

COMPARATIVE EVALUATION OF SIDE-DAYLIGHTING STRATEGIES

Michael J. Holtz, FAIA
LightLouver LLC
685 S. Arthur Avenue
Louisville, Colorado 80027
mholtz@lightlouver.com

Zack Rogers, PE, IESNA
LightLouver LLC
685 S. Arthur Avenue
Louisville, Colorado 80027
zrogers@lightlouver.com

ABSTRACT

Electric lighting accounts for 17.4 % of primary energy use in the U.S. commercial buildings sector. In individual commercial buildings, electric lighting typically accounts for 30 to 50 % of the building's annual energy cost. Substituting daylight for electric lighting during daytime hours is essential for meeting current and future stringent energy and environmental regulations and for achieving significant energy savings (including net-zero energy and carbon buildings). In multi-story commercial buildings, side-daylighting strategies are the primary approach to daylighting interior space. Five general approaches to side-daylighting are interior or exterior light shelves, automated interior or exterior shades and blinds, and passive optical daylight distribution devices. However, not all of these side-daylighting approaches are created equal when evaluating their performance and cost. Some effectively address sunlight distribution, some effectively address solar / glare control, some effectively address architectural integration -- while few effectively address all evaluation criteria. This paper evaluates these five common side-daylighting approaches using both qualitative and quantitative criteria.

1. INTRODUCITON

Electric lighting accounts for 17.4 % of primary energy use in the U.S. commercial buildings sector. (1) In individual commercial buildings, electric lighting, including cooling energy consumed to remove the heat generated by electric lighting, typically accounts for 30 to 50 % of the building's annual energy cost.(2) Substituting daylight for electric lighting during daytime hours is essential for meeting stringent energy and environmental regulations and for achieving significant energy savings (including net-zero energy and carbon buildings). In multi-story commercial buildings, side-daylighting strategies are the primary approach to daylighting interior space. Five common approaches to side-daylighting are interior or exterior light shelves, automated interior or exterior shades and blinds,

and passive optical daylight distribution devices. These side-daylighting strategies are evaluated using qualitative and quantitative criteria, and a number of observations and conclusions are made.

2. DAYLIGHTING DESIGN CHALLENGES

Architectural and engineering design teams face numerous challenges when designing for the use of side-daylighting in commercial buildings, including the following:

Glare – Visual discomfort due to large amount of sunlight in the occupants' field of view, typically in combination with a high contrast ratio between the daylight entering the space and the surrounding window frame or wall surfaces.

Daylight distribution – Excessive daylight levels near the windows and inadequate daylight levels deeper in the space resulting in non-uniform and shadowy illumination.

Selection of electric lighting system – Layout, control zoning and selecting electric lighting fixtures, ballasts and lamps that will effectively integrate with the daylighting system.

Daylight responsive electric lighting controls – Selection and design of the electric lighting system controls to balance occupant comfort and satisfaction and to maximize "daylight harvesting" / energy savings derived from dimming or turning off electric lights.

Interior window treatment – Design of interior window treatment to effectively block or diffuse direct sunlight when necessary and to provide adequate glare control.

Interior design and furniture selection -- Choice of wall colors, ceiling color / reflectance, partition height and color, furniture placement, and other interior design decisions which have a significant impact on daylighting system performance.

3. SIDE-DAYLIGHTING STRATEGIES

Five commonly known side-daylighting approaches are briefly defined below.

3.1 Interior or Exterior Light Shelves

A light shelf is a horizontal element, typically 24 to 30 inches wide, installed below a “daylight window” and above the “vision window”. The light shelf can be installed in the interior or on the exterior of the building. The light shelf is opaque, with a reflective (specular or diffusing) upper surface and a diffusing white bottom surface. An image of a typical interior light shelf is shown below.



3.2 Interior or Exterior Automated Shades and Blinds

Window shades or blinds are devices which control the amount of sunlight allowed to enter the space. They can be manually or automatically controlled to open or close based on exterior solar radiation levels or a computer with an astronomical clock. Automated window shades and blinds are primarily a solar control device, blocking direct sunlight from entering the space while allowing filtered daylight and views to be maintained.



