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Monitored lighting energy savings from dimmable lighting controls in The New York Times Headquarters Building

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Abstract

Digital addressable, dimmable lighting controls were introduced to the US market in the early 2000s with the promise of facilitating capture of potential energy savings with greater flexibility over their historic, typically unreliable, analog counterpart. The New York Times Company installed this emerging technology, after having tested the system thoroughly prior to procurement, in their new building in New York, New York. Four years after full occupancy in 2007, the owner agreed to participate in a post-occupancy monitored evaluation of the dimmable lighting system to verify actual performance in the field. Annual lighting energy savings from daylighting, setpoint tuning and occupancy controls were determined for the daylit, open-plan office areas on three typical floors (6, 11, and 20th floors) of the 51-story high-rise tower. Energy savings were calculated from ballast control signal and occupancy data recorded by the manufacturer's lighting control system. The ballast data were calibrated with independent measurements of lighting energy consumption. Savings from dimming controls (daylighting and setpoint tuning) were 12.6 kWh/m^2-yr (1.17 kWh/ft^2-yr) for the daylit spaces on the three floors overall, or 20%, relative to ASHRAE 90.1-2007. Compared to the prescriptive code in effect at the time of the building's construction (ASHRAE 90.1-2001), savings were 21.0 kWh/m^2-yr (1.95 kWh/ft^2-yr) or 28%. Annual lighting energy use with all lighting control strategies was 33.9 kWh/m^2-yr (3.15 kWh/ft^2-yr) in the daylit, open plan zones on average for the three floors. A simple payback analysis was conducted.

Keywords: Building energy-efficiency; Daylighting; Lighting control systems

1. Introduction

Dimmable lighting controls have long been promoted as a promising energy-efficiency measure for commercial buildings but historically have been hindered by technical and market barriers associated with cost, complexity, and as a result often inadequate performance, such as under- or over-dimming, or cycling [1-4]. In early 2000, however, digital addressable, dimming electronic ballasts and sensors began to enter the market, offering consumers an alternative to the conventional grouped analog systems which were difficult to commission upon initial installation and costly to reconfigure as space use changed over the life of the building. Subsequent studies with this type of technology have showed significant savings in a

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variety of settings [5-7]. Nevertheless, as an emerging technology, the first cost of these digital ballast alternatives was, at the time, as high as for their analog counterparts and significantly higher than for conventional on-off ballasts. As a consequence, the new technology had been adopted by very few building owners and developers.

In 2003, The New York Times Company considered use of dimmable lighting in a new high-rise building they were constructing in New York, New York but faced the challenge of whether to risk procurement of a new, unproven technology where even the communications protocol (e.g., digital addressable lighting interface (DALI)) had not yet been ironed out within the industry. With support from the New York State Energy Research and Development Authority (NYSERDA), the Times Company collaborated with the Lawrence Berkeley National Laboratory (LBNL) to evaluate several early-market, dimmable lighting control systems in a 422 m^2 (4500 ft^2) full-scale mock-up of a corner of their building. The 18-month monitored evaluation enabled the owner to fully verify reliability and energy-efficiency performance, and more confidently specify and procure the dimmable system at a competitive price [8]. Commissioning tools developed and tested at the mock-up were used in the building, after construction, to ensure that workplane illuminance levels were being adequately maintained. The building was completed and occupied in 2007. In the end, the Times Company had made the single, largest procurement of dimmable lighting in the US, installing the system in all perimeter zones on all floors occupied by the Times Company: floors 2-21 (58,372 gross m^2 (628,000 ft^2) of the 142,000 m^2 (1.5 Mft^2) 51-story building.

The Times Building has been promoted world-wide as a "successful" demonstration of daylighting and dimmable lighting controls, but its actual post-occupancy performance has been unverified. Innovative building systems are rarely evaluated after occupancy due to lack of resources, lack of interest on the part of the owner, or concerns regarding inconvenience to the occupants, impositions on privacy, or liability or defamation of the owner's or architect and engineer's reputation. On-going real time measurement and feedback on energy use and occupant satisfaction as part of building operations is not yet standard practice. And yet, post-occupancy data are invaluable to the building industry, providing factual, non-anecdotal feedback on whether innovative systems work as claimed: delivering energy and demand savings to the degree predicted, meeting occupant requirements, and running smoothly under facility management. Without well documented performance data, opportunities to maximize the impact of the lessons learned are lost.

To further assist in accelerating adoption of innovative energy efficient technologies, in 2011 the Times Company agreed to participate in a post-occupancy evaluation as a partner in the US Department of Energy's Commercial Building Partnership program with additional support from the California Energy Commission through its Public Interest Energy Research (PIER) Program. This study details the research conducted to monitor and verify the energy-efficiency benefits of the dimmable lighting control system. Assessment of the energy performance of the automated shading system and underfloor-air distribution system, and occupant response to the three technologies is documented in [9].

In this building, the dimmable lighting control system automatically operates the ambient electric lighting in perimeter zones[2] based on occupancy, setpoint tuning, and daylight availability. Data from the manufacturer's lighting control system were used to determine power use. These data were calibrated using data from independent measurements of lighting energy use (see section 2.4.2). Energy savings over a one year, solstice-to-solstice period were determined in the daylit open plan office zones for three typical floors of the 51-story tower with a conventional daytime office occupancy pattern. Savings were calculated relative to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)

[2] i.e. excluding the service core of the building – see Figure 1.

90.1-2001 [10] baseline, which was the prescriptive standard at the time of construction, and the ASHRAE 90.1-2007 baseline [11]. Data are presented by window orientation but not distance from the window, since the manufacturer aggregated data by dimming zone, not by the subset daylighting zones. A simple payback analysis is also presented.

2. Experimental Method

2.1 Facility description

2.1.1 Building

The New York Times Building, completed in 2007, is a 51-story high-rise building situated at the corner of 8th Avenue and West 40th Street in Manhattan, New York. The floors occupied by the Times Company were designed to provide ample daylight penetration, and to that end open plan office areas were placed by the façade, with private offices toward the core on most floors, contrary to customary high-rise design practice. Figure 1 shows the layout of the 20th floor overlaid with the lighting control zones evaluated in this study. The layout of the daylit, open plan office zones was identical on the other floors that were evaluated (6th and 11th floors) except that the 6th floor had a conference room in the place where zone E2 would be. The depth of the daylit zones (measured as maximum distance to the nearest window) varied from approximately 7.15 m (23.45 ft), for zones W2, W4, E2 and E4, to approximately 13.25 m (43.45 ft), for zones E3 and W3. Zones W1, W5, E1, and E5 had corner window conditions. Ceiling height was higher than customary for this type of building, with the purpose of admitting more daylight: 2.92 m (9.58 ft), rising to 3.15 m (10.33 ft) in a cove by the windows. Open plan work stations had 1.2 m (4 ft) high partitions.

The windows consisted of two layers of 6 mm (0.25 in), low-iron, clear, water-white glass with a spectrally-selective, low-emittance coating on the outboard layer. The window-to-exterior-wall ratio was 0.76 and the center-of-glass window transmittance was 0.75. For most façade orientations, approximately 50% of the window area was shaded by cylindrical, off-white, horizontal ceramic tubes (4.12 cm, 1.625 in diameter), placed 0.46 m (1.5 ft) from the exterior surface of the glazing. The view portion of the window wall was unshaded from 0.76 m (2.5 ft) to 2.13 m (7 ft) above the floor. The cylinders above the view portion of the window were spaced 8.9 cm (3.5 in.) on center. For the cylinders below the view window, the spacing decreased from 15.4 cm (6.06 in.) at the top to 9.68 cm (3.81 in.) at the bottom. Automated, interior shades are described in Section 2.1.4.

2.1.2 Lighting system

The lighting system in the perimeter zones consisted of recessed, 0.30 x 1.62 m (1 x 5 ft) linear, parabolic-troffer luminaires with two, 61-cm (2-ft), 14 W, T5 fluorescent lamps per luminaire. Luminaires were placed end-to-end and were spaced 1.52 m (5 ft) apart within the 1.52 x 1.52 m (5 x 5 ft) ceiling grid. The two lamps were operated by a single, rapid start, digital-addressable dimming ballast (Lutron EcoSystem model CE 3 T514 C 277 2) with a light output range of 10-100%. A small fraction of the ballasts were replaced by similar ballasts of a subsequent generation (model EC5T514JUNV2) due to premature failure. According to data from the manufacturer, maximum power consumption per luminaire was approximately 33 W, making the installed lighting power density (LPD) approximately 14 W/m^2 (1.3 W/ft^2) and in compliance with the prescriptive energy-efficiency code in effect at the time (ASHRAE 90.1-2001). In each zone, a few luminaires were part of the emergency lighting system (Table 1) and were controlled differently from the others, as detailed in Section 2.1.3.

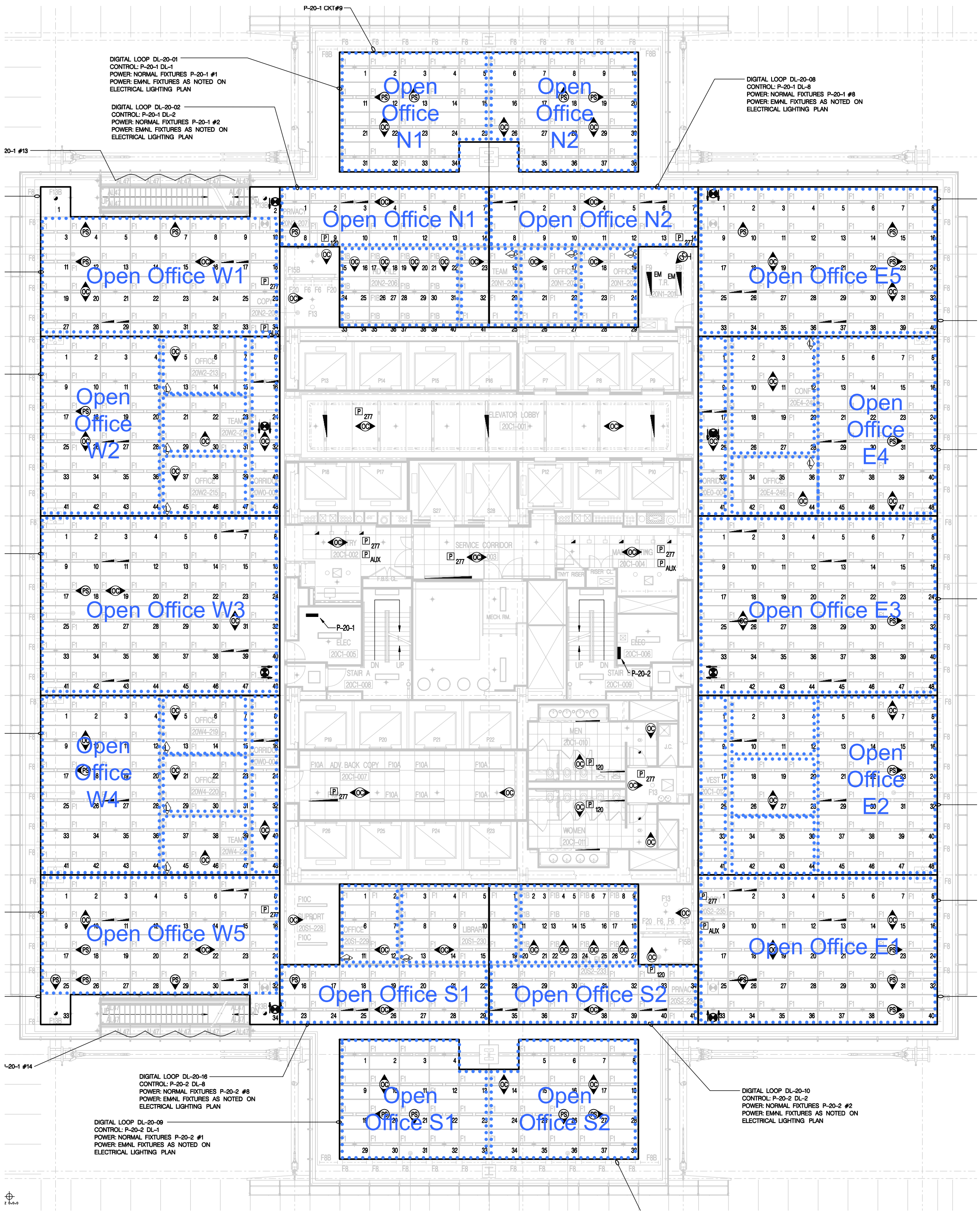

Figure 1. Floor plan showing the 20th floor lighting circuits (black solid) and lighting control zones (blue dash). The position of daylighting photosensors (symbol labeled PS) and occupancy sensors (symbol labled OC) are delineated for each zone with the direction of view indicated with the point of the triangle. Only the daylit areas of each floor were studied (in the 20th floor, they are the open plan areas labeled in this figure.

Table 1
Emergency luminaire distribution per lighting control zone and estimated* power consumption when zone was unoccupied.

Lighting control zone	No. of emergency luminaires	Estimated power consumption (W)
Open Office E1	3	51
Open Office E2	1	17
Open Office E3	4	68
Open Office E4	1	17
Open Office E5	2	34
Open Office N1	1	17
Open Office N2	2	34
Open Office S1	1	17
Open Office S2	2	34
Open Office W1	2	34
Open Office W2	1	17
Open Office W3	4	68
Open Office W4	1	17
Open Office W5	3	51

* *Interpolated from laboratory ballast power consumption measurements.*

2.1.3 Lighting control system

The perimeter zone electric lighting was controlled by an automated lighting control system (Lutron Quantum) based on three criteria: occupancy, setpoint tuning, and daylighting.

Occupancy control

Open plan and private office zones (Figure 1) were equipped with infrared and ultrasonic occupancy sensors (Lutron models LOS-CDT-1000-WH, LOS-CDT-2000-WH and LOS-WDT-1000-WH). When no occupancy was reported for more than 8 minutes, lights were turned off. When a zone was occupied, emergency luminaires were controlled by the lighting control system (LCS) in the same way as the non-emergency luminaires in the same group. When a zone was not occupied, emergency luminaires stayed on, dimmed to 25% light output level (17 W per luminaire, according to laboratory measurements of ballast power consumption, described in Section 2.3).

Daylighting control and setpoint tuning

Daylighting controls were implemented in all open-plan perimeter zones, while setpoint tuning was implemented in both the open plan office zones and supporting spaces (copy rooms, archives, etc.) within the perimeter zone. The installed lighting produced a maximum workplane illuminance of 510 lux (50 fc), but the Times Company selected 323 lux (30 fc) for all zones unless the department requested a specific setpoint level (i.e., zone N2 on the 6th floor at 215 lx (20 fc)).

