Integrated Envelope and Lighting Systems for Commercial Buildings: A Retrospective

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ABSTRACT

Daylighting systems in use world-wide rarely capture the energy-savings predicted by simulation tools and that we believe are achievable in real buildings. One of the primary reasons for this is that window and lighting systems are not designed and operated as an integrated system. Our efforts over the last five years have been targeted toward 1) development and testing of new prototype systems that involve a higher degree of systems integration than has been typical in the past, and 2) addressing current design and technological barriers that are often missed with component-oriented research. We summarize the results from this body of cross-disciplinary research and discuss its effects on the existing and future practice of daylighting in commercial buildings.

Introduction

Daylighting is an energy-efficiency strategy that allows one to offset electric lighting needs with daylight. In a limited number of cases, the conscientious occupant already implements this strategy: when sufficient daylight levels are noted, the occupant switches off the lights. At its greatest potential, daylighting can yield reliable and substantial reductions in both electricity consumption and peak demand throughout the perimeter zone, most often in commercial buildings, with the use of automatic dimming lighting controls and the careful specification of the window system. Economic benefits can be obtained by the building owner such as reduced energy bills and lower equipment first cost due to reductions in chiller capacity and air distribution duct size. With proper fenestration design, other non-economic benefits can be obtained such as greater occupant visual and thermal comfort (possible satisfaction or productivity benefits), or greater design freedom to specify larger window area.

The difficulty in obtaining the potential benefits described above is due to numerous design, implementation, and technological barriers. Daylighting is unique in that it requires designers to solve not only complex technical issues on a case-by-case basis, but also qualitative issues as well (e.g., glare, brightness contrasts, view and design aesthetics). It requires the participation and cooperation of multiple disciplines—architecture, lighting design, mechanical system design—to implement correctly. Most often, the fenestration system is designed without regard to lighting and mechanical system requirements (and vice versa). And since the fenestration system is a predominant element that defines the exterior architectural "character" of a building, windows are often designed without considering the comfort of interior inhabitants. Energy-efficiency standards may encourage designers to substitute conventional components with new and better technologies, independent of whole building considerations. Even when the proper components are selected, poor design and commissioning practices often lead to unreliable performance and uncomfortable work environments.

The notion of an *integrated* whole-building approach resulted from these cross-disciplinary problems. Since 1991, we have conducted a multi-year research project to promote daylighting in commerwhile targeting peak demand reductions of 15-40% in cooling-dominated climates. The research was funded by the California Institute for Energy Efficiency (CIEE), with support from major California utilities and co-support from the U.S. Department of Energy (DOE). As such, our approach differed substantially from much of our prior DOE-supported research in that it cut across traditional areas of basic research and sought to derive near-term solutions for commercial buildings.

The research was structured to 1) address *future* daylighting opportunities, by developing reliable and high-performance integrated envelope/lighting prototypes that can be used in most commercial buildings today, and 2) to address *current* daylighting issues, by developing tools to promote integrated design and solve interdisciplinary technological problems that are often missed with component-oriented research.

We focused our work primarily on the first task, while feedback from prototype design, development and evaluation activities was used to inform our research on current daylighting practice. Within the first task, two key daylighting concepts were explored: 1) *dynamic* envelope/lighting systems respond in real-time to temporal changes in sun and sky conditions in order to control daylight intensity and solar heat gains, and provide a more uniform, comfortable interior work environment, and 2) *light-redirecting* envelope systems reflect daylight flux from the window or skylight aperture and distribute it more uniformly and at greater depths throughout the interior. Light-redirecting systems maximize the efficiency of daylight distribution so that solar heat gains are minimized for each element of electric light that is displaced.

We summarize our work from this multi-year research project and discuss our findings in terms of their effect on the future and current practice of daylighting in commercial buildings. Detailed results are reported in specific publications denoted in the Bibliography section below.