3.3 Passive Optical Daylighting System

Optical side-daylighting strategies rely on an optical design to redirect sunlight into the daylit space. A “passive” optical side-daylighting device means that the daylight reflecting elements do not move or have to be adjusted to perform their sunlight collection and redirection function. This is to be contrasted with an “active” optical side-daylighting device, whose daylight reflecting components must be adjusted hourly, daily, or seasonally to perform its sunlight collection and redirection function, or with “passive” optical devices used for solar control only. An example of a passive optical daylighting device, the LightLouver™ Daylighting System, is shown below, followed by an image of the LightLouver Daylighting System installed in a elementary school classroom.



4. QUALITATIVE EVALUATION

A number of criteria must be considered when selecting and designing a side-daylighting system. The matrix below compares the five common side-daylighting design alternatives. Thirteen evaluation criteria are listed, representing the most common factors that designers and owners consider important when selecting a side-daylighting system.

	Side-Daylighting Strategies				
	Passive Optical Daylighting System	Conventional Interior Lightshelf	Conventional Exterior Lightshelf	Automated Interior Shades	Automated Interior Blinds
Deep uniform daylight distribution	Yes	Partial (1)	Partial (1)	No	Yes (2)
Self-shading design -- complete solar cutoff and glare control	Yes	Partial (3)	Partial (3)	No	Partial (2)
No moving parts (passive optics) and no daily or seasonal adjustments	Yes	Yes	Yes	No	No
Effective daylight distribution and solar control on east and west glazing	Yes	No	No	No	Yes (2)
Custom fabrication to fit specified window dimensions	Yes	Yes	Yes	Yes	Yes
Quick and easy installation (less than 10 minutes)	Yes	No	No	No	No
Low lifetime maintenance costs	Yes	Partial (4)	Partial (4)	Varies (5)	Varies (5)
Significant energy savings (when used in combination with effective lighting controls)	Yes	Partial	Partial	No	Partial
Low initial and life cycle costs	Yes	No	No	No	No
Made in the USA	Yes	Yes	Yes	Some	Some
Unobtrusive architectural integration	Yes	No	No	No	No
Minimizes building system integration impacts - sprinkler, HVAC, and lighting systems	Yes	No	No	Partial (6)	Partial (6)
Notes:					
1. Commercially available interior and exterior lightshelves are not designed / optimized to redirect incident sunlight deep onto the ceiling of the daylit space.					
2. Deep and uniform daylight distribution (and solar control) will only occur if an effective reflecting slat design and sophisticated automated rotational control of the slats are used.					
3. Interior and exterior lightshelves do not provide full solar cutoff; thus, during certain times of the day or year direct sunlight will miss the lightshelf and create glare and sunlight patches on work surfaces. An automated interior blind will only provide effective solar control if a sophisticated automated rotational control of the slats is used.					
4. Interior and exterior lightshelves, by their very nature, make it difficult to access the "daylight" window glazing for cleaning.					
5. Because these systems have numerous mechanical and electrical components, maintenance costs can be significant if and when there are problems.					
6. Because these systems are automated, electricity must be provided for the motors and controls which increase the integration impacts and costs.					

Because passive optical side-daylighting systems have been developed to overcome many of the inherent limitations of conventional side-daylighting strategies, such as elimination of glare, deep and uniform daylight distribution, applicability to east and west facing facades, and ease of architectural integration, it is not surprising that this type of side-daylighting approach receives high marks when compared to the other side-daylighting alternatives.

5. QUANTITATIVE EVALUATION

Plots of illuminance versus time of day answer the question, “How much light does the each side-daylighting strategy provide on a work surface throughout the year?” The figures below display the average illuminance, in foot candles (fc), versus time of day that each side-daylighting strategy provides to a 42 foot deep south-facing daylit space located at 40° N latitude. The Radiance lighting simulation software was used to generate the plotted results. (3) Each figure has four plots. Three of them show the illuminance at the winter solstice, summer solstice, and the equinox (which occurs in Spring and Fall). Each figure also has a fourth plot which shows the average illuminance on a cloudy day. A 25 fc target illuminance value is show across all figures as a straight green line. Other figures and plots (not shown) present illuminance levels in a 16 foot south zone and a 16 foot north zone. In all scenarios, a 5’ wide perimeter

walkway is assumed so the daylight zone starts 5’ in from the south window wall.

In all figures, regardless of the side-daylighting strategy being analyzed, it is assumed that when direct sunlight is striking the fenestration that all blinds or shades on the “vision windows” are closed to eliminate direct sunlight penetration into the space.

