ASSESSMENT OF DAYLIGHT QUALITIES IN SUSTAINABLE BUILDINGS

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Abstract

This paper presents the findings of a study that is evaluating the daylight performance of three recently built certified "sustainable buildings" located in a hot and humid climate (Houston, Texas). These buildings are illuminated mainly through sidelighting windows, clerestories, and diffusing skylights. The evaluation consisted of site visits, occupant's surveys, annual computer simulations implemented with new dynamic daylight metrics. The goal of this research project was to demonstrate that the good practice of sustainable daylight design is more complex than what current rating systems require.

Preliminary results of the evaluations have confirmed that the buildings achieved the illuminance levels required by the rating systems. However, simulations of overall annual illuminance levels showed inadequate illuminance levels to offset electric lighting throughout the year, and also identified the presence of glare at several locations throughout the buildings. Occupant's surveys demonstrated that high percentage of occupants enjoy and find visually-attractive the lighting in their workspaces, however, there are occupants that reported problems of glare (about 20% of the surveyed sample). Those occupants seated next to large south- and west-facing windows, unshaded clerestories, and under diffusing skylights reported problems of glare, as was measured onsite and predicted by annual simulation tools. Other occupants reported problems related to uncomfortable temperature, as well as being unable to work with the electric lights off.

1. INTRODUCTION

Office buildings consume the most energy of all building types. Since lighting in office buildings accounts for 29% of the total energy use, the potential impacts of using daylighting to increase energy savings and reduce demand are huge. This paper presents the preliminary findings of a study that is currently evaluating the daylight performance of recently built certified “sustainable buildings” located in the Houston area, in Texas. This study focused primarily in three office buildings located in a hot and humid climate (latitude 29.75°N, longitude 95.37°W, 43ft above sea level.) The buildings are illuminated mainly thru side lighting windows (facing N, S, E and W), clerestories (facing N, S, E and W), and diffusing skylights. The evaluation is based on a set of dynamic metrics currently used in the good practice of sustainable daylighting design: reduce energy consumption, avoid glare, and provide adequate light levels for occupants. These new dynamic metrics were developed as a set of climatically and temporally sensitive metrics to quantify the annual daylight performance over an entire space grid (Reinhart et al. 2006). This research project intends to demonstrate that daylight design is a more complex process than what current rating systems require, i.e. LEED (Leadership in Energy and Environmental Design).

The LEED Green Building Rating System is a program developed by the U.S. Green Building Council (USGBC), a voluntary non-governmental organization (USGBC 2009a). The daylight requirements for new and existing buildings in the LEED rating system have been evolving. LEED versions 1.0, 2.0 and 2.1 required to achieve a minimum Daylight Factor (DF) of 2% (excluding all direct sunlight penetration) at 30 inches above the floor in 75% or more of all regularly occupied areas, in order to obtain one point in Credit EQ-8.1. LEED version 2.2 in November 2005 changed the DF metric for achieving illuminance levels of 25 foot-candles (fc) or 269 lux (lx) under clear sky conditions at 12pm, on the equinox in 75% of
occupied areas (USGBC 2006). The current version of LEED 3.0 requires a minimum illuminance of 25 fc and a maximum of 500 fc (5,389 lux) in a clear sky condition on the equinox (March or September 21) at 9am and 3pm in 75% of regularly occupied spaces (USGBC 2009b).

2. THE BUILDINGS

The three buildings of this study are the Kirksey Corporate Headquarters, Spawglass Corporate Headquarters, and the Satterfield & Pontikes Construction Office Building. They were designed by the Houston based architectural firm Kirksey. All of them are LEED certified buildings under different rating programs. The Kirksey building achieved a LEED EB (Existing building) certification. The Spawglass building achieved a LEED NC (New Construction) Silver certification. The Satterfield and Pontikes building achieved a LEED C&S (Core and Shell) Gold certification. The three buildings were built between the years 2000 and 2006.

Kirksey Corporate Headquarters

The Kirksey office building is a 26,000 ft² single-level facility built in the year 2000. It accommodates a staff of 150 employees. It was the first LEED Certified Existing Building in the state of Texas in 2006. It is constructed of sandblasted concrete panels with exposed structural steel framing (Kirksey 2009). A large south-facing window with exterior and interior louvers, north-facing punched windows (Figure 1) and eight translucent skylights illuminate the almost 20,000 ft² daylit zone. The spacing between skylights varies from height/distance (H/D) ratios of 1:1.2 and 1:2.1. The main office space is based on an open-plan workstation layout.

A new addition was built in 2008 to accommodate additional office space towards the West end of the existing building. The main office space is illuminated by a large North-facing window, small punched West-facing windows with electrochromic glass, and by ten translucent skylights spaced with H/D ratios of 1:0.8 and 1:1.5 which introduce daylight to more than 4,000 ft² office space. The office space has an open-plan layout, similar to the main building. A summary of the window types of each building are presented in Table 1.

