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The New York Times Headquarters Daylighting Mockup: Monitored performance of the daylighting control system

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Abstract

A nine-month monitored field study of the performance of automated roller shades and daylighting controls was conducted in a 401 m^2 unoccupied, furnished daylighting mockup. The mockup mimicked the southwest corner of a new 110 km^2 commercial building in New York, New York, where The New York Times will be the major tenant. This paper focuses on evaluating the performance of two daylighting control systems installed in separate areas of an open plan office with 1.2-m high workstation partitions: 1) Area A had 0-10 V dimmable ballasts with an open-loop proportional control system and an automated shade controlled to reduce window glare and increase daylight, and 2) Area B had digital addressable lighting interface (DALI) ballasts with a closed-loop integral reset control system and an automated shade controlled to block direct sun. Daylighting control system performance and lighting energy use were monitored. The daylighting control systems demonstrated very reliable performance after they were commissioned properly. Work plane illuminance levels were maintained above 90% of the maximum fluorescent illuminance level for 99.9±0.5% and 97.9±6.1% of the day on average over the monitored period, respectively, in Areas A and B. Daily lighting energy use savings were significant in both Areas over the equinox-to-equinox period compared to a non-daylit reference case. At 3.35 m from the window, 30% average savings were achieved with a sidelit west-facing condition in Area A while 50-60% were achieved with a bilateral daylit south-facing condition in Area B. At 4.57-9.14 m from the window, 5-10% and 25-40% savings were achieved in Areas A and B, respectively. Average savings for the 7-m deep dimming zone were 20-23% and 52-59% for Areas A and B, respectively, depending on the lighting schedule. The large savings and good reliability can be attributed to the automatic management of the interior shades. The DALI-based system exhibited faulty behavior that remains unexplained, but operational errors are expected to be resolved as DALI products reach full maturity. The building owner received very competitive bids ($30-75 US/DALI ballast) and was able to justify use of the daylighting control system based on operational cost savings and increased amenity. Additional energy savings due to reduced solar and lighting heat gains were not quantified but will add to the total operational cost savings.

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

1. Introduction

The US building sector's energy consumption is expected to increase by 35% between now and 2025. Commercial energy demand is projected to grow at an average annual rate of 4.7×10^{14} Wh (1.6×10^{15} Btu), reaching 7.4×10^{15} Wh (25.3×10^{15} Btu) by 2025 with business-as-usual practices. The US Department of Energy's (DOE) Energy Efficiency and Renewable Energy Building Technologies (BT) overall program goal [1] is to instead achieve net "zero energy buildings" (ZEB) by 2025, where the right mix of innovative technologies are combined with proper design, controls integration, and on-site renewable energy supply systems to achieve net zero energy use. Switchable windows, such as electrochromics and reflective hydrides, and daylighting control systems have significant technical potential to reduce energy use and peak demand. But while the technical potential is significant for many of these technologies, market barriers typically slow the rate of adoption in buildings. For example, conventional automated shades and daylighting controls have been commercially available for over two

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decades with less than 1-2% market penetration in the US. Therefore, another key aspect to realizing the ZEB goal is to accelerate market adoption of emerging technologies.

As with all innovations, the problem is of decreasing risk and cost. Most building owners and architectural-engineering (A/E) teams are risk averse and are reluctant to be the first to adopt a new technology and pay the premium for using a new technology. As the building owner and A/E team researches technology options, the usual questions surface that concern the purchase of any new product: how much will it cost, how will it work for my application, are the manufacturer claims valid, what risks are incurred, and will the performance benefits be sustained over the life of the installation? Most designers and owners do not have ready access to answers to these questions, slowing the adoption rate of innovative technologies. Inadequate simulation tools lead to incorrect conclusions as to the overall benefits of such systems. The design team must determine if such innovations increase cooling, visual discomfort, occupant dissatisfaction, or have other unknown impacts. Increased design, capital and maintenance costs are also major deterrents.

In early 2003, The New York Times approached the Lawrence Berkeley National Laboratory (LBNL) for advice having seen LBNL's research on dynamic shading and lighting systems. Automated roller shades and daylighting controls were under consideration. The building owner was willing to consider these technologies but needed third-party data to understand the risks and cost-benefits associated with the use of such technologies. A partnership was subsequently created between the building owner, LBNL, industry, and three public funding agencies to conduct a six-month solstice-to-solstice[1] monitored field test to evaluate commercially available automated roller shade and daylighting control systems. At minimum, the field test was designed to obtain objective lighting energy use, control system performance, and visual comfort data. In parallel, the field test formed a key strategic cornerstone for accelerating industry's response to the building owner's challenge to create a competitive market and drive costs down. At the end of the six-month field test, the building owner incorporated lessons learned about each type of system and created a procurement specification. This procurement specification was let out to all eligible manufacturers for competitive bidding. The winning manufacturers then partnered with the building owner and LBNL to develop, test, and prove the capabilities of their systems in the daylighting mockup prior to installation in the final building.

This paper documents part of this effort: dimmable daylighting control system performance and lighting energy savings under unoccupied conditions in an open plan office with an automated roller shade. While the application is specific, the field test demonstrates the energy-savings potential of the combined use of two integrated emerging technologies under real sun and sky conditions, illustrates operational characteristics and reliability, and identifies the possible risks associated with the use of such technologies. The field test was not a controlled experiment, rather a living laboratory in which multiple players with different agendas tested and observed control system behavior. This was not an exercise to determine which type of daylighting control system performed better or worse and why – the physical layout of the space prohibited such comparisons. The focus of the work was to determine if the systems did work, how much effort was required to make the systems work, and how much energy savings could be garnered and under which circumstances. The analysis was confounded by the use of prototyped digital addressable lighting interface (DALI) ballasts, which were just coming onto the market. There was considerable effort invested to determine how these ballasts performed in a real-world context, what innovative features could be implemented, and to troubleshoot operational errors. The resultant procurement specifications and other papers documenting the automated shade system performance and the environmental quality of the space (visual discomfort, access to view, interior brightness, subjective study results) can be found at the project website [2].

2. Experimental method

2.1. Facility description

2.1.1. Building description

A new 51-storey high-rise building is under construction in downtown Manhattan between 7th and 8th Avenue and West 40th and West 41st Street of New York City and is due to be completed by 2007. To evaluate daylighting, a 401 m^2 one-storey, full-scale, fully-furnished, outdoor mockup was built in 2003 by The New York Times in the

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[1] To avoid confusion, the intent was to conduct a six-month solstice-to-solstice test but the field test was later extended to nine months and useful data were collected for only the equinox-to-equinox solar condition (late February to September).

parking lot of their nearby printing press site in Flushing, New York. The mockup reproduced the southwest corner of a typical floor in the 51-storey tower (Figure 1). It was located at latitude 40.8° and longitude 73.9° and its orientation matched the orientation of the Manhattan site. The “south” and “west” windows faced 28.7° and 118.7° west of true south, respectively.

Fig. 1. Exterior view of the west façade of The New York Times daylighting mockup (left) and interior view of Area B (right) on February 23, 2004 with south-facing windows on the left-hand side of the photograph.

The view immediately out the south-facing windows was of a parking lot with a black asphalt surface. Cars and snow caused the ground surface reflectance to vary from 0.05-0.10 (black asphalt) to ~0.8-0.9 (snow). The interior finished floor height was 1.78 m above the ground. The printing plant to the southeast and trees to the west had an altitude of no greater than 10° in any direction.

The interior daylit space (Figure 2) was 13.34 m deep along the east-west axis from the west window wall to the face of the core wall and 23.62 m wide along the north-south axis from the south window wall to the face of the mirror wall. A mirror was placed along the entire length of the north wall so that the daylighting conditions would be nearly representative of a continuous open plan office. The mirror caused specular reflections of direct sunlight for some sun angles that would not normally occur in the actual building. These effects were judged to have little impact on the overall results from this field study particularly since direct sun was blocked automatically by the shades. Private offices with clear glazed fronts (facing west) were placed 7 m from the window wall. The ceiling height at the window wall was 3.15 m then stepped down to 2.92 m high after a setback of 1.07 m from the window.

Several types of open plan office furniture were installed in the mockup but all were of similar dimensions (1.22-m high) and nearly the same surface reflectances. Desk surfaces were white composite material (r=0.84), low partition walls were gray fabric (r=0.226), and the carpet was gray (r=0.071). The interior lobby corridor wall was initially a gray fabric (r=~0.70) but was painted with a saturated red (r=0.176) and blue color (r=0.20) after 1/19/04[2]. The ceiling was composed of white gypsum acoustical tiles (r=0.87).

The space was conditioned using an underfloor air distribution (UFAD) system. Conditioned air was supplied at floor level through 15.24-cm diameter floor diffusers and a 10.16-cm wide continuous grille register at the window wall. Return air was brought back through registers at the east corridor and through the ceiling plenum. The temperature in the ceiling plenum was roughly the same as the air temperature of the upper stratified air layer in the main interior space.

2.1.2. Façade description

The curtainwall façade was an all-glass façade shaded by exterior ceramic tubes. On the west façade, the window wall was composed of a continuous band of floor-to-ceiling double-pane low-iron spectrally-selective windows. The window-to-exterior-wall ratio was 0.76 and the center-of-glass window transmittance was T_v=0.75.

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[2] Dates are cited in the text using the month/day/year or day of year (DOY) convention.

Approximately 50% of the west façade was shaded by 4.12-cm diameter, off-white, horizontal, exterior ceramic tubes spaced at variable center-to-center distances and placed 0.46 m off the face of the glazed façade. The tubes shaded the upper and lower portions of the glazed facade. A vision portion of the window wall from 0.76-2.13 m above the floor was left open for view for a standing or seated occupant.

