The Assessment of Advanced Daylighting Systems in Multi-Story Office Buildings Using a Dynamic Method

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Abstract: The performances of light shelf systems are evaluated in the context of various interior configurations typical of multistory office buildings by using CBDM (climate-based daylight modeling). A physical scale model of one of the light shelf systems is tested in the first phase under real sky conditions in Raleigh, North Carolina, USA. The data collected from the experiments are used to validate the simulations by a computer-based dynamic daylighting research tool - DAYSIM which is based on the concept of CBDM (Radiance + Perez Sky Luminance Model + Daylight Coefficient). In the second phase, additional simulations utilizing the validated tool are conducted to study the effects of system geometries and interior space characteristics. Specifically, the following parameters are identified and assessed: light shelf length, ceiling height, and interior configurations typical of North American office building settings. The findings have displayed the impact of various system parameters and interior design approaches on daylighting performances. The limitations of the study include possible errors in both computational simulations and the physical testing, and errors caused by the process of generating the sky models from solar radiation data for DAYSIM.

Keywords: *Lightshelf, Ceiling Height, Interior Configuration, CBDM, Simulation*

1. Introduction

Although electric lighting has now assumed the role of being the primary means of illumination for many buildings, people generally express a strong preference for natural light in their work environment. There also has been an interest in daylighting as a means of reducing nonrenewable energy use. In multistory office building, one of the strategies for achieving the comfortable interior environment is to redirect daylight from primary surfaces, such as a light shelf, to secondary room surfaces (ceiling and walls), which in turn will illuminate horizontal work surfaces. A light shelf is a small area of horizontal reflecting surface mounted just below the daylight glazing in the façade. Typically, the designer of the building will have a high degree of control over the placement and optical properties of that reflective surface, which makes it a much better candidate light reflecting source than the ground plane. Furthermore, this reflecting surface can be placed above eyelevel for the building occupants, thereby avoiding the potentially severe glare effects of intense upward light in the eyes of occupants near the window. There are two functions to a light shelf system: To reflect light deeper into the building, thereby providing more light in the interior, and to block excessive light from entering spaces close to the perimeter wall.

There have been a limited number of studies on light shelves. The early studies focused on flat simple light shelves. Simple light shelf is referred to the system with interior shelf length of about 4-6 feet. In a study presented by Selkowitz, et al. [1], it was concluded that “in general, simple light shelf designs provide improvements in light penetration.” This study did not assess the effects of changing the length of the shelf. Burt Hill Kosar Tittelmann Associates also presented a study on simple light shelves, showing that light shelves do improve the quality and quantity of light in perimeter zones. In this study, a fixed length exterior light shelf was investigated [2]. Advanced light shelf systems were also developed and tested. Some of these studies focused on ceiling configuration. Fardeheb found that exterior shelves in conjunction with a sloped ceiling were most effective among nine different light shelf designs that they studied [3]. Another category of advanced light shelf research dealt with the shape and movement of the shelf. Place and Howard developed and assessed two advanced daylighting systems, one involving a static curved-mirror and the other involving a tracking flat-mirror system [4]. Based on the behaviors of the two systems in different seasons under different sun angles, design guidelines were developed. An external curved light deflector was designed and tested by Close as one of the three features of the daylighting system designed for a high-rise building in Hong Kong [5]. The performance of the system was simulated by computer and then verified against physical scale models. Finally, some researchers were interested in the effects of varying the reflectance of light shelf surfaces. Claros and Soler investigated the performances of two light shelves with different types of reflecting materials [6].

This list of studies generally delineates a picture of what has been covered by the efforts of previous researchers. It also introduces the three topics to be explored in this study:

- ***Length of light shelves*** - Throughout the literature there has been little effort to systematically assess the impact of light shelf geometries, especially, of longer light shelves (more than 6 feet).
- ***Ceiling height*** **-** Ceiling height is a crucial factor in daylighting design. This is also the area where “battles” tend to occur between daylighting designers and other members of the design team, such as the structural and mechanical engineers. It is thus important to quantify the importance of ceiling height for delivering light into a space.
- ***Interior configuration*** - Very few researchers have considered the impacts of interior partition designs (layout & material) on lighting environment. Almost all the experiments were performed in an open space. Modern office buildings take on a variety of interior layouts, which can drastically affect lighting performances.