Figure 1: Passive Optical Daylighting System. Radiance results show that illuminance levels remain above the target illuminance of 25 fc throughout daytime hours for most of the year, even on a typical cloudy day. When direct sunlight is striking the south fenestration, the “vision windows” are shaded; however, the “daylighting glazing” with the LightLouver units is redirecting sunlight deep into the space without glare or direct sunlight striking work surfaces.

Figure 2: Interior Light Shelf. Radiance results show that illuminance levels exceed the target illuminance level for the winter and fall / spring season, but are below the target illuminance level in the summer and on cloudy days. Although not easily shown in these plots, direct sunlight is coming over the top of the light shelf and striking occupants and work surfaces during the winter months creating visual discomfort and disabling glare.

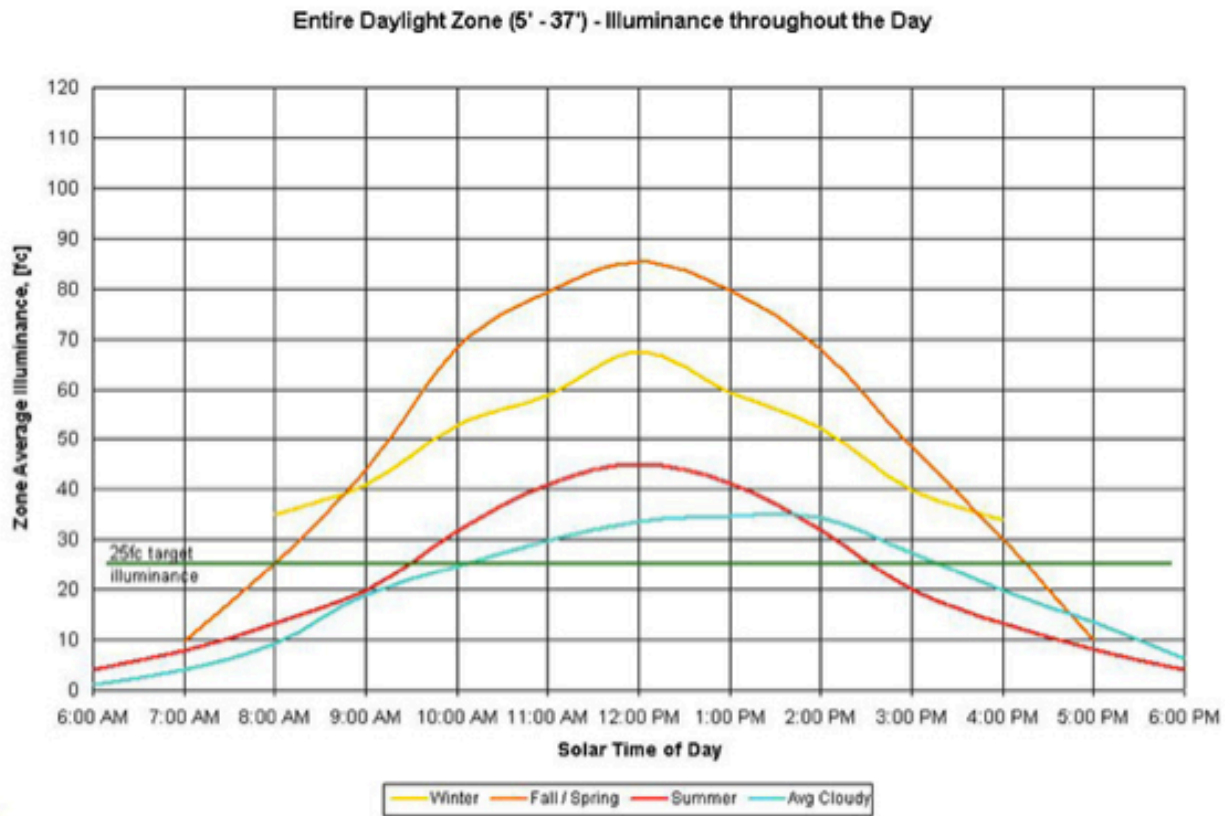


Fig. 1: Average Entire Zone Illuminance Levels – Passive Optical Daylighting System