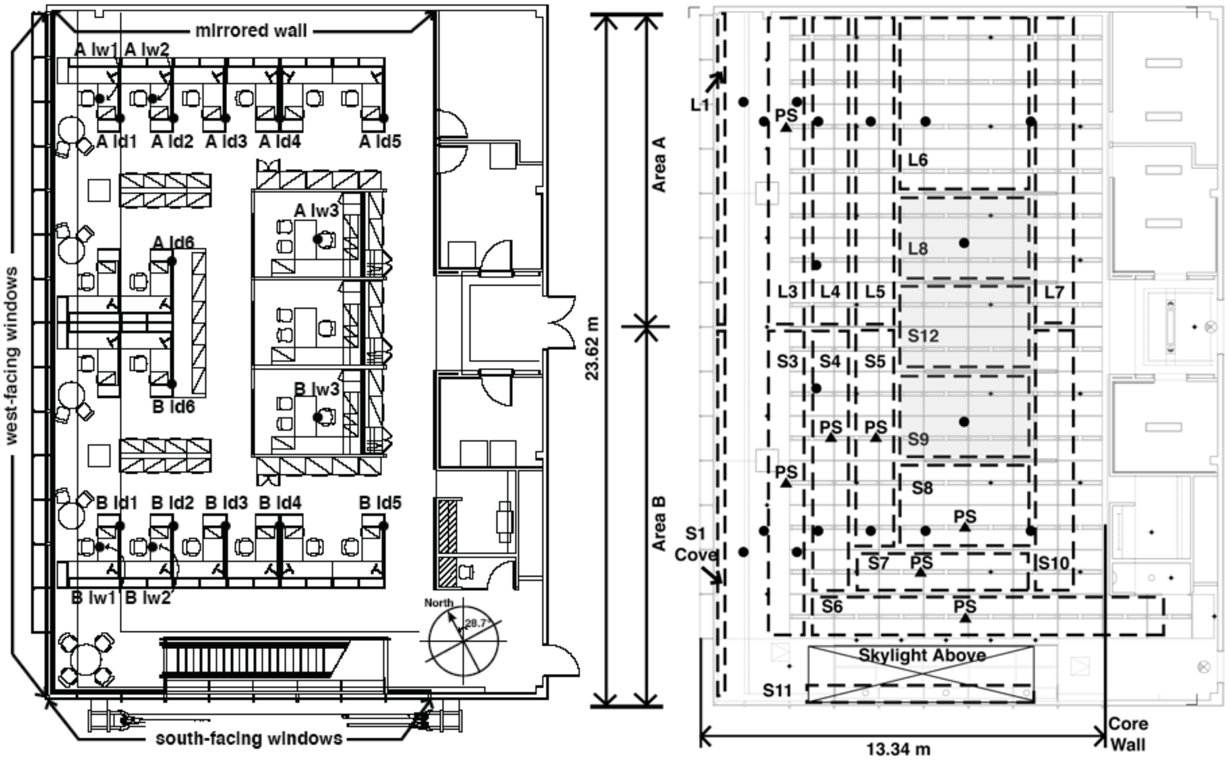

Fig. 2. a) Floor plan showing the location of the interior illuminance sensors (left) and b) reflected ceiling plan (right) showing the lighting zones and location of photosensors (PS – triangle symbols). Note that there was not a one-to-one correspondence between illuminance sensors and the lighting zones above – illuminance sensor locations are shown on the reflected ceiling plan for reference. Photosensor in S4 was used to control grouped zone S4/S5 and photosensor in S7 was used to control zone S7/S8.

On the south façade, the same window type was used on some sections of the façade while on other sections, a 50% horizontal stripe frit pattern was applied in a diagonal pattern matching the stringer course of the stairway. Most of the south façade was not shaded by ceramic tubes; a small section was shaded its entire height by ceramic tubes near the southwest corner. Structural columns and cross-bracing also provided partial exterior shading near the southwest corner. The stair itself had open treads and a 96.5-cm high opaque handrail. A clear glazed skylight (T_v=0.76) was constructed above the stair to approximate the daylight contributions from the upper floors.

2.1.3. Shading and lighting system descriptions

The mockup was divided into two nearly equal areas where two different automated roller shade and dimmable lighting systems were installed in each area. There was no physical wall dividing the two areas. Since Area B was south of Area A, the control sensors and monitoring equipment in Area A were placed so as to be minimally influenced by the daylighting conditions in Area B.

2.1.4. Shading systems

In Area A, automated roller shades were installed at the west façade and controlled to reduce window glare and admit daylight. The shades were controlled to five preset heights designated by the building owner: full up, full down, two positions that aligned with the top and bottom of the vision portion of the window wall, and a position that was mid-height within the upper ceramic tube array. The roller shade fabric was white on one side and gray on the other. The gray side was faced toward the interior. Visible transmittance at normal incidence was 0.06. The openness factor (percentage of open space to opaque fabric) was 3%.

In Area B, automated roller shades were installed on the west and south façades and controlled to block direct sun. On the west window wall, direct sun was controlled to a depth of 0.91 m from the window at floor level. On the south window wall, direct sun was controlled to a depth of 0.91, 1.83 or 3.05 m from the window at floor level (depth was varied over the monitored period). The west shade's control algorithm was later modified to reduce window glare and block direct sun (to 0.91 m). The same preset heights used in Area A were used in Area B. The roller shade fabric was similar to that installed in Area A. See Tables 2-3 for a summary of test configurations.

2.1.5. Lighting system in Area A

The fixtures in the open plan area were custom made, recessed fluorescent downlights with two 17-W T8 fluorescent lamps (3500°K, CRI=86) placed end to end (essentially a single-lamp fixture), a metal vertical fin reflector, lightly frosted extruded acrylic diffuser, and integral electronic dimming ballast. Two 38.7 cm^2 return air diffuser slots were located at each end of the fixture to allow heat to pass to the ceiling plenum.

Two types of 0-10 V dimming electronic ballasts were used and for some lighting zones in Area A, both types of ballasts were used within the same zone. Both ballasts were 277 V, 4-wire, 2-lamp, T8, 0-10 V dimming ballasts with a light output dimming range of 10-100% or 5-100% and a power dimming range of ~35-100% or 13-37 W per fixture.

All recessed fixtures in the open office area including the corridor were designated as daylight-controlled fixtures. These fixtures were grouped into six zones that ran parallel to the west window wall (Figure 2). All lighting zones were controlled using a single ceiling-mounted shielded photosensor with a diffusing lens. The photosensor had a 180° field of view looking toward the window (no significant view toward the back of the room) and a vertical angle (angle from a vector normal to the floor) of ~60° so that its view was broad (cosine spatial response) toward the window wall. This same photosensor was used to control the shades. The sensor was located in zone L3 (3.35 m back from the west window wall) so that it was not significantly influenced by the lighting conditions in Area B. The supervisory control system used input from the photosensor to control each lighting zone. The lighting control system was essentially an open-loop system, but in the first zone closest to the window wall, the photosensor was influenced by the electric lights. The control algorithm was proportional control.

The daylighting control system was designed to dim all lighting zones in the open plan office area in response to daylight so as to maintain the design work plane illuminance setpoint range of 484-538 lux (45-50 fc is typical design practice for office tasks) from sun up to sun down. However, the average work plane illuminance at 100% power was on average ~400 lux across most work surfaces, so the design setpoint was met only when there was sufficient daylight. During most of the test period, the lights were only dimmed down to minimum power. For a limited test period, the lights were shut off if there was sufficient daylight (0% light output, 0 W). The dimming response occurred over 60 s (same rate for up versus downward dimming) with a variable turn-off delay once the low end dimming range was reached.

The system was commissioned once in mid-December 2003 during the day with Area B's lights on. Adjustments were made to the photosensor gain (values unknown) via a control panel setting in the supervisory control system located in the electrical closet simultaneous to hand-held work plane illuminance measurements (1-day visit). The control system was readjusted after two one-day visits between December and late January 2004.

The same types of fixtures and ballasts were used in the north private office (Office 106) except that the lighting was manually controlled using a wall-mounted keypad. Cove uplighting was installed parallel to the west window wall to provide architectural lighting at night. The cove lighting was scheduled to turn on to full power 20 min after sunset and turn off 15 min before sunrise.

2.1.6. Lighting system in Area B

Similar fixtures and the same lamps used in Area A were used in Area B. The ballast and lighting control system differed. A prototype 277 V, 4-wire, T8 DALI dimming ballast was used throughout the space with an light output dimming range of 3-100% and power dimming range of ~35-100% or 13-37 W per fixture. Daylight-controlled zones S3-S8 are shown in Figure 2. An interior shielded integral reset ceiling-mounted photosensor served each zone and communicated via a European installation bus (EIB, now Konnex (KNX)) communications network to the supervisory controller. The photosensor was pointed downward and had a 360° field of view with an unspecified cone of view (~60°). Control output from the supervisory controller was sent via a 5-conductor cable to the DALI ballasts (62 per group). Individual ballasts were addressable and could be quickly reassigned to a new zone using software. Lighting control system operations were monitored using a separate lighting control panel.

Like Area A, the daylighting control system was designed to dim all lighting zones in the open plan office area in response to daylight so as to maintain the design work plane illuminance setpoint range of 484-538 lux from sun up to sun down. The average work plane illuminance at 100% power was on average ~400 lux for most work surfaces. The lights were shut "off" if there was sufficient daylight (0% light output, 4% of full power consumption). The daylighting control system was commissioned during a one-day visit in mid-December 2003 during the day with Area A's lights on. Adjustments were made in software to the photosensor setpoint level via the supervisory controller located in the electrical closet. On 2/28/04, the system was rezoned and recommissioned during a second one-day visit (a prior one-day visit was used to troubleshoot operations). In the new configuration, zones S4 and S5 were grouped and the photosensor in zone S4 was used to control both zones. Zones S7 and S8 were grouped and the photosensor in zone S7 was used to control both zones. This analysis focuses on the performance of this latter configuration.

The private office and cove lighting were similar to Area A, except that the cove lighting was scheduled to dim up linearly from off to full power over a 30-min period starting 30 min before sunset and dim down from full power to off over a 30-min period starting 30 min before sunrise.

2.2. Monitored data

The mockup was instrumented with LBNL sensors to monitor outdoor solar conditions, lighting energy use, shade positions, and interior lighting levels throughout the day. Data were recorded every 1 min over a full 24-h day from December 21, 2003 to September 21, 2004 (monitoring continued for three months beyond the initial six-month test period). All data were sampled and recorded in Standard Time within a few milliseconds of the time stamp. Data were post-processed at LBNL using automated scripts to first verify that the test conditions at the site were correctly implemented then used to compute various performance metrics. Written logs maintained by the manufacturers, the Times, and LBNL were used to corroborate the errors found in the data.

Interior horizontal illuminances were monitored with photometric sensors (±1-2% of reading if greater than 12 lux) on either the desk surface 0.73-0.76 m above finished floor (designated as "Iwn") or on the top edge of the workstation partitions 1.22 m above finished floor (designated as "Idn") since the building owner wished to have some of the workstations usable (Figure 2 and Table 1). Lighting energy use was monitored for each lighting zone using a watt transducer (±0.2% of reading). Lighting energy data were sampled every 6 s then averaged and recorded every 1 min. The height of each roller shade group was monitored using a shade height transducer (±0.1% of full scale output).