Methods

Our initial activities explored the context for the development of specific envelope/lighting prototypes. Conceptual daylighting designs were identified from an array of commercially-available glazing, shading, optical, and lighting technologies. An assessment was made of the potential energy and peak demand reductions that would result from an integrated approach. Market barriers were delineated. Then, across four phases of research, we designed, built, and evaluated daylighting prototypes at increasing levels of detail. Prototype designs were exposed to more complex and realistic environmental conditions as research progressed; e.g., field tests versus simulations, in-situ building installations versus physical scale models. Methods of evaluation included:

Energy simulations. DOE-2 building energy simulations were used to evaluate the annual energy and peak demand performance of promising systems, and with the dynamic system, to parametrically determine energy-efficient control algorithms. With both systems, we could not use the existing DOE-2 daylighting algorithms because our systems were optically-complex, so we combined experimental measurements taken in a scanning radiometer with mathematical calculations to produce daylight factors that could be substituted for the internal calculations in DOE-2. For larger systems, we took experimental measurements in the Hemispherical Sky and Sun Simulator. For small flat glass samples such as holographic glazings, we used a goniospectrometer to measure bi-directional transmittance and reflectance properties. Thermal properties were taken from existing research or derived from spectral data gathered from the goniospectrometer.

Visual quality simulations. The RADIANCE ray-tracing visualization program was used to evaluate the visual comfort associated with dynamic systems. The program produces illuminance and luminance data for specific viewpoints within the room and for specific times of the year. Glare indices may also be calculated. An important and powerful product of these studies are the realistic renderings that enable one to visualize problems with reflected glare on computer screens, direct source glare from the window plane, and the qualitative distribution of daylight across the entire room cavity.

Reduced-scale field measurements. We monitored lighting energy use and control system performance of the dynamic system under real sun and sky conditions over the course of a year in a 1:3 reduced-scale rooftop model of a typical office space. Complete window and lighting systems were built and installed in the scale model room to operate as they would in a full-scale room. The control system was designed in software, rather than being breadboarded with hardware, to facilitate a quick design-test-redesign sequence. Window and lighting heat flow measurements were made of the dynamic system in the Mobile Window Thermal Test facility, a dual-chamber calorimeter facility (Figure 1). These measurements provided a real-world check against the DOE-2 estimations of peak cooling load performance.

Full-scale demonstrations. Full-scale demonstrations were used to further refine the design and operational characteristics of the systems. A full-scale testbed facility, consisting of two side-by-side private office test rooms, was built to monitor the cooling load, lighting energy, and control system performance of the dynamic system (Figure 2). Time-lapse videos and continuous measurements of illuminance were used to characterize the quality of the lighting environment. A human subjects survey was conducted to assess user acceptance and potential improvements to lighting quality. With the light-redirecting prototype, we built and installed a skylight prototype in two pairs of windowless offices in an

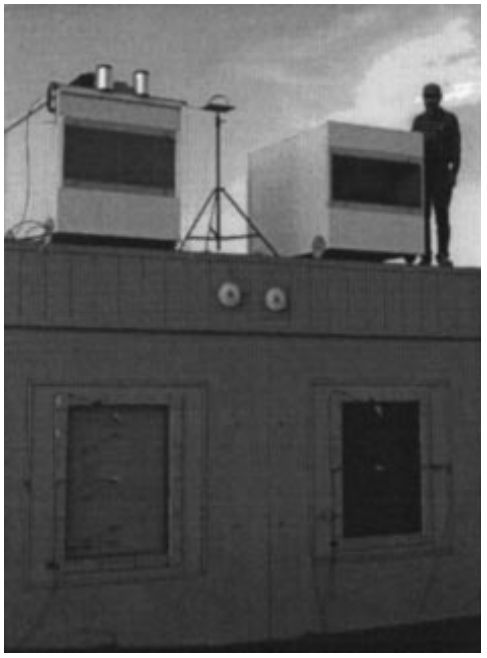


Figure 1. The Mobile Window Thermal Test facility, a dual-chamber calorimeter was designed to measure heat flow in the lower chambers and illuminance in the upper, office-like modules.