Entire Daylight Zone (5' - 37') - Illuminance throughout the Day

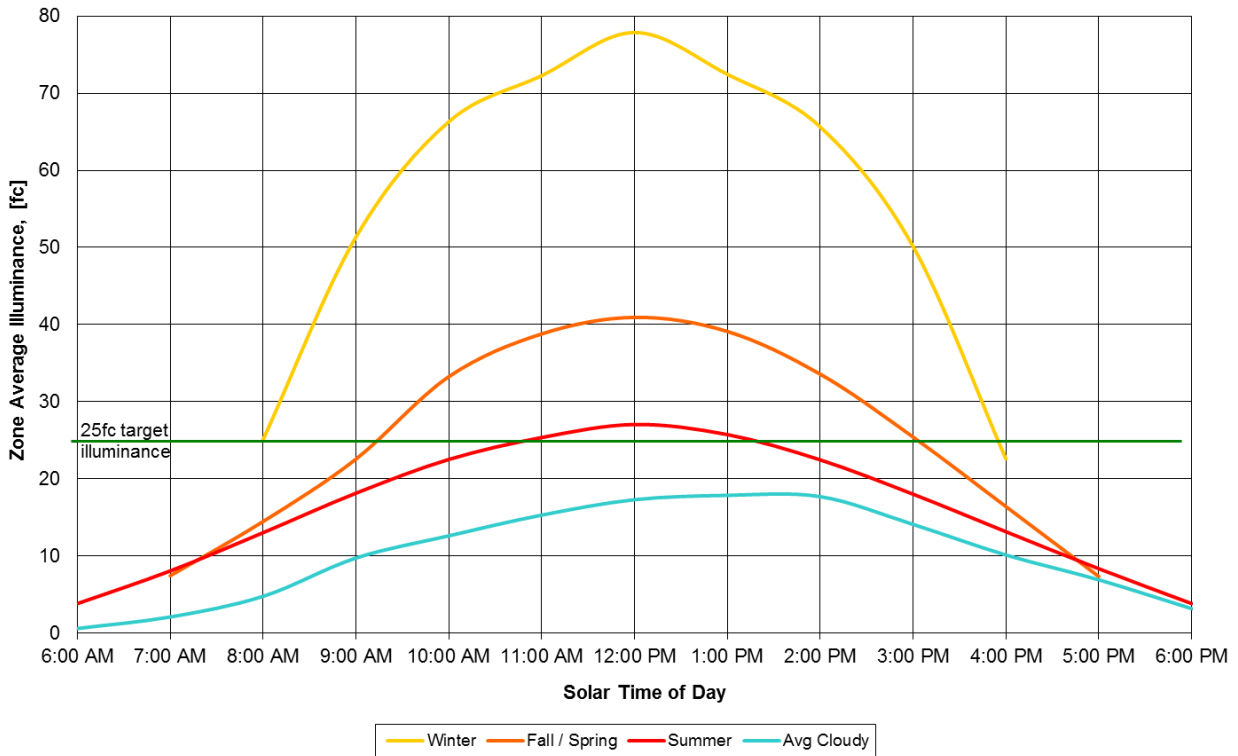


Fig. 2: Average Entire Zone Illuminance Levels – Interior Light Shelf