Additional data were monitored every 1 min and 24-h day by each of the manufacturers. All manufacturers logged sensor and control data to troubleshoot operations and evaluate performance independently from LBNL. All data were synchronized to within 2-3 s of LBNL data. Several lighting zones were not monitored by LBNL. These zones included the cove lighting in both areas, stair lighting, and private Office 107. The on-off status of these lighting zones was determined using the manufacturers' data. Occupancy was also monitored by the manufacturers. If the space was occupied, interior illuminance data were deleted for that day. Interior dry-bulb air temperature was monitored using a wall-mounted platinum RTD temperature sensor (±0.39°C) shielded from direct solar radiation. If the average daytime interior dry-bulb temperature was not within 18.3-23.9°C, then the monitored data were deleted for that day.

Table 1
Location of illuminance sensors

Sensor	Area A			Area B		
	d1 (m)	d2 (m)	h (m)	d1 (m)	d2 (m)	h (m)
Iw1	1.88	20.73	0.73	1.88	5.03	0.76
Iw2	3.74	20.73	0.73	3.74	5.03	0.76
Id1	2.55	19.58	1.22	2.55	6.32	1.22
Id2	4.37	19.58	1.22	4.37	6.32	1.22
Id3	6.18	19.58	1.22	6.18	6.32	1.22
Id4	8.01	19.58	1.22	8.01	6.32	1.22
Id5	11.73	19.58	1.22	11.73	6.32	1.22

d1: distance from west window wall; d2: distance from south window wall; h: height above finished floor.

2.3. Methods of data analysis

2.3.1. Overall approach

Although the initial intention of this field test was to maintain the same shading and lighting control configuration over the entire monitored period in order to obtain statistically significant results that would reflect annual performance, adjustments of the control system were later permitted to improve overall system performance. When significant changes to the shading or lighting control system occurred, summarizing the data (e.g., averaging) is of limited statistical significance because the solar angles, weather conditions, and length of the test period differed between the datasets. Analyzing the data to correlate the performance values to deterministic factors and thus explain or extrapolate the measured performance to annual performance was beyond the scope of this work. When possible, some data were related to deterministic factors such as daylight availability, but for the most part this analysis simply discusses the incremental changes in performance as the systems were tuned.

Lighting performance between areas was not compared because of the differences in space and window geometry. This analysis was not focused on a side-by-side comparison to determine who provided the "best" product. This analysis focused on understanding within a specific Area of the mockup what the performance would be and how it could be improved.

2.3.2. Tested configurations

The monitored field test was designed to isolate energy and comfort impacts to the automated shading and daylighting control systems. The manufacturers were therefore requested to configure their systems so that the non-daylight-controlled lighting systems were held constant throughout the test period when the sun was up. The shades were also to be in the automatic mode. For the majority of the monitored period, these conditions were adhered to. When complications occurred, the data were either analyzed as alternate configurations or deleted.

Manufacturers were encouraged to tune their products in response to feedback from the building owner and LBNL. In both areas, the shade control system settings were tuned several times throughout the monitored period to either respond to new building owner requirements or to improve performance. In Area B, the lighting control system was rezoned in order to improve performance. These test configurations or control algorithm adjustments are given in Tables 2-3.

Table 2
Tested configurations in Area A

Automated Roller Shade

From mm/dd/yy	(DOY)	To	(DOY)	Config. No.	Shade algorithm
12/21/03	-11	01/20/04	20	1	Improperly adjusted: ignore data
01/21/04	21	02/09/04	40	2	Daylight mode 1: more daylight, less glare control
02/10/04	41	04/13/04	104	3	Daylight mode 2: more daylight than config. 2
04/14/04	105	04/22/04	113	4	Glare mode 1: more glare control, less daylight
04/23/04	114	09/21/04	265	5	Glare mode 2: more glare control than config. 4

Daylight-controlled Lighting System

From	(DOY)	To	(DOY)	No.	Ballast errors	Lights off?
12/21/03	-11	02/05/04	36	1	L4 out +	yes*
02/06/04	37	02/23/04	54	2	All ok	yes
02/24/04	55	04/14/04	105	3	All ok	no**
04/15/04	106	06/20/04	172	2	All ok	yes
06/21/04	173	08/06/04	219	4	L6 out ++	yes
08/07/04	220	09/21/04	265	2	All ok	yes

DOY: day of year; mm/dd/yy: month/day/year
\+ 1 fixture in zone L4 was non-operational; no effect on data.
++ 1 fixture in zone L6 was non-operational; lighting energy data adjusted, illuminance data eliminated.
* The fluorescent lights were dimmed between full to minimum power and turned off if sufficient daylight.
** The fluorescent lights were dimmed between full and minimum power in response to available daylight.

Table 3
Tested configurations in Area B

Automated Roller Shade

From mm/dd/yy	(DOY)	To	(DOY)	Config. No.	Sun penetration depth (m) West	Sun penetration depth (m) South	Glare control West
12/21/04	-11	01/11/04	11	1	0.91	0.91	no
01/12/04	12	03/01/04	61	2	0.91	3.05	no
03/02/04	62	04/15/04	106	3	0.91	3.05	no
04/16/04	107	08/04/04	217	4	0.91	1.83	no
08/05/04	218	09/21/04	265	5	0.91	1.83	yes

Daylight-controlled Lighting System

From	(DOY)	To	(DOY)	No.	Ballast errors	Zoning
12/21/03	-11	02/06/04	37	1	S6 off, S7 error+	All separate zones
02/07/04	38	02/26/04	57	2	All ok	All separate zones
02/27/04	58	03/10/04	70	3	All ok	S4/S5 and S7/S8 grouped
03/11/04	71	05/25/04	146	4	S3 error	S4/S5 and S7/S8 grouped
05/26/04	147	07/25/04	207	5	S3 off	S4/S5 and S7/S8 grouped
07/26/04	208	08/02/04	215	6	S3 off, S6 error+	S4/S5 and S7/S8 grouped
08/03/04	216	08/06/04	219	5	S3 off	S4/S5 and S7/S8 grouped
08/07/04	220	09/03/04	247	4	S3 error	S4/S5 and S7/S8 grouped
09/04/04	248	09/21/04	265	6	S3 and S6 error+	S4/S5 and S7/S8 grouped

DOY: day of year; mm/dd/yy: month/day/year
If there was sufficient daylight, the fluorescent lights were turned off.
+: error: unknown effect on data; off: lighting energy adjusted, S3 illuminance deleted, S6 illuminance unaffected.

2.3.3. Daylighting control system performance

The daylighting control system performance was evaluated by determining the percentage of day (sun up) when the total horizontal illuminance (from daylight and fluorescent lighting) was less than:

1) 90% of the maximum nighttime fluorescent illuminance level (Imax) achieved at each sensor (or –10% “sag” in the illuminance), or
2) the minimum design setpoint of 484 lux at sensors Iw1 and Iw2.

The lighting design did not produce the desired 484 lux at the work plane even with the fluorescent lights at full power. Illuminance levels at partition height were significantly greater than that at the work plane due to lack of obstructions (e.g., 534 lux at sensor B Id3 versus ~400 lux at the adjacent work plane). Therefore, the daylighting control system was evaluated using the maximum fluorescent lighting level instead of the setpoint level (method 1). The setpoint level was used to evaluate control performance at work plane sensors Iw1 and Iw2 (method 2), but at these locations, the maximum nighttime level was significantly below the setpoint level due to the lighting design (the design was later modified). The maximum fluorescent illuminance levels were defined when all the open plan daylight-controlled lighting zones in a single Area were set to full power at night for at least 30 min (nighttime tests were performed every month). All other lights were turned off. Maximum levels were adjusted if ballast failures occurred and there were nighttime data available to establish new maximum levels. If there were no nighttime data, data were deleted.

2.3.4. Lighting energy use savings

Daily lighting energy use savings were determined for each daylight-controlled zone where:

- the base case was defined by the installed fluorescent lighting system without daylighting controls operating at 100% power over the entire day, and
- the test case was defined by the same installed fluorescent lighting system with daylighting controls being dimmed in proportion to available daylight over the entire day.

Total power use in Areas A and B were 1495 W and 1510 W, respectively. Lighting power density at full power levels was 16.1 W/m^2 (1.495 W/ft^2) and 15.48 W/m^2 (1.44 W/ft^2), respectively.

The savings were computed using several different schedules (hourly, weekday, or holiday lighting load schedules were not applied to the computation):

- Sun up to sun down.
- Lighting energy use during the 12-h period from 6:00-18:00 (daylight-savings time (DST)).
- Lighting energy use during the 10-h period from 8:00-18:00 (DST).

Daily total perimeter zone lighting energy savings were computed by summing the lighting zone energy use of all daylight-controlled zones (L3-L7 or S3-S8) in each Area using the three above schedules. Data were corrected or flagged in the analysis when there were ballast failures or when light sources were erroneously controlled as described below.

2.3.5. Ballast errors

There were three types of lighting control errors that occurred at the mockup:

1. A ballast failed and the two lamps within the fixture failed to operate (no light output). However, the non-functioning ballast did not affect the control of its zone nor the adjacent zones.
2. A ballast failed and the non-operational fixture (no light output) did affect the control of its zone and the adjacent zones.
3. The operation of a ballast was intermittent or different from the operation of the other ballasts in the same zone. Its operations did affect the control of its zone and the adjacent zones.

For type 1 errors, the non-operational ballast was assigned the same power level as the ballast in its zone and maximum fluorescent illuminance levels were determined using additional nighttime tests. There were no negative ramifications on the data set. For type 2 errors, lighting energy savings were computed relative to an adjusted maximum baseline power level and maximum fluorescent levels were re-determined. Type 3 ballast errors occurred in zones S3, S6, and S7. These occurrences were frequent enough to severely reduce the entire dataset. However, since only one ballast was affected per zone and no more than two ballasts were affected in Area B at any one time, these data were retained in the analysis. Field observations indicated that the fixtures were either on, off or dimmed compared to the rest of the fixtures in the same zone. No adjustments could be made to correct the lighting energy or illuminance sensor data. The impact on performance trends is unknown, but likely to be small and isolated to the single affected zone because the photosensor's field of view was restricted to see only the zone it controlled and the adjacent fixtures in that zone had to compensate for the erroneous ballast.