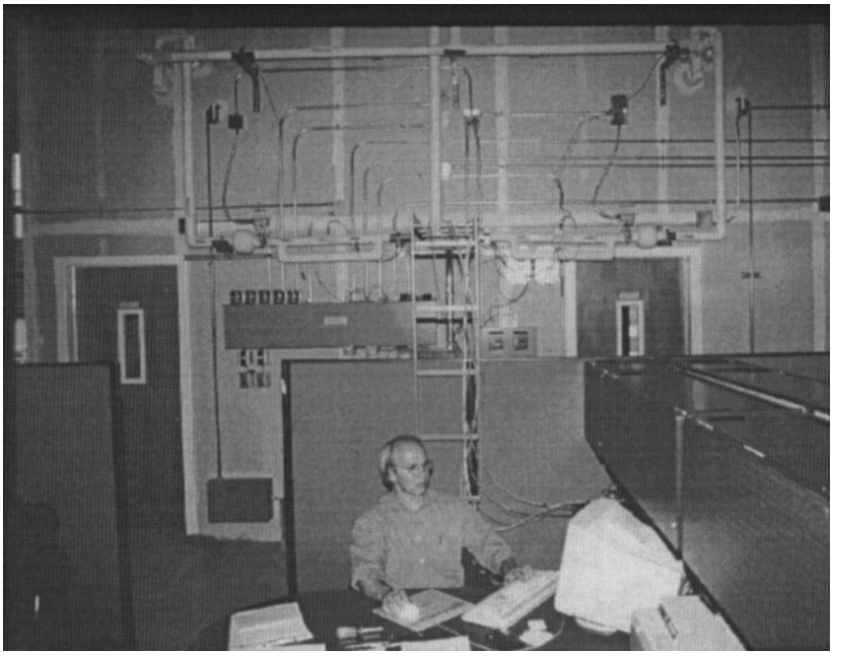


Figure 2. Data monitoring and control workstation outside the two test rooms of the Oakland Federal Building Testbed Demonstration Facility. The mechanical system and monitoring instrumentation are arrayed on the wall behind.

existing small office building with the cooperation of the local utility, the architect, and industry partners. A less formal survey combined with spot illuminance and luminance measurements was conducted to assess the success of the design.

Design assistance. We provided one-on-one design assistance on building projects where the integrated approach could be applied and showcased. These opportunities allowed us to better understand design, institutional, and market barriers associated with the current practice of daylighting and infused our work on the prototypes with more concrete design criteria. Assistance was provided at several levels of involvement, from short telephone calls to detailed simulation analysis. We advised designers of approximately forty projects across the United States and Canada.

Benefits to Future Practice

The primary barrier to the future use of daylighting is technological. There are a lack of good modular integrated building systems that perform well across energy-efficiency and qualitative criteria and can be easily used in most buildings. Concepts of future technologies also need to be comprehensively tested to determine if they are truly viable and acceptable. Evaluation methods are not well established. This research benefited future practice and increased the use of integrated approaches to envelope/lighting systems design in several ways:

Fully developed a dynamic envelope/lighting system. To actively modulate daylighting and solar heat gain, we designed, built and tested a motorized venetian blind system coupled to a dimming electric lighting system for use in typical office spaces. Venetian blinds, widely used in U.S. commercial buildings, can control thermal loads and daylighting intensity by varying slat angle. We designed our system to prevent direct sun penetration and control glare, permit view out when available, and actively manage incident daylight and electric light to provide 500 lux on the workplane whenever possible. The system was built from readily-available components, which might be interchanged later with more advanced technologies. While conceptual differences certainly exist, this system can be seen as a present day precursor to technologies that are being developed for future use in buildings; e.g., switchable electrochromic glazings (switches from a clear to colored state with a small applied voltage). Our work

Table 1. DOE-2 Annual Electricity and Peak Demand Savings Compared to Dual-Pane Spectrally Selective Glazing (WWR=0.5) without Shades in Los Angeles

Perimeter Zone	Annual Electricity Savings Near-Term Electrochromic	Automated Venetian Blind	Peak Demand Near-Term Electrochromic	Automated Venetian Blind
North	-2%	-3%	-2%	7%
East	24%	18%	22%	21%
South	30%	26%	23%	24%
West	23%	16%	19%	17%

WWR: Window-to-wall ratio. See: Lee and Selkowitz 1995.

Table 2. Monitored Daily Lighting Electricity, Cooling Load, and Peak Cooling Load Reductions with a Dynamic Venetian Blind and Lighting System compared to a Basecase Static Venetian Blind System with the Same Daylighting Control System. Monitored in a Full-Scale Private Office with a Southeast-Facing Window in Oakland, California.

