16.49	2.88	2	0	67%	0%
3-14	37	96	3	1	16.49	2.88	2	0	67%	0%
3-15	37	96	5	21	1.90	4.72	1	0	20%	0%
3-16	37	96	4	21	2.05	4.61	0	0	0%	0%
3-17	37	94	4	17	2.15	2.63	0	0	0%	0%
3-18	37	94	4	18	2.15	2.56	0	0	0%	0%
3-19	37	94	4	19	2.15	2.44	0	0	0%	0%
Sm. totals			97	306			31	0		

Another noticeable difference between 1998 and 1999 was in the average first morning "on" time, which in some zones differed by as much as 23 minutes between the two years as seen in Figure 7. The first morning "on" time is unrelated to the operation of the time-scheduling system, but affected the total "on" time during the day. The first "on" event of the day varied over time according to occupant habits or changes in personnel. The lights on these floors are turned on by the first occupant to arrive in the morning[6]. The percentage savings are affected by the first morning "on" event because the moving baseline technique counts the total time between first and last events as the baseline.

[6] Personal communication with building staff.

Table 8: Time Schedule Savings Estimates

1999 Weekday Savings Estimates

Zone	Nominal Savings (hours/day)	Moving Baseline (last off - first on)	Nominal % savings
Large			
3-1	0.09	13.02	0.7%
3-2	0.53	13.61	3.9%
3-3	0.72	14.41	5.0%
3-4	0.73	14.40	5.1%
3-5	1.03	15.72	6.6%
3-6	0.94	15.47	6.1%
3-7	0.95	15.18	6.3%
Small			
3-8	0.10	12.92	0.8%
3-9	0.56	13.64	4.1%
3-10	0.56	13.64	4.1%
3-11	0.56	13.61	4.1%
3-12	0.68	14.33	4.8%
3-13	0.73	14.39	5.1%
3-14	0.73	14.39	5.1%
3-15	0.83	15.28	5.4%
3-16	0.96	15.59	6.1%
3-17	0.90	15.01	6.0%
3-18	0.97	15.36	6.3%
3-19	0.96	15.30	6.3%

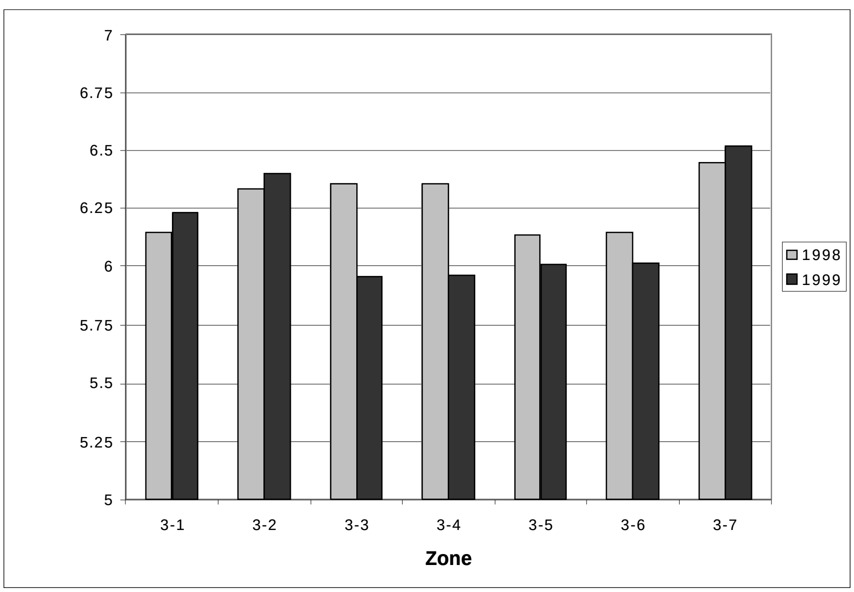

Figure 7. Illustration of changes in first morning "on" event over test period

On weekends in this building, the total savings from the time schedule are small, in part because there are few total weekend days when lights were turned on. There are no custodians on weekends, and we noticed that occupants left the lights on all night in several of the zones in 1998 (see Table 7, Weekends). In large zones, lights were left on overnight on 12 of the total 29 weekend zone-days on which lights were used in 1998, or 41% of those days, and in small zones 31 out of 97 (32%). In 1999 the schedule always turned off the lights. Applying these percentages to the 1999 days with any lights on, we can speculate that the schedule saved a nights' worth of energy on 32 days in large zones, and 98 days in small zones.