2.3.6. Unintended light sources

The private office lights were sometimes left on inadvertently by visitors touring the mockup. In Area A, the control photosensor was beyond the influence of the private office lighting so this error had no effect on dimming levels. In Area B, the private office lights affected daylighting control of the adjacent lighting zones S4 and S5 (e.g., corridor illuminance levels outside the offices increased by 80-130 lux if all three office lights were on at 100% power). Since this represented a realistic case that will occur in the actual building, lighting energy use data were flagged (9 days total) if any one of the three private office lights were on for greater than 60 min during the day and at an arbitrary dimming level. Maximum fluorescent lighting levels were not adjusted in either Area for the daylighting control system evaluation.

If the corridor lighting zone S10 was off for greater than 30 min during the day when it was supposed to be on at 100% power, the lighting energy savings data for Area B were flagged, primarily to broaden Area B's dataset. Lighting energy savings would have been slightly greater had S10 been on, since photosensors controlling zones S6 and S7/S8 could have been slightly influenced by S10 operations. Data for sensor B Id5 were eliminated from the daylighting control system evaluation.

3. Experimental results

3.1. Daylighting control system performance

3.1.1. Area A

Dimming profiles showing lighting power and total illuminance (daylight + fluorescent lighting) versus time of day are given for clear sky conditions in Figure 3 (4/24/04) to illustrate the operation of the open-loop proportional control system in Area A. For this west-facing window, daylight contributions were from the sky during the morning hours when the shades were fully retracted, then from brighter diffused sunlight as the sun moved into the plane of the window and the shades were gradually lowered to control glare and direct sun in the afternoon. The fluorescent lights dimmed down gradually to minimum power (~35% of full power) then were turned off when there was sufficient daylight (e.g., zone L3 at 11:15). All sensors maintained illuminance levels above maximum nighttime levels (Imax) during daytime hours (for each sensor, the Imax value can be seen at 5:00 in Figure 3).

One might argue that for this day at least, greater lighting energy savings could have been attained since Imax or the 484 lux setpoint (at the work plane sensors) were exceeded significantly at all sensor locations throughout the majority of the day. Sensors Iw2 and Id2 were on the border between zones L3 and L4. Sensor Iw2, which was shadowed by the 1.2 m-high partitions, measured total illuminance levels that were greater than 520 lux for the majority of the day. Illuminance levels at sensor Id2 (unobstructed by vertical partitions) were greater than 600 lux for the majority of the day (Imax=505 lux). Lighting zone L3 could have been dimmed more given the setpoint level of 484 lux. Other days may have been less conservative.

The daylighting control system was responsive to changes in daylight levels. Nearly instantaneous changes in the fluorescent lighting occurred when the shade was adjusted. For example, in Figure 3 at 14:30, zone L3 was switched between 0% and 60% power in less than 2 min. The building owner did not notice or complain about the rate of these adjustments.

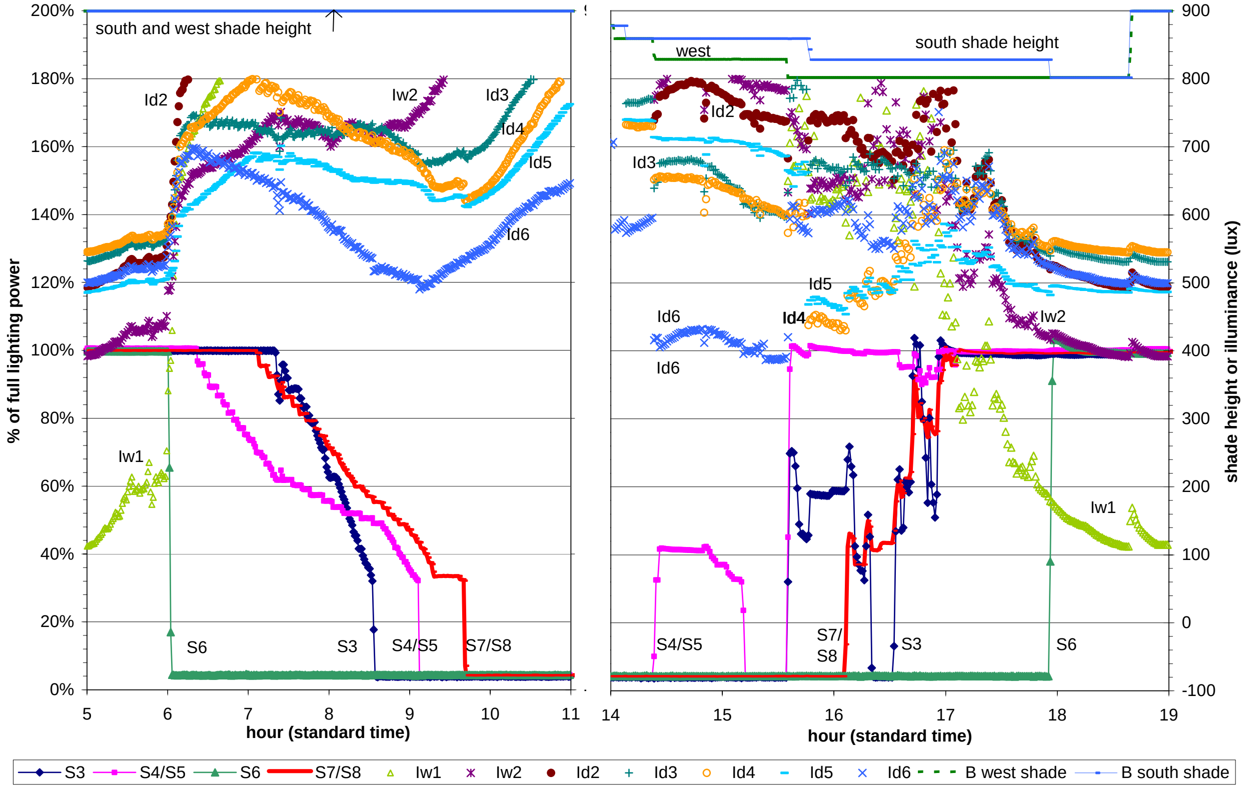

Fig. 3. Area A (west-facing window): Dimming profiles for zones L3-L6 and total illuminance on a clear sunny day, April 24, 2004. The dimming profiles are shown as a percentage of full power (left y-axis). Total illuminance levels are given on the right y-axis (values are truncated above 800 lux), where maximum values (lux) were: Iw1=111, Iw2=391, Id2=505, Id3=556, Id4=563, Id5=502, Id6=482 lux. The right y-axis also shows the position of the shades (900=up, 800=down). Zone L7 (not shown) was dimmed down to 97% minimum. The work plane illuminance setpoint was 484 lux. Automated shade in glare control mode. Sunrise: 5:06, sunset: 18:54.

Initially, the daylighting control system was not commissioned properly so the performance criteria were met for as little as 38% of the day at some sensor locations. The system was tuned following two one-day site visits (one to troubleshoot operations, the second to re-commission the system) between late December and late January. Good control system performance was achieved over the remaining monitored period. The control system maintained total illuminance levels above 90% of Imax for greater than 98% on all days at all sensor locations and on average 99.9±0.5% of the day at all sensor locations from 1/21/04 to 9/21/04. The 484 lux work plane setpoint level was maintained at sensors Iw1 and Iw2 for 75% and 78% of the day, respectively, on average. This lesser performance was likely due to the limited capacity of the fluorescent lighting system, where the setpoint was not met just after sunrise and just before sunset as illustrated in Figure 3.

3.1.2. Area B

The dimming profiles for Area B differed from those of Area A because daylight was admitted from both the south- and west-facing windows and the zones were laid out differently from Area A. The illuminance profiles also differed because unlike the sensors in Area A, which progressed back from the west window wall, the sensors in Area B progressed back from the west window but also ran parallel to the south window wall with an intervening staircase and skylight affecting sensors Id3-Id5.

Dimming profiles are shown for 4/24/04 under clear sky conditions in Figure 4 to illustrate the operation of this closed-loop integral reset system. Plentiful daylight came from both the south and west windows enabling all dimming zones to be turned off from 9:45-14:10. Under clear sky conditions in the morning, south and west shades were fully retracted. Direct sun was controlled to 1.82 m from the south window and later in the day, to 0.91 m from the west window wall. Sensor Id4 was positioned just south of the photosensor (located in zone S7) controlling grouped zone S7/S8. Its total illuminance was greater than Imax (=556 lux) throughout the morning. Under slightly cloudy conditions in the afternoon, however, its illuminance was less than 90% of Imax (556*0.90=500 lux) for ~30 min or 5% of the day. Illuminance levels were maintained above 90% of Imax throughout the day for all other sensors. For sensors Id2 and Id3, which correspond roughly to grouped zone S4/S5, illuminances were maintained well above Imax (=496 and 534 lux, respectively) in the morning and afternoon. Sensor Id6 data are also shown in Figure 4 for reference, but this sensor was influenced by Area A's shade and lighting operations and so was not used to evaluate operations.