Daylighting control was implemented via a single, ceiling-mounted photosensor per open plan zone for most zones (Lutron model MW-FPSIR-WH-CPN3100). The photosensor monitored light levels coming from the window and a small area near the window at a distance of about 3.3 m (10 ft) from the window. All fluorescent lights in the open plan zone were continuously dimmed in response to the photosensor signal to maintain the prescribed horizontal illuminance setpoint. Luminaires within the open plan zone were grouped by rows that were for the most part parallel to the windows: Figure 2 shows the daylit sub-zones for each open plan zone on the 20^{th} floor – zoning was similar for the 6^{th} and 11^{th} floors. Each daylit zone was controlled independently. When there was sufficient daylight, the grouped row of lights was shut off with a 6-minute time delay. If the photosensor signal dipped below the setpoint level, the lights were turned on again without delay. When turned off, power consumption was reduced from minimum (35% of full power) to standby levels (3%). When space was occupied, emergency lighting was dimmed and shut off like the other luminaires within its daylight control group.

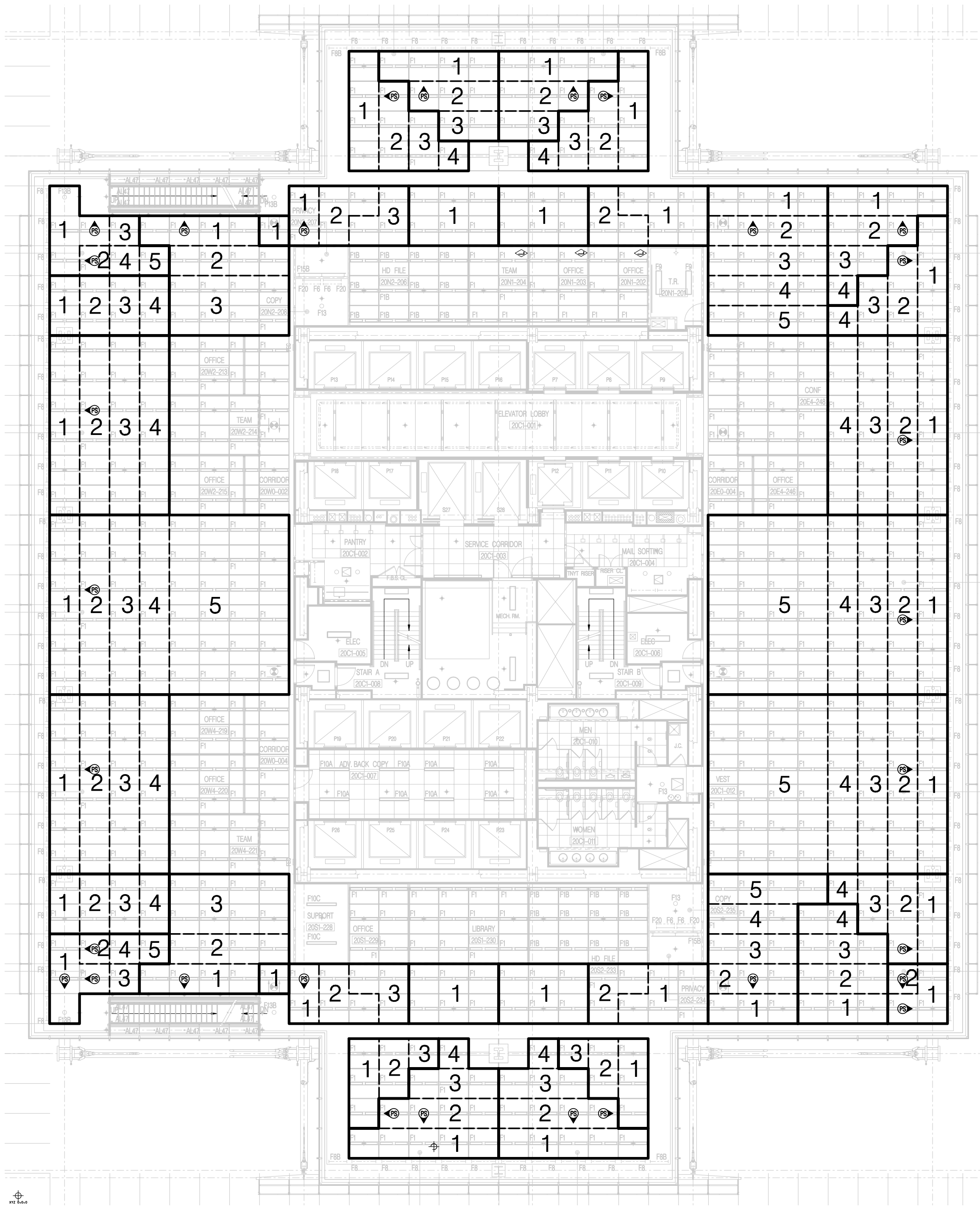

Figure 2. Floor plan showing the daylighting zones on the 20th floor. The positions of daylighting photosensors (symbol labeled PS) are delineated for each open plan zone with the direction of view indicated with the point of the triangle.

User control

User control of the lighting was not enabled in open plan office zones or corridors. In private offices, conference rooms and support rooms, users could control the lights using wall-mounted dimming switches.

2.1.4 Automated shading system

The façade was equipped with an automated shading system that lowered roller shades to control direct sun, window glare, daylight, and view. The shading system was a roller shade with a light gray fabric facing the indoors and a medium gray facing the outdoors. The fabric had an openness factor of 1.5% on all south-, east-, and west-facing orientations and a 3% openness factor on the north. The shading system had five preset heights, two of which corresponded to the upper and lower bounds of the view portion of the window wall unobstructed by the exterior fixed shading. The shades were adjusted on a minute-to-minute basis (depending on the control algorithm) typically in widths of 9.15 m (30 ft). Additional details can be obtained from [9,12].

2.2 Lighting energy consumption data

2.2.1 Data obtained from lighting control system (LCS) manufacturer

In this study, the determination of lighting energy savings was based on LCS data provided by the manufacturer for the solstice-to-solstice period from June 21, 2010 to June 20, 2011[3]. Analysis was conducted on LCS data collected about a year prior to the start of on-site monitoring (May 2011) because the configuration settings (e.g., setpoints) were held constant over this period, according to the facility management team. The LCS data comprised of calculated power consumption and system activity data (Tables 2 and 3), the latter including occupancy and daylighting mode status. Data were logged only when there was a change in value. The estimated power consumption was calculated by the manufacturer from the digital control signal corresponding to the ballast control voltage sent to each ballast. This was done using a relationship between ballast signal level and power consumption determined previously by the manufacturer's bench measurements (Figure 3). Estimated power consumption data provided by the manufacturer were aggregated for the zones delineated by dashed lines in Figure 1, so analysis of the smaller daylighting groups shown in Figure 2 was not possible.

Preliminary inspection of these data showed that peaks in power consumption were registered when there was an abrupt transition between power levels, such as turning the lights on or off (Figure 4). That these were spurious and did not correspond to real power consumption was confirmed with the manufacturer.

[3] The manufacturer's LCS data were calibrated using LBNL measured data, as described in Section 2.4.2.

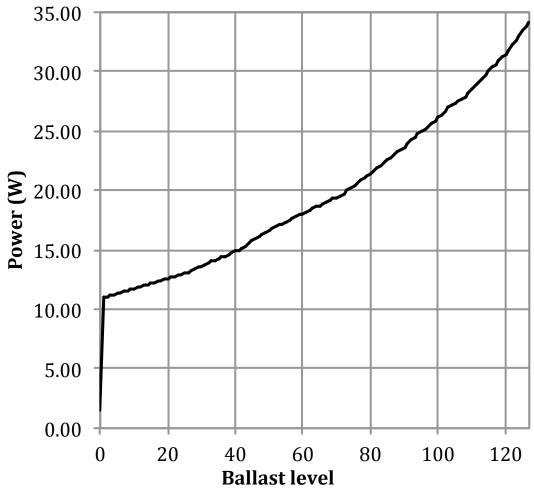

Figure 3. Digital ballast signal level versus power consumption used by the manufacturer to derive estimated luminaire power consumption.

Table 2
Sample of LCS power consumption data for the open plan office zone W3 on the 20th floor.

Time stamp	Value (W)
2010-06-21 06:52:14.327	48
2010-06-21 06:53:32.327	147
2010-06-21 06:53:35.327	1632
2010-06-21 06:54:38.423	744
2010-06-21 06:54:56.453	743
2010-06-21 06:55:02.453	742
2010-06-21 06:55:05.453	741
2010-06-21 06:55:11.453	740
2010-06-21 06:55:14.453	739
2010-06-21 06:55:20.453	738
2010-06-21 06:58:29.577	737
2010-06-21 06:58:35.673	736
2010-06-21 06:58:41.673	735
2010-06-21 06:58:44.673	734
2010-06-21 06:58:47.703	733
2010-06-21 06:58:53.703	732
2010-06-21 07:02:44.827	731
2010-06-21 07:02:50.827	730
2010-06-21 07:02:53.827	729
2010-06-21 07:02:59.827	728
2010-06-21 07:03:02.843	727

Note: Data points were recorded only when there were changes in status.

Table 3
Sample of LCS activity data for the 20th floor.

Time Stamp	Floor	Zone	Originator	Action ID	Display Text
6 20 11 8:22 AM	20th Floor	Office 213	Occupant	67	Office 213 went Unoccupied
6 20 11 8:24 AM	20th Floor	Team Room 214	Occupant	67	Team Room 214 went Unoccupied
6 20 11 8:41 AM	20th Floor	Corridor 20W0-004	Occupant	67	Corridor 20W0-004 went Occupied
6 20 11 8:41 AM	20th Floor	Office 213	Occupant	67	Office 213 went Occupied
6 20 11 8:41 AM	20th Floor	Open Office S1	Occupant	67	Open Office S1\South went Occupied
6 20 11 8:43 AM	20th Floor	Team Room 214	Occupant	67	Team Room 214 went Occupied
6 20 11 8:43 AM	20th Floor	Team Room 214	System Status	69	Team Room 214 changed to Scene Unknown
6 20 11 8:48 AM	20th Floor	Office 230	Occupant	67	Office 230 went Occupied
6 20 11 8:48 AM	20th Floor	Office 230	System Status	69	Office 230 changed to Scene Unknown
6 20 11 8:51 AM	20th Floor	Office 203	Occupant	67	Office 203 went Occupied
6 20 11 8:54 AM	20th Floor	Office 202	Occupant	67	Office 202 went Occupied
6 20 11 8:54 AM	20th Floor	Office 202	System Status	69	Office 202 changed to Scene Unknown
6 20 11 8:54 AM	20th Floor	Open Office W4	Occupant	67	Open Office W4\West went Occupied
6 20 11 8:54 AM	20th Floor	Open Office W4	System Status	71	Open Office W4\West is Daylighting
6 20 11 9:00 AM	20th Floor	Team Room 204	Occupant	67	Team Room 204 went Occupied
6 20 11 9:00 AM	20th Floor	Team Room 204	System Status	69	Team Room 204 changed to Scene Unknown

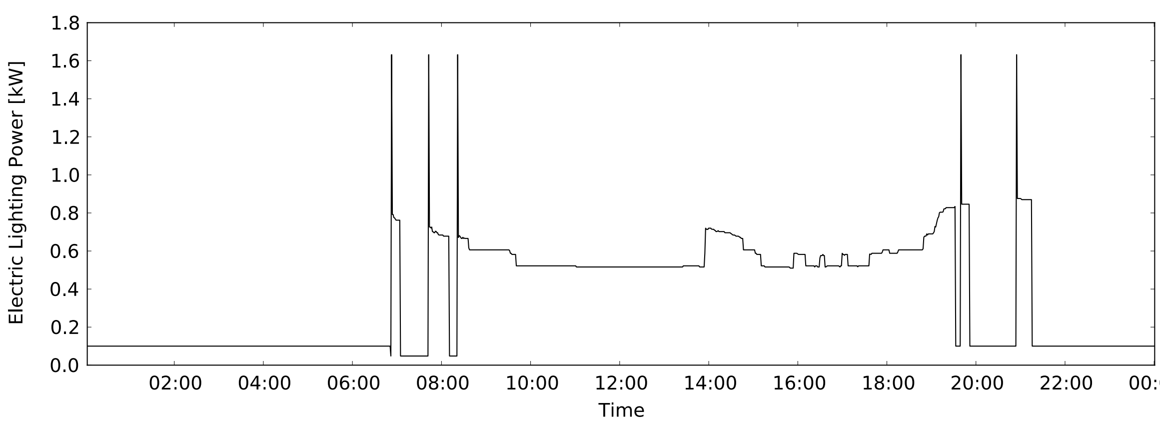

Figure 4. LCS estimated power consumption data for the 13.25 m (43.45 ft) deep zone W3, 20th floor, on May 12, 2011. The lighting control system data recorded abrupt peaks in power consumption in the morning and evening hours when lights were turned on or off, but actual power use did not exhibit this behavior.

2.2.2 Data obtained by on-site monitoring

In order to verify the accuracy of the manufacturer's LCS data, we conducted independent, 1-minute measurements of power consumption for the sixteen main lighting circuits (eight per panel) on the 20th floor, covering the zones delineated by black solid lines in Figure 1. The monitored circuits did not include power for the emergency luminaires whereas LCS data accounted for them. Measurements were performed from May 2011 to January 2012 and were performed using current transducers[4] coupled to 15 A current transformers[5]. The transducers were set up to generate a pulse for every 83.1 J (1.385 watt-minute) consumed by the circuit. The number of pulses generated each minute was recorded by data loggers (Onset Hobo U30), which communicated with a remote server through the cellular telephone network.

2.2.3 Data management and storage

The large amount of data involved in this study was managed with a PostgreSQL [13] database. LCS data was event-based (i.e., data were recorded whenever there was a change in value), whereas measured data was timestep-based (i.e., data were recorded at regular intervals). To enable comparisons between the two datasets on a 1-minute timestep, it was necessary to retrieve, for each measurement timestep, the latest LCS data value. A database function was developed for this purpose.

2.3 Luminaire power consumption measurements

To resolve discrepancies between LBNL's measured power consumption data and the manufacturer's estimated power consumption data recorded by the LCS, bench tests were undertaken to determine actual luminaire power consumption versus LCS estimated power based on the ballast control signal. The power consumption of a single luminaire versus digital ballast control signal was measured in the laboratory using a Voltech PM3000A power analyzer[6]. To check possible issues with LBNL monitoring equipment, bench measurements were also performed with instruments of the same type that were installed in the field. Both original and new-generation ballasts were tested. The lamps were allowed to fully warm up. At least 10 minutes were allowed between different control levels to permit lamp output stabilization. Data from these tests are discussed in Section 2.4.2.

