THE IMPACT OF SYSTEMS INTEGRATION ON THE DAYLIGHTING PERFORMANCE OF SKYLIGHTS IN OFFICES

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ABSTRACT

This paper focuses on evaluating and optimizing certain features of skylight roofing systems as applied to office buildings. It is the first step in a longer-term research effort on the design, evaluation, and optimization of Roof Daylighting Systems (RDS) in office buildings, which will correlate architectural design features and parameters with illumination quantity and quality and overall energy performance. The primary tools in the study will be Radiance and Daysim for illumination performance (as enabled by Diva for Rhino), and Energy plus for understanding thermal performance. This research will be the focus of several papers and will culminate in the dissertation of the lead author on this paper.

INTRODUCTION

Toplighting has substantial potentials for energy saving in buildings. For a properly designed daylighting roofing sytems, well over 90% of the lighting electricity can be displaced during daylight hours.

However, roof daylighting has not been extensively used in office buildings because of concerns regarding the initial cost of the system. In cost/benefit analyses, it has been common to only account for the dollar value of the Kilowatt-hour savings from reduced light electricity consumption and to ignore psychological benefits and benefits of having natural light to facilitate people working through power outages. When these benefits are excluded from the analysis, the pay-back period for skylight systems in office buildings are often longer than most investors would want.

Also, prevailing perceptions regarding the performance of roof daylighting systems are strongly influenced by the failures of skylight systems, which are the most widely experienced of roof daylighting systems. Skylights have the disadvantage that they face up towards the midday summer sun. When they are sized large enough to provide adequate light quantity from diffuse skylight, then beam sunlight causes a thermal overload of approximately a factor of ten. When they are sized smaller, to avoid thermal overload, then they are only providing enough illumination when beam sunlight is available. Since beam sunlight is only available during about half the daylight hours in most

locations, a substantial amount of energy is lost during times when beam sunlight is not available. Finally, highly responsive electric lighting dimmer controls are required to make the adjustments in lighting level to accommodate the coming and going of clouds. These dimmers add substantially to the cost of the system, they are sometimes unreliable, and they draw substantial amounts of electric power, even when there is an abundance of illumination from the daylight.

The illumination and energy benefits of skylights, are also less than they could be, because of the context in which they are typically used. In most flat-roof construction, the systems are accommodated in a kind of layering scheme. The layers are (from top to bottom):

1. A layer for rigid insulation on top of decking.

2. A structural layer that extends over the entire footprint of the building and that is deep enough to accommodate the deepest spanning member.

3. An air-handling layer that extends over the entire footprint of the building and that is deep enough to accommodate the largest duct in the system (and possibly deep enough to handle a horizontal air-handling unit placed in the volume above the ceiling).

4. An electric-lighting and hung-ceiling layer that extends over the entire footprint of the building and that is deep enough to accommodate the depth of the electric lighting fixtures plus the depth to the inverted Ts in the ceiling grid, plus additional vertical dimension in which to maneuver the fixtures as they are moved around above the ceiling grid.

In this manner huge amounts of volume are filled only with air and the depth of this interstitial volume contributes substantially to the surface area of the building through which unwanted thermal gains and losses can occur. These system layers are normally not coordinated spatially. In fact, the scheme of layered volumes was developed as a way of minimizing the need for coordination. In this layered scheme, introducing skylights involves searching for paths to "tunnel" up through the systems to get to daylight. The common way of dealing with the interior finishes is to finish off a vertical shaft, or light well, that is roughly

the sized of the glazing panel in the skylight (see Figure 1A). This light well is often much deeper than it is wide. For example, when frame effects are accounted for, the light well for a standard 4'x4' skylight will only be on the order of 3'-6" by 3'-6" wide. By comparison, the depth of the light well is almost always over 5 feet. The light well causes much of the low-angle light to undergo multiple bounces, thus attenuating that light substantially. This causes the light in the occupied space to be diminished in quantity and to be spatially much more variable, with the greatest illuminance directly below the light skylight. This variability become particularly accute in spaces with low ceilings, which tends to be the case for office spaces. More uniform lighting can be achieved by placing the skylights closer together, but this drives up the system cost (Lawrence & Roth, 2008) and increases the likelihood of thermal overload.