Spawglass Corporate Headquarters

The Spawglass office building is a single-story 20,000 ft² building constructed in the year 2003. The building was the first LEED Certified building in Houston, Texas. Windows are located throughout the building to provide daylight and views for more than 75% of all occupied spaces (USGBC GHAC 2009). Daylight is introduced to the building mainly through sideloighting windows facing North, South and East; and clerestories (Table 1). Small overhangs are provided to the South and East-facing small punched windows (Figure 2). The private offices are organized around three central open-plan workstations. Most of these private offices are windowless, and are illuminated indirectly through the clerestories of the central open-plan offices. Only perimeter offices have a sidelight window. For this study only three quarters of the building has been modeled in the daylighting simulations.
Satterfield and Pontikes Office Building

The Satterfield and Pontikes office is a 65,000 ft² three-story building completed in October 2006. The building is massed as two connected slightly shifted rectangular boxes. A glass curtain wall introduces daylight to the interior office spaces in all four directions (Table 1). Window shading devices (on the East side) and fritted glass was used to control glare in the offices. On the second floor, the West-facing windows of the individual offices have an interior opaque wall that reduces the window size and glare (USGBC GHAC 2009). All perimeter offices have dark colored interior screens. Interior offices are indirectly illuminated by daylight that spills over the corridors with transparent glass.

<table>
<thead>
<tr>
<th>Building</th>
<th>Sidelighting</th>
<th>Clerestory</th>
<th>Skylight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kirksey</td>
<td></td>
<td></td>
<td>Translucent</td>
</tr>
<tr>
<td>Kirkey Addition</td>
<td></td>
<td></td>
<td>Translucent</td>
</tr>
<tr>
<td>Spawglass</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Satterfield &amp; Pontikes</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: 1. Shading, 2. Electrochromics, 3. Partial shading

3. METHODOLOGY

Site visits to the buildings were conducted at different times of the year to collect detailed data i.e. physical properties of materials, illuminance, and luminance measurements using High Dynamic Range HDR photography, as well as occupant’s surveys. Representative spaces used for the sustainable
certification were modeled and simulated using the Ecotect and Daysim lighting programs (Reinhart 2006). Simulations were done hourly for an entire year using climatic-based data and grids with 500 sensors at Kirksey, 360 sensors at Spawglass, and 1,200 sensors at Satterfield & Pontikes. To assess the annual daylighting performance were used several dynamic daylight metrics, such as: Daylight Autonomy (based on 300 lx), Useful Daylight Illuminance (UDI) [<100 lx, 100-2000 lx and >2000 lx], as well as the Daylight Factor (DF) and the daylight metrics required in the LEED rating system. These daylight metrics were also used to assess the qualitative and quantitative characteristics of the daylighting systems of each building as well as their energy impact. Occupant's surveys were compared to the daylight performance variables measured at the sites and to the simulated dynamic daylight metrics. The evaluation of visual comfort were based on statistical analysis of High Dynamic Range (HDR) images and luminance mapping techniques to detect the presence of glare in the spaces. In addition, sun path diagrams were also generated from occupant’s workstations to determine the hours of sunlight penetration in the spaces.

4. EVALUATION AND ANALYSIS

Dynamic daylight Metrics

Each building is evaluated using the dynamic daylight metrics. Daylight Autonomy (DA) is the percentage of occupied times of the year (9am-5pm) when the minimum illuminance requirement (>300 lx) in a specific location is met by daylight alone. UDI is defined as the percentage of the year when illuminance levels in a specific location in a space are between 100 and 2,000 lx. UDI defines boundaries of both whether minimum illuminance levels (<100 lx) are maintained in a space through daylight, as well as how often daylighting levels might be too high (>2,000 lx) that can create problems of glare.

Kirksey Building

Results from the Daysim simulations is presented in Tables 2 and 3. The results indicate that the Kirksey office space achieved: DF (>2%) over 69% of the office space, >25 fc at noon on the equinox over 100% of the space, and illuminance levels >25 fc and <500 fc over 94% to 100% of the office space; therefore it complies with the requirements of LEED 2.0, 2.2 and 3.0 to obtain the Daylight 8.1 Credit. However, occupants reported direct sunlight passing through the shading devices, and entering the space for few hours in the afternoon. Information of the daylighting performance over an entire year is provided by the dynamic daylight metrics, presented in Table 3. Low DA values indicate that electric lighting is needed to reach the minimum 300 lx (i.e. the 31% DA value is achieved towards the West-side of the space, this means that this area would require electric light for about 69% of the occupied hours of the year). The UDI<100 lx confirms that in this West-side about 8% of the year the light levels are below 100 lx. The UDI (<100 lx and >2,000 lx) ranges between 22% to 98% with an average of 84%, this confirms that most part of the floor area receives adequate daylight levels. The UDI>2,000 lx is most noticeable towards the South side of the space.