Entire Daylight Zone (5' - 37') - Illuminance throughout the Day

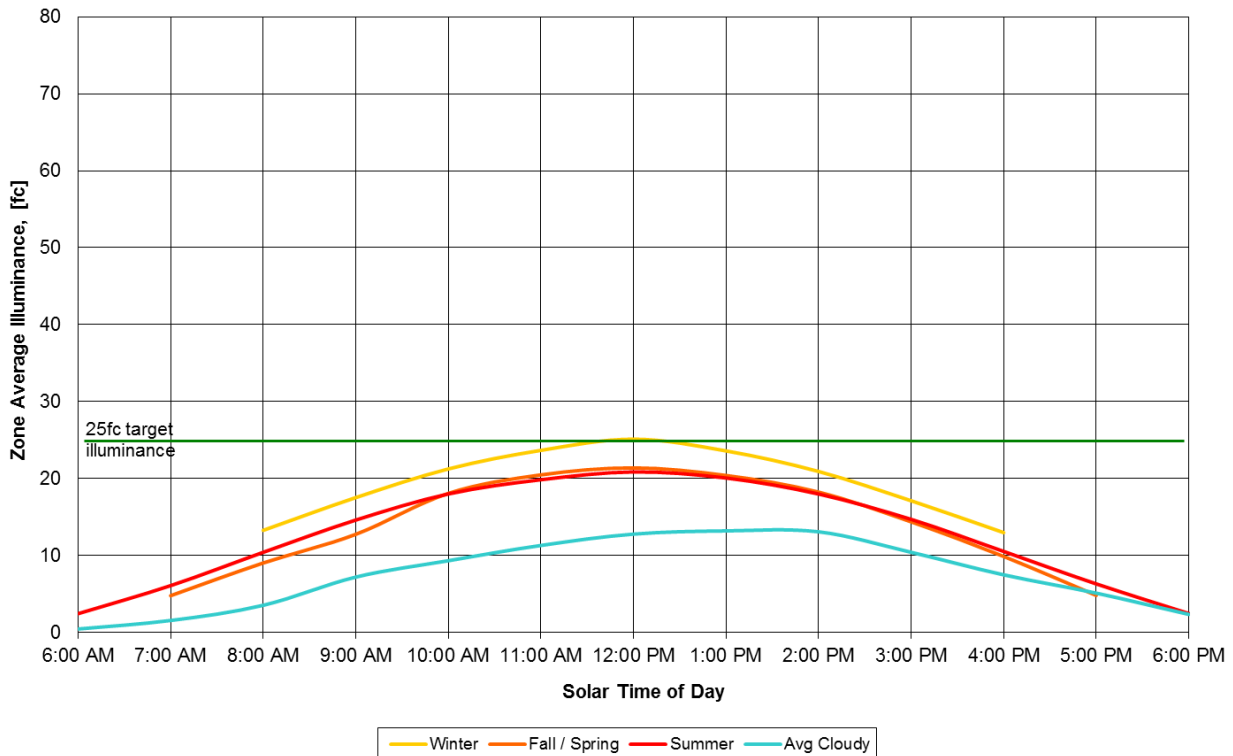


Fig. 3: Average Entire Zone Illuminance Levels – Interior Blinds in a Fixed Position