2.4 Methods of data analysis

2.4.1 Zone aggregation

Comparing LCS estimated and LBNL measured lighting power consumption data was straightforward for some zones, such as E3 or W3, where the boundaries of the LCS zones and metered lighting circuits coincided. Elsewhere, it was necessary to add data from different LCS zones and lighting circuits to make same-area comparisons between the two datasets. Comparisons were made for five zones each on the west and east sides of the floor, one on the north and one on the south (Figure 5).

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[4] Wattnode Model WNB-3Y-480-P Opt P3, Hz=50 with 0.5% accuracy down to 5% of maximum current, 1% accuracy between 1% and 5% of maximum current.

[5] Continental Control Systems, CTM-0360-015, with accuracy of 1% down to less than 5% of maximum current.

[6] Accuracy is 0.04% divided by the power factor.

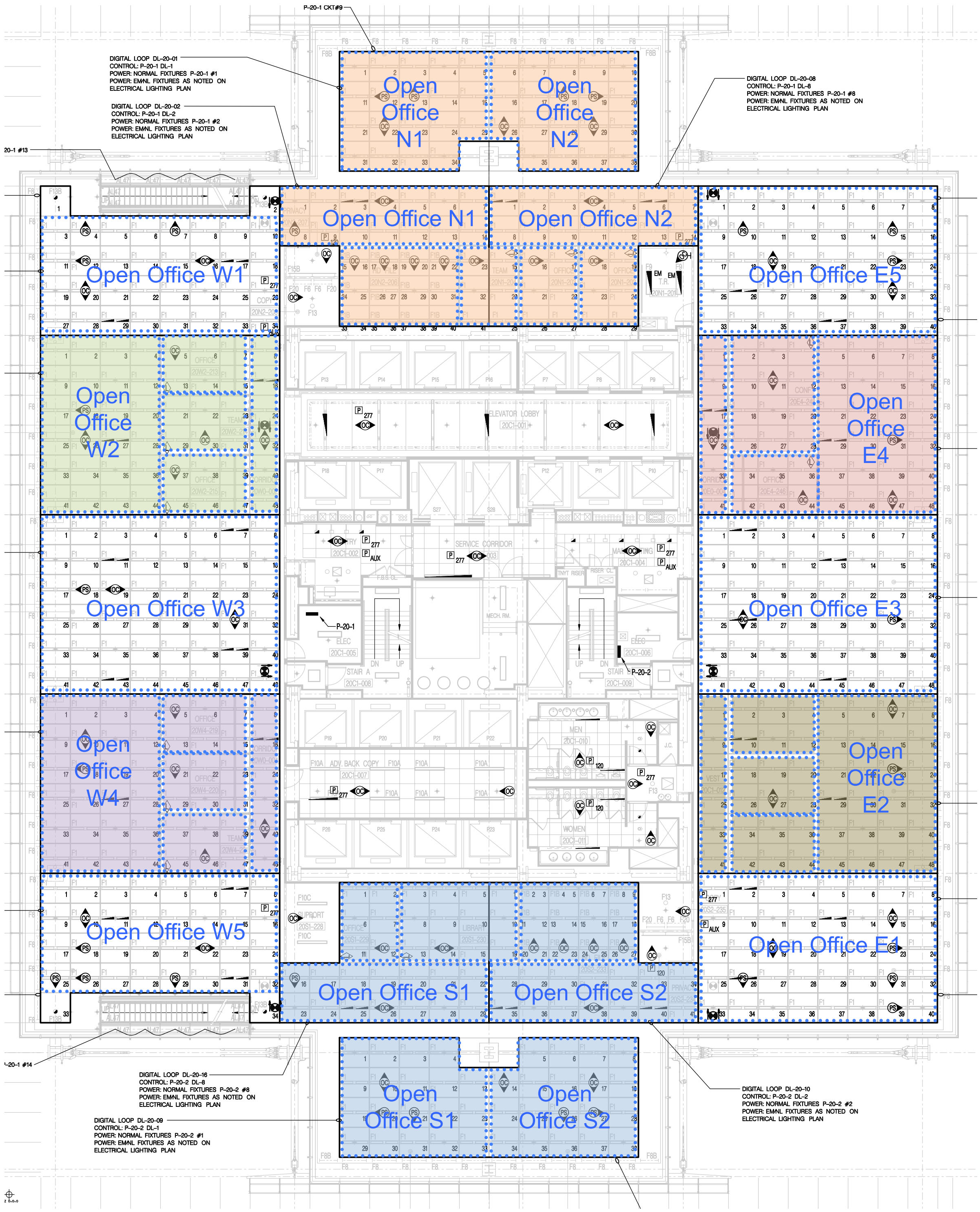

Figure 5. Zone aggregation (shaded) for comparison between LBNL measured and the manufacturer's LCS lighting power consumption data. Unaggregated zones, where measured and LCS zones coincided exactly, are shown as unshaded.

2.4.2 LCS data calibration

The LCS data did not agree with the LBNL metered data. LBNL metered data could have been used for the analysis, but the metered data corresponded to the lighting circuit zones, not the daylit zones of interest. In order to determine actual lighting energy consumption for the daylit zones, we first derived the relationship between LBNL measured and LCS power data for the 20th floor, then used the correlation to correct the LCS data for the final energy analysis. The correlation was used for zones on all three floors, under the assumption that the relationship would hold throughout the other two, non-metered floors.

The measured power consumption is plotted against the LCS data in Figure 6 for every minute between May 10, 2011 and July 27, 2011[7]. This comparison showed that measured values tended to be systematically greater than their LCS counterparts, a discrepancy that increased with increasing power level in all zones except W5.

[7] Excluded are spurious points for which the LBNL dataset showed impossibly high power consumption. This issue was investigated for zones W3, W5, E3 and E5 and only one data point was affected in each area over the two-month period.

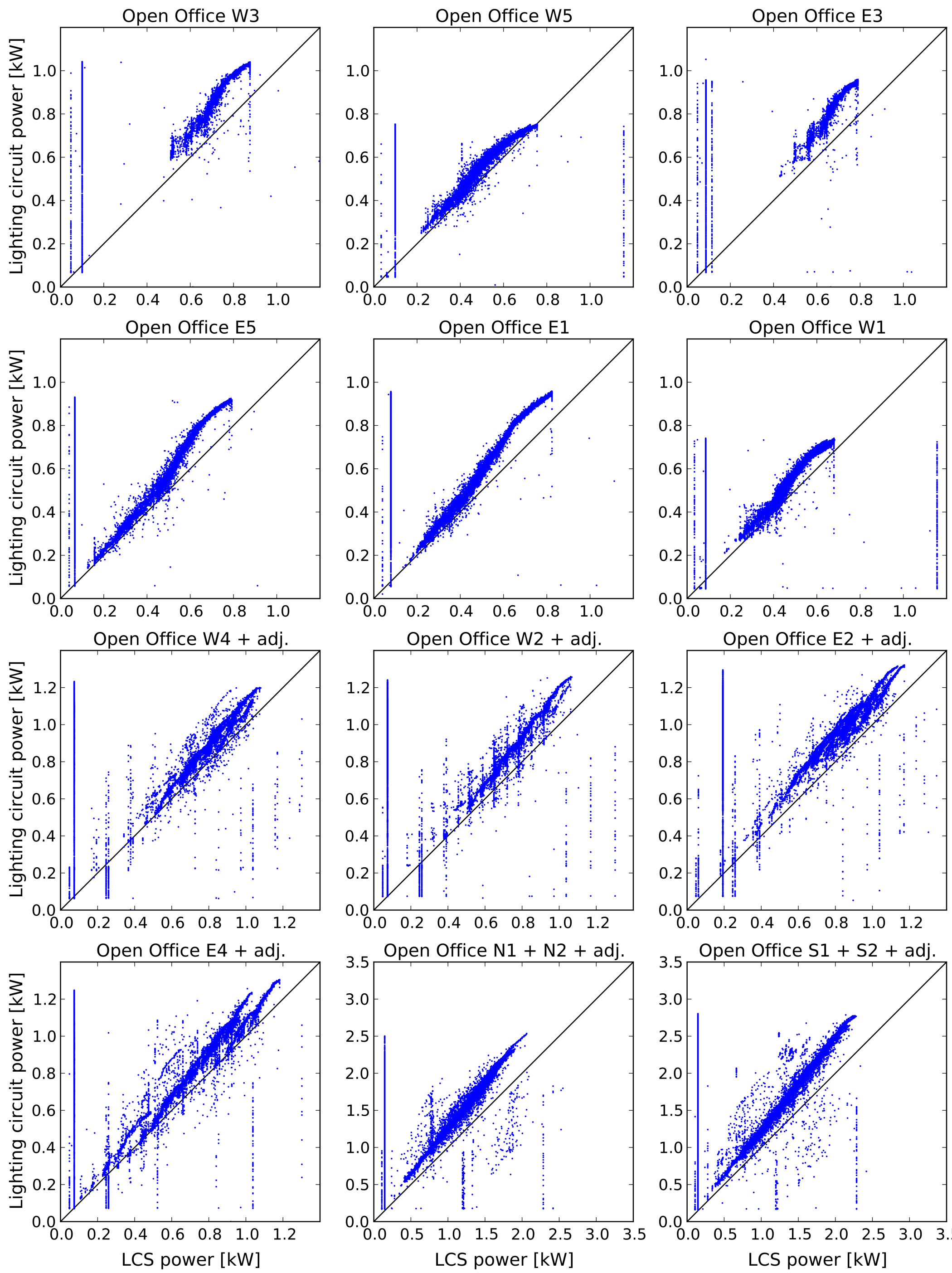

Figure 6. Measured power consumption data plotted against LCS estimated power consumption data. Note the varying scale. Plots marked "+ adj." denote data for aggregated LCS zones as shown in Figure 5.

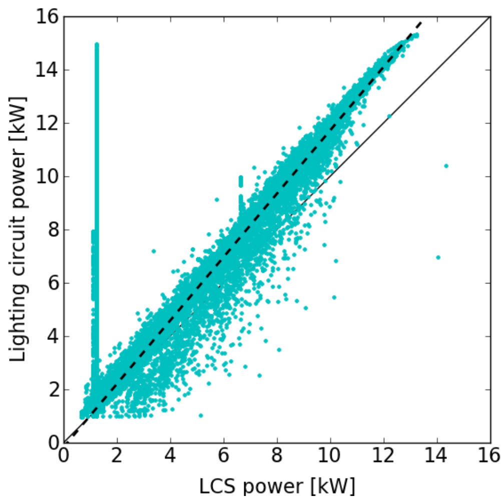

Figure 7. Measured data plotted against LCS estimated power consumption data for the 20th floor for the period from May 10, 2011 to July 27, 2011.

To attempt to correct for this, a simple calibration function was developed. A linear fit to summed data for all twelve zones on the 20th floor (Figure 7) yielded a slope of 1.18 (the points that form a vertical straight line along the left edge of the plot were excluded). Calibrated LCS power consumption values were then calculated by:[8]

$$P_{cal} = 1.18 P_{LCS} \tag{1}$$

where P_{cal} is calibrated power and P_{LCS} is original LCS power.

The normalized mean squared error (NRMSE) between calibrated LCS data and measured values was calculated for each of the six zones in which LCS and metering boundaries coincided (unshaded in Figure 5):

$$NRMSE = \frac{\sqrt{\frac{\sum_{i=1}^{n}\left(P_{cal,i}-P_{meas,i}\right)^2}{n}}}{P_{meas,max}-P_{meas,min}} \tag{2}$$

where P_{cal} is calibrated power, P_{meas} measured power, n the number of data points (n=112,930), $P_{meas,max}$ is the maximum measured power, and $P_{meas,min}$ the minimum measured power. $P_{meas,max}$ and $P_{meas,min}$ were determined for the range of data used in the linear regression.

Results varied between 3.0% and 5.6%, with the exception of zone W5, for which NRMSE was 10.9% (Table 4). This suggested that the linear correction would provide reasonable accuracy. In zone W5 of the 20th floor, the calibration function in Equation 1 likely overestimates energy consumption, and therefore underestimates savings. It was used nevertheless to keep the analysis simple.

[8] For simplicity, this approximation disregards the fact that the relationship between LCS and measured data is not exactly linear or strictly proportional (i.e., the straight line in Figure 7 passes close to, but not exactly through the origin of the plot, possibly due to power for emergency luminaires).

Table 4
Normalized mean squared error (NRMSE) between calibrated LCS data and measured lighting power consumption values.

Zone	NRMSE
Open Office E1	3.0%
Open Office E3	4.0%
Open Office E5	3.3%
Open Office W1	5.6%
Open Office W3	3.1%
Open Office W5	10.9%

Luminaire power consumption measurements

Results from laboratory power consumption measurements using ballasts and lamps of the same type as those installed in the building and the Voltech power analyzer are shown in Table 5. The measured dimming power range was 36-100% for the stated 10-100% light output. When the same measurements were taken with instruments of the same type as those installed in the field, results were within 1% of the results obtained with the more accurate Voltech instrument.

LBNL measured values were greater than those used by the manufacturer to calculate zone power consumption. Figure 8 shows the LBNL measured values plotted against the manufacturer values. (Figure 3 shows the manufacturer measured data as a function of ballast control signal.) A discrepancy similar in magnitude to that already visible in Figure 6 emerges. When contacted, the manufacturer confirmed that incorrect ballast performance had been used in the calculation of LCS zone power consumption.

Table 5
Luminaire power consumption measurement results.

Digital ballast level (7-bit)	Manufacturer measured power (W)	LBNL measured power (W)	Error
4	11.2	12.3	9.3%
7	11.5	12.4	8.2%
17	12.3	13.4	8.3%
22	12.8	14.6	14.3%
29	13.5	16.5	22.0%
38	14.6	18.5	26.4%
50	16.6	20.9	25.8%
66	18.9	24.2	28.0%
87	22.8	28.4	24.3%
127	34.2	34.5	0.8%

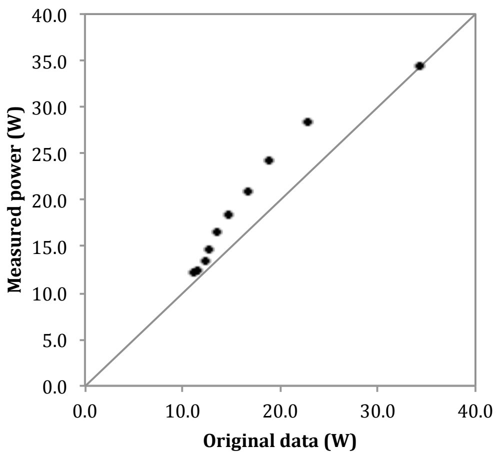

Figure 8. Original manufacturer luminaire power consumption data versus LBNL measured data.