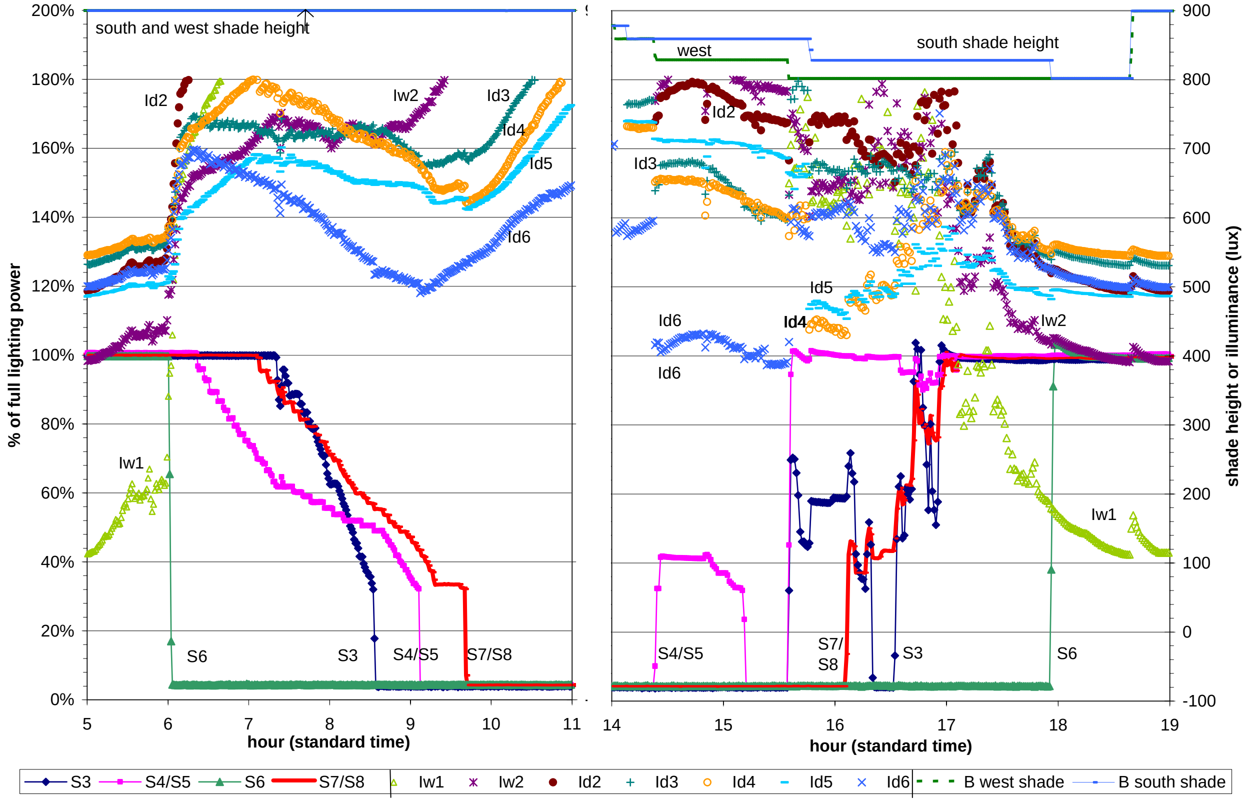

Fig. 4. Area B (south and west-facing windows): Dimming profiles for zones S3-S8 and total illuminance on April 24, 2004. The dimming profiles are shown as a percentage of full power (left y-axis). Total illuminance levels are given on the right y-axis (values are truncated above 800 lux), where maximum values (lux) were: Iw1=115, Iw2=392, Id2=496, Id3=534, Id4=556, Id5=492, Id6=471 lux. The right y-axis also shows the position of the shades (900=up, 800=down). Work plane illuminance setpoint was 484 lux. Sunrise: 5:06, sunset:18:54. Hours 11-14 are not shown because lighting was turned off in all zones.

After some adjustments to the lighting control zones, photosensors, and commissioning parameters, the control system maintained the total illuminance levels above 90% of the maximum fluorescent illuminance level for greater than ~60% of the day at most sensor locations and on average 97.9±6.1% of the day at all sensor locations over the monitored period from 2/27/04 to 9/21/04 (Figure 5). There were 16 days out of the total 72 useable days that met these criteria for less than 90% of the day. When this occurred, illuminance levels at numerous sensors were inadequate, possibly due to erratic ballast behavior such as that in zone S3 or S6, poor commissioning, or inadequacy of the photosensor control system. These outlier datapoints occurred initially at sensors Id3, Id4, and Id5 (until ~6/28/04 or DOY=180), then later included the sensors near the west window.

The control system maintained the work plane illuminance setpoint of 484 lux for 77% and 80% of the day on average at sensors Iw1 and Iw2, respectively. Like Area A, the setpoint level was typically not met just after sunrise and just before sunset because of the limited capacity of the fluorescent lighting system.

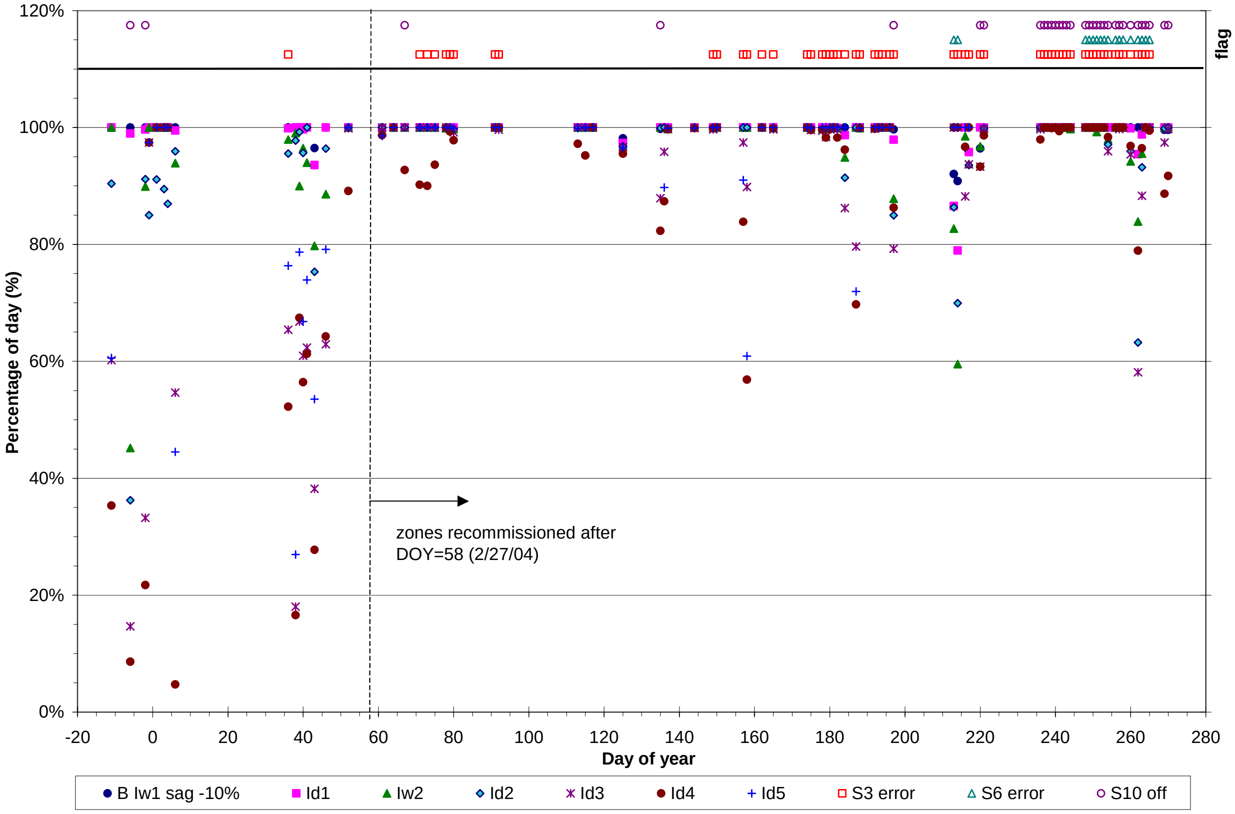

Fig. 5. Area B: Percentage of day when the illuminance at each sensor was greater than 90% of the maximum fluorescent illuminance level. S3 flag: likely to reduce Id1 illuminance very slightly; S6 flag: not likely to affect data; S10 flag: Id5 data deleted.

3.2. Lighting energy use savings

3.2.1. Area A

Daily lighting energy use savings (sun up schedule) for each lighting control zone are shown for all shading and lighting configurations in Figure 6. Lighting energy savings were inversely proportional to the distance from the window wall: savings were greater closer to the daylight source. This window source was largely diffuse since direct sun was always controlled to within 0.91 m from the window wall by the roller shade. As expected, savings were also linearly proportional to daylight availability. Sunnier conditions yielded greater lighting energy savings. Total daily lighting energy use savings for Area A to a depth of 7 m (zones L3-L5) are also shown for the sun-up schedule in Figure 6. These average area savings were computed to a zone depth of 7 m so as to enable comparisons between this sidelit space and the 7-m deep bilateral sidelit Area B space. Daily area lighting energy savings from the 6:00-18:00 DST and 8:00-18:00 DST schedule correlated linearly to the sun-up schedule by a factor of 1.08 (r^2=0.89) and 1.15 (r^2=0.91), respectively.

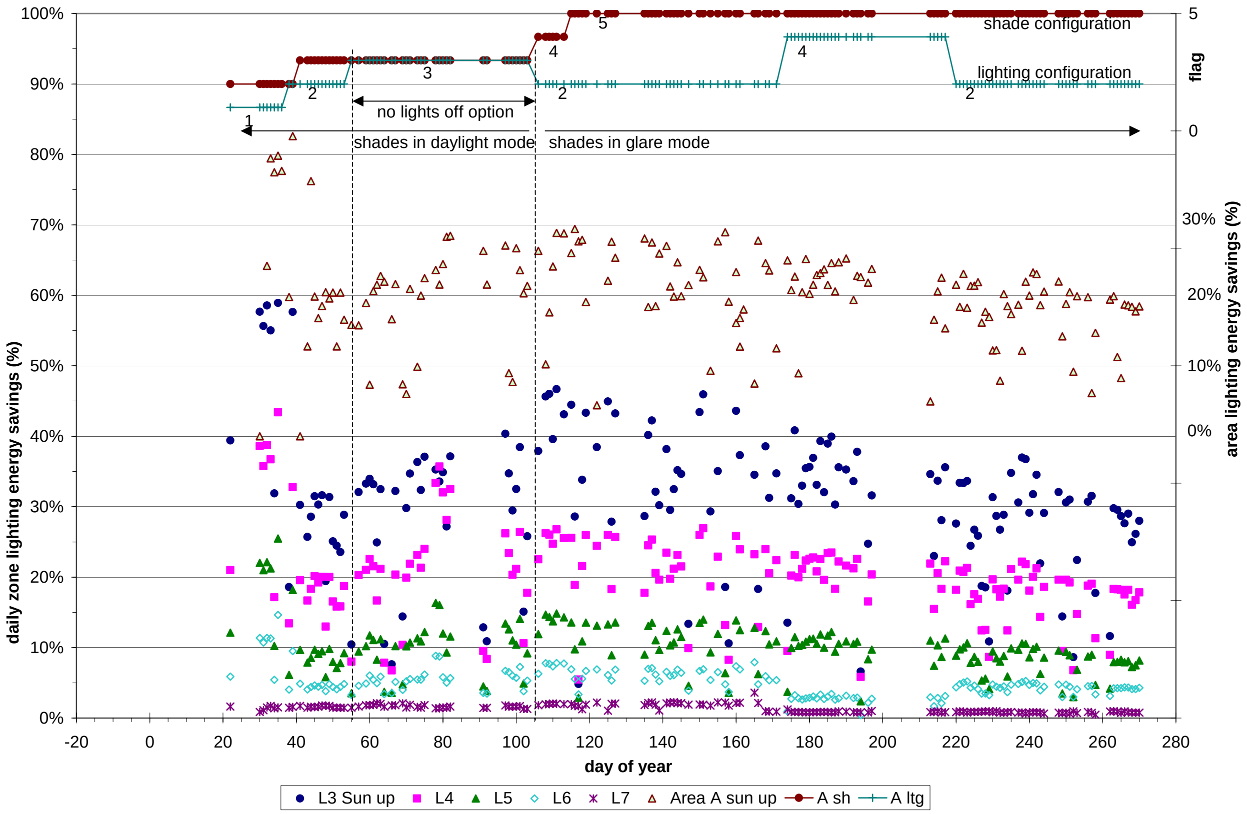

Fig. 6. Area A (west-facing window): Percentage daily lighting energy savings for each lighting zone (L3-L7) and for Area A to a depth of 7 m from the window compared to the reference case with no daylighting controls (16.1 W/m^2 (1.495 W/ft^2)). Savings were computed for the sun-up schedule. On second y-axis ("flag"), shade ("A sh") and lighting ("A ltg") configuration numbers are noted (see Table 2).