2. Methodology

The traditional daylighting research approach – the Daylight Factor method, only addresses overcast conditions and leaves out important design factors, such as building orientation. Understanding daylight from a climate-based point of view would therefore be more practical to assess daylighting systems in areas with a highly luminous climate, in which case various types of sky conditions (e.g. clear sky or intermediate sky) are all taken into considerations. However, climate-based experimental testing can be time consuming, since monitoring design options in a full year is normally not feasible for most design projects. As an alternative, a dynamic Radiance-based simulation tool - DAYSIM can be adopted for carrying out Climate-Based Daylight Modeling (CBDM) using meteorological dataset [7, 8, & 9]. By the comparisons with experimental measurements, DAYSIM has been proven to be accurate for performing annual daylight predictions for regular daylit spaces [8]. However, it would be prudent to validate the tool before it is used for assessing any advanced daylighting systems, such as light shelves in conjunction with various interior design approaches in this study.

2.1. Validation of DAYSIM simulations by experimental measurements

A physical scale model (scale: 1:6) is established to represent a 30’ x 40’ (9.14M x 12.19M) portion of a typical office floor (Figure 1). A daylighting system incorporating a 6-ft (1.83 M) lightshelf and a 3-ft (0.92 M) overhang is integrated on the south elevation (Figure 2). The ceiling height is 11’ (3.35M) and the top of view glazing is at 7’-2” (2.18M) above the finish floor. The surface reflectances are: ceiling and walls: 90%; floor: 20%; lightshelf top and bottom surfaces: 90%; overhang top and bottom surfaces: 15%; exterior ground reflectance is assumed at 20%; glazing transmittance: 70%. The interior space is divided into five equal daylit zones. Annual daylight levels in each zone are predicted by both physical experiments and DAYSIM.

Fig. 1. Physical scale model being tested on a heliodon.

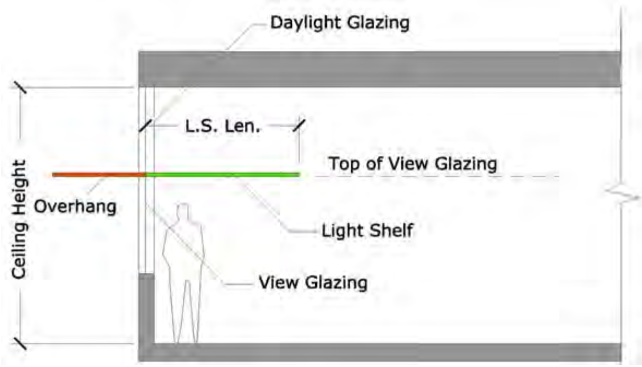

Fig. 2. The daylighting system with a light shelf and an overhang

2.1.1. *Physical experiments*

To simplify the experimental procedures, the model is only tested under a diffuse sky – a blue sky in this case (clear sky without the sun component), because a diffuse sky is a much more reliable light source than the sun. Sunlight is highly variable depending on seasons, solar angles and weather conditions. A Licor photocell sensor (Model 210L) is installed at the center of each daylit zone (Sensor Ez1 through Ez5). An exterior sensor (Ev) is mounted on a vertical plane facing the same direction as does the window. To simulate a blue sky condition on a clear day, the system designed for facing south is rotated so that it faces only diffuse sky (Figure 3). This approach allows for the system to be tested only under diffuse blue sky by eliminating the sun component. A Coefficient of Utilization can then be developed for each zone to establish the relationship between the sky and interior illuminances. Using Zone 1 as an example, the CU is calculated by the following formulas: CU1 = Ez1 / Ev. Note that a CU relates the interior illuminance to exterior vertical illuminance while a Daylight Factor relates the interior illuminance to exterior horizontal illuminance. Exterior horizontal illuminance only depends on solar altitude, which makes the factor of building orientation out of the question, whereas exterior vertical illuminance depends on both solar altitude and azimuth. Therefore, vertical illuminance is a better indicator of lighting conditions outside especially for assessing sidelighting systems. In addition, the exterior vertical illuminance (Ev), which is taken at the window surface, provides a direct measurement of how much light actually enters the room.