On this floor, we do not know how much people may have worked on weekends without lights because we have no occupancy data. The savings potential is highly dependent on whether or not workers use the wall switches on weekends, either to turn the lights on or off.

DISCUSSION

The potential for savings from switching controls such as occupant sensors and time schedules depends on the type of space and the behavior of occupants of the space, whether cubicle occupants or custodians. Such controls can save a great deal of energy in areas that are frequently unoccupied and where the lights are left on. However, they have very little effect during normal working hours or in areas where occupants are diligent in turning out lights when they leave rooms, and they can cause some waste if their presence causes occupants NOT to use the wall switches. The usefulness of these controls in large spaces is in ensuring that lights are switched off when not needed. If the last occupant to leave always turns out the lights, no switching control system, occupant sensing or time scheduling included, can save any energy. But in most buildings, some people forget, and control systems act as valuable insurance against wasted energy.

Large open office areas are very different in character than small private offices. In small private offices, occupant sensors can save very significant amounts of energy right in the middle of the day for occupants who frequently leave their offices. In larger spaces during normal working hours, there is no clear ownership of the area. With multiple occupants potentially unseen behind cubicle walls there is reduced incentive to turn off wall switches, an effect much more pronounced in the presence of automatic controls. But while the percentage savings from controls in large spaces is much smaller, the larger size of the space means that the actual savings potential from a single occupant sensor or time-scheduled switch is greater. For example, in a private office with two 3-lamp light fixtures, the potential savings for an hour of unoccupied time with an occupant sensor set at 15 minute time delay would be 3/4hr * 180Wh = 135 Wh, or .135 kWh. In a large area with 36 3-lamp fixtures, the potential for savings from the same unoccupied hour is 3/4hr * = 2430Wh, or 2.43 kWh. Though in a small private office you may achieve an average of 26% savings from occupant sensors on a weekday[1], the result for each sensor is a small number. In the large office, a savings of 10% can have a much more substantial benefit for the relatively small cost of installing the sensor.

Large spaces behave much more like private offices during normally unoccupied hours with individual people working overtime. Workers who stay late are likely to be aware that they are the only person in a large office area, so they are much more likely to switch off the lights by hand.

Occupant Sensors

Occupant sensors "see" a diverse population, and can only turn off the lights when every one of the occupants in an area is gone. Similarly, time schedules are overridden for the entire area controlled by a single switch when only one person is left requesting that the lights remain on. These characteristics limit the ability of these control methods to save energy to a degree which depends on the number of occupants and the diversity of their schedules in the area controlled by a single switch.

False ons with occupant sensors (due to passersby) caused some energy waste (and reduction in savings) that would not have occurred with time scheduling, but the occupant sensors also turned off lights soon after the last occupant left rather than waiting until the scheduled time. The total "on" hours on a given day include these false ons, because they are part of the typical operation of occupant sensors. Their effect varies with the programmed time delay in the occupant sensors. Occupant sensors that are adjusted not to "see" corridors will have a lower incidence of false ons. False ons can occur when individuals working late in one area pass through other areas on the way to the coffee room or the elevator, causing lights to be turned on unnecessarily. The emergency lighting is designed to be adequate for this incidental traffic.

Specific limits to the potential savings of occupant sensors include the likelihood of passersby triggering occupant sensors (causing a "false on"). The much larger fraction of days with wall switch on at night in the area controlled by occupant sensors is an illustration of 1) Reduced use of wall switches because occupants trust the occupant sensor to turn off the lights, and 2) Increased likelihood of passersby triggering occupant sensors and causing a "false on."

Occupant sensor time delays can be set at lower values, thereby diminishing the effect of false ons, but potentially adding to occupant dissatisfaction. This is a matter of choice for building operations personnel. In open offices, the occupant sensor time delay has little effect on savings during normal working hours, but it can be significant after hours if the light switch is left on. The total effect depends on the amount of traffic near enough to the controlled area to cause the sensor to trip, and can vary widely from day to day. For this paper, we did not modify the calculation to include the error due to occupant sensor time delays. A potential improvement to the state of the art for occupant sensors would be to permit reduced time delays on weekends.

On weekends, the percentage savings from occupant sensors can appear much larger than on weekdays, if wall switches are not turned off. The total savings depend on how often occupants actually work on weekends and whether or not they are conscious of the need to flip the switch when they leave. We also noted that workers put in significant hours without turning on the lights on weekends, probably using task lights which are available in all cubicles in these open areas. Task lights also permit lower general lighting levels, and we believe that they should be included in all office spaces.