On the comparison between measured and LCS data

In Figure 6, data grouped along a vertical line originate because the time stamp alignment of the LCS and measured datasets in the vicinity of abrupt transitions was not perfect. One reason for this is that abrupt transitions in the lighting control signal do not translate to equally abrupt transitions in power consumption. Another possible cause is drift between the LCS and power monitoring equipment clocks. For single-zone data, abrupt transitions are to be found primarily for standby and full power[9], but for multiple-zone data, these occur at different levels for each dataset that takes part in the summation, an effect that is compounded by the fact that many of these spaces are private offices or conference rooms, which have a number of preset lighting levels. These differences can be ignored because these points represent a very small fraction of the total number of points used for the final correlation (Equation 1, Figure 7).

Finally, it is also noticeable, especially in non-summed zones, that the relationship between the two datasets is not strictly linear throughout the dimming range. Again, this is caused by the difference between ballast performance assumed in the calculations of LCS ballast level to power performed by the manufacturer and actual measured performance. It can be seen in Figure 8 that this difference does not vary linearly as power increases, which is the likely cause of the observed non-linearity. The calibrated LCS power incorporated the adjustment factor from Equation 1 to correct for this difference.

2.4.3 Determination of energy savings

Area of study

Since the purpose of the study was determining energy savings from dimming, areas in which dimming due to daylighting and setpoint tuning were enabled were selected for analysis. These areas consisted of open plan offices, and excluded enclosed spaces far from the façade, such as individual offices and most conference rooms. The only exception was a conference room on the 6th floor, in the position equivalent to zone E2 but 1.52 m (5 ft) less deep.

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[9] And also for the level of spurious peaks observed in LCS data in the vicinity of abrupt transitions. This level is higher than full power.

Baseline

The ASHRAE Standard 90.1-2001 [10] and 90.1-2007 [11] were used as the benchmark baselines for comparison of energy consumption and determination of savings. The 90.1-2001 Standard was in effect at the time the building was designed, so the installed lighting power density for the building was 14 W/m^2 (1.3 W/ft^2). The 90.1-2007 Standard is currently the most widely adopted version in the US, which prescribes a maximum lighting power density for open plan offices of 12 W/m^2 (1.1 W/ft^2).

Both versions of the Standard also require luminaires to be controlled automatically either by scheduling (i.e., on/off at scheduled times) or occupancy (i.e., lights off when zone is not occupied, with a maximum delay of 30 minutes). We assumed that the baseline included scheduling but not occupancy controls, since this is the simplest equipment configuration that complies with the Standard and because detailed occupancy sensing (to the degree implemented in the Times Building) is rarely used in open plan office zones.

The Times Company indicated that they would have scheduled the lighting system to be off between 1:00 AM and 6:00 AM on every non-holiday weekday, since cleaning was conducted during evening hours, and off for all hours on weekends and holidays. For the monitored period, there was a maximum of 4010 hours of the total 8760 hours (46%) in the year when the lighting was scheduled to be off. However, if the zone was occupied during scheduled off hours, then it was assumed that the occupant would call the building manager to have the lights in the zone(s) turned on. The LCS monitored data was used to determine status of occupancy per zone during scheduled hours. When turned off, power use was set to zero assuming that the baseline specified on-off ballasts.

Tuned setpoint power level

The power consumption of the lighting system when dimmed to the desired setpoint level (e.g., 323 lux; 30 fc) was determined for each open plan office zone by calculating the maximum power value that held constant for five minutes or more during the twelve months studied. Using these setpoint power levels, effective lighting power density was calculated, assuming a floor area defined by the fixtures alone. A comparison of tuned power to the power use at full light output for the installed, ASHRAE 90.1-2001-compliant, Times Company baseline and the ASHRAE 90.1-2007 baseline is given in Table 6.

Table 6. Power consumption for open plan office zones at the tuned, setpoint light level of 323 lux (30 fc).[10]

		Installed power (ASHRAE 90.1-2001)	ASHRAE 90.1-2007 full power level	Setpoint power level	Floor area	LPD
		W	*W*	*W*	*m^2*	*W/m^2*
20th Floor	Open Office E1	1320	1100	966	93	10.4
	Open Office E2	792	660	572	56	10.3
	Open Office E3	1584	1320	946	111	8.5
	Open Office E4	792	660	522	56	9.4
	Open Office E5	1320	1100	927	93	10.0
	Open Office N1	1089	907.5	834	77	10.9
	Open Office N2	1089	907.5	828	77	10.8
	Open Office S1	1089	907.5	813	77	10.6
	Open Office S2	1089	907.5	838	77	10.9
	Open Office W1	1056	880	799	74	10.7
	Open Office W2	792	660	536	56	9.6
	Open Office W3	1584	1320	1031	111	9.2
	Open Office W4	792	660	543	56	9.8
	Open Office W5	1056	880	886	74	11.9
11th Floor	Open Office E1	1320	1100	1068	93	11.5
	Open Office E2	792	660	565	56	10.1
	Open Office E3	1584	1320	979	111	8.8
	Open Office E4	792	660	529	56	9.5
	Open Office E5	1320	1100	881	93	9.5
	Open Office N1	1089	907.5	849	77	11.1
	Open Office N2	1089	907.5	838	77	10.9
	Open Office S1	1089	907.5	819	77	10.7
	Open Office S2	1089	907.5	828	77	10.8
	Open Office W1	1056	880	746	74	10.0
	Open Office W2	792	660	522	56	9.4
	Open Office W3	1584	1320	1031	111	9.2
	Open Office W4	792	660	551	56	9.9
	Open Office W5	1056	880	856	74	11.5
6th Floor	Open Office E1	1320	1100	943	93	10.2
	Conference Room 141	594	495	461	42	11.0
	Open Office E3	1584	1320	1016	111	9.1
	Open Office E4	792	660	529	56	9.5
	Open Office E5	1320	1100	927	93	10.0
	Open Office N1	1089	907.5	814	77	10.6
	Open Office N2	1089	907.5	595	77	7.8
	Open Office S1	1089	907.5	798	77	10.4
	Open Office S2	1089	907.5	806	77	10.5
	Open Office W1	1056	880	762	74	10.3
	Open Office W2	792	660	536	56	9.6
	Open Office W3	1584	1320	992	111	8.9
	Open Office W4	792	660	551	56	9.9
	Open Office W5	1056	880	832	74	11.2

[10] All zones at 323 lux (30 fc) setpoint except Open Office N2 on the 6th floor, which has a lower illuminance setpoint of 215 lx (20 fc).

Energy savings calculation

Savings relative to the two ASHRAE 90.1 baselines were calculated for each open plan office zone using 24 h, 1-min interval, calibrated LCS power consumption data for all days over the monitored period from June 21, 2010 to June 20, 2011 (Figure 9). During scheduled-on times (6:00 AM to 1:00 AM weekdays), savings were considered to be due to occupancy controls when the space was unoccupied. When the zone was occupied (including during scheduled off hours), any savings were attributed to daylighting controls together with setpoint tuning.

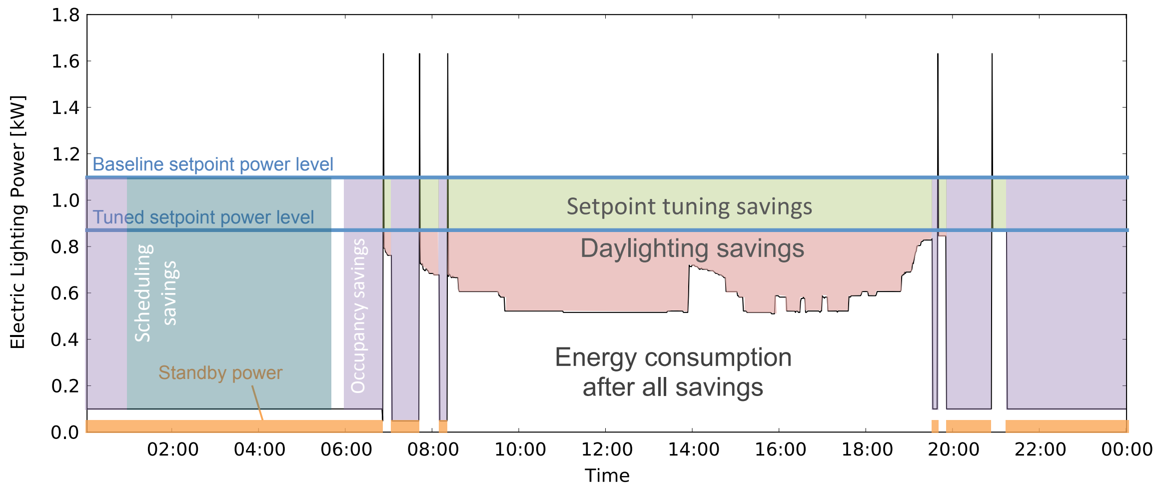

Figure 9. Lighting energy savings calculation for a typical weekday (Zone W3, 20th floor, May 12, 2011). The baseline energy use is at the installed full power level (shown as "baseline setpoint power level") prescribed by ASHRAE 90.1-2001 or ASHRAE 90.1-2007 for all hours except from 1:00-6:00 AM when the lighting is scheduled to be off (0 W). Occupancy savings occurred from the same baseline full power level at night from 0:00-1:00 AM, intermittently during the day, and then from about 20:00 to 24:00 at night. When unoccupied, the lighting power use was at the standby power levels. Setpoint tuning and daylight savings occurred during the day. Daylight savings were determined relative to the tuned setpoint power level.

Accounting for ballast standby power

Dimming fluorescent ballasts consume a small amount of power when lights are turned off, whereas on/off ballasts do not consume power at all. This standby power was estimated from measured data for six zones on the 20th floor (E1, E3, E5, W1, W3, and W5) and it was observed to be approximately 3% of installed power, again with the exception of zone W5, with a value of 4%. We assumed that the value of 3% would apply throughout the rest of the building.

Because energy savings were calculated based on the monitored power consumption data of dimmable ballasts, the results of this calculation had to be corrected for the fact that neither the baseline nor adding occupancy controls requires dimmable ballasts. For each minute during which lights were off either due to scheduling or occupancy, savings from these types of controls were increased by the amount of the standby losses. Conversely, annual savings from dimming were reduced by the cumulative amount of those losses.

2.4.4 Cost-effectiveness

As a basic measure of the cost-effectiveness of introducing controls, simple payback period per unit of floor area was used:

$$P = \frac{C_{install}}{S_{energy}} \quad (3)$$

where P is the payback period, $C_{install}$ is the incremental installation cost of dimming controls per unit area, and S_{energy} is the annual energy cost savings per unit area. Although the automated shading system was likely to have increased daylight availability to perimeter zones (shades were raised when direct sun and glare were absent), the actual contribution of the automated shades to lighting energy savings was not measured or quantified (assuming manually-operated shades as the baseline, as opposed to an unshaded window in the case of the ASHRAE 90.1 Standard). Therefore, the effect of the shading system was not included in this cost analysis.

The cost of energy was calculated using the local time-of-use utility rate for large commercial buildings (Consolidated Edison, Category 9, Rate II) – see Table 7 [14,15].

Table 7
Utility rates (in US dollars) used in cost-effectiveness calculations.

	Demand Delivery Charges (per kW of maximum demand for each time period)	Capacity market supply charge (per kW of maximum demand for each time period)	Energy Delivery Charge (per kWh)
Jun, Jul, Aug, Sep			
Mon-Fri, 8 AM - 6 PM	$8.28	$15.31	
Mon-Fri, 8 AM - 10 PM	$15.49		
All hours of all days	$16.62		$0.82
Other months			
Mon-Fri, 8 AM - 10 PM	$11.42	$15.31	
All hours of all days	$5.33		$0.82

3. Results

3.1 Lighting energy consumption and savings

Lighting energy consumption and savings, obtained by the method described in the previous section, are shown in Tables 8-9 and Figures 10-12 and 16 for the ASHRAE 90.1-2007 baseline. After all savings, single-zone consumption varied between 17.1 and 56.5 kWh/m^2-yr (1.59-5.25 kWh/ft^2-yr), and savings from daylighting and setpoint tuning (we grouped these because they are enabled by the same hardware – dimming ballasts) were between 7.1 and 21.0 kWh/m^2-yr (0.66-1.95 kWh/ft^2-yr).

In terms of percentages relative to the ASHRAE 90.1-2007 baseline, savings from dimming varied between 11% (zone W5 on the 20th Floor) and 31% (zone E4 on the 20th Floor) for open plan office zones. If savings were aggregated by floor, savings were greatest for the 20th floor (21%) and lowest for the 6th floor (18%). It should be noted that the 6th floor had two zones that probably inflated savings slightly relative to the other two floors: zone N2, due to the lower electric lighting setpoint (215 lx versus 323 lx for the other zones), and Conference Room 141 (same location as E2), which was slightly shallower than corresponding open plan office zones (4.6 m versus 6.1 m; 15 ft versus 20 ft).

Table 8
Annual lighting energy consumption (kWh/yr) and savings (daylit zones only) with ASHRAE 90.1-2007 baseline.