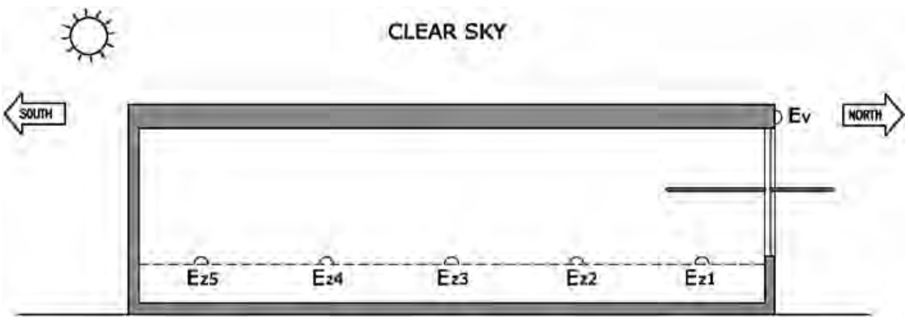

Fig. 3. Model being tested under blue sky. (The lightshelf system is designed for south-facing. However, it is rotated in the experiment to face away from the sun, towards diffuse sky light only)

Hourly daylight levels in Lux in all zones can be developed in a full year by multiplying the CUs by the annual exterior illuminance data (Ev), which were made available by the Daylighting Research Lab at NC State University. The data set, including hourly Ev values in a full year, was collected in a two-year period (1991 & 1992) in Raleigh, North Carolina [10]. Table 1 shows this process for the 1st day (From 7:00am to 5:00pm) of the year.

Table 1: Using CUs to predict hourly illuminances (Lux) for the 1st day of the year by multiplying CUs by the south-facing vertical sky illuminances (Ev in Lux) from the annual sky illuminance data set.

		CU	**0.0938**	**0.06647**	**0.05194**	**0.04342**	**0.04227**
Day	Time	**Ev**	Ez1	Ez2	Ez3	Ez4	Ez5
1	700	**66**	6	4	3	3	3
1	800	**3,074**	288	204	160	134	130
1	900	**7,804**	732	519	405	339	330
1	1000	**13,424**	1,259	892	697	583	567
1	1100	**12,617**	1,183	839	655	548	533
1	1200	**28,730**	2,695	1,910	1,492	1,248	1,214
1	1300	**29,434**	2,761	1,956	1,529	1,278	1,244
1	1400	**64,603**	6,060	4,294	3,355	2,805	2,731
1	1500	**52,715**	4,945	3,504	2,738	2,289	2,228
1	1600	**11,934**	1,119	793	620	518	504
1	1700	**528**	50	35	27	23	22

2.1.2. DAYSIM simulations

A virtual model of the building is built in a CAD tool, which coincided with the physical model. Similarly, five study points are placed along the center line of the daylit zones. The weather file of the site (Raleigh-Durham International Airport) is used as the climate data for the simulation. With a proper ambient parameter setting, the annual illuminance values are calculated by DAYSIM 3.0 and can be presented in the same format as in Table 1.

2.1.3. Comparison

Daylight Autonomy, the numbers of hours in which interior illuminances are above minimum light level for performing the designed tasks (500 Lux in this case), is used as the indicator to assess the two methods (Figure 4).

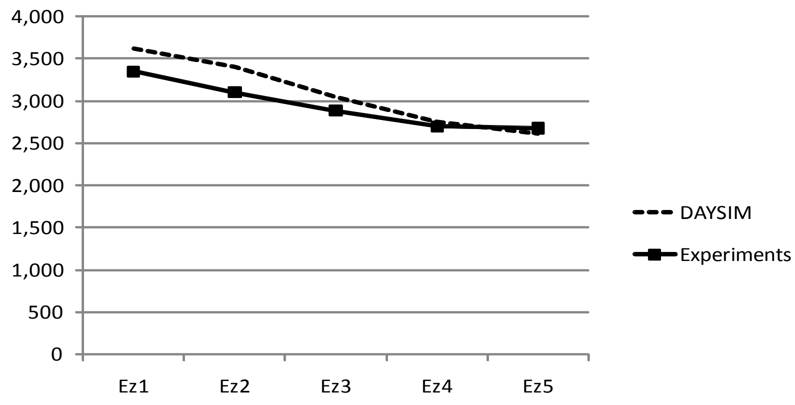

Fig. 4. The numbers of hours in which interior illuminances are above 500Lux predicted by DAYSIM and the experimental methods

To estimate how close the results are between DAYSIM and the experimental methods, the differences in percentage between the two methods are shown in Table 2. DAYSIM generates reasonably close predictions comparing with the experiments. The differences are below 9% in all five zones. For internal zones (Ez3 through Ez5) where daylight levels are lower, the results are even closer (5% and below).