These design failures in the common application of skylights cause reduced lighting and energy performance of skylights and, as a consequence, reduced market penetration. To address this issue in this paper, four lightwell and ceiling geometries have been evaluated for illumination performance:

- The basecase, squared-off light well (Figure 1A).

- Splaying the ceiling around the edges of the light well (Figure 1B).

- Integrating the structure and the ductwork to reduce the depth of the light well (Figure 1C)

- Taking both measures of spaying the ceiling and integrating the structure (Figure 1D).

Using this range of configurations will facilitate understanding the performance limitations of the current practice and understanding the potentials for skylights to perform more effectively when situated within a properly integrated and configured building system.

While this is the goal of this paper, this will not be the end product of the larger research effort, which is to consider several different daylight roofing types, including:

- Skylights in flat roofs.

- Sawtooth roofs with glazing facing south and protective overhangs and light diffusing elements.

- Sawtooth roofs with glazing facing north and photovoltaics on the south-facing sloped surfaces.

- Roof monitors incorporating both north-facing and south-facing glazing.

- Other innovative systems currently being conceptualized and developed.

This study will clearly ground the research analyses in architectural reality, with all the assumptions regarding the daylight glazing, thermal envelope, building structure, thermal conditioning system, and electric lighting type, layout, and controls clearly identified in the context of the overall building design. As part of this study, systems-integration issues will be vigorously pursued for each daylight roofing type.

BUILDING PARAMETERS

The baseline parameters for the building are:

- An office space of dimension 30-ft x 30-ft has modeled. To avoid complicating the outputs with wall or partition effects, this 30-ft x 30-ft space has been surrounded on all sides by eight other identical spaces. Readers should remain cognizant of the fact that introducing partitions or walls will complicate the analysis and fairly radically alter the results.

- The height of the flat portion of the ceiling is 9 feet (2.74 m) in all cases.

- Four nominal 4-ftx4-ft skylights with diffuse glazing are located on top of the flat roof.

- The skylights are located at the center of each quarter of the space (Figure 2) resulting in a uniformly spaced grid throughout the building.
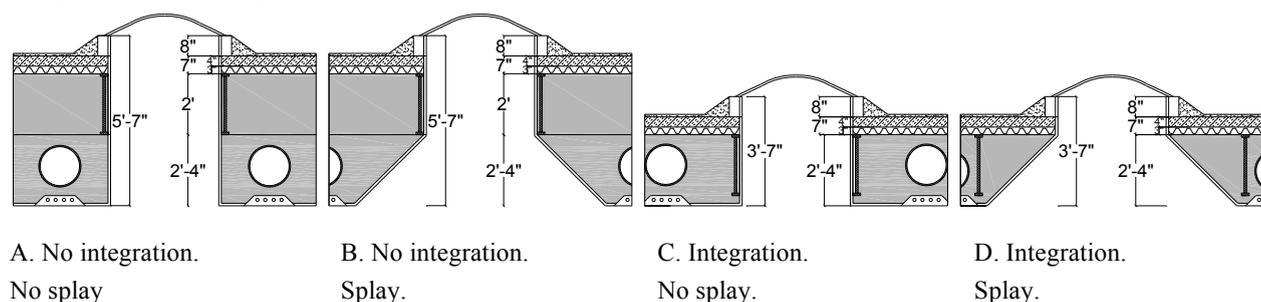

A. No integration. No splay

B. No integration. Splay.

C. Integration. No splay.

D. Integration. Splay.

Figure 1: Four skylight roofing schemes.