		Energy use, lights always on	Scheduling savings	ASHRAE 90.1-2007 baseline energy use	Occupancy savings	Daylighting and setpoint tuning savings	Energy use after all savings	Occupancy savings	Daylighting and setpoint tuning savings
		kWh/yr	*kWh/yr*	*kWh/yr*	*kWh/yr*	*kWh/yr*	*kWh/yr*	*%*	*%*
6th Floor	Open Office E1	9628	3924	5704	1807	1069	2828	32%	19%
	Conference Room 141	4330	1839	2491	1358	417	715	55%	17%
	Open Office E3	11554	4328	7226	1531	1244	4451	21%	17%
	Open Office E4	5776	2397	3380	1332	662	1385	39%	20%
	Open Office E5	9628	3918	5710	2235	960	2515	39%	17%
	Open Office N1	7943	3192	4751	1562	739	2450	33%	16%
	Open Office N2	7943	3192	4752	1581	1255	1916	33%	26%
	Open Office S1	7943	3213	4730	1637	748	2344	35%	16%
	Open Office S2	7943	2964	4980	1311	856	2812	26%	17%
	Open Office W1	7702	3083	4619	1562	589	2468	34%	13%
	Open Office W2	5777	2371	3406	1061	649	1696	31%	19%
	Open Office W3	11554	4196	7358	1508	1504	4345	20%	20%
	Open Office W4	5777	2409	3368	1343	518	1506	40%	15%
	Open Office W5	7702	3013	4689	1574	773	2343	34%	16%
	All daylit zones	111201	44038	67163	21404	11984	33775	32%	18%
11th Floor	Open Office E1	9626	3990	5636	1953	947	2735	35%	17%
	Open Office E2	5774	2440	3334	1354	593	1386	41%	18%
	Open Office E3	11560	4204	7356	1599	1693	4064	22%	23%
	Open Office E4	5774	2442	3332	1483	665	1183	45%	20%
	Open Office E5	9632	3687	5945	1792	1415	2739	30%	24%
	Open Office N1	7946	2899	5047	1320	780	2947	26%	15%
	Open Office N2	7947	2789	5158	1061	978	3119	21%	19%
	Open Office S1	7946	1973	5973	565	1081	4327	9%	18%
	Open Office S2	7946	2058	5888	418	1188	4282	7%	20%
	Open Office W1	7704	2832	4871	1236	956	2680	25%	20%
	Open Office W2	5774	2409	3365	1477	675	1213	44%	20%
	Open Office W3	11562	3420	8141	624	2108	5409	8%	26%
	Open Office W4	5775	2335	3441	1204	566	1670	35%	16%
	Open Office W5	7708	2272	5436	604	922	3910	11%	17%
	All daylit zones	112674	39748	72926	16693	14568	41666	23%	20%
20th Floor	Open Office E1	9627	3848	5778	1655	1509	2615	29%	26%
	Open Office E2	5776	2374	3402	986	651	1766	29%	19%
	Open Office E3	11552	3990	7562	1084	2113	4365	14%	28%
	Open Office E4	5776	2022	3754	770	1171	1814	21%	31%
	Open Office E5	9627	4003	5625	1120	1479	3026	20%	26%
	Open Office N1	7942	3283	4660	1369	858	2432	29%	18%
	Open Office N2	7942	3290	4652	1706	744	2202	37%	16%
	Open Office S1	7943	3291	4652	1560	886	2207	34%	19%
	Open Office S2	7942	3212	4730	1432	973	2325	30%	21%
	Open Office W1	7703	3016	4686	1422	777	2487	30%	17%
	Open Office W2	5775	2398	3377	1298	754	1324	38%	22%
	Open Office W3	11554	4586	6968	2055	1373	3541	29%	20%
	Open Office W4	5775	2418	3357	1402	502	1454	42%	15%
	Open Office W5	7702	2889	4812	1117	526	3169	23%	11%
	All daylit zones	112635	44619	68016	18976	14314	34726	28%	21%
All daylit zones		336509	128404	208105	57073	40866	110166	27%	20%

Table 9
Annual energy consumption density (kWh/m^2-yr) and savings (daylit zones only) with ASHRAE 90.1-2007 baseline.

		Energy use, lights always on	Scheduling savings	ASHRAE 90.1-2007 baseline energy use	Occupancy savings	Daylighting and setpoint tuning savings	Energy use after all savings
		kWh/m^2-yr	*kWh/m^2-yr*	*kWh/m^2-yr*	*kWh/m^2-yr*	*kWh/m^2-yr*	*kWh/m^2-yr*
6th Floor	Open Office E1	103.6	42.2	61.4	19.5	11.5	30.4
	Conference Room 141	103.6	44.0	59.6	32.5	10.0	17.1
	Open Office E3	103.6	38.8	64.8	13.7	11.2	39.9
	Open Office E4	103.6	43.0	60.6	23.9	11.9	24.8
	Open Office E5	103.6	42.2	61.5	24.1	10.3	27.1
	Open Office N1	103.6	41.6	62.0	20.4	9.6	32.0
	Open Office N2	103.6	41.6	62.0	20.6	16.4	25.0
	Open Office S1	103.6	41.9	61.7	21.4	9.8	30.6
	Open Office S2	103.6	38.7	65.0	17.1	11.2	36.7
	Open Office W1	103.6	41.5	62.2	21.0	7.9	33.2
	Open Office W2	103.6	42.5	61.1	19.0	11.6	30.4
	Open Office W3	103.6	37.6	66.0	13.5	13.5	39.0
	Open Office W4	103.6	43.2	60.4	24.1	9.3	27.0
	Open Office W5	103.6	40.5	63.1	21.2	10.4	31.5
	All zones	103.6	41.0	62.6	19.9	11.2	31.5
11th Floor	Open Office E1	103.6	43.0	60.7	21.0	10.2	29.4
	Open Office E2	103.6	43.8	59.8	24.3	10.6	24.9
	Open Office E3	103.7	37.7	66.0	14.3	15.2	36.5
	Open Office E4	103.6	43.8	59.8	26.6	11.9	21.2
	Open Office E5	103.7	39.7	64.0	19.3	15.2	29.5
	Open Office N1	103.7	37.8	65.9	17.2	10.2	38.5
	Open Office N2	103.7	36.4	67.3	13.8	12.8	40.7
	Open Office S1	103.7	25.7	77.9	7.4	14.1	56.5
	Open Office S2	103.7	26.8	76.8	5.5	15.5	55.9
	Open Office W1	103.7	38.1	65.5	16.6	12.9	36.1
	Open Office W2	103.6	43.2	60.4	26.5	12.1	21.8
	Open Office W3	103.7	30.7	73.0	5.6	18.9	48.5
	Open Office W4	103.6	41.9	61.7	21.6	10.2	30.0
	Open Office W5	103.7	30.6	73.1	8.1	12.4	52.6
	All zones	103.7	36.6	67.1	15.4	13.4	38.3
20th Floor	Open Office E1	103.6	41.4	62.2	17.8	16.2	28.1
	Open Office E2	103.6	42.6	61.0	17.7	11.7	31.7
	Open Office E3	103.6	35.8	67.8	9.7	19.0	39.2
	Open Office E4	103.6	36.3	67.3	13.8	21.0	32.5
	Open Office E5	103.6	43.1	60.5	12.1	15.9	32.6
	Open Office N1	103.6	42.8	60.8	17.9	11.2	31.7
	Open Office N2	103.6	42.9	60.7	22.3	9.7	28.7
	Open Office S1	103.6	42.9	60.7	20.3	11.6	28.8
	Open Office S2	103.6	41.9	61.7	18.7	12.7	30.3
	Open Office W1	103.6	40.6	63.1	19.1	10.5	33.5
	Open Office W2	103.6	43.0	60.6	23.3	13.5	23.8
	Open Office W3	103.6	41.1	62.5	18.4	12.3	31.8
	Open Office W4	103.6	43.4	60.2	25.1	9.0	26.1
	Open Office W5	103.6	38.9	64.8	15.0	7.1	42.6
	All zones	103.6	41.0	62.6	17.5	13.2	31.9
All daylit zones		103.6	39.5	64.1	17.6	12.6	33.9

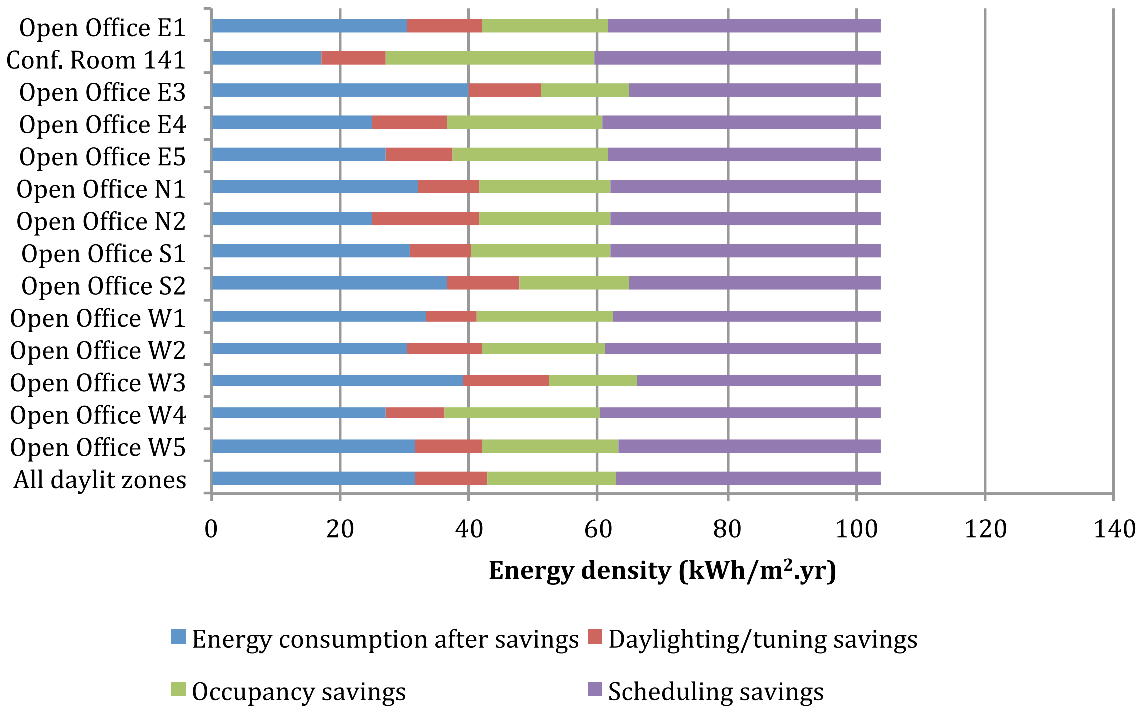

Figure 10. Annual energy use (kWh/m^2-yr) and savings, 6th floor (daylit zones only), ASHRAE 90.1-2007 baseline. The 90.1 baseline energy use is defined by the left edge of the "scheduling" savings bar.

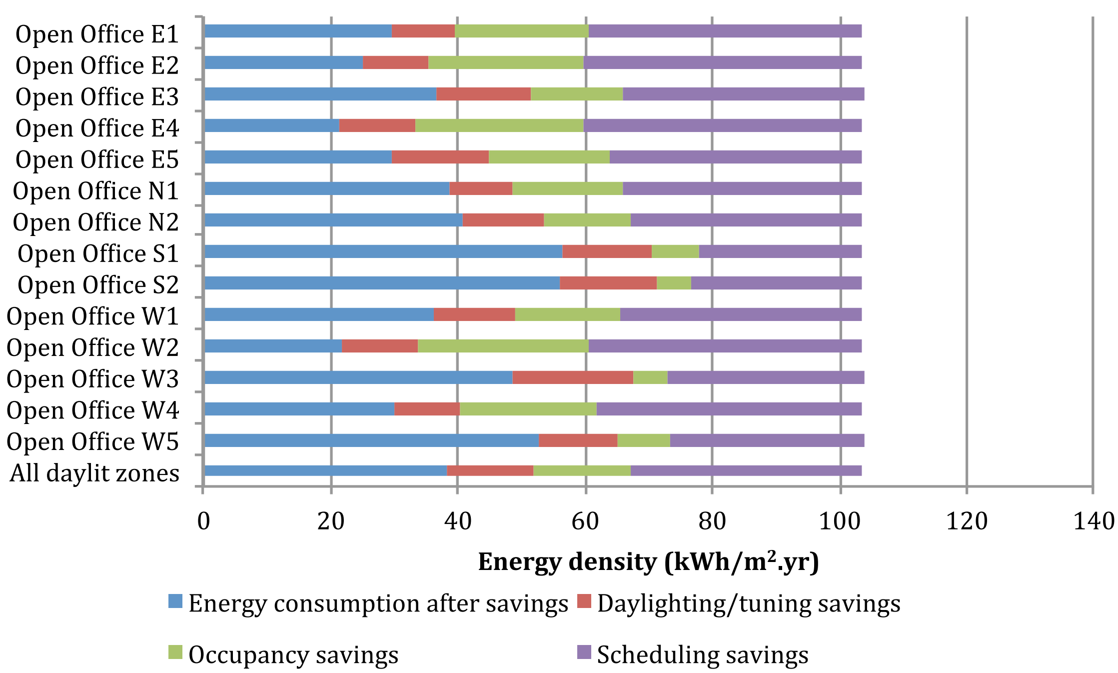

Figure 11. Annual energy use (kWh/m^2-yr) and savings, 11th floor (daylit zones only), ASHRAE 90.1-2007 baseline. The 90.1 baseline energy use is defined by the left edge of the "scheduling" savings bar.

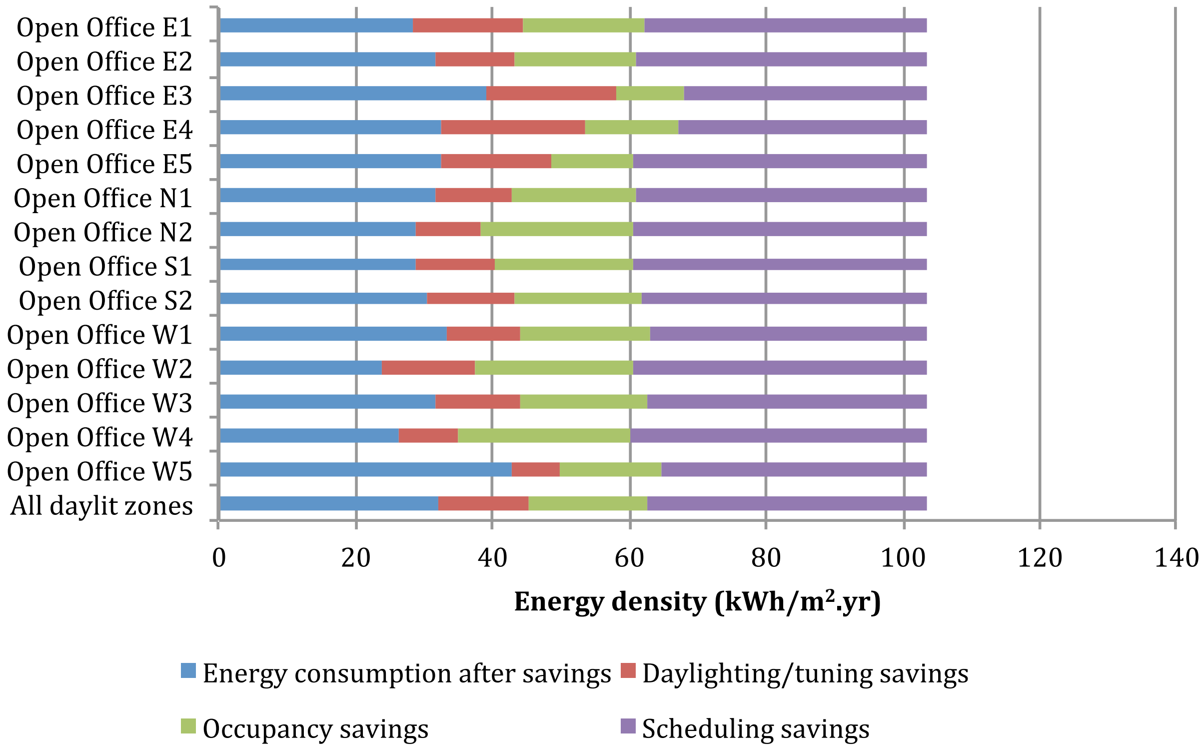

Figure 12. Annual energy use (kWh/m^2-yr) and savings, 20th floor (daylit zones only), ASHRAE 90.1-2007 baseline. The 90.1 baseline energy use is defined by the left edge of the "scheduling" savings bar.