Table 2: Daylight Autonomy values in each daylit zone and percentage of differences when comparing results from the experimental method with those from DAYSIM.

	Ez1	Ez2	Ez3	Ez4	Ez5
DAYSIM	3,615	3,405	3,044	2,747	2,609
Experiment	3,348	3,101	2,885	2,699	2,678
Difference	-7.39%	-8.93%	-5.22%	-1.75%	2.64%

2.2. Assessments of daylighting systems and interior configurations

The validation study reported in section 2.1 demonstrates the effectiveness of the computer-based simulation tool – DAYSIM for predicting climate-based performances of the light shelf system. The tool is then used for the following assessments of the parameters in various daylighting systems and interior configurations.

2.2.1. Length of light shelves

The light shelf lengths of 2’, 4’, 6’, 8’ 10’, and 12’ are simulated in DAYSIM respectively based on the model in Figure 3. Ceiling height, light shelf mounting height, overhang length, and all interior surface reflectances are kept constant. The interior space is open layout.

2.2.2. Ceiling height

Again, based on the model in Figure 3, ceiling heights of 9’, 10’, 11’, and 12’ are assessed assuming other systems parameters remain constant (Light shelf length is 6’ long in this case).

2.2.3. Interior configuration

Four interior configurations typical of multistory office buildings are identified and compared by using the same method as in the above comparison studies (Figure 5). The same five daylit zones are incorporated in these plans, where there are always two measuring points in the private offices and three in the open area. These configurations are:

Configuration 0: Open office plan where there are no private offices. A section of this design is illustrated in Figure 3.

Configuration 1A: Private offices are located at the perimeter of the floor plate. The partition parallel to the window wall consists of a lower portion (7’ high) and an upper portion. The lower portion is an opaque wall; the upper portion is clear glazing (transmittance: 90%). The partitions perpendicular to the window wall are opaque (Figure 5).

Configuration 1B: Same as 1A except that the lower portion of the partition parallel to the window wall is constructed with translucent glazing (transmittance: 50%) (Figure 5).

Configuration 2: Private offices are located at the core area of the floor plate. The lower portion of the partition parallel to the window wall is made of translucent glazing (transmittance: 50%); the upper portion is clear glazing (transmittance: 90%). The partitions perpendicular to the window wall are opaque (Figure 5).

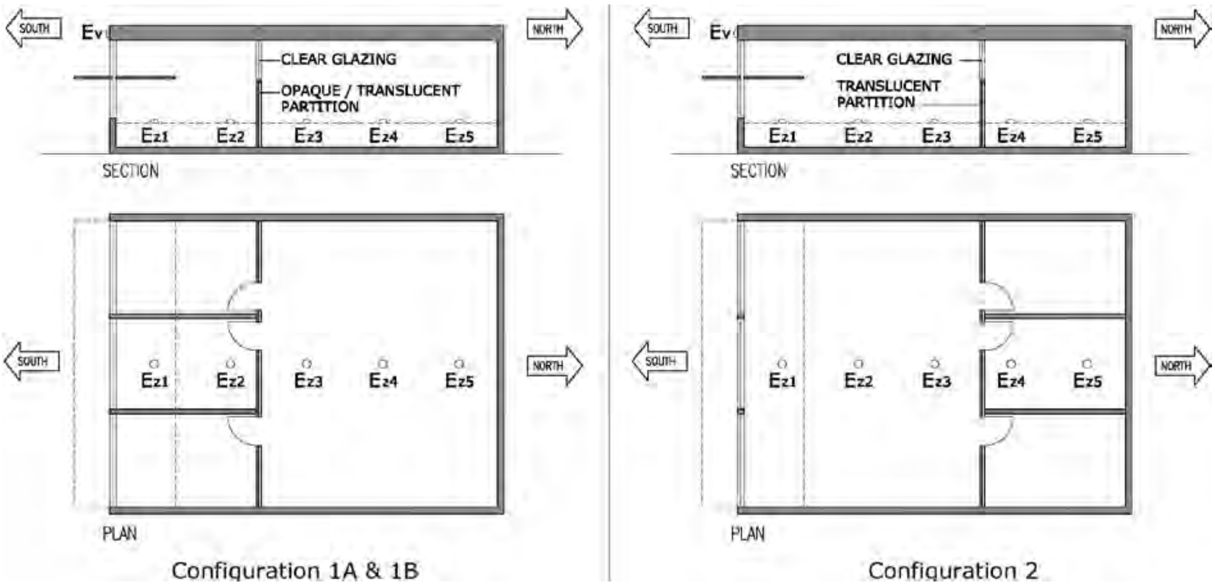

Fig. 5. Interior configuration 1A, 1B and 2.