Entire Daylight Zone (5' - 37') - Illuminance throughout the Day

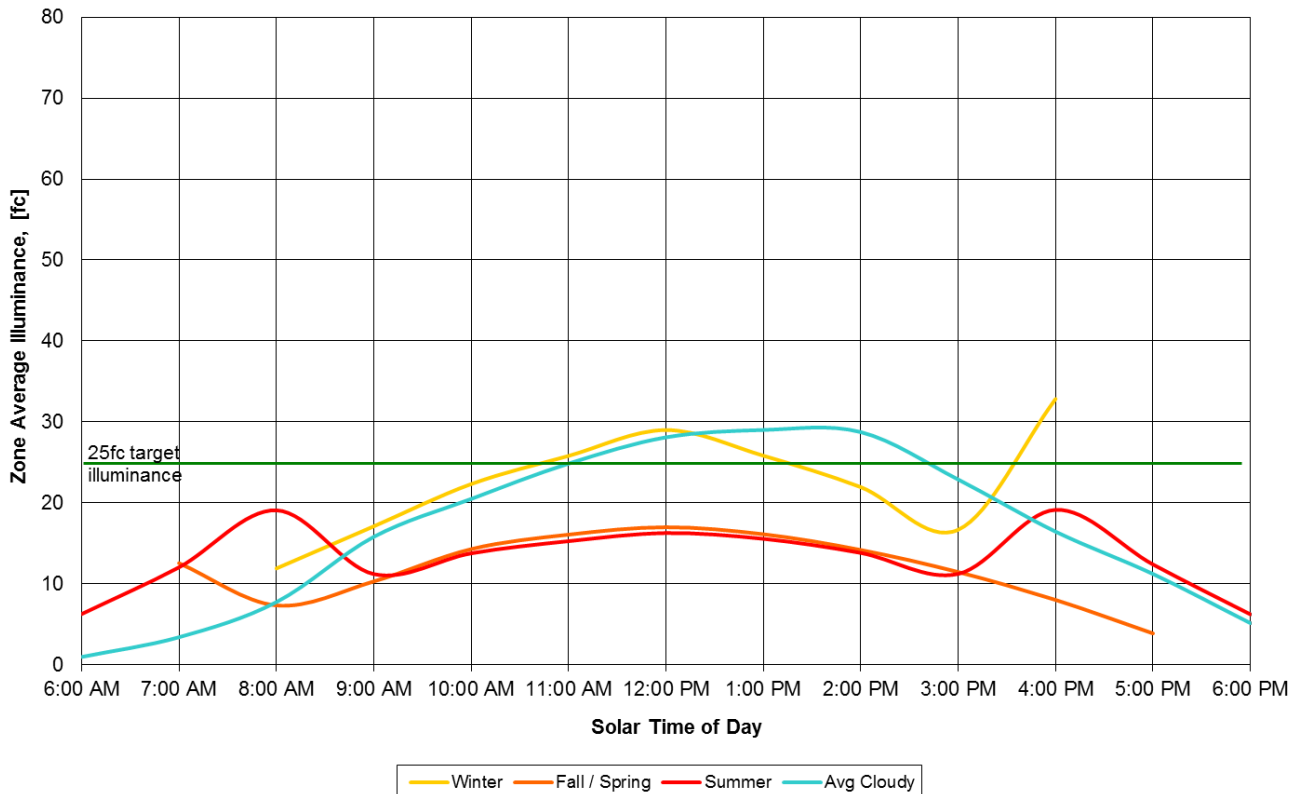


Fig. 4: Average Entire Zone Illuminance Levels – Automated Interior Shades

Figure 3: Interior Blinds in a Fixed Position. Radiance results show that interior blinds, fixed in a position to control direct sunlight penetration, do not provide adequate daylight to achieve that the target illuminance. When direct sunlight is striking the south fenestration, the blinds are down and positioned to block direct sunlight from striking work surfaces, thus limiting daylight distribution into the space

Figure 4: Automated Interior Shades (3% openness factor). Radiance results show that automated interior shades achieve the target illuminance a few afternoon hours during the winter and on a typical cloudy day. When direct sunlight is striking the south fenestration, the shades are down, thus limiting daylight distribution into the space.

5.1 Economic Evaluation of Side-Daylighting Systems

The table below compares the economic performance of the five side-daylighting approaches for a 30 foot deep classroom or office space.

The average depth of daylight penetration, defined as maintaining an annual average of 25 fc on the work surface during daylight hours, is in this example 30 feet for the passive optical daylighting system, 15 feet for the interior and exterior light shelves, and 10 feet for the automated window shades and blinds as determined through Radiance

modeling. The product cost per lineal foot of window is \$74 for the passive optical daylighting system, \$120 for the light shelves, and \$175 for the automated window blind and shade systems. A more telling indicator of value and economic performance is the cost per daylit square foot of building floor area. The passive optical daylighting system provides daylighting at roughly \$2.47 per square foot, compared to \$8.00 per square foot for light shelves and \$17.50 per square foot for automated window shades and blinds.

The passive optical daylighting system appears from this analysis to be the most cost effective method for side-daylighting. It has better performance and lower cost than any of the other side-daylighting strategies.

The passive optical daylighting system is also the clear choice from a performance standpoint. In an existing building (retrofit situation) with a lighting power density of 2.2 W/sf and located where the average/blended cost of electricity is \$0.14 per kWh, the passive optical daylighting system will save \$9.60 each year per lineal foot of window. This compares to \$4.80 for light shelves and \$3.00 for automated shades and blinds. The simple payback for the passive optical daylighting system is 7.7 years, compared to 25 years for light shelves and 58 years for automated shades and blinds.

In a new building situation, with a lighting power density of 1.0 W/sf and located where the average/blended cost of electricity is \$0.14 per kWh, the passive optical daylighting system will save \$4.35 each year per lineal foot of window, while the light shelves will save \$2.20 and the automated shades and blinds will save \$1.35.

The low cost and excellent performance of the passive optical daylighting system makes it an excellent choice for new construction and retrofit commercial building side-daylighting applications.