Monitored data in April (DOY=96-112) gave some indication of the differences in lighting energy use one could expect if the shade control algorithm was changed from a daylight to glare control mode. No clean comparisons could be made between the two control modes because the electric lighting control algorithm differed before and after the changes in the shade control algorithms. To make this comparison, the lighting energy use for the glare/ lights-off mode was first corrected to the no-lights-off mode using the minimum dimming power level (35% of full power). Then, specific days were selected where solar conditions were comparable. If the sun path was nominally the same (within an 16-day period) and the range in average daily horizontal exterior illuminance was kept to within 10% (52±2 klux), then the change in shade control mode produced less than a 1% difference in lighting energy use in all zones. Greater differences may occur at different times of the year and with more stringent glare control setpoint levels.

Turning the lights off (0% power), instead of dimming them to minimum power level (35% power) when there was sufficient daylight, increased daily lighting energy use savings from 37-39% to 44-47% in zone L3 but had no effect in zones L4-L7 because the daylight levels were never great enough to allow the lights to be turned off (glare control mode, 4/17/04-4/24/04). From 4/14/04 to 9/21/04 (glare control mode), the lights-off option saved at most 9% and on average 1% in additional daily lighting energy savings in zone L3 located 3.35 m from the window. In zone L4 located 4.88 m from the window, this option saved at most 1% and on average 0% per day in lighting energy use.

3.2.2. Area B

Daily lighting energy use savings (sun up schedule) for each lighting control zone are shown in Figure 7. Lighting energy savings were greater than Area A because of the bilateral sidelit south and west-facing condition and because the lights were turned off when there was sufficient daylight. Data after DOY=58 (2/27/04) are valid. Data prior to this day are not valid because the daylighting system was not providing sufficient illuminance on the work plane. For the days with faulty S3 and S6 ballast operations and zone S10 corridor lighting off for greater than 30 min/day, lighting energy savings may be greater than that depicted on the graph. For days when the private office lights were on erroneously, lighting energy savings in S4/S5 may be slightly less than that depicted on the graph.

Lighting energy savings in zones S3-S5 were inversely proportional to the distance from the west window wall: savings were greater closer to the daylight source. There was less of a difference in lighting energy savings between zones S3 and S4/S5 in Area B than for the same zones in Area A, due perhaps to the contributions of daylight from the south windows in Area B and because Area B grouped the control of zones S4 and S5.

The savings in the S6 south zone were significantly greater than that in the S3 west zone even the distance from the window wall was nominally the same. Daylight availability was greater on this south-facing façade because direct sun was in the plane of the window for a greater percentage of the day than the west-facing façade. Direct sun was also allowed to penetrate deeper from the south window than from the west. Lighting energy savings in zones S6-S8 were inversely proportional to the distance from the south window wall. Lighting energy savings were also proportional to daylight availability: sunnier conditions yielded greater energy savings with zone S6 attaining 67% daily lighting energy savings on the most overcast day.

Total lighting energy use savings for Area B to a zone depth of 7 m (all zones) for the three schedule types are shown in Figure 8. There was no evident correlation between the three schedules. With a bi-laterally daylit space, daily lighting energy savings ranged from 40% to 80% (sun up schedule) between 2/27/04 to 9/21/04. Turning the lights off when there was sufficient daylight instead of simply dimming to minimum power (35% of full power) yielded up to 25% greater daily lighting energy savings in all west and south zones. The lights-off option saved significant lighting energy use even in the zones further from the window.

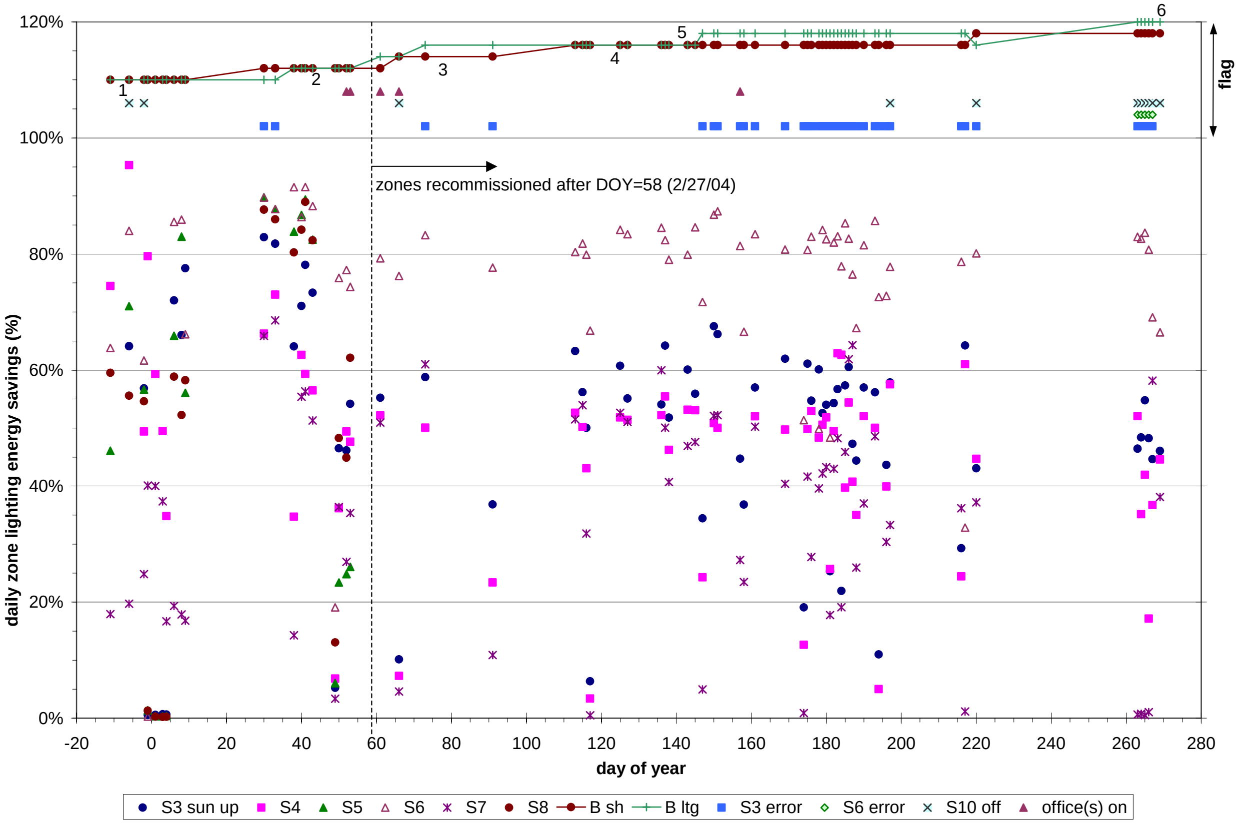

Fig. 7. Area B (south and west-facing windows): Percentage daily lighting energy savings for each zone (S3-S8) compared to reference case with no daylighting controls. Savings were computed for the sun-up schedule. On the second y-axis, shade ("B sh") and lighting ("B ltg") test configurations are given (see Table 3). S3 and S6 error: effect unknown but likely to be small; S10 off: savings in S6 and S7/S8 slightly greater if S10 on; office on: S4/S5 savings may be slightly less if offices were off.

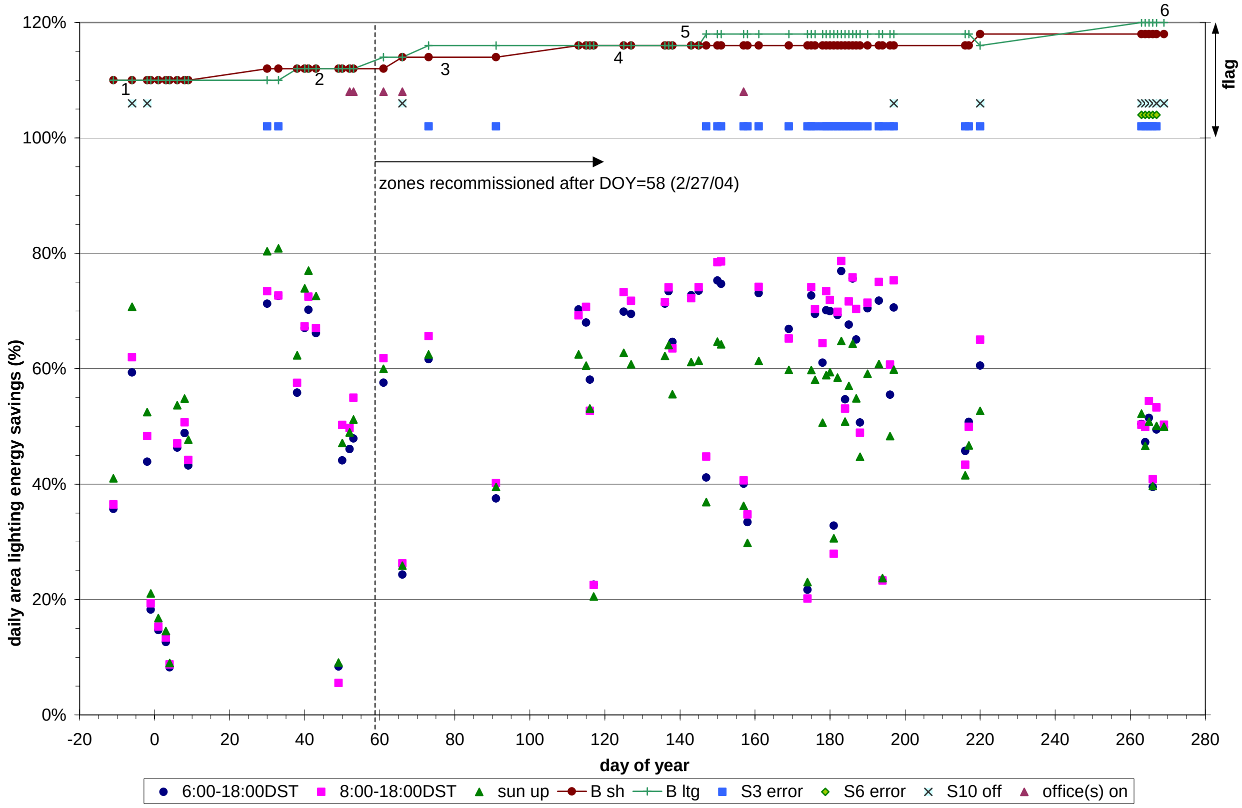

Fig. 8. Area B (south and west-facing windows): Percentage daily lighting energy savings for Area B (zone depth from south and west windows of 7 m) compared to reference case with no daylighting controls (15.48 W/m^2 (1.44 W/ft^2)). Savings were computed for the three different lighting schedules.