3. Results & Discussions

Hourly illuminance data in each zone are generated for the above comparison studies. Daylight Autonomy data are then developed based on these values as performance indicators.

3.1. Length of light shelves

The performances of light shelves with various lengths (2' through 12' with 2' increment) are illustrated in Figure 6. For internal zones (Ez3 through Ez5), the 4-ft light shelf performs slightly better than the 6-ft version. However, the longer light shelf outperforms the shorter one for the purpose of blocking the direct sunbeam penetration through the daylight glazing (Figure 7). In general the 6-ft light shelf appears to be the optimal solution among all the lengths tested and will be used for later phases of the study.

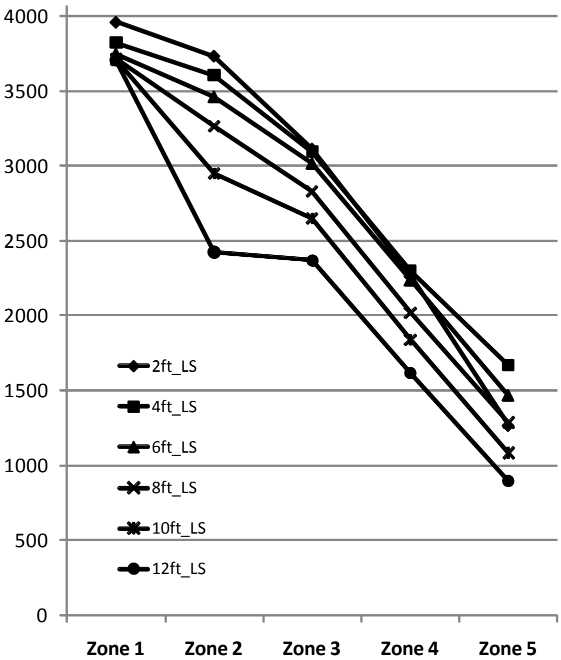

Fig.6. The numbers of hours in which interior illuminances are above 500Lux for light shelves with various lengths

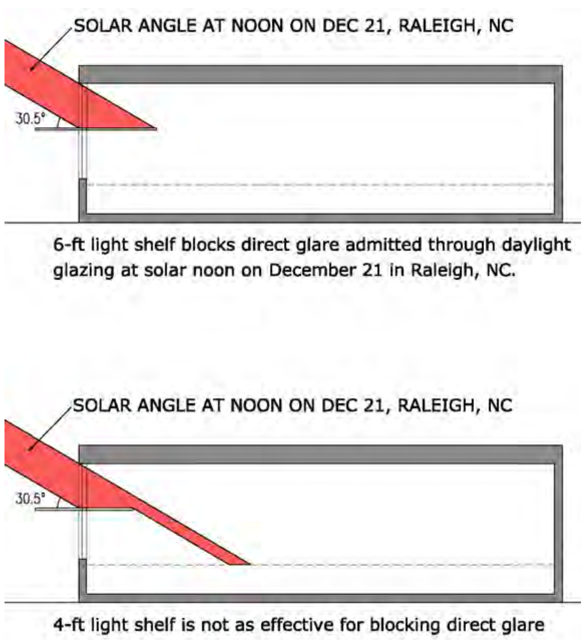

Fig.7. Direct glare admitted through daylight glazing with 4-ft and 6-ft light shelves. 6-ft version performs better for blocking direct glare

3.2. Ceiling height

The impact of ceiling height on light quantity is fairly significant as illustrated in Figure 8. In conjunction with the light shelves, higher ceilings are obviously desirable for the purpose of delivering daylight deeper in the space.