<table>
<thead>
<tr>
<th>Buildings</th>
<th>LEED 2.0 DF&gt;2%, 75%</th>
<th>LEED 2.2 &gt;25fc, 75%</th>
<th>LEED 3.0 &gt;25fc &amp; &lt;500fc, 75%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12pm</td>
<td>12pm</td>
<td>9am</td>
</tr>
<tr>
<td>Kirksey</td>
<td>69%</td>
<td>3%</td>
<td>100%</td>
</tr>
<tr>
<td>Kirksey Addition</td>
<td>35%</td>
<td>2%</td>
<td>92%</td>
</tr>
<tr>
<td>Spawglass</td>
<td>61%</td>
<td>2%</td>
<td>71%</td>
</tr>
<tr>
<td>Satterfield &amp; Pontikes</td>
<td>40%</td>
<td>6%</td>
<td>66%</td>
</tr>
</tbody>
</table>

Note: *Not required by LEED 2.0
Table 3. Summary of dynamic daylight metrics (% of occupied hours)

<table>
<thead>
<tr>
<th>Buildings</th>
<th>DA (min-max%)</th>
<th>Avg. (min-max%)</th>
<th>UDI (min-max%)</th>
<th>Avg. (min-max%)</th>
<th>UDI (min-max%)</th>
<th>Avg. (min-max%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kirksey</td>
<td>31-98%</td>
<td>88%</td>
<td>0-8%</td>
<td>2%</td>
<td>22-98%</td>
<td>84%</td>
</tr>
<tr>
<td>Kirksey Addition</td>
<td>28-80%</td>
<td>67%</td>
<td>13-31%</td>
<td>20%</td>
<td>43-85%</td>
<td>76%</td>
</tr>
<tr>
<td>Spawglass</td>
<td>0-100%</td>
<td>47%</td>
<td>0-100%</td>
<td>23%</td>
<td>0-98%</td>
<td>67%</td>
</tr>
<tr>
<td>Satterfield &amp; Pontikes</td>
<td>0-99%</td>
<td>72%</td>
<td>0-100%</td>
<td>11%</td>
<td>0-99%</td>
<td>46%</td>
</tr>
</tbody>
</table>

Notes: 1. Based on 300 lx, 2. UDI<100 lx, 3. UDI 100-2,000 lx, 4. UDI >2,000 lx

Simulations of the Kirksey Addition office space indicate that it achieved: DF (>2%) over 35% of the office area, >25 fc at noon on the equinox over 92% of the office area, and illuminance levels >25 fc and <500 fc over 91% of the office area, consequently it complies with the requirements of LEED 2.0, 2.2 and 3.0, respectively. However, occupants reported the presence of glare under the ten translucent skylights. The results from the dynamic daylight metric simulations (Table 3) show a DA ranging from 28% to 80% with an average DA of 67%. The lowest DA is noticeable towards the South side of the space where there is limited access to the West-facing windows and skylights (Figure 4). The UDI<100 lx of 13% confirms also the low light levels over the South side. The UDI (<100 lx and >2,000 lx) varied between 43% to 85% with an average of 76%, this indicates that the space is well lit. The UDI>2,000 lx is noticeable under the skylights, as was confirmed by illuminance measurements during site visits and occupant’s comments.

**Spawglass Building**

The results of the simulations showed: DF (>2%) over 61% of the office area, >25 fc at noon on the equinox over 71% of the office area, and levels >25 fc and <500 fc over 60% of the office area; therefore it does not comply with the requirements of LEED 3.0. The DA showed that there are areas in the building that requires electric lighting at all times (0%), while other areas are illuminated by daylight at all working hours (100%). The average value of DA of 47% indicates that there is sufficient daylight in the space for working with daylight alone, and 53% of occupied hours need electric lighting. The three UDI values also show a high variation from 0 to 98%, from dark (windowless offices) to extremely bright areas (central open spaces). The average annual UDI>2,000 lx of 11%, confirms what occupants has reported as “too bright”. The central open spaces receives direct sunlight in the morning and afternoon hours year-round (as shown in the sun path diagram of Figure 6, left, and Figure 7). To block sunlight entering into the central office space, occupants have placed black screens over the East- and West-facing clerestories (as shown in Figure 8, right).