Static Blind Angle	Season	No. of Days	Lighting Electricity	No. of Days	Cooling Load	No. of Days	Peak Cooling Load
45°	Spring	9	27% ± 5%	4	15% ± 7%	8	11% ± 6%
	Summer	8	52% ± 9%	8	6% ± 6%	8	6% ± 8%
	Autumn	18	37% ± 12%	13	7% ± 3%	16	8% ± 5%
	Winter	4	19% ± 4%	0		4	15% ± 11%
15°	Spring	12	14% ± 8%	7	28% ± 16%	11	22% ± 6%
	Summer	14	22% ± 17%	12	13% ± 5%	13	13% ± 10%
	Autumn	3	7% ± 2%	3	22% ± 11%	3	21% ± 6%
	Winter	4	1% ± 1%	0		1	28% ± 0%
0°	Spring	13	-1% ± 4%	10	32% ± 16%	11	25% ± 8%
	Summer	11	-14% ± 19%	11	17% ± 6%	11	24% ± 7%
	Autumn	6	11% ± 10%	5	17% ± 10%	6	18% ± 11%
	Winter	5	-1% ± 3%	0		3	32% ± 3%

Basecase static blind angle defined as downward angle from horizontal, occupant view of ground. Static settings (0° and 15°) may allow direct sunlight to penetrate the room. See: Lee, DiBartolomeo, & Selkowitz 1998a.

permitted testing of basic research premises at full-scale, enabling us to examine the validity of advanced material concepts that cannot be tested until large prototypes can be built.

Energy, control status, and illuminance data were collected for over a year in both the reduced-scale and full-scale field test facilities and initial occupant response studies were conducted. DOE-2 building energy simulations predicted that 16-26% annual energy savings and peak demand reductions could be obtained with the automated venetian blind/lighting system compared to an advanced spectrally-selective window system in Los Angeles for all exposures except north (Table 1). Monitored daily lighting energy savings averaged 35% in winter and ranged from 40-75% in summer, when compared to a similar static partly closed blind system with the same daylighting control system. If compared to a non-daylighted space, daily lighting energy savings ranged from 22-86%. Summer daily cooling load reductions were measured to be 5-25%, while peak cooling load reductions were even larger (Table 2). The control

system met all design objectives to within 10% for 98% of the year. A small number of occupants performed a limited set of visual tasks in the full-scale testbed. These occupants reported that they were generally satisfied with the performance of the automated system. Although their satisfaction increased when they were given control over the system, they also reported more dissatisfaction with specific problems with glare. They also indicated a desire for lighting levels above those typically provided (500 lux).

The incremental cost of the automated venetian blind/ lighting system should be approximately $3-5/ ft^2-glazing for the motor, computer chip, power source, sensors, installation, commissioning, and maintenance. Because the system crosses traditional component boundaries, marketing and commercializing integrated products pose unique challenges; i.e., sold by a windows or lighting manufacturer? Perhaps the best solution would be to define a new sub-industry where envelope and lighting systems could be tailored and assembled for individual clients by "system integrators." Considering energy and peak demand savings alone, we estimate that the technology has a simple payback of about ten years for the Los Angeles climate (at $0.09/kWh). An assigned value for qualitative benefits would make this system more economical. Few technologies have such an immediate impact on the quality of the inhabited environment and the comfort of its occupants. Aside from energy-efficient qualities, window and lighting technologies can change the mood of the interior, the comfort of occupants sitting beside it, and the character of the building. Demonstrating value for the amenity these systems deliver could increase market viability. As an example, the market growth popularity of low-E window glazing may have been partly due to its improvement in thermal comfort, not simply to its increased energy-efficiency. Correlating increases in worker satisfaction and productivity would build an even stronger economic argument but will require a significant R&D investment.

Developed light-redirecting systems. We designed prototype lightshelves, lightpipes, and skylights to 1) extend the daylighted area of the perimeter zone of buildings from approximately 5 m to 10 m, and 2) to provide more brightness in the back of typical spaces without the associated high light levels near the windows. While the research was devoted to solving the optics problem of redirection with a variable sun source without introducing direct sun or creating glare, we also restricted the window aperture size to minimize solar heat gains. Prototypes were developed, simulated and tested in scale-model rooms, both outdoors and within indoor simulators. Both light-redirecting systems were designed without moving parts to reduce costs and maintenance. While designed as modular systems, the light shelf, light pipe, and skylight systems will require custom integration with the architectural fabric of the building. Added engineering for mass production may bring the cost of these systems down.