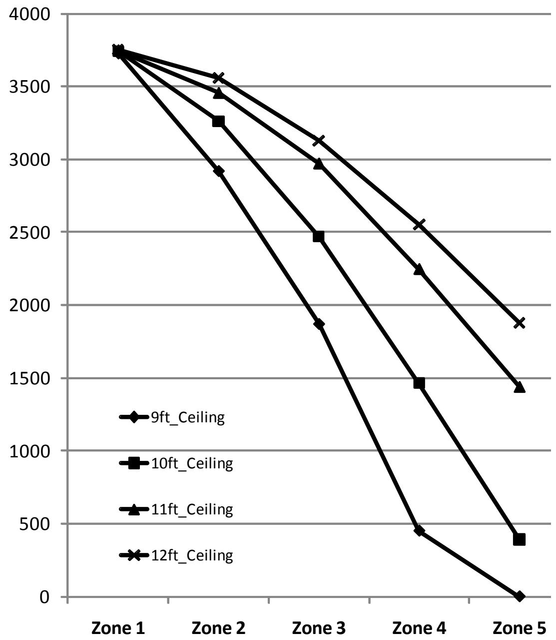

Fig.8. The numbers of hours in which interior illuminances are above 500Lux for interior space with different ceiling heights

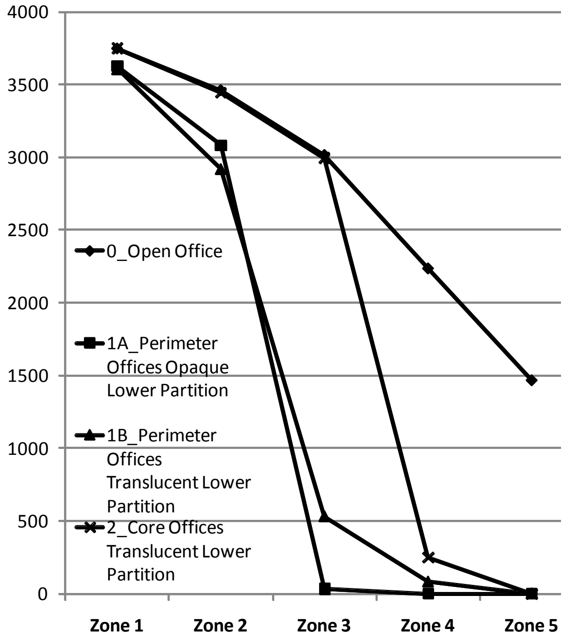

Fig.9. The numbers of hours in which interior illuminances are above 500Lux for different interior configurations

3.3. Interior configuration

As shown in Figure 9, among the four interior configurations proposed in section 2.2.3, open office layout (Configuration 0) certainly gives the best performances in that it maintains higher light levels across the space and produces a fairly uniform distribution without any abrupt change of light levels. Introducing private enclosed offices at the perimeter of the floor plate (Configuration 1A) dramatically lowers the daylight quantity in the inner open office. Switching the material from opaque to translucent for the lower portion of the partition that divides the perimeter offices and the open office improves the condition to some extent (Configuration 1B). However, if private offices have to be provided, relocating them to the core of the space and leaving the open office at the perimeter greatly (Configuration 2) improve the overall lighting conditions, especially at the open area which is occupied by more users. In addition, comparing the results between Configuration 0 and 1A, by adding partitions perpendicular to the window wall to define the private offices in 1A, the light levels in the perimeter zones (Zone 1 and 2) are lowered as well as in the inner open office.

4. Conclusions

Although light shelves generally help project daylight deeper in the space under certain solar angles, it is a misunderstanding that the longer a light shelf is, the better it performs. It is the proportion of the daylighting glazing height and light shelf length that determines the performance of the system. Therefore, the length needs to be optimized based on other geometries of the system, such as ceiling height and daylight glazing height, and the system needs to be evaluated in terms of both light quantity and quality. For the particular daylight system assessed in this study, the 6-ft light shelf is proven to be the optimal solution.

The benefits of raising the ceiling are significant. Even though there are many factors motivating towards lowering the ceiling, including construction cost, fire rating, accommodating structure, duct work, etc., a carefully designed and highly integrated building system needs to be in place to assure adequate ceiling height for daylighting.

Adding partitions that are either parallel or perpendicular to the south-facing window wall to divide open space into small offices creates a fairly big drop in the illuminance deeper inside the space. If private offices have to be incorporated in the floor plate due to programmatic requirements, it is recommended that the small offers be located at the core of the building. Comparing with opaque partitions, translucent partitions give superior illuminance levels deep inside the building and they also produce superior light quality in the form of less extreme luminance ratios in both interior and perimeter spaces. It is highly desirable to use clear glazing above the level required for visual privacy (e.g., from the top of the door up to the ceiling). It is also desirable to minimize the number and width of mullion elements, to allow as much light as possible through the partition.

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