**Satterfield & Pontikes Building**

Daysim simulation results indicate that this building achieved: DF (>2%) over 40% of the building area (the low DF is due to the deep floor plan layout), >25 fc at noon on the equinox over 66% of the building area, and illuminance levels >25 fc and <500 fc over 57% of the building area. This building would not earn the LEED 3.0 daylight credit. The DA varied from 0 to 99% (72% average) throughout the building showing that there are spaces that will need electric lighting at all times. The three UDIs also varied between 0 and 100% due to the high variations of dark and extremely bright areas. The average values of the UDI >2,000 lx indicates that 43% of the year there are areas too bright that may cause glare to occupants. This indicates that the building needs sun controls to reduce the bright areas, mostly over the South- and West-facing facades.
**Visual Comfort Assessment**

During site visits, the presence of glare was observed in several locations of Spawglass and Satterfield & Pontikes. Direct sunlight entering South-, East- and West-facing windows were the major sources of discomfort glare in occupants workspaces. HDR photographs of the central spaces of Spawglass (Figure 7) show reflected glare of about 10,000-18,000 cd/m² occurring in the early morning and late afternoon hours, with a Unified Glare Rating (UGR) of 22.3 which is over the recommended UGR value (19) for offices. Luminance ratios within the occupant’s field of view were above the recommended by lighting standards (1:10 to 1:100) confirming the presence of glare in the central offices. The South- and West-facing offices of Satterfield & Pontikes offices presented similar conditions, high luminance values over workplane, high UGR values and luminance ratios above the recommended by standards.

We found office spaces where occupants had taken different measures to improve the lighting conditions in their workspaces. Most of them had used different devices to protect their work space from direct sunlight coming from unshaded windows (Figure 8, center and right). In other spaces, workers had built devices to shield their computer screen to avoid reflections (Figure 8, left). In one of the buildings, interiors louvers were added to translucent skylights to reduce its brightness and light levels over work plane. All occupant’s solutions reduce the ambient illuminance levels of their workspaces, therefore, increasing the demand for electric lighting during peak hours.

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**Figure 4. Kirksey Addition office space: (top) LEED rating systems, (bottom) dynamic metrics.**
Figure 5. Spawglass central office space: (top) LEED rating systems, (bottom) dynamic metrics.

Figure 6. Stereographic diagram taken from occupant’s viewpoint at Spawglass, (left) at open-plan central space, and (right) next to South-facing window.
Figure 7. HDR and luminance map images of central office space at Spawglass on March 7, 4pm. Luminance (cd/m²): min. 8, max. 18,500, avg. 520; vertical illuminance at viewpoint: 1,868 lx; UGR 22.3.

Figure 8. Occupant’s response to glare: skylights (left), west window (center), and clerestories (right).

Surveys

Preliminary results of surveys conducted during site visits showed the degree of satisfaction of the building’s occupants with the daylight levels in their workspaces (Figure 9). They enjoy and find visually-attractive the lighting in their workspaces, however, there are occupants that reported problems of glare (about 20% of the surveyed sample). Most of these occupants seat next to large South- and West-facing windows, unshaded clerestories, and under diffusing skylights, as was documented onsite. These locations were the same bright areas that were identified by the dynamic metrics. Other occupants reported problems related to uncomfortable temperature, as well as being unable to work with the electric lights off (Figure 10).

Figure 9. Mean overall satisfaction score from occupants of two buildings.
5. CONCLUSIONS

The findings of this research confirm the need of integrating dynamic daylight metrics to current rating systems and building codes. This research also showed the effectiveness of the dynamic daylight metrics in predicting the overall daylight performance of spaces. However, additional metrics would need to be included that are based on luminance variation of interior surfaces, vertical illuminance, window contrast, and glare indexes based on occupant’s field of view. These metrics can be used as a tool to adjust “design variables” (i.e. window size, orientation, sun controls) to satisfy the visual and lighting needs of occupants in workspaces and to minimize the use of electric lighting to offset energy use in buildings; thus reducing the negative impact of energy production on the environment.

The current LEED 3.0 rating system is an improved version of its predecessors. The requirement for the daylight credit is targeted to check building’s daylighting performance at crucial hours (9am and 3pm) on the equinox, when the sun is lower in the sky and at an oblique azimuth angle towards the East and West (except in the equator). The intent of this requirement is to minimize East- and West-facing windows, to include sun controls in the building envelope, and to avoid deep floor plan buildings.

Daylighting is complex and fraught with potential problems (Brown 2009). But the benefits that daylighting can bring to building occupants are numerous, not only quantifiable in energy savings, but on the psychological positive effects regardless of the building type. As was illustrated in this study, building occupants enjoy working in spaces with high ambient daylight levels, and only complain when they cannot control daylight in their workspaces. Current daylighting simulation tools have the potential to prevent architects of unforeseen consequences of their designs that can affect building occupants, the environment and the planet.

6. ACKNOWLEDGMENTS

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5. REFERENCES