A: No Integration_ No Splay   B: No Integration_ Splay

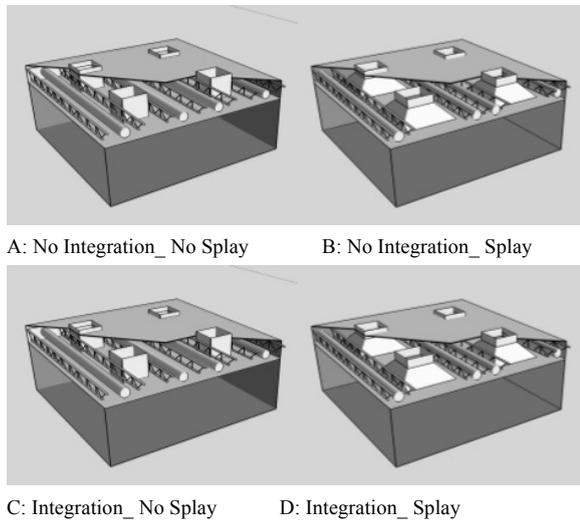C: Integration_ No Splay   D: Integration_ Splay

Figure 2 Skylight Schemes

The parametric variations in the study are:

1. Depth and shape of the light-well through which the daylighting is entering:

    *   The basecase, squared-off light well, consisting of a vertical shaft with a vertical dimension of 5'-3" and a flat ceiling everywhere between the light wells (Figure 1A). The deep lightwell shaft is a manifestation of the allocation of deep layers to each of the the primary systems: structure, air handling ducts, and electric lighting/hung ceiling.

    *   Splaying the ceiling back 45º around the lower edges of the light well (Figure 1B, 2B). For nomenclature clarity, we will say that the light well is the vertical shaft, having a vertical dimension of 3'-3". The sloped surface will be referred to as the sloped portion of the ceiling, having a vertical dimension of 2'-4" and being set at a slope of 45º. This will be distinguished from the flat portion of the ceiling, which will always be located at 9'-0" above the finished floor.

    *   Integrating the structure and the ductwork to reduce the vertical dimension of the light well shaft to 3'-3" (Figure 1C). For this configuration, the roof of the building has been lowered, the keep the flat portion of the ceiling at 9'-0" above the finished floor.

    *   Taking both measures of spaying the ceiling and integrating the structure, which reduces the vertical dimension of the light well shaft to 1'-3" (Figure 1D). As in the previous case, the roof height has been lowered in response

to integrating the ducts with the structure, to keep the flat portion of the ceiling at 9'-0" above the finished floor.

2. The glazing area, expressed as the Skylight to Floor area Ratio (SFR):

    *   5%
    *   6%
    *   7%
    *   8%

3. The transmissivity of the glazing:

    *   40%
    *   54%

This variation in SFR is required because of two primary issues:

*   There are variations among standard skylights. Most of them have glazing with dimensions less than the nominal 4-ft x 4-ft. In addition, the framing elements clamp and obscure even more of the glazing area.

*   There exist many options in terms of how the light well is framed and finished.

Based on their nominal dimensions of 4-ft x 4-ft, the skylights are covering about 7% of the floor area: (4x4)/(30x30)=0.0711. However, it is generally reasonable to assume a lower value for SFR, somewhere between 5% and 6%, as is clear from the following table.

Table 1 Skylights Glazing to Floor Area Ratio

FLOOR AREA ILLUMINATED		SKYLIGHT CLEAR GLAZING DIMENSION		SFR	SFRs SIMULATED
ft^2	m^2	ft	m		
900	83.6	3.50	1.067	0.0544	0.05
		3.75	1.143	0.0625	0.06
		4.00	1.219	0.0711	0.07
		4.25	1.295	0.0803	0.08

The climate chosen for this study is Boston, MA. All schemes are composed of: curb, waterproofing, insulation, structure, HVAC, electrical power, communications, plumbing and fire protection (Figure 1).