Tables 10-11 and Figures 13-15 and 17 show the same results with the ASHRAE 90.1-2001 baseline instead of the ASHRAE 90.1-2007 baseline. As would be expected, single-zone annual energy consumption after all savings is the same as for the ASHRAE 90.1-2007 baseline. Daylighting and setpoint tuning savings, however, are greater due to the higher installed power density and now vary between 14.6 and 31.8 kWh/m^2-yr (1.36-2.95 kWh/ft^2-yr), or 20% to 39%. Floor-level savings were 25%, 29% and 29% for the 6th, 11th and 20th floors, respectively.

Savings from occupancy controls varied widely between spaces, ranging from 7% (zone S2 on the 11th floor) to 55% (Conference Room 141, 6th floor). The open plan office space with greatest savings was zone E4 on the 11th floor, with approximately 45%. In absolute terms, savings varied depending on the assumed lighting power density, with overall savings for the three floors of 17.6 and 21.4 kWh/m^2-yr (1.63 and 1.99 kWh/ft^2-yr) for ASHRAE 90.1-2007 and 90.1-2001, respectively.

Table 10
Annual energy consumption (kWh/yr) and savings (daylit zones only) with ASHRAE 90.1-2001 baseline.

		Energy use, lights always on	Scheduling savings	ASHRAE 90.1-2001 baseline energy use	Occupancy savings	Daylighting and setpoint tuning savings	Energy use after all savings	Occupancy savings	Daylighting and setpoint tuning savings
		kWh/yr	*kWh/yr*	*kWh/yr*	*kWh/yr*	*kWh/yr*	*kWh/yr*	*%*	*%*
6th Floor	Open Office E1	11554	4768	6785	2197	1762	2826	32%	26%
	Conference Room 141	5196	2226	2970	1644	612	714	55%	21%
	Open Office E3	13865	5263	8602	1869	2285	4448	22%	27%
	Open Office E4	6932	2905	4027	1617	1025	1385	40%	25%
	Open Office E5	11554	4753	6801	2713	1576	2513	40%	23%
	Open Office N1	9532	3873	5659	1895	1313	2450	33%	23%
	Open Office N2	9532	3866	5666	1916	1836	1914	34%	32%
	Open Office S1	9531	3893	5638	1987	1308	2343	35%	23%
	Open Office S2	9532	3600	5932	1594	1528	2811	27%	26%
	Open Office W1	9242	3753	5489	1903	1120	2467	35%	20%
	Open Office W2	6932	2874	4059	1288	1076	1695	32%	27%
	Open Office W3	13865	5104	8761	1832	2586	4343	21%	30%
	Open Office W4	6932	2920	4011	1629	878	1505	41%	22%
	Open Office W5	9243	3677	5565	1923	1302	2341	35%	23%
	All daylit zones	133441	53475	79966	26006	20206	33754	33%	25%
11th Floor	Open Office E1	11552	4849	6702	2379	1590	2733	35%	24%
	Open Office E2	6929	2957	3972	1643	944	1385	41%	24%
	Open Office E3	13871	5111	8761	1951	2747	4063	22%	31%
	Open Office E4	6929	2960	3968	1801	985	1182	45%	25%
	Open Office E5	11558	4471	7087	2178	2170	2740	31%	31%
	Open Office N1	9536	3520	6015	1608	1462	2946	27%	24%
	Open Office N2	9536	3378	6158	1290	1751	3117	21%	28%
	Open Office S1	9535	2391	7144	684	2130	4330	10%	30%
	Open Office S2	9535	2502	7033	513	2240	4280	7%	32%
	Open Office W1	9245	3453	5792	1511	1602	2678	26%	28%
	Open Office W2	6929	2919	4010	1793	988	1228	45%	25%
	Open Office W3	13874	4160	9714	763	3544	5407	8%	36%
	Open Office W4	6930	2830	4100	1463	968	1669	36%	24%
	Open Office W5	9250	2778	6471	741	1821	3909	11%	28%
	All daylit zones	135209	48280	86929	20320	24941	41668	23%	29%
20th Floor	Open Office E1	11552	4676	6876	2014	2249	2613	29%	33%
	Open Office E2	6931	2877	4054	1199	1090	1765	30%	27%
	Open Office E3	13862	4852	9010	1322	3325	4363	15%	37%
	Open Office E4	6931	2452	4479	936	1731	1812	21%	39%
	Open Office E5	11553	4855	6698	1363	2311	3024	20%	34%
	Open Office N1	9531	3985	5546	1671	1444	2431	30%	26%
	Open Office N2	9531	3987	5544	2069	1274	2200	37%	23%
	Open Office S1	9531	3986	5545	1891	1450	2205	34%	26%
	Open Office S2	9530	3898	5632	1741	1568	2323	31%	28%
	Open Office W1	9243	3684	5559	1742	1332	2485	31%	24%
	Open Office W2	6930	2907	4023	1575	1125	1323	39%	28%
	Open Office W3	13865	5575	8290	2503	2248	3539	30%	27%
	Open Office W4	6930	2931	3999	1701	846	1452	43%	21%
	Open Office W5	9242	3540	5702	1371	1160	3172	24%	20%
	All daylit zones	135162	54204	80958	23099	23152	34707	29%	29%
All daylit zones		403811	155958	247853	69425	68299	110129	28%	28%

Table 11
Annual energy consumption density (kWh/m^2-yr) and savings (daylit zones only) with ASHRAE 90.1-2001 baseline.

		Energy use, lights always on	Scheduling savings	ASHRAE 90.1-2001 baseline energy use	Occupancy savings	Daylighting and setpoint tuning savings	Energy use after all savings
		kWh/m²-yr	*kWh/m²-yr*	*kWh/m²-yr*	*kWh/m²-yr*	*kWh/m²-yr*	*kWh/m²-yr*
6th Floor	Open Office E1	124.4	51.3	73.0	23.6	19.0	30.4
	Conference Room 141	124.3	53.2	71.0	39.3	14.6	17.1
	Open Office E3	124.4	47.2	77.2	16.8	20.5	39.9
	Open Office E4	124.4	52.1	72.2	29.0	18.4	24.8
	Open Office E5	124.4	51.2	73.2	29.2	17.0	27.0
	Open Office N1	124.4	50.5	73.8	24.7	17.1	32.0
	Open Office N2	124.4	50.4	73.9	25.0	24.0	25.0
	Open Office S1	124.4	50.8	73.6	25.9	17.1	30.6
	Open Office S2	124.4	47.0	77.4	20.8	19.9	36.7
	Open Office W1	124.4	50.5	73.9	25.6	15.1	33.2
	Open Office W2	124.4	51.6	72.8	23.1	19.3	30.4
	Open Office W3	124.4	45.8	78.6	16.4	23.2	39.0
	Open Office W4	124.4	52.4	72.0	29.2	15.7	27.0
	Open Office W5	124.4	49.5	74.9	25.9	17.5	31.5
	All zones	124.4	49.8	74.5	24.2	18.8	31.5
11th Floor	Open Office E1	124.3	52.2	72.1	25.6	17.1	29.4
	Open Office E2	124.3	53.0	71.3	29.5	16.9	24.8
	Open Office E3	124.4	45.8	78.6	17.5	24.6	36.4
	Open Office E4	124.3	53.1	71.2	32.3	17.7	21.2
	Open Office E5	124.4	48.1	76.3	23.4	23.4	29.5
	Open Office N1	124.4	45.9	78.5	21.0	19.1	38.4
	Open Office N2	124.4	44.1	80.3	16.8	22.8	40.7
	Open Office S1	124.4	31.2	93.2	8.9	27.8	56.5
	Open Office S2	124.4	32.6	91.8	6.7	29.2	55.8
	Open Office W1	124.4	46.5	77.9	20.3	21.6	36.0
	Open Office W2	124.3	52.4	71.9	32.2	17.7	22.0
	Open Office W3	124.5	37.3	87.1	6.8	31.8	48.5
	Open Office W4	124.3	50.8	73.6	26.2	17.4	29.9
	Open Office W5	124.5	37.4	87.1	10.0	24.5	52.6
	All zones	124.4	44.4	80.0	18.7	22.9	38.3
20th Floor	Open Office E1	124.3	50.3	74.0	21.7	24.2	28.1
	Open Office E2	124.3	51.6	72.7	21.5	19.5	31.7
	Open Office E3	124.3	43.5	80.8	11.9	29.8	39.1
	Open Office E4	124.3	44.0	80.4	16.8	31.1	32.5
	Open Office E5	124.4	52.3	72.1	14.7	24.9	32.6
	Open Office N1	124.3	52.0	72.4	21.8	18.8	31.7
	Open Office N2	124.3	52.0	72.3	27.0	16.6	28.7
	Open Office S1	124.4	52.0	72.3	24.7	18.9	28.8
	Open Office S2	124.3	50.9	73.5	22.7	20.5	30.3
	Open Office W1	124.4	49.6	74.8	23.4	17.9	33.4
	Open Office W2	124.3	52.1	72.2	28.3	20.2	23.7
	Open Office W3	124.4	50.0	74.4	22.5	20.2	31.7
	Open Office W4	124.3	52.6	71.7	30.5	15.2	26.1
	Open Office W5	124.4	47.6	76.7	18.4	15.6	42.7
	All zones	124.3	49.9	74.5	21.3	21.3	31.9
All daylit zones		124.4	48.0	76.3	21.4	21.0	33.9

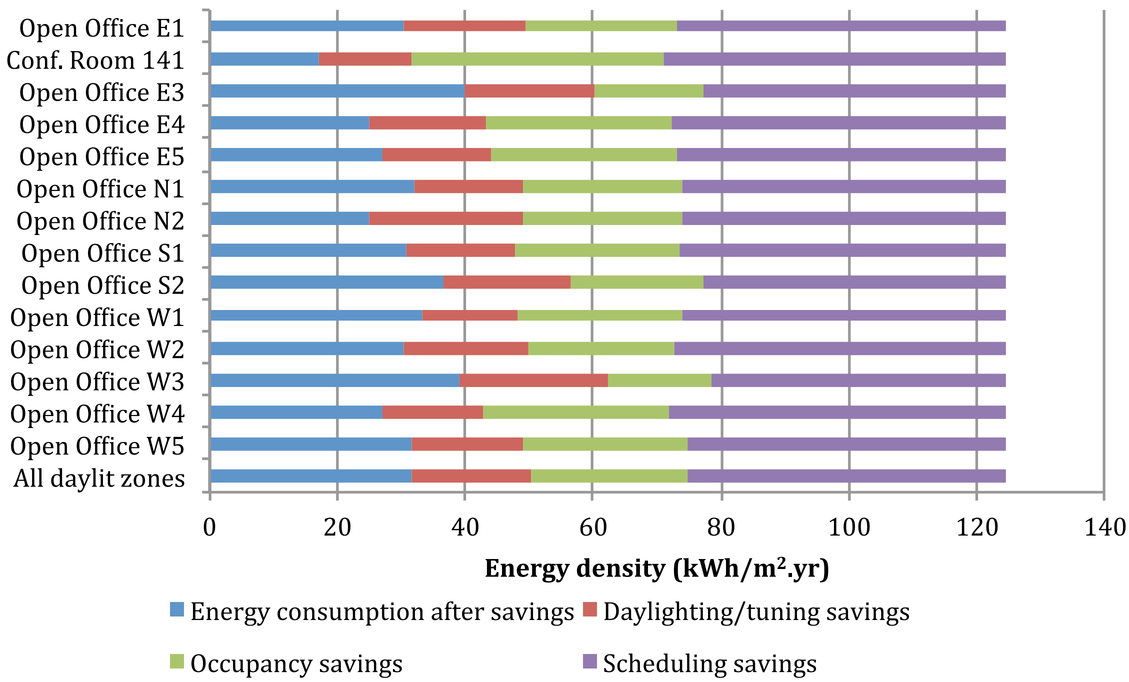

Figure 13. Annual energy use (kWh/m^2-yr) and savings, 6th floor (daylit zones only), ASHRAE 90.1-2001 baseline. The 90.1 baseline energy use is defined by the left edge of the "scheduling" savings bar.

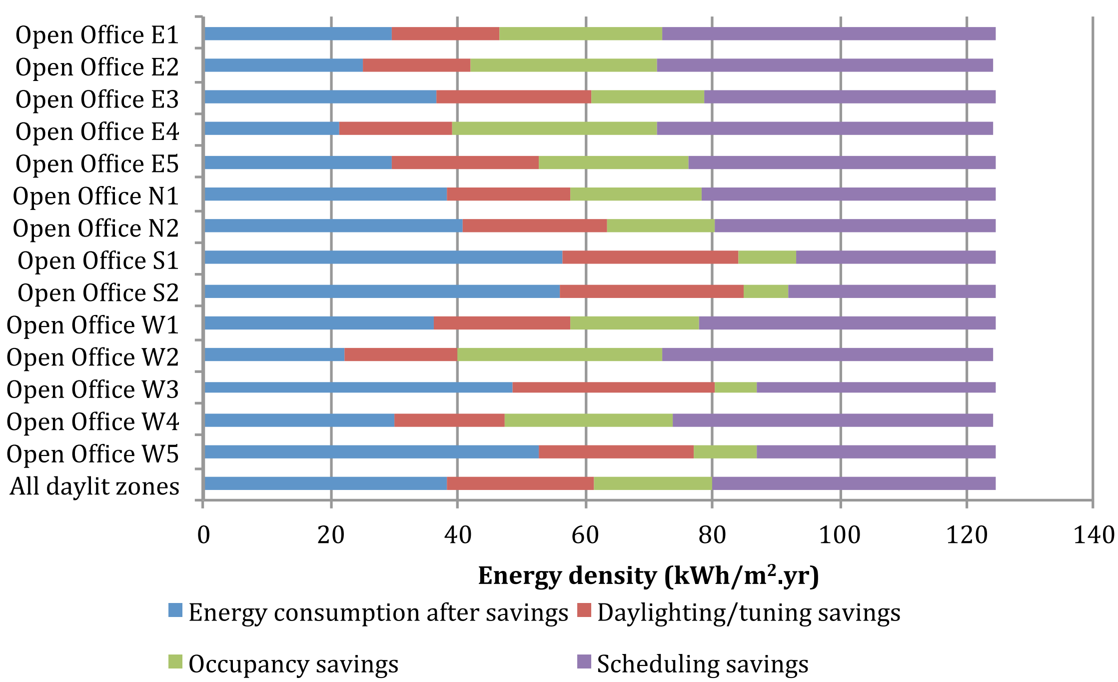

Figure 14. Annual energy use (kWh/m^2-yr) and savings, 11th floor (daylit zones only), ASHRAE 90.1-2001 baseline. The 90.1 baseline energy use is defined by the left edge of the "scheduling" savings bar.