Our initial testing showed the potential for substantial energy savings with improved lighting quality. DOE-2 simulations predicted annual energy savings of 10-20% with improved lighting quality compared to a clear glazed window with daylighting controls in the 5 m deep lighting zone (Table 3 below). Performance was best for sun azimuth angles that were within ±45° of the window's outward surface normal, but a side reflector geometry improved performance for more extreme obtuse sun azimuth angles. Although their benefit is limited to sunny climates, we believe these systems show enough promise to pursue further development and testing activities. A full-scale demonstration of a light-redirecting skylight, based on the same design principles, was conducted in the Palm Springs Chamber of Commerce. Because cooling loads are a major problem in this climate and sunlight is almost always available, we designed a solution around a small skylight that admits and redirects direct sunlight to the ceiling of two separate interior rooms. The geometry of the internal skylight reflector was designed to provide daylight under all seasonal solar conditions, without allowing direct sunlight penetration to the task areas. The optical materials (reflectors and diffusers) were selected to provide good optical efficiency throughout the year. Initial surveys of the occupants indicated that they enjoyed the variability intrinsic in such a system and that it met their lighting needs well even during the winter.

Advanced the knowledge on human factors. There have been unsubstantiated claims that daylighting benefits the health, satisfaction, and even productivity of humans. Both prototypes were designed to improve comfort as well as increase energy-efficiency. With this research, we began the process of quantifying the qualitative benefits of dynamic and light-redirecting window/lighting systems using simulation tools, reduced-scale field tests, and full-scale demonstrations. Some of our arguments for quality improvements compared to conventional systems were made based on meeting well-known design constraints, thresholds set by experimental field data (e.g., glare or thermal comfort indices), or industry

Table 3. DOE-2 Annual Total Electricity and Lighting Electricity Reductions of Light Shelves and Light Pipes with Daylighting Controls in the 0-30 ft Lighting Zone Compared to a Clear Glazed Window with Daylighting Controls in the 0-15 ft Zone in a South-Facing Office in Los Angeles

	Lighting Electricity	Total Electricity
Light Shelves		
Single Level	29%	18%
Single with Side Reflectors	28%	18%
Bi-Level	29%	19%
Mult-Level	23%	10%
Light Pipes		
Design A	43%	9%
Design B	44%	5%
Design C	44%	5%
Design C with Two Pipes	44%	-1%

See: Beltrán, Lee & Selkowitz 1997.

guidelines (e.g., IES RP-1 for visual comfort). These methods only partially describe the fitness of a design solution to meet qualitative criteria because a) daylighting is constantly changing with solar position and sky conditions and b) one's complete experience of the daylit environment cannot always be reduced to "measurable" terms (Figure 3). Indeed, we found our understanding and evaluation methods of human factors most enriched by full-scale demonstrations.

For example, we demonstrated light-redirecting concepts at the Palm Springs Chamber of Commerce and took simple lighting spot measurements on site to confirm that design criteria were met. Direct experience with the daylit space was ultimately more compelling (Figure 4). Occupants spoke of the visual interest, the unique connection to the outdoors conveyed by the passive skylight system, and the bright or soft mood created by the color and intensity of daylight. A lighting designer, however, was not pleased with the system saying that the bright patches of daylight on the ceiling contradicted (electric) lighting standards which require shielding of bright luminous sources. This raises the issue of the extent to which standards set for electric lighting quality can be applied to daylight. Prior studies suggest that occupants are more tolerant of glare from windows because the lighting source is accompanied by a view. For dynamic window/lighting systems, will users find the improved control in daylight intensity "unnatural" and less desirable despite its benefits in controlling glare? Would the provision of user-operated controls cause the dynamic system to be more acceptable? Long-term human factors studies with a sufficient sample size are necessary to better understand the basic underlying concepts of occupant response to daylighting systems. In addition, full-scale demonstrations play an important part in assessing the market acceptance of new technological solutions.