	Passive Optical Daylighting System	Conventional Interior Light Shelf	Conventional Exterior Light Shelf	Automated interior shades	Automated interior blinds
Average depth of daylight penetration (feet)	30	15	15	10	10
Construction cost per lineal foot of window	\$74.00	\$120.00	\$120.00	\$175.00	\$175.00
Cost per daylight sq foot	\$2.47	\$8.00	\$8.00	\$17.50	\$17.50
Product cost per sq foot of daylight aperture	\$37.00	\$60.00	\$60.00	\$87.50	\$87.50
Value of energy saved per lineal foot of window (2.2 W/sf)	\$9.60	\$4.80	\$4.80	\$3.00	\$3.00
Value ratio (value of energy saved/technology cost)	3.89	0.60	0.60	0.17	0.17
Value relative to LightLouver Daylighting System	1.00	0.15	0.15	0.04	0.04
Simple payback (years)	7.71	25.00	25.00	58.33	58.33
Value of energy saved per lineal foot of window (1.0 W/sf)	\$4.35	\$2.20	\$2.20	\$1.35	\$1.35
Value ratio (value of energy saved/technology cost)	1.76	0.28	0.28	0.08	0.08
Value relative to LightLouver Daylighting System	1.00	0.16	0.16	0.04	0.04
Simple payback	17.01	54.55	54.55	129.63	129.63

Table 1: Economic Performance of Five Common Side-Daylighting Approaches

6. CONCLUSION AND OBSERVATIONS

On the basis of the qualitative and the quantitative evaluation of five common side-daylighting approaches presented above, the following observations and conclusions can be made:

Daylighting must be a primary strategy for achieving current and future energy and environmental regulations in commercial buildings. Low power density electric lighting alone, whether through fluorescent or LED lighting, will not be sufficient to meet stringent energy code requirements.

Side-daylighting approaches will be the primary means for daylighting multi-story commercial buildings. Thus, architectural massing and orientation will have a large influence on achieving significant daylighting contribution.

Side-daylighting approaches must address the daylighting design challenges or they will not be effective or accepted by the building owners and occupants, or the building design profession. Many architects think that greater window area equals more daylighting. However as Michael Holtz, FAIA and author of this paper says “Don’t confuse daylighting with windows and view™”. Building fenestration must be designed and specified based on the function that the fenestration is serving. Effective daylighting systems must collect and redirect daylight deep

into the daylit space and do so without glare and direct sunlight patches on work surfaces.

Only one of the common side-daylighting approaches - the passive optical daylighting system - evaluated effectively addresses the daylighting design challenges of glare, solar control, deep daylight distribution, and integration with electric lighting, daylight responsive controls, HVAC systems, and interior design elements. Consequently, the remaining side-daylighting strategies are generally compromised by the building occupants through their actions, such as keeping the blinds or shades closed all the time, or placing cardboard panels in the “daylight windows” above light shelves to block direct sunlight from striking their work surfaces or creating disabling glare in their field of view.

Glare or limited daylight distribution are the primary limitations of most side-daylighting approaches. If side-daylighting strategies are to be widely used in multi-story commercial buildings, they must be able to daylight a large portion of the floor plate – deep daylight penetration, and do so without glare and direct sunlight striking work surfaces.

The passive optical daylighting design approach currently best addresses the daylighting design challenges. Looking at the qualitative and quantitative evaluation criteria and the analysis results, the passive optical daylighting approach appears to satisfactorily address more criteria than any of the other evaluated side-daylighting strategies.

Deepest uniform daylighting is provided by the passive optical daylighting approach. While interior or exterior light shelves can allow for daylight deeper into a space, they have not been optically designed to collect and uniformly distribute sunlight throughout the year (angle in incidence = angle of reflectance), and to provide complete glare /solar control. For most manufactured or site built light shelf designs, during low (winter) sun conditions, sunlight will come over the top of the light shelf and create glare conditions at the window and allow direct sunlight patches on work surfaces. Passive optical daylighting systems intercepts direct sunlight (down to a 5° cut-off angle for the LightLouver Daylighting System) and redirect this sunlight up and deep into the space, thus minimizing any glare and direct sunlight penetration onto work surfaces.

When direct sunlight strikes south, east and west facing fenestration, interior or exterior window shades and blinds must be closed to block direct sunlight from entering the space and creating disabling glare, high contrast ratios, and direct sunlight patches on work surfaces. Thus, side-daylighting strategies, such as automated blinds and shades, are limited in the depth of daylighting they can provide. However, passive optical daylighting devices can continue to collect and distribute sunlight during periods of direct sunlight on the fenestration, as their optical geometry has been design to redirect sunlight while minimizing glare and eliminating direct sunlight patches on work surfaces.

7. REFERENCES

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- (3) Radiance Lighting Simulation Software, Greg Ward, Lawrence Berkeley National Laboratory, (www.radiance-online.org).