4. Discussion

4.1. On the bad reputation of daylighting control system reliability

LBNL has consistently promoted the superior performance of closed-loop proportional (P) control algorithms over integral-reset (IR) control algorithms for reliable daylight control [3]. Area A used an open-loop proportional algorithm and controlled all of the open-plan dimmable lighting zones reliably for 99.9±0.5% of the day on average over the monitored period. Area B used an integral reset algorithm and did indeed appear to have a great deal of trouble from the outset to meet the control performance requirement. Without prompting from LBNL, the manufacturer may never have realized that the lighting control system was over-dimming for the majority of the day. When notified, the manufacturer made adjustments to the lighting control system by first broadening the lighting control zones (the narrow zones were initially a constraint in the lighting design) then re-commissioned the system. The manufacturer admitted to not having checked their control system after the initial commissioning phase when there was no furniture in the mockup. Two one-day visits to the mockup (one to run diagnostics, the second to commission the system) produced reliable performance after 2/27/04. While the control performance in Area B was still less reliable than Area A for the remainder of the test, the IR control system in Area B was able to meet the design illuminance setpoint for 97.9±6.1% of the day on average over the monitored period.

There are several reasons why these field data refute prior findings (i.e., 97.9% reliability in Area B is most likely acceptable): 1) the IR photosensor had a restricted field of view, 2) the IR photosensor was commissioned during the day with the shades adjusted to block direct sun, and 3) the automated shading system reduced variations in the spatial distribution of daylight. On the first two items, Rubinstein et al. [4] found that P control outperformed IR control because the ratio of work plane illuminance (lux) to photosensor input signal (V) differed significantly between sidelit (daylight) and toplit (fluorescent lighting) conditions given an unshielded photosensor. The IR photosensor was typically commissioned at night and would therefore tended to undershoot the setpoint during the day. With a restricted field of view and daytime commissioning of the IR photosensor in Area B, the lux/V ratio better approximated the ratios that occurred during the day, hence the more reliable performance.

On item 3, use of the automated fabric roller shades resulted in a significantly more uniform daylit environment than that with manually-operated shades. Direct sun skews the lux/V relationship, causing lights to overdim. Area A performed better than Area B because direct sun was always controlled in Area A to 0.91 m from the window. In Area B, the depth of direct sun penetration was allowed to vary over the test period from 0.91 m to 3 m from the window. Most of the south-facing windows were not shaded by ceramic tubes, so sunlight was also admitted through the roller shade fabric.

Generally, the relationship between fluorescent work plane illuminance and photosensor response is well characterized and degrades slightly due to lamp aging and dirt over time, while the relationship between daylight workplane illuminance and photosensor response can be extremely variable and is often the root cause of poor daylighting control performance [5-6]. Open-loop and closed-loop proportional control photosensors aggregate the two relationships into a single constant lux/V proportional gain setting (and nighttime offset level) that is commissioned once at the job site. If the setting is not conservative, over-dimming will occur. While this field study was not focused on analyzing and characterizing the reasons behind poor performance, we attempted to characterize how much the lux/V ratio varied with daily and seasonal variations in the distribution of daylight. Systems (which are a combination of photosensor spatial and spectral response and location) with less variation in this ratio would tend to be more reliable. This involved correlating lighting power use to fluorescent task illuminance for each of the 17 zones and each of the 16 sensor locations, then computing the minute-to-minute ratio of daylight work plane illuminance to photosensor signal, using the actual lighting power use of the 17 zones during the day. This detailed matrix calculation was done for one of the early test periods, but the manufacturers failed to follow the nighttime fluorescent lighting protocols consistently throughout the entire test period and hardware failures and intermittent errors complicated the analysis. Despite our desire to explain why one system performed better than the other, there were simply inadequate data and resources to determine the source of differences in performance.

The manufacturer in Area A may simply have commissioned the system more conservatively than the manufacturer in Area B and sacrificed potential lighting energy savings to achieve good reliability. If one compares the total illuminance (fluorescent plus daylight) and dimming curves in Area A versus B, one might quickly come to the conclusion that Area A was insensitive to available daylight compared to Area B because the dimming curves were very gradual throughout the morning, while in Area B, the dimming curves were very abrupt. Part of this behavior is due to the behavior of the two control algorithms that convert the photosensor signal into a ballast control signal: integral reset algorithms exhibit a sharp step function response due to its infinite gain while proportional algorithms exhibit a more gradual response. Another factor is that there was greater daylight availability in Area B due to the bilateral window design so dimming levels should be greater than that in Area A. This confounds the analysis and does not allow us to determine whether one system was commissioned more conservatively than the other.

The overall reliability of both systems was quite good, indicating that existing commercial systems are capable of achieving reliable performance and delivering significant energy savings given sufficient attention to commissioning. The challenge is how to achieve such performance routinely and cost-effectively. To be critical, one might say that the best engineering expertise was brought to bear on this project in an effort to prove to the owner of a landmark status building (with monitored data that would be publicly disseminated) that a product was worth purchasing. Such reliable performance may not be expected in normal applications because either the technical expertise would not be of such high caliber or the amount of time dedicated to commissioning each zone cannot be as long given cost constraints. Each vendor made a total of three visits (up to one day each) to calibrate their systems in order to deliver reliable performance.

Several tactics will be used by the building owner to prevent poor performance in the actual building: 1) the manufacturer will be held responsible for commissioning all daylighting zones in the actual building prior to occupancy, and 2) the performance specifications mandate that reliable performance (work plane illuminance levels must be maintained above -10% of setpoint for greater than 90% of the day) in all zones of the actual building be proven by the manufacturer before final payment is made. The selected manufacturer was asked to test their lighting zone layout, photosensor designs and locations, and commissioning procedures in the mockup after the competitive bid process. By mid-2005, the selected manufacturer had demonstrated to the owner that their DALI-based open-loop proportional control system could meet the performance specification in the mockup (LBNL monitored this second phase of testing). Basic instrumentation and protocols for commissioning and evaluating the system in the final building have been prototyped and discussed. These procedures continue to be refined prior to execution in the final building in mid- to late-2006.

One might argue that such tactics can only be used by building owners who have the leverage to demand this of a manufacturer (due to the high visibility of the project or the large volume of the purchase). However, if the design team stipulates tactics 1 and 2 in the procurement specifications, has the manufacturer include these costs in their bid, then follows through with the requirements, daylighting control systems may enjoy a larger market share in the future.

4.2. Pros and cons of the lighting control systems

Comparing open-loop versus closed-loop systems, the open-loop (proportional) control system in Area A had several advantages over the closed-loop system in Area B. One photosensor was used to control multiple zones thereby reducing costs. The open-loop lighting control zones can be fairly small and narrow without causing hunting or oscillations between adjacent zones. This enables one to achieve greater lighting energy savings over closed-loop systems (with photosensors that have a broad field of view) that require large zones to achieve reliability. This is pertinent to DALI-controlled systems where one can now define a zone down to a single fixture, as is being done in the final Times building. On the other hand, to commission the system, the open-loop system relies on a predictable daylight distribution as a function of distance from the window wall to set the lux/V constants in the control system. This predictable distribution is being supplied by the automated shade. One will encounter less reliable control if manual override of the shade allows direct sun to enter the space because the open-loop sensor cannot “see” the impact of direct sun on the lighting zones behind it.

Closed-loop systems, like that in Area B, do have the advantage of being able to harvest light from any source – the private office lights, corridor lights, or daylight. In Area B, dimming was affected by the private office lighting operations. The building owner noticed this effect and noted it in their log. When the private lights were turned on, the lighting in zone S4/S5 dimmed. Such systems require a one-to-one mapping between photosensor and zone, however, which increases costs.

Although the cost of a static versus dimmable electronic ballast is at this time significantly less, this particular building owner would never consider a daylight-controlled on-off switching system for several reasons: 1) the owner saw value in being able to tune setpoint levels for each department, circulation zones, etc. (dimmable ballasts will be installed throughout the building), 2) sudden changes in light output or on-off hunting are known to be distracting and annoying, 3) rezoning in software is cheaper than altering hardware, and 4) dimmable ballasts enable the owner to shed significant loads during periods when utility rates are high (e.g., dim or shut lights off depending on time-of-use rate schedule or curtailment signal from a demand-response program). To reduce capital outlay, on-off static ballasts could be installed in the zone closest to the window (e.g., zones L3, S3, and S6) with dimmable ballasts installed in the remaining floor area, but the labor cost of troubleshooting improperly installed ballasts can be a major deterrent, particularly given electrical labor rates.