Forum for advanced daylighting technologies. This multi-year project provided a mechanism for investigating advanced daylighting technologies, strategies, commercial prototypes, and demonstrations. Through networking with designers, manufacturers, owners, and researchers, we encountered a wide array of new technologies or design concepts that required some degree of scrutiny. We provided guidance to industry to ensure that their market perspective was sufficiently broad—many materials or technology developers were solving problems from either a lighting or windows discipline and therefore had a limited approach. In some select cases, we provided detailed analyses of product performance; e.g., holographic glazings, advanced skylights, angular-selective glazings, etc. With designers, we leveraged these opportunities by dispensing quick assistance on demonstration projects (depending on their schedule) or conducting detailed analysis when we felt our involvement would advance the science and application of daylighting in the real-world. In most cases, we felt that we were able to influence the perspective of the developer or designer to encompass integration issues.

For example, we worked with a skylight manufacturer to develop and evaluate new skylighting systems, to be demonstrated in a new "green" department store. Our approach emphasized not only control

Figure 3. RADIANCE ray-tracing simulations were used to predict the visual quality improvements associated with electrochromic glazings compared to static window glass.

of heat gains and light intensity but also improving the flux distribution for better visual quality. In another case, we were able to advise developers of electrochromic windows on how to tune the material's solar-optical properties for visual comfort as well as energy-efficiency, a previously unexplored design criteria. We contributed to the conceptual design of the Sacramento Municipal Utility District's New Customer Center, which was built using a broad array of daylighting strategies, including skylights, spectrally selective glazing, light shelves, exterior overhangs and fins for shading, atria, an "articulated" building form, integrated task and ambient lighting, and daylighting controls.

Daylighting performance algorithms. The tools for describing the performance of daylighting systems are limited, in part because there is currently very little research activity within industry and the business community to advance the science of daylighting from "advanced" window systems, such as automated blinds or holographic glazings. A new approach was devised that combined experimental measurements with simulation tools to produce an accurate characterization of interior illuminance levels. The method can be combined with an energy simulation engine such as DOE-2 to produce estimates of annual energy usage. The work provides a basis for more flexible daylight modeling tools that can ultimately be used by conventional engineering consultants.

Benefits to Existing Practice

Past research has attested to the substantial energy savings that can potentially be obtained with daylighting. We believe that the primary near-term obstacles to the successful use of daylighting in building today are design and implementation barriers. This research benefited *existing* practice and increased the use of integrated approaches to envelope/lighting systems design by in the following ways:

Design tools. A concise how-to document was produced to enable designers to implement key window and lighting integration design concepts. The eleven-section document was designed with rules-of-thumb and short calculations to quickly determine if daylighting is a viable strategy, with additional pointers to more detailed tools and resource. The tool targets the work style of the majority of architects who conduct business within the context of tight fees, insufficient resources, and multiple design considerations. More importantly, it reminds designers of the far-reaching effects of merely specifying the style of a window—from the capacity of the mechanical system and comfort of the occupants to its impact on the environment. Since the design of windows with daylight involves knowing how to balance solar heat gains against the admission of useful light, this tool informs designers of this complex balance point and enables them to assess design trade-offs sensibly within these energy-efficiency boundaries (e.g., larger glazing area with acceptable comfort is possible with spectrally selective glass). The document can be read or downloaded from the World Wide Web[1] and has been distributed to participating utilities, some universities, and international research institutions.

[1] Available on the web: http://eande.lbl.gov/BTP.html. Click on "Publications" then click on "Tips for Daylighting with Windows: The Integrated Approach."

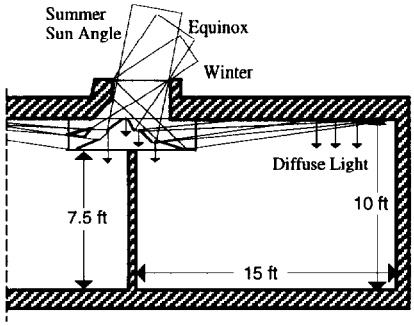


Figure 4. The Palm Springs Chamber of Commerce skylighting system was designed to redirect daylight to the ceiling plane in two separate rooms.

Re-engineering daylighting controls. Daylighting controls in the U.S. have fundamental design flaws that simplify installation and reduce cost but decrease reliability. This unreliable performance is a significant barrier to its widespread and satisfactory use in buildings. Daylight from sidelight windows produces an illuminance pattern that changes with time of day and season, while fluorescent top lighting produces a predictable pattern (Figure 5). The simple control system is unable to adjust for these differences in lighting patterns so interior illuminance levels are often too low. To avoid occupant complaints, facility managers will decrease the sensitivity of photoelectric sensors so that the electric lighting is dimmed very conservatively, but this adjustment can severely undermine the energy-efficiency of the system.