SIMULATION

The building configurations were drawn in Rhinoceros. Diva-for-Rhino, was used to export scene geometries, material properties, and sensor grids into the format,

required to enable the use of Radiance and Daysim to perform the illumination simulations (Lagios et al. 2010).

Radiance parameters are set in a way to achieve reasonable results for the case of toplit space, consisting of: ab 7, ad 2024, ad 512, as 256, a1 300, aa 0.05 (Lash 2004).

Materials used for the scene models have 80% light reflectance from the ceiling, 50% from the walls, 20% from the floor area.

Illuminance inside the occupied space has been examined in terms of overall quantity, spatial variability, and temporal variability. Simulation outputs have been summarized in terms of some common daylighting metrics, such as:

- Daylight Factor, which is the ratio of available illuminance on the task surface to the available illuminance incident on the skylight.

- Useful Daylight Index (UDI), which is the percentage of the time that the illuminance level on the task surface is between 100 and 2000 lux (Nabil & Mardaljevic 2005). This index has become popular recently because it accounts for glare and washout on computer screens by discounting the contribution of the daylight when the illuminance level gets too high (in the case of the UDI, 2000lux).

The authors caution against attaching too much significance to any of these simplified metrics. They should only be taken as rough indicators of performance. Of particularl concern is the lower limit of 100 lux for the UDI, which would not be regarded as a satisfactory illuminance level in many situations. More to the point of where this study is headed, estimates have also been made of the potential savings in lighting electricity. For a future study, the design and controls for the electric lighting system will be refined and specified in more detail. The resulting electric lighting schedule, as impacted by the presence of the daylighting, will be used as input to Energy Plus to assess the thermal impacts of the skylight configurations. When all those energy pieces are in place, energy costs and systems costs will be assembled and cost/benefit analyses presented.

DISCUSSION AND RESULTS ANALYSIS

Radiance was used to do an analysis for a single sky condition, which was taken to be a clear sky at Noon on an Equinox day in Boston, MA. A 25 by 25 array of illuminance sensors was distributed over the task surface in the building module being simulated.

Figure 3 shows the results of those simulations. In those graphs, the illuminance readings shown correspond to a string of sensors along the diagonal of the space, since that is the line over which the greatest variations in illuminance were observed.

Not surprisingly, the base-case configuration with the deep, squared-off light well is the poorest performer both in terms of the low amount of light reaching the task surface and in terms of the extreme variations in illuminance levels. The low quantity of light is attributable to the high numbers of bounces and the high absorption of light on the surfaces of the light well. The high variations in the illuminance on the task surface are attributable to the light well selecting against low-angle light and easily passing the light rays moving nearly vertically down through the light well. This tends to create high illuminance directly below the skylights and relative darkness between the skylights.

High variations in the daylight illuminance level create the following problems:

- Electric lighting systems with control algorithms that control uniformly across the space must control based on the lowest daylight illuminance in the space. Otherwise, the occupants at those locations will be deprived of the appropriate illuminance. In that case, parts of the space with relatively high illuminance may have an excess of light for certain tasks, such as working on computer screens. The excess daylight in those locations will also be a source of thermal overload that will drive up the cooling costs for the building.

- Electric lighting systems with control algorithms that tailor the distribution of illuminance from the electrical sources to compensate for the wide variations in daylight illuminance will be complex and expensive and will never work perfectly effectively in filling in the "holes" in the daylighting, without expending additional energy in the form of excess electric illumination in some places.

These factors work strongly against the deep, squared-off light well.

Splaying the ceiling back is very beneficial in raising the average illuminance on the task surface. It is also very beneficial in making the illuminance on the task surface more uniform across the space. The rise in the average illuminance is attributable to reducing the depth, and hence the number of light bounces, in the light well. The greater uniformity is attributable in part to reducing the vertical dimension of the light shaft, which selects against laterally moving light, and in part to the spread of the light that results from the fact that the opening at the bottom of the light shaft has been raised 2'-4' higher above the task surface.