Comparing these results with earlier estimates of savings in private offices [1], it is clear that greater savings are achievable where occupant sensors are designed to control smaller areas. A narrower field of view from the occupant sensor would eliminate a portion of the false on events relative to the size of the area covered, and a shorter time delay would reduce the waste from such false ons.

Light switches are a very important part of any lighting control system, because they can allow lights to be turned off positively, but as always their effect depends greatly on how they are used. In an office where people pass through often on their way to another area or while making security rounds, occupant sensors can waste a great deal of energy if the wall switches are not available to override them or are hidden. Wall switches that are all in the same place are at risk of being turned on and off all at once, particularly if they are remote from the lights they control, but this effect is reduced after normal working hours. Large offices are required by code to have emergency lighting which is adequate for passersby, and in this testbed data showed that occupant sensors without wall switches would have saved no more than wall switches alone in the areas in which they were installed. We believe that all commercial office buildings should have manual switches capable of overriding the occupant sensors even if they are not required by code, and even if automatic switching controls such as occupant sensors or time scheduling are used.

Time Scheduling

Time scheduling controls could save a great deal of energy if there were nobody who regularly turned off light switches. On the other hand, if there were someone who diligently turned the lights off every night at 6pm, a time schedule that turned the lights off at 7pm would not produce any savings at all, and might cause energy waste.

Lights in time-scheduled zones are not typically turned on by passersby if emergency lighting is properly designed, so energy is not normally wasted in this way. However, since the automatic switching takes place only at preset hours, energy may be wasted between the time the last occupant leaves and the time-scheduled switching if the wall switch is not used. The amount of such potential waste can be adjusted by increasing the frequency of scheduled switching events, but this must be balanced against potential annoyance of the occupants.

Part of the custodial crew's job in this building is to turn off lights in this building when they have finished cleaning their area or floor, so the time-scheduled off times include some amount of time that might otherwise have been wasted. On the other hand, the schedule might also have switched out the lights before the custodian got around to it. In addition, we have observed that occupants will turn off lights, particularly when they are likely to be the last person left in a particular area. It is also possible that the custodian will learn to forget to turn off the light switch if they think the control system will do it for them.

Conclusion

In a long-term test of functioning office spaces with diverse occupants, we determined that both occupant sensors and time scheduled controls have the potential to save significant energy, but that the savings that can be attributed to controls depend greatly on occupant habits and custodial practices. We found that both methods saved energy consistently, but that he presence of lighting controls affects occupant behavior. Since our moving-baseline method ignores potential savings from the last "off" event in any day, our nominal savings results are conservative.

Occupant sensors in general turned the lights off well before the wall switches were turned off, saving a nominal average of 10% of lighting energy in the zones they controlled. On weekends, the percentage savings from occupant sensors was much larger at 47% -- a number that is highly dependent on occupancy patterns, and applicable only to a small amount of time. Overall savings averaged 10% form occupant sensors. Savings from occupant sensors in the areas studied were negligible in the absence of wall switches that positively turned off the lights, avoiding occupant sensor "false ons."

A nominal average savings of 5% was calculated in the time scheduled areas with a period of 2 hours between scheduled off events. Time scheduling was responsible for 76% of all "off" events in these areas.

Our findings contrast with results for private offices in which only a single occupant is present and "ownership" of the lighted space is more personal. In private offices, the occupant usually turns out the light switch when leaving at night, knowing that no one else is in the space. Casual passersby are more frequent in larger zones, and the diversity of occupant schedules means that the lights are almost always on in large zones during the normal workday regardless of the lighting control technique.

Occupant behavior has a marked effect on the savings attainable by lighting controls and the appropriateness of one control technique versus another, because occupants operate wall switches. No savings can be attributed to controls whenever a wall switch is used to turn off the lights in any of these zones, but the presence of wall switches allows occupants to save additional energy over that which could be saved by automatic controls (for this to be true, it is important that wall switches be able to positively turn off the lights). Occupants who assiduously turned out their light switches in areas controlled by either technology were responsible for considerable energy savings, none of which was attributable to the control technologies.

The decision to choose one particular control system over another should be based on an analysis of expected occupant behavior (including custodial or service personnel) in the area to be controlled. Both control systems considered in this study save energy consistently, though how much they save depends on how they are commissioned and coordinated with the needs of the users of the space. We propose that, in addition to lighting controls, building managers advise their occupants that they should turn off the lights when they leave.

Acknowledgment

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