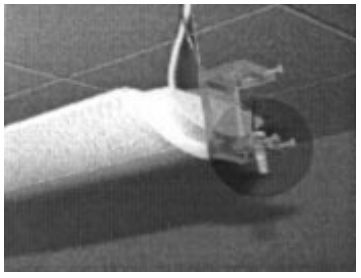
The performance of closed-loop proportional control systems (offered by European manufacturers) can be improved substantially at no added cost by using existing information from the control system to separate the electric lighting illumination contribution from the daylight contribution.[2] This algorithmic solution was tested at full-scale over a year and was found to perform very well. Monitored workplane illuminance levels did not fall below 10% of the design level for 98% of the year, and if it did, the failure occurred an average of 13 minutes per day within a 12-hr day. Market adoption of our algorithmic refinements will need a solid commitment from U.S. manufacturers to redesign their systems.

Commissioning guidelines for daylighting controls. Past daylighting controls research has been devoted to control improvements such as photosensor design and placement to reduce the occurrence of insufficient illuminance. Taken from a cross-disciplinary approach, we have characterized how *windows* affect the performance of the daylighting control system. This work enabled us to add to the fairly sparse guidelines given to installers on how and when to commission daylighting control systems. For example, guidelines were developed on how to position venetian blinds, whether to commission with or without direct sun, and whether to commission with the sun in or out of the plane of the window. Further research is required to determine whether the characterization is truly generalizable to other daylighting control systems and interior spaces, since this work builds on case-specific monitored data taken in the full-scale testbed facility.

Process. While there were less tangible deliverables resulting from the design assistance and demonstration activities of this research project, we better understood the process of achieving integration in the real-world. We found the typical process of designing the envelope *and* the lighting system for new construction to be dysfunctional if the goal is to capture energy savings and to achieve occupant satisfaction and comfort with the built environment.

To achieve success in this work, we learned that a) the concept of an integrated approach must be introduced at the start of the project when design solutions such as building orientation, articulated floor plans, or exterior shading systems can still be considered, and b) the final design choice must embed

2 The U.S. industry offers only integral reset and open-loop proportional control solutions, which do not allow one to tune the system for luminance pattern differences between electric light and daylight.