Integrating the duct volume with the structural volume is very beneficial in raising the average illuminance on the task surface. The rise in the average illuminance is attributable to reducing the depth of the light well and, hence, the number of light bounces in the light well. The integration of the ducts with the structure is not as beneficial as splaying the ceiling back in making the illuminance more uniform on the task surface. In this simulation process, the extra volume freed up by integrating the ducts and the structure has been used to lower the roof. As a consequence the opening at the bottom of the vertical light-well shaft has not been raise any higher above the task surface. This is in contrast to the configuration where the bottom of the light well was raised by splaying back the ceiling. This suggests that, if the primary design goal is achieve

dimension of the light shaft would be the same in both cases, but, for the integrated systems case, there would be no sloped ceiling surface to block or absorb light. However, the differences would be extremely small, since the sloped portions of the ceiling does very little to inhibit the movement of the daylight. An interesting question is the relative cost and design effort involved in integrating the systems versus splaying the ceiling. Integrating the systems would appear to require more design coordination and thought, but achieving a presentable appearance for the interior surfaces of the building is also a challenging issue. This would all suggest the need for a product to assist in the design and construction of the sloped surfaces around the bottom of the light well.
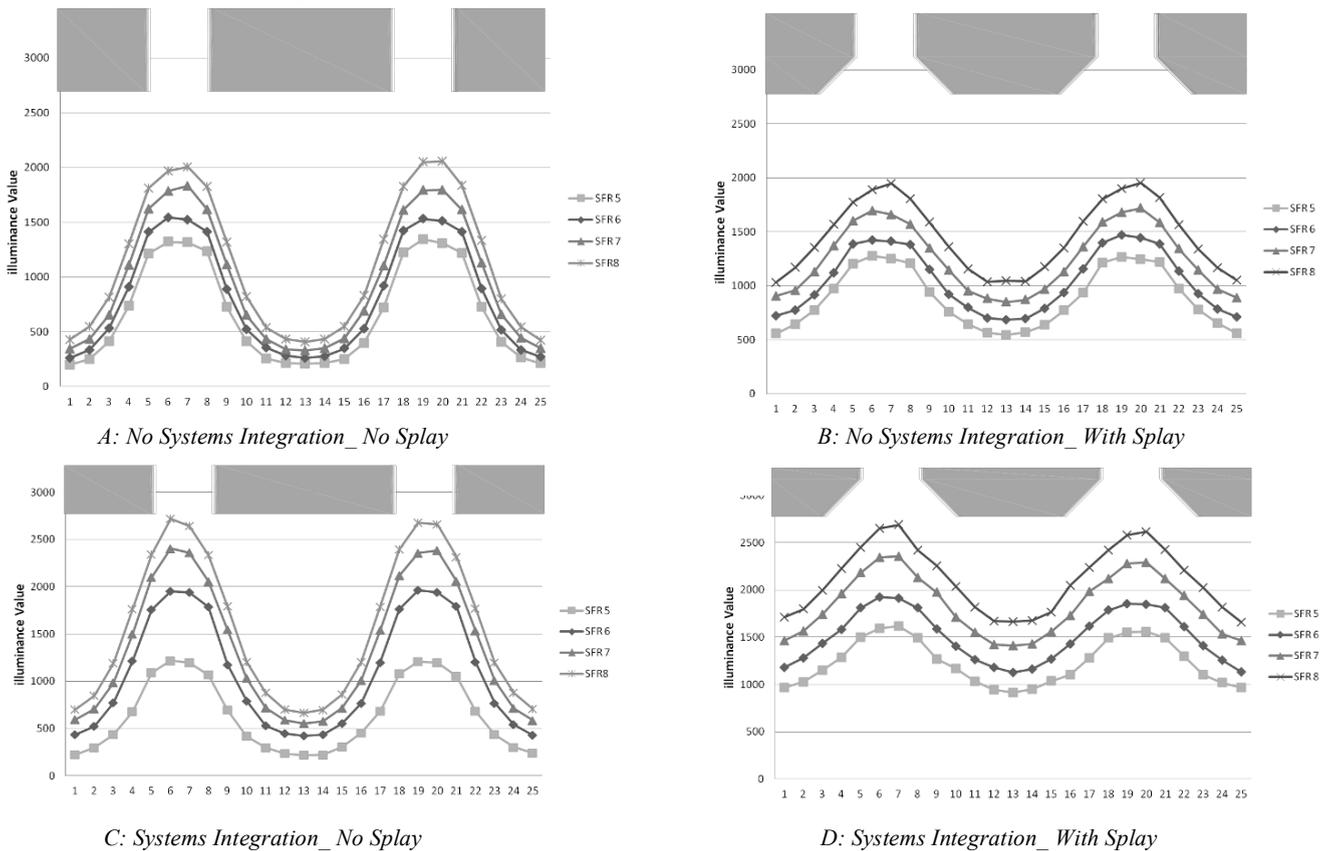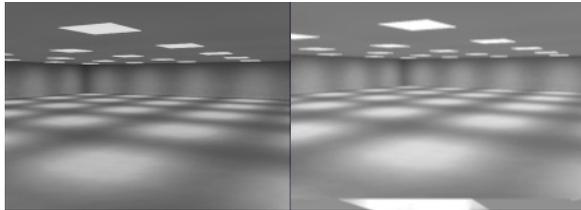
A: No Systems Integration_ No Splay