Historically, daylighting control systems have been dismissed as viable options based on manufacturer quotes of $60-120 US/ballast, particularly since static electronic ballasts cost ~$15/ballast. High-low static ballasts that provide stepped switching (0, 50%, 100% of full power) add a premium over on-off static ballasts. LBNL explored market trends and costs and concluded that it should be feasible to profitably manufacture and sell dimming ballasts at prices that are much lower (e.g., $20-30/ballast). The owner received final bids between $30-75 per dimmable electronic ballast, with manufacturers expressing willingness to continue to reduce costs down to commodity levels. The owner reduced design, installation, and commissioning costs in numerous ways; for example, by pre-wiring fixtures prior to shipping to the job site and providing hands-on wiring demonstrations to installers prior to bidding to minimize markups due to an unfamiliar technology. The system was cost-justified by reducing first and operating costs through setpoint tuning, daylight dimming, occupancy, and demand response lighting control strategies in conjunction with the automated shade. Additional energy savings due to reduced solar and lighting heat gains were not quantified in this study but will add to the total operational cost savings. Given control of peak cooling conditions (solar and lighting heat gains constitute up to 30-40% of the total peak cooling load in typical commercial buildings), first costs can also be reduced by downsizing the chiller plant and distribution system.

4.3. Qualifying the lighting energy savings

Daily lighting energy savings were shown to be significant at depths of up to 7 m from the window wall, the cause of which can be attributed to the façade and interior design and the use of automated shades. Without active shade management, lighting energy savings are expected to be significantly less due to non-optimal control by the occupants. In an attempt to simplify one’s view of the analysis, a lumped average of all test conditions was computed, despite the fact that this is statistically incorrect since test conditions were non-comparable across the dataset (Figure 9 and Table 4). In Area B, savings were the same at depths of ~4.57-7.62 m from the window because the inner lighting control zones S7/S8 were grouped (Figure 9). In Table 4, average savings for each area are given to the same depth (7 m) so as to make an equitable comparison between a west-facing sidelit and south- and west-facing bilateral sidelit condition.

Lighting energy savings were accomplished while generally meeting visual comfort criteria, particularly in Area A, which controlled the shades for daylight and glare. Lighting energy savings are expected to decrease when glare control is implemented in Area B – the degree of reduction is dependent on the final fabric choice and how stringently window luminance is controlled at the expense of daylight admission. With respect to site context, the lower floors of the 52-story tower in downtown Manhattan will receive significantly less daylight due to urban obstructions, while the upper floors will receive significantly more. We attempted to calibrate Radiance simulations to field monitored data so as to extend the results to the Manhattan site, but were unable to calibrate standard sky models to match field data.

Direct extrapolation of the monitored data to other building projects is not advised. First, the façade design was unique: exterior shading provided by the ceramic tubes reduced interior daylight levels considerably. The interior design was also rather unique: the open plan office design used 1.22-m high partitions throughout increasing daylight levels at greater depths from the window. This case study provides useful objective data and demonstrates the need for A/E firms to create building-specific designs that can accomplish energy-efficiency and a pleasing and comfortable environment.

Table 4

Average lighting energy savings and average lighting power density savings for a sidelit (A) and bilateral-sidelit (B) 7-m deep zone

Schedule	Area A			Area B			Area A		Area B	
	avg		stdev	avg		stdev	W/m^2	W/ft^2	W/m^2	W/ft^2
sun up	20%	±	6%	52%	±	12%	3.17	0.29	8.00	0.74
6:00-18:00 DST	22%	±	7%	58%	±	16%	3.52	0.33	8.96	0.83
8:00-18:00 DST	23%	±	7%	59%	±	17%	3.75	0.35	9.16	0.85

Average: Area A to a depth of 7 m from west window, zones L3-L5, 2/10/04-9/21/04; Area B to a depth of 7 m from west or south window, zones S3-S8, 2/27/04-9/21/04.

DST: Daylight savings time; avg: average; stdev: standard deviation

Lighting power density at full power: Area A: 16.1 W/m^2 (1.495 W/ft^2); Area B: 15.48 W/m^2 (1.44 W/ft^2).

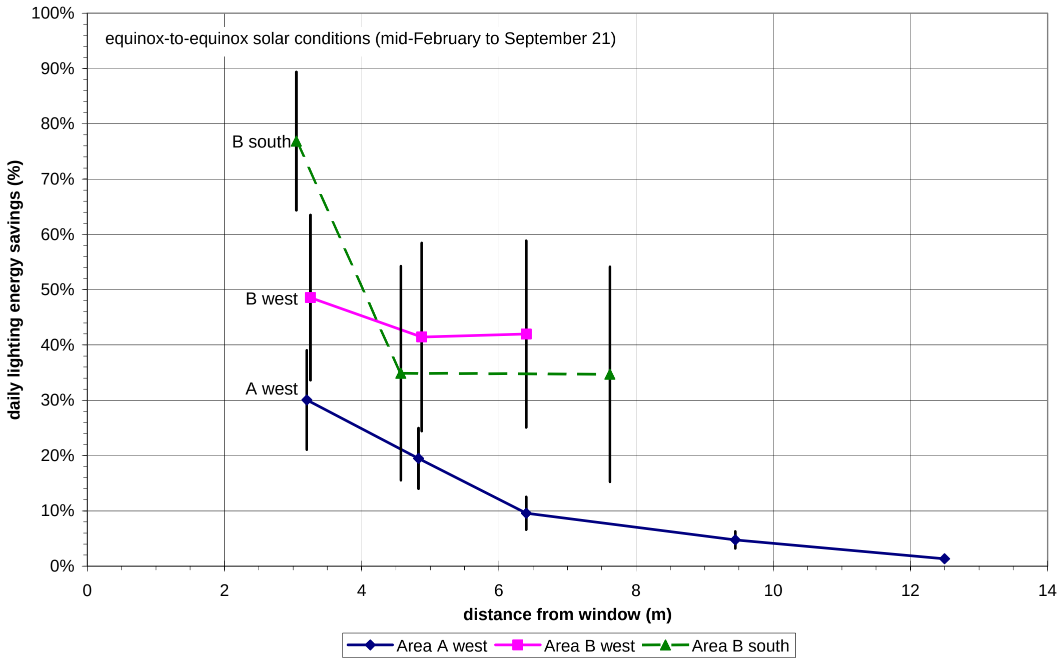

Fig. 9. Average and standard deviation of daily lighting energy use savings versus distance from the west window wall in Area A or west or south window wall to the center of the lighting zone in Area B. For Area B, zones S3 and S4/S5 data are given in relation to the west window wall and zones S6 and S7/S8 data are given in relation to the south window wall.

4.4. On the performance of the DALI ballasts and control system

DALI ballasts were controlled by an EIB supervisory control system in Area B and this combination seemed to have caused a fair number of problems. Aside from ballast failures, which occurred at a greater rate in Area B than in Area A (four ballasts were replaced in Area B, two ballasts were replaced in Area A), the assignment and control of individual DALI ballasts were not reliable. Errors cannot be explained entirely by the improper control system reset after brief (20-30 s) bi-weekly power failures that occurred when the power generator was undergoing maintenance. The lighting control system manufacturer in Area B conducted some tests toward the end of the monitored period and provided some possible explanations. Some DALI ballasts either stopped being automatically controlled and were on at all times, some ballast(s) became part of two different zones and would respond to whichever zone gave the last command, and some ballast(s) remained dimmed at all times. At the EIB/DALI gateway level, the manufacturer found that all ballasts in a zone could be commanded to on or off but the individual faulty ballasts could not be commanded. The control manufacturer's interpretation is that the address at the ballast-level was somehow being corrupted or lost. The ballast manufacturer stated that the mockup DALI ballasts used the same circuit board as their conventional 0-10 V ballast and their DALI interface module. While both components have been used separately on other applications with no faults, the combination of these two components to control a 17-W T8 lamp had not been previously attempted. The manufacturer stated that there were no unresolved design issues with this prototype ballast. The ballasts were compliant with an evolving DALI ballast protocol being developed by the National Electrical Manufacturers Association (NEMA) DALI working group. Faulty ballasts were returned to the ballast manufacturer to determine the cause of failure. Separately, LBNL conducted limited bench-scale tests on non-faulty DALI ballasts from the mockup by creating various groups (with different control software) then simulating power failures. No problems occurred with the addresses nor were there any changes in the zoning. The exact cause of these problems remains unknown.

5. Conclusions

A nine-month monitored field study of the performance of automated roller shades and daylighting controls was conducted in a 401 m^2 unoccupied, furnished daylighting mockup. The mockup mimicked the southwest corner of a new 110 km^2 commercial building in New York, New York, where The New York Times will be the major tenant. This paper focuses on evaluating the performance of two daylighting control systems installed in separate areas of an open plan office with 1.2-m high workstation partitions.

The overall reliability of both systems was quite good, indicating that existing commercial systems are capable of achieving reliable performance and delivering significant energy savings given sufficient attention to commissioning. The open-loop proportional control system in Area A performed very reliably, meeting the design illuminance level 99.9±0.5% of the day on average after it was commissioned properly. The closed-loop integral reset control system in Area B performed less reliably due possibly to the more complex bi-lateral daylit environment. The design illuminance level was met 97.9±6.1% of the day on average after the control system was commissioned properly. The well-controlled daylight from the automated shade contributed to both area's level of reliability. Each manufacturer invested three one-day site visits to achieve this level of performance. The bid package and performance specifications were designed to ensure similar control performance in the final building.

Lighting energy savings were significant over equinox-to-equinox solar conditions in both areas of the mockup compared to a non-daylit reference case. For the sidelit Area A, average daily lighting energy savings between mid-February to September 21st were 30% and 5-10% at 3.35 m and 6.10-9.14 m from the west-facing window (29° north of west), respectively. For the bilateral daylit Area B, daily lighting energy savings were 50-60% at 3.35 m from the window and 25-40% at 4.57-7.62 m from the west- or south-facing (29° west of south) windows. Average savings for the 7-m deep dimming zone were 20-23% for the sidelit Area A and 52-59% for the bilateral sidelit Area B, depending on the lighting schedule. Unlike Area A, Area B turned lights off when there was sufficient daylight, increasing savings. Newer DALI ballasts with a wider power dimming range (~20-100% versus the ~35-100% power range of ballasts used in this field study) will yield even greater savings. Exerting glare control will decrease savings – the degree will depend on how stringently the automated roller shade controls glare to the detriment of daylight admission.

The 0-10 V ballasts had two ballast failures over the nine-month monitored period but in all other respects exhibited faultless operations. The DALI ballasts and/or supervisory control system exhibited faulty operations throughout the test period, the cause of which is unknown. This was a prototype system. Operational errors are expected to be resolved as DALI ballast products reach full maturity.

The building owner received very competitive bids ($30-75 US/ballast) and was able to justify use of the daylighting control system based on operational cost savings and increased amenity. Industry indicated willingness to continue to reduce costs down to commodity levels.

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