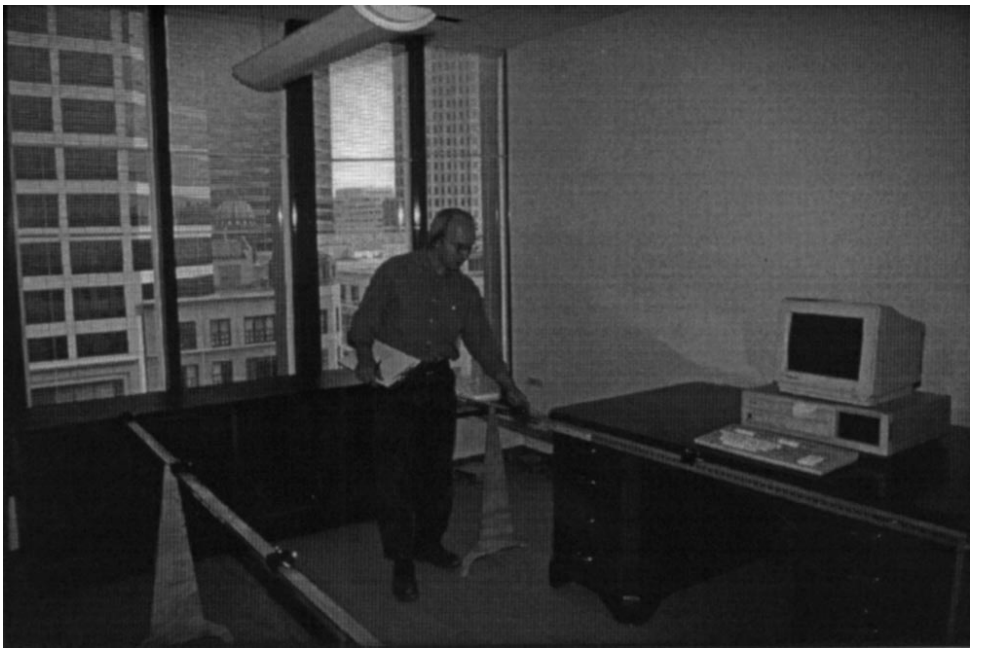


Figure 5. A simple photosensor (above) is required to characterize the lighting from both daylight and electric lighting in order to dim the fluorescent lighting system accurately. A view of the interior of a test room (right) within the Oakland Federal Building Testbed Demonstration Facility shows the illuminance distribution from daylight.

value for human factors or amenity. Design decisions based on bottom-line first cost may ultimately cost more because of the large cost of altering or modifying the building envelope once a foreseeable problem is identified when occupants move in. If not altered, occupants and building owners will have to contend with the design solution, since envelope systems last at least 15 to 20 years. A 1.2 Mft^2 office building erected in Oakland in 1987 is a typical example. The design team considered advanced low-E glazing but ultimately selected monolithic single-pane lightly-tinted glass, presumably on the basis of first cost. After occupancy, the facility manager has had to address the constant complaints of heat and glare from building occupants. Heat-absorbing window film would increase the thermal discomfort of those situated near the window, while reflective window film was unacceptable on the grounds of aesthetics. The added installed cost for the films of \$3-5/ft^2-glass or \$400K for the building could not be justified on the basis of energy-efficiency alone. Expensive window coverings (interior shades at \$2/ft^2-glass) have been purchased by individual tenants. No long term solution has been reached.

With retrofit applications, the process was dysfunctional primarily because the facility manager was not as well informed, having less resources than an A/E team. Economic and process barriers frustrated even the most well-intentioned facility manager. The order of what to retrofit is based on either when systems break down or by approved alterations (lobby upgrades, energy-efficiency, etc.). Mechanical and lighting systems are usually replaced first, since they are not as long-lasting and the energy-efficiency upgrades of such components (VFDs, T8 lamps) usually require less total capital and have a shorter payback than envelope systems. Often, advanced windows cannot be implemented as a retrofit because the energy-efficiency cost-benefits of recently upgraded lighting (daylighting controls) and mechanical systems (downsizing capacity) cannot be folded in. We encountered several such situations. In Sacramento, a previously naturally-ventilated office building was upgraded with a new mechanical system. The ceiling height was reduced by 1 m to accommodate new ventilation ducts, blocking daylight from the upper third of the window. The entire building was upgraded with new finishes (window shades, painting, etc.). New light fixtures were installed with multi-level switching. After this complete renovation, the building managers turned to the upgrade of the exterior of the building, including replacement of the single-pane, clear glass windows. If an integrated perspective had been taken initially, the facility manager may have been able to a) reduce the capacity of the chiller and possibly the depth of the air distribution ducts, b) design the layout of the lighting zones to accommodate future installation of daylighting controls, and c) design the window-to-ceiling detail to admit more daylight and reduce the visual contrast in brightness between the interior and window. Retrofits must not be conducted piecemeal as events come about, rather with a proactive perspective of what is to come. We conveyed this approach in a document on spectrally-selective glazings to Federal energy managers. Institutional changes

in policy or design approach could also affect the way retrofits are conducted in businesses that manage a large number of facilities.

Conclusions

Daylighting strategies can provide large reductions in lighting and cooling-related energy use, as well as improved amenity, satisfaction, and perhaps performance. But the successful adoption of daylighting in the marketplace requires an integrated approach to the design, specification, and implementation of envelope and lighting technologies. Through this research project, we believe we were able to take a small but important first step to change how architects, facility managers, and industry perceive the notion of daylighting commercial buildings by supplying design tools, credible energy performance data, demonstrations of future daylighting concepts, and commissioning protocols that address key window *and* lighting interactions. Clearly, the simple conceptual solution of manually switching off the lights when sufficient daylight is available from an unmanaged window in a naturally lit space doesn't work. We have developed systems that save energy consistently and reliably while delivering amenity, satisfaction, comfort, and health to its occupants through sensitive control of daylight intensity and distribution. A longer term and much stronger effort will be needed to transform these initial results to mainstream practice in the building profession.

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