B: No Systems Integration_ With Splay

C: Systems Integration_ No Splay

D: Systems Integration_ With Splay

Figure 3 Light Levels in Four Skylight Schemes

good daylighting, splaying the ceiling back is much more effective than systems integration. However, this is like comparing apples and oranges, since the systems integration has reduced the height and cost of the building and has also reduced the external surface through which unwanted thermal gains and losses can occur. If systems integration was done without lowering the roof, then the daylighting performance of the integrated system would be even better than for the case of the splayed back ceiling, since the vertical

The best performance in terms of both quantity and uniformity of the illuminance occurs for the configuration with the splayed ceiling and the ducts integrated into the structural volume.

Figure 4 shows the illuminance variation in rendered images of the two extreme cases: the base case and the configuration with both integrated systems and splayed ceiling.

A: No Integration.
No Splay.

B: Integration.
Splay.

Figure 4 Interior View of the Spaces

Figure 5 shows the Daylight Factor, which is the ratio of the average illuminance on the task plane to the illuminance incident on the skylight.

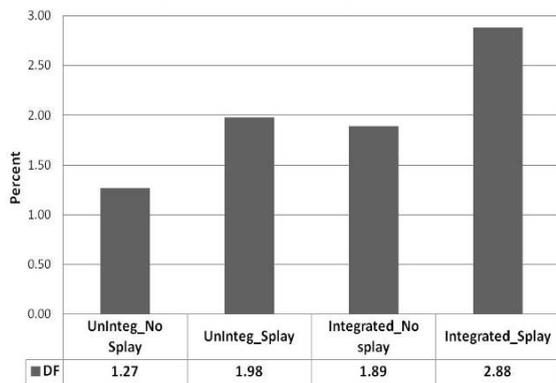|	UnInteg_No Splay	UnInteg_Splay	Integrated_No splay	Integrated_Splay
DF	1.27	1.98	1.89	2.88

Figure 5 Daylight Factor in Four Skylight Schemes

Figure 6 shows the average illuminance for each of the configurations. This is an indicator of the quantity of light available on the work plane.