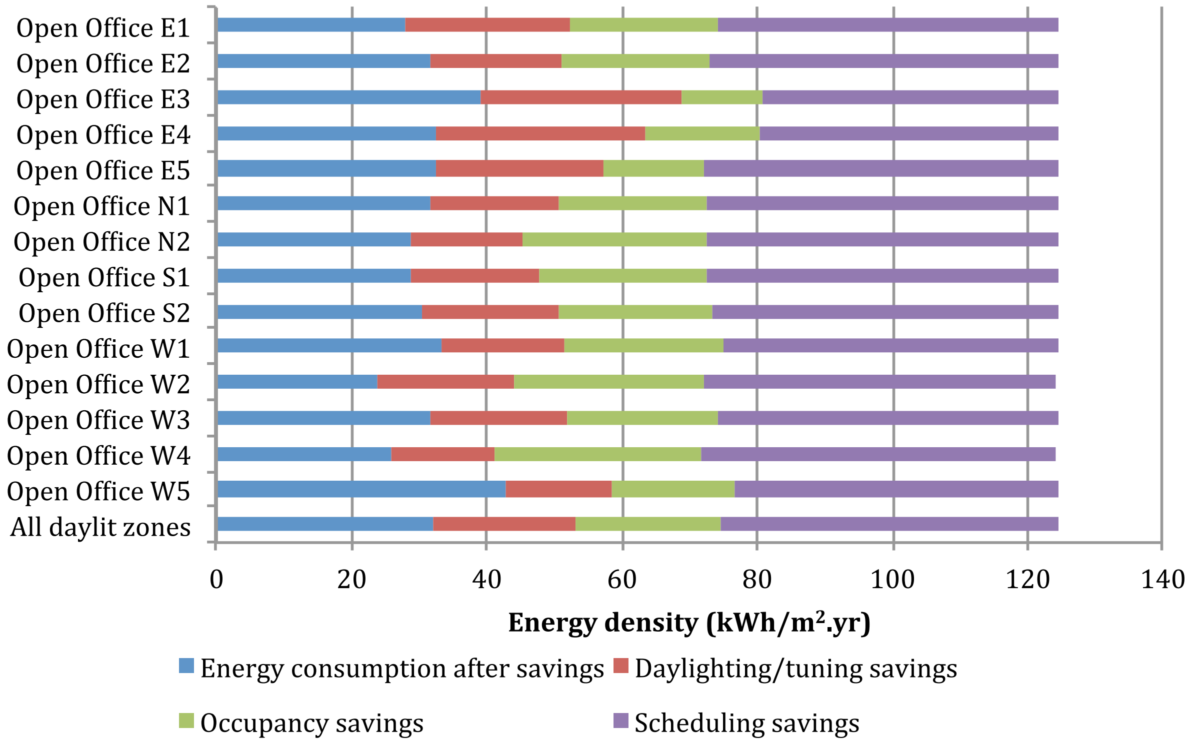

Figure 15. Annual energy use (kWh/m^2-yr) and savings, 11th floor (daylit zones only), ASHRAE 90.1-2001 baseline. The 90.1 baseline energy use is defined by the left edge of the "scheduling" savings bar.

3.2 Cost-effectiveness

Exact values for installation and energy costs were not disclosed for this building. For this reason, simple payback was calculated for a range of possible costs. Results are shown in Table 12, and indicate that the addition of occupant and automatic dimming controls pays for the initial investment in one to eight years for incremental installed costs in the range of \$5.40/m^2 to \$43.00/m^2-floor (\$0.50-4.00/ft^2) and the installed, 90.1-2001 lighting power density of (14 W/m^2,1.3 W/ft^2). This assumes that the automated shading system has, on average, a neutral impact on daylight availability.

For dimming controls only (tuning and daylighting), payback is between one and ten years for the same installed cost range. Note that dimming payback periods are highly dependent on patterns of occupancy during the daytime. For the shallow daylit zones with few workstations (e.g., E2, E4, W2, and W4 had 4 workstations), average occupancy savings were 37%, well above the average for the three floors (28%) and dimming savings were 26%, slightly below the three-floor average of 28%. For deeper daylit zones with many workstations (e.g., N1, N2, S1, and S2 had 10 workstations, W3 and E3 had 12 workstations), occupancy savings were below average (23%) and dimming savings were slightly above average (29%).

Using the ASHRAE 90.1-2007 baseline (12 W/m^2, 1.1 W/ft^2), payback times are longer: 2-12 and 2-18 years for occupancy plus dimming and dimming only, respectively.

Table 12
Simple payback (yr) for dimmable lighting controls.

	Lighting Power Density (W/m^2)	
	14 (90.1-2001)	12 (90.1-2007
Annual energy cost (USD), daylit areas of floors 6 + 11 + 20		
Always on	$ 52,602.59	$ 43,835.49
Scheduling (baseline)	$ 42,466.50	$ 35,479.00
Scheduling + occupancy	$ 38,217.69	$ 31,983.48
Scheduling + occupancy + dimming	$ 24,286.94	$ 24,282.71
Payback for occupancy + dimming		
Savings from baseline (scheduling)	$ 18,179.56	$ 11,196.29
Savings density ($/m^2)	$ 5.60	$ 3.45
Installed cost ($/m^2)	Payback (yrs)	
5.38	1.0	1.6
10.76	1.9	3.1
16.15	2.9	4.7
21.53	3.8	6.2
26.91	4.8	7.8
32.29	5.8	9.4
37.67	6.7	10.9
43.06	7.7	12.5
Payback for dimming only		
Savings from baseline (scheduling + occupancy)	$ 13,930.75	$ 7,700.77
Savings density ($/m^2)	$ 4.29	$ 2.37
Installed cost ($/m^2)	Payback (yrs)	
5.38	1.3	2.3
10.76	2.5	4.5
16.15	3.8	6.8
21.53	5.0	9.1
26.91	6.3	11.3
32.29	7.5	13.6
37.67	8.8	15.9
43.06	10.0	18.2

4. Discussion

4.1 Daylighting trends between zones

When considering floors as a whole and zones with similar levels of occupancy savings, results show a slight 2-3% increase in dimming savings for the higher floor levels (11th and 20th). When analyzing Tables 8-11 and Figures 16-17, however, it is difficult to discern clear trends at the individual zone level. Some zones, such as E3, show a clear decrease in savings as floor level decreases, but that trend is not generalizable to other zones. Within each floor, clear trends are also not apparent with façade orientation.

As detailed in the sections above, when calculating savings we assumed that when the zone was unoccupied and lights were scheduled to be on, savings were attributed to occupancy controls. One consequence of this is that zones with the *same* daylight availability could have different savings from dimming controls (daylight + setpoint tuning) if their daytime occupancy patterns were different. Baseline energy use also differed because some zones (e.g., S1 and S2 on the 11th floor) were occupied significantly more during scheduled off hours (nights and weekends) than other zones. To understand if this was significantly affecting our results, we calculated the average annual workday occupancy for each zone so that lighting energy savings due to dimming could be compared for zones with similar patterns of daytime occupancy.

Average annual workday occupancy for each zone is shown in Figure 18, along with the average occupancy of all zones combined. It is evident that, on average, occupancy is very high during core daytime work hours, getting close to 100% between approximately 10 AM and 6 PM. When we recalculated annual energy savings only for standard workday hours (9 AM to 5 PM), occupancy savings varied much less across zones. The primary benefit of occupant sensor based controls occurred when occupants arrived early or left late in the day.

These common patterns of occupancy enabled us to evaluate whether perimeter zone lighting energy savings due to dimming controls correlated to daylight availability. Typical results are shown in Figure 19 for the 20th floor and ASHRAE 90.1-2001 baseline. In Figure 20, data are grouped based on comparable daylit zones (same depth and sidelit or corner window configuration). Across all three floors, clear trends between zones were still not readily apparent, although when we analyzed savings from daylighting only (Figure 21), the deepest spaces (E3 and W3) now had the lowest savings in each floor as would be expected. This lack of clear general trends at the zone level can probably be ascribed to the influence of several factors: exterior urban obstructions, the attached fixed outdoor shades, and automated indoor shading system. All factors affected different zones in complex ways, making daylight availability difficult to predict without detailed analysis of incident daylight at the façade and the shading system activity. Generally, the automated shading system probably reduced differences in daylight availability; e.g., for lower floors or orientations with less sun and sky exposure, the automated shades were raised more frequently than the upper floors.

Separately, analysis of lighting control system reliability was not conducted in this post-occupancy evaluation. To determine whether the dimming controls under- or over-dimmed the lighting would have required determination of daylight work plane illuminance. The LCS data were provided by dimming zones, not daylighting control zones, and even if the data were provided, deriving the relationship between dimming level and electric lighting workplane illuminance for each dimming zone (and shade height) in order to calculate daylight workplane illuminance is non-trivial and beyond the scope of this project. This work was conducted in the mock-up to verify performance of the final system prior to installation in the building and to develop commissioning tools and procedures [16] and was therefore not repeated in the actual building.

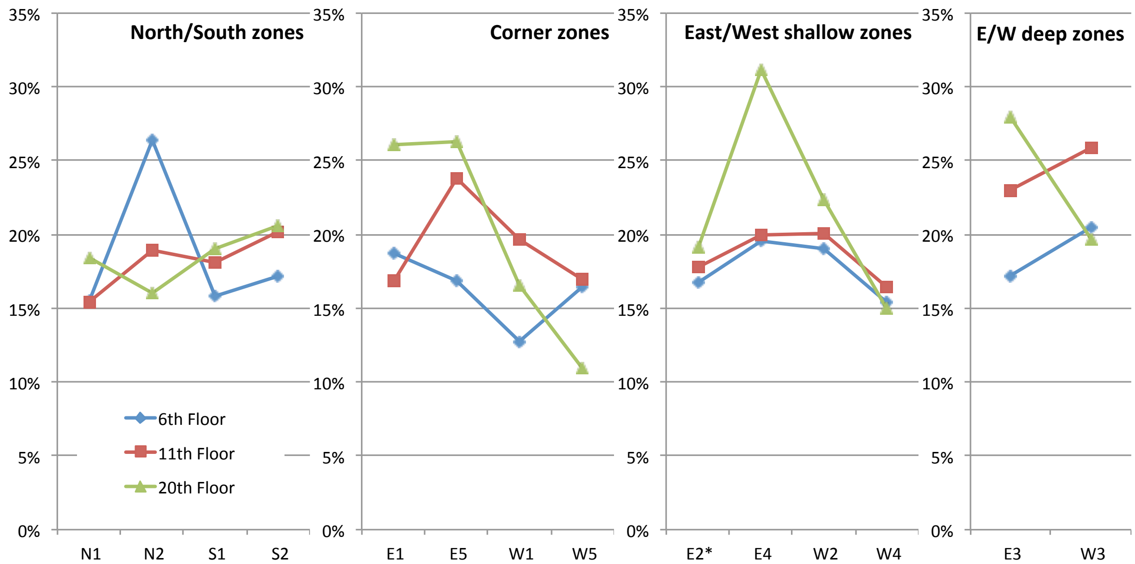

Figure 16. Percent lighting energy savings from daylighting controls and setpoint tuning, ASHRAE 90.1-2007 baseline.

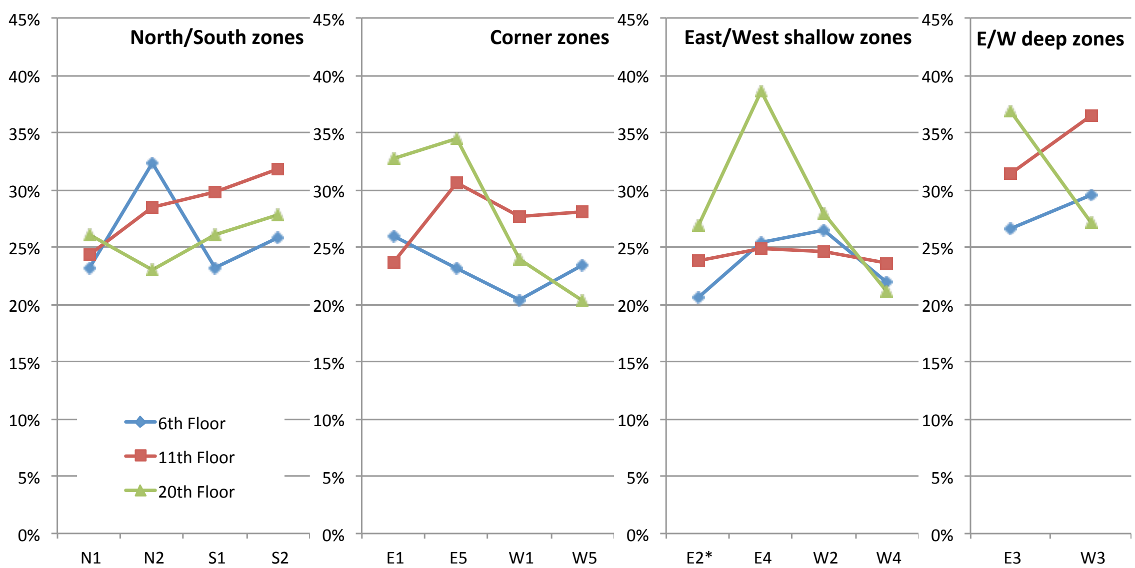

Figure 17. Percent lighting energy savings from daylighting controls and setpoint tuning, ASHRAE 90.1-2001 baseline.