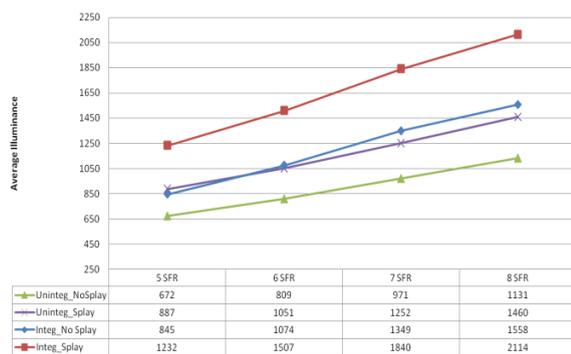|	5 SFR	6 SFR	7 SFR	8 SFR
Uninteg_NoSplay	672	809	971	1131
Uninteg_Splay	887	1051	1252	1460
Integ_No Splay	845	1074	1349	1558
Integ_Splay	1232	1507	1840	2114

Figure 6 Average Illuminance in Spaces with Various levels of SFR

Figure 7 shows the variations in the illuminance on the work plane. For all the reasons discussed above, high variations in daylight illuminance are not desirable, since they cause glare, thermal overload, and add to the complexity and cost of the electric lighting control system.
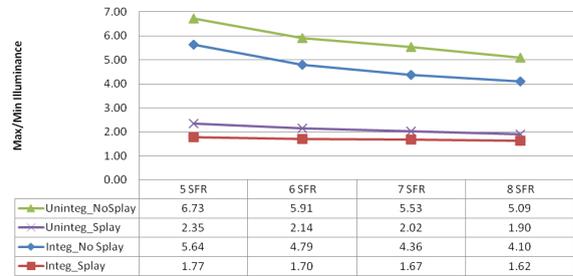

	5 SFR	6 SFR	7 SFR	8 SFR
Uninteg_NoSplay	6.73	5.91	5.53	5.09
Uninteg_Splay	2.35	2.14	2.02	1.90
Integ_No Splay	5.64	4.79	4.36	4.10
Integ_Splay	1.77	1.70	1.67	1.62

Figure 7 Illuminance Variations in Spaces with Various levels of SFR

All of the metrics presented so far repesent the daylighting performance under a single sky condition using Radiance. DaySim has been used to assess system performance under the full range of sky conditions that represent a year in Boston.   Figure 8 shows one of the outputs of those simulations,which is the Useful Daylighting Index (UDI). The UDI is the fraction of the time that the daylight is in the range of 100 to 2000 lux (Nabil & Mardaljevic 2005). The UDI ir repesented by the light gray parts of the bars in Figure 8. The dark gray areas at the bottoms of the
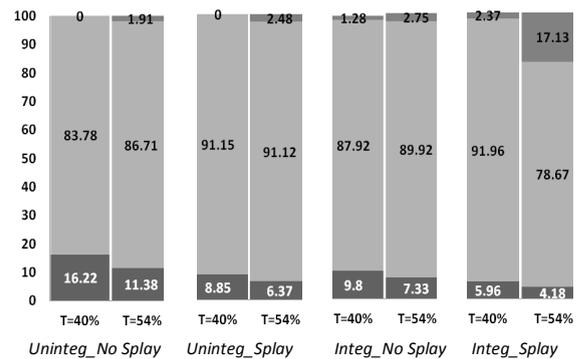

Figure 8 Annual Daylight Performance for the Four Skylight Schemes with SFR=7% (T=40%, 54%)

bars represent the percentage of time when the illuminance level is below 100 lux. The medium gray areas at the tops of the bars represent the percentage time when the illuminance level is above 2000 lux. Figure 8 shows the UDIs for all four skylight schemes for two different glazing transmittances, 40% and 54%. As mentioned previously, the UDI has questionable aspects, such as giving credit to just barely achieving 100 lux. However, as a rough indicator of system performance, it has some applicability.

DaySim has also been used to generate annual lighting electricity savings. In DaySim, the presumption is that there is an electric lighting system that fills in the deficiencies in the daylighting perfectly, in both time and space, and that there is no power draw from the

electric lights when the daylight is present in sufficient quantities. In other words, it is a perfectly linear continuous dimming system that has no power draw when daylight is meeting the lighting need. It is also capable of putting light exactly where it is needed at all times, without any excess electric lighting introduced to the space. Such an electric lighting system does not exist and approximating it would be extremely complex and expensive. However, it provides an indication of the ideal potential of the daylighting system. Future studies by the authors will account for more realistic electric lighting parameters and will also account for thermal tradeoffs associated with the skylights. Table 2 shows the DaySim predictions for the lighting electricity consumption reductions associated with the daylighting. It also shows the annual operating cost savings associated with the lighting electricity reductions. Those data are shown graphically in Figures 9 and 10.

Table 2 Electricity Use in the Base Case without Skylights and Four Skylight Schemes (Kwh/ft^2/yr), SFR=5%, T=54%, Area=900ft^2

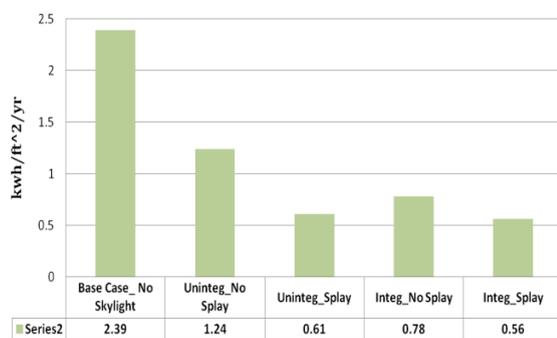| SCHEMES	ELECTRICITY USE Lighting Power Density is 1.0 W/ft^2 (kwh/ft^2/yr)	ANNUAL ELECTRICITY COSTS Average Electric Cost is $0.15/kwh in Boston Dollars
Base Case_ No Skylight	2.39	322.65
Uninteg_No Splay	1.24	167.4
Uninteg_Splay	0.61	82.35
Integ_No Splay	0.78	105.3
Integ_Splay	0.56	75.6

Figure 9 Electricity Use in the Space without Skylights and Four Skylight Schemes (Kwh/ft^2/yr), SFR=5%, T=54%
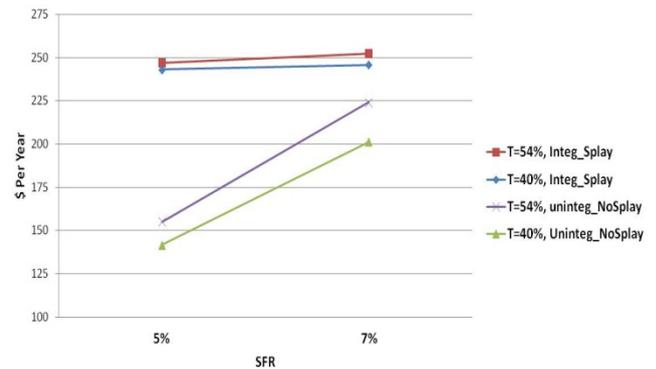
A: Integration_Splay,   B: No Integration_NoSplay
With 40% and 54% Transmittance
(Compared to the case without Skylights)
Figure 10 Annual Savings from Electric Lighting

CONCLUSIONS

1. Splaying the ceiling or integrating the duct volume and structural volume together substantially benefits the daylighting system in terms of:

   - Increasing the quantity of useful illuminance on the task surface.

   - Decreasing the variations of the illuminance on the task surface.

   - Increasing the potential lighting electricity savings from the daylighting.

2. Taking both measures of splaying the ceiling and integrating the duct into the structural volume works even better from a daylighting point of view and it allows the roof to be lowered, reducing the cost of the building and surface area through which unwanted thermal gains and losses will occur.

3. A product that would assist in the design and construction of sloped ceilings around the light wells would be very helpful in improving the performance, economics, and market penetration of skylights for low spaces with hung ceilings.

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