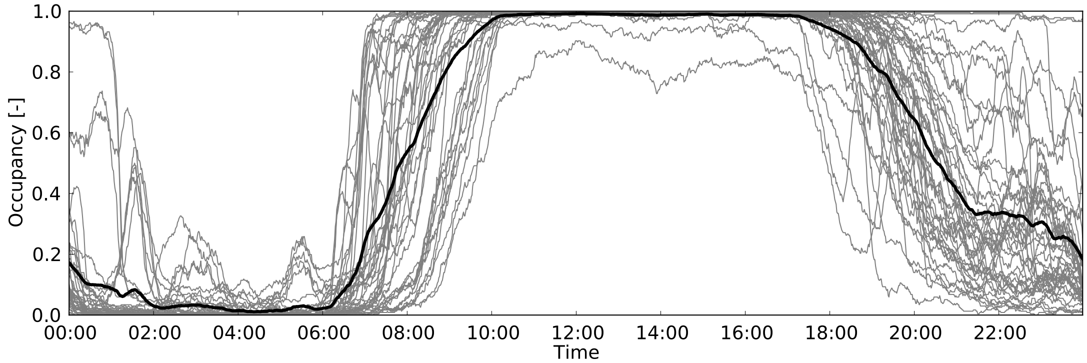

Figure 18. Average workday occupancy. The average occupancy of each zone is shown in light gray. Average of all zones is shown in black.

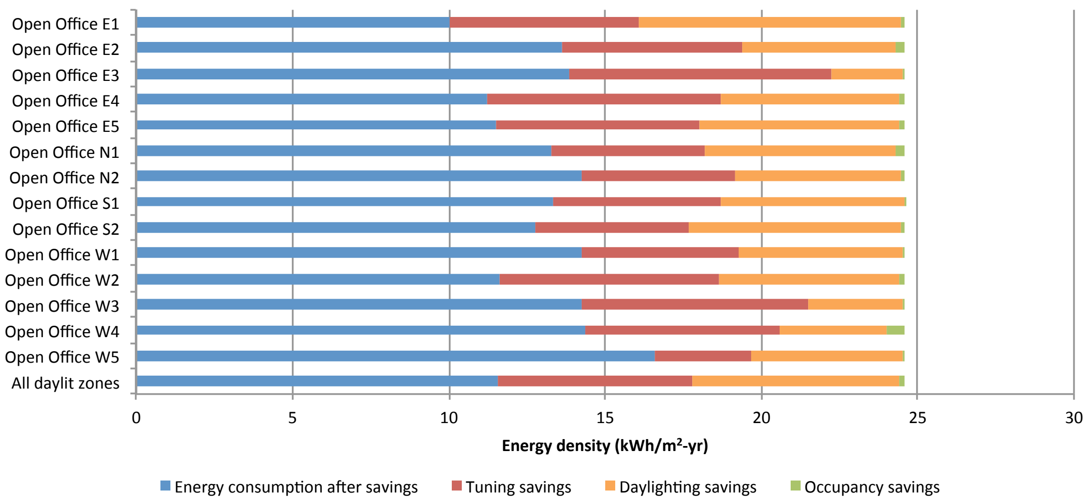

Figure 19. Annual lighting energy use (kWh/m^2-yr) and percent savings, 20th floor (daylit zones only), ASHRAE 90.1-2001 baseline, for all workdays in the year from 9 AM to 5 PM only.

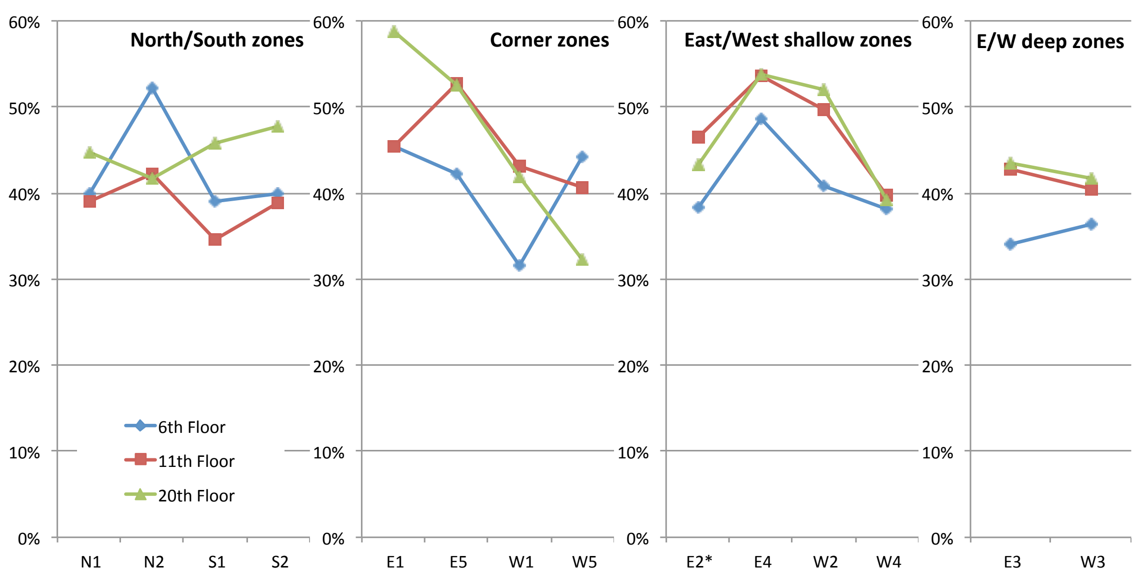

Figure 20. Percent lighting energy savings from daylighting controls and setpoint tuning, ASHRAE 90.1-2001 baseline, for all workdays in the year from 9 AM to 5 PM only.

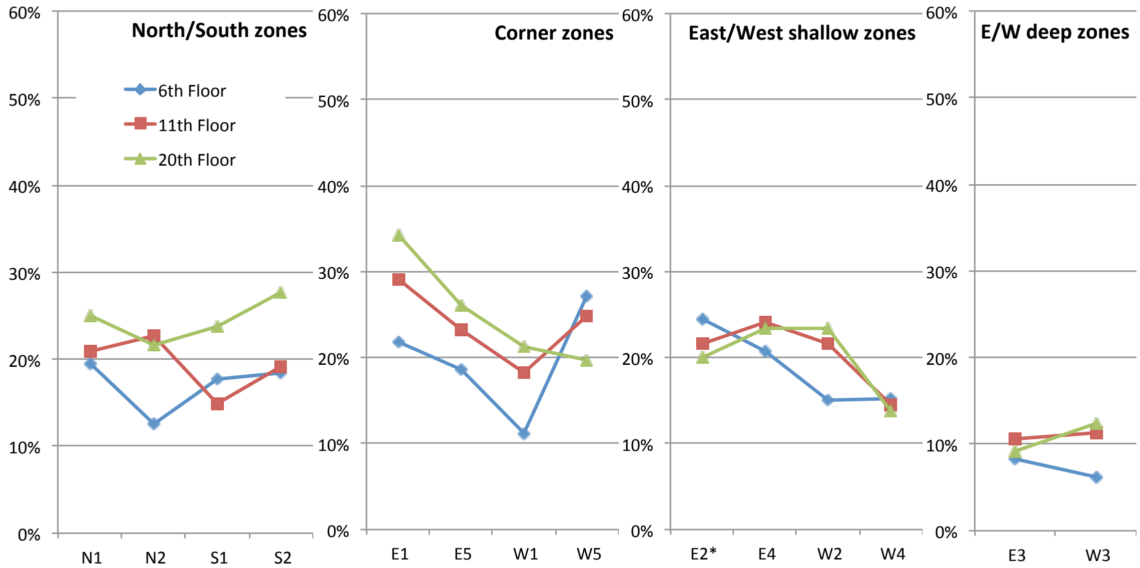

Figure 21. Percent lighting energy savings from daylighting controls only, ASHRAE 90.1-2001 baseline, for all workdays in the year from 9 AM to 5 PM only.

4.2 Payback periods

Payback periods are naturally driven by installed cost. Table 12, however, shows that baseline lighting power density (LPD) is also an important factor and that lower densities will result in longer paybacks. This is less relevant when the addition of controls is being considered as a retrofit to an existing lighting system with high installed LPD. In the case of newer buildings, which are subject to lower LPD requirements and tighter controls (e.g., the ASHRAE 90.1-2010 Standard requires 0.98 W/ft^2 for office spaces and automated daylight switching in the zone immediately adjacent to the window [17]), it should be noted that cost-effectiveness could increase beyond what is shown here if the present trend for increased energy costs during times of peak use continues.

Power usage over the dimming range has improved over the past few years. The minimum power use for the dimming ballasts installed in the Times Building was 35% – digitally addressable ballasts were just being introduced to the market at the time of procurement. Since then, minimum power use has dropped to 17% (with T5 lamps) with associated light output dropping to 1% for some digital dimmable ballasts. Minimum and standby power use are not routinely reported in manufacturers' dimmable ballast technical specifications; unfortunately, end users must measure this quantity in order to compare different products. In the case of this analysis, since the lights were turned off 6 min after there was sufficient daylight, the high level of minimum power is less of an issue in this case study compared to systems where the dimming system is never turned off or is delayed for a long period prior to turning off. These measures were implemented historically to minimize occupant distraction when light output levels were high (20-30%) at minimum power levels – people noticed the on-off flicker of the lights on partly cloudy days when interior daylight levels were fluctuating widely. With the minimum light output level now at 10% or less, this visual distraction is less of an issue.

5. Conclusions

Monitored lighting energy savings from dimmable lighting controls were determined for the daylit, open-plan office areas on the 6th, 11th, and 20th floors of The New York Times Building, a 51-story building in New York, New York, of which the Times Company occupies floors 2 through 21. The building was designed with floor-to-ceiling windows, transparent clear glass (WWR=0.76, center-of-glass Tvis=0.75) shaded with an attached, open, exterior shading system and automated, densely woven interior roller shades (openness factor of 1.5% for most window orientations). The building was located in a dense urban environment. The interior had deep perimeter open plan work areas with light colored finishes and 1.2 m (4 ft) high open plan workstations. The ambient lighting system consisted of recessed fixtures with T5 lamps and early market, digital addressable, dimmable ballasts (10-100% light output, 35-100% power). The lighting was controlled for occupancy based on sensors in the open plan office zones, setpoint tuning, and daylighting. When in the daylight mode, the lights were turned off after a 6 min delay if there was sufficient daylight and turned on with no delay if there was insufficient daylight. The setpoint level was 323 lux (30 fc) for almost all zones. Typical office tasks were conducted in these zones during standard daytime work hours.

The solstice-to-solstice period of analysis was from June 21, 2010 to June 20, 2011. For dimming controls (daylighting and setpoint tuning), results showed savings of 12.6 kWh/m^2-yr (1.17 kWh/ft^2-yr) after occupancy-based controls, a reduction of 20% relative to the ASHRAE 90.1-2007 baseline, which prescribed an installed maximum lighting power density of 12 W/m^2 (1.1 W/ft^2) and automated scheduling controls. Savings were 18%, 20% and 21% for the zones on the 6th, 11th and 20th floors, respectively. Ranges for single zone savings were 13-26%, 15-26% and 11-31%, respectively.

For the prescriptive standard for which this building was designed (ASHRAE 90.1-2001 with installed lighting power density of 14 W/m^2 (1.3 W/ft^2) and automated scheduling controls), overall savings were 21.0 kWh/m^2-yr (1.95 kWh/ft^2-yr), an overall reduction of 28%. Savings were 25%, 29%, and 29% for the zones on the 6th, 11th and 20th floors, respectively.

Savings obtained by implementing sensor-based occupancy controls per zone were also computed. Overall savings were in the vicinity of 27% or 17.6 kWh/m^2-yr (1.63 kWh/ft^2-yr) (ASHRAE 90.1-2007 baseline) and 21.4 kWh/m^2-yr (1.99 kWh/ft^2-yr) (ASHRAE 90.1-2001 baseline). Savings occurred primarily at night from about 6 PM to 1 AM during the period when the Times Company would not have scheduled the lighting to be off (1-6 AM) and during early morning and evening hours outside of the primary daytime work hours when occupancy tended to be irregular.

If one considered standard workday hours (9 AM – 5 PM) only, annual lighting energy savings due to dimming controls (setpoint tuning and daylighting) were, relative to the ASHRAE 90.1-2001 baseline, 32-59%, relative to the ASHRAE 90.1-2001 baseline, across open plan perimeter zones up to 13.25 m (43.45 ft) deep with sidelit or corner windows on lower and upper floors in a dense urban environment. Daylighting savings across the same zones varied between 6% and 34%. Occupant sensor-based controls provided small to negligible savings during this period (0.6% for 20th floor, 0.9% for 11th floor and 3.8% for the 6th floor, excluding Conference Room 141). No clear trends were identified regarding savings variations by façade orientation within the same floor, or between similar spaces on different floors, with the exception of lower daylighting savings for the deepest zones (E3 and W3). This was possibly due to the automatic shading system which moderated variations in daylight availability, providing more daylight to lower floors and controlling direct sun and glare but reducing daylight on upper floors.

For dimming controls, energy savings translated into payback periods of 1-10 years (90.1-2001) and 2-18 years (90.1-2007) for installed costs in the \$5.40-43.00/m^2 (\$0.50-4.00/ft^2) range. Shorter payback periods would have been attained if occupancy controls were not implemented in the open plan office zones or if the more efficient digital dimming ballasts that are now available today were used instead. The Times Company installed an emerging ballast technology – power management has been improved significantly since the initial procurement in 2004. For example, the power range of a comparable dimmable ballast is now 17-100% for a light output range of 1-100%. When savings from occupancy controls were also taking into account, payback times were shortened to 1-8 years (90.1-2001) and 1-12 years (90.1-2007).

Payback would also be shortened if amenity factors were included. Digital addressable ballasts enable individual fixture control and reconfiguration, reducing the labor and material costs for rezoning when spaces are reconfigured or controls are adjusted over the life of the installation. Analog dimmable ballasts are typically grouped to reduce costs for communications and control, so while lower in initial cost, these systems may cost more in the long term if the rate of churn is high.

The discrepancies observed between measured power consumption and values calculated based on information from the building's lighting control system highlight the importance of using direct measurements when evaluating the field performance of energy-efficient technologies.

Codes and standards have for several years required occupancy or scheduling controls for large buildings and the high savings obtained with occupancy controls in this building confirm that this has been correctly identified as a very large energy savings opportunity. Digitally addressable, dimmable lighting has come down significantly in cost and the energy use of dimmable ballasts over the dimming range (e.g., minimum power use and standby power) has also been improved significantly. While on-off switching controls do provide a low-cost option for commercial buildings, it is expected that dimmable lighting will become more widespread due to not only the energy-efficiency benefits it can provide but also the amenity features that can be used by the facility management team as space use and lighting requirements change over the life of the building.

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