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Analysis of the Impacts of Light Shelves on the Useful Daylight Illuminance in Office Buildings in Toronto

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Abstract

Modern envelope technologies and architectural trends often encourage the construction of buildings with large glazing surfaces. Glazed facades are often proposed with the intent to guarantee high daylight levels and wide exterior views. However, an increasing attention is nowadays recognized to glare issues and indoor comfort levels. Consequently, light shelves are often proposed to help reducing glare issues, providing better illumination distribution, and increasing the homogeneity of daylight distribution into the spaces. In this paper, the impact of light shelves over the illuminance levels in a south facing office building in Toronto is evaluated. The Useful Daylight Illuminance (UDI) is considered as the metric of analysis. Annual simulations for four different window-to-wall ratios (WWR) are compared with and without light shelves. Results show that light shelves enhance the UDI levels mainly in the first six meters in front of the windows, and provide a more homogeneous daylight distribution with an increase of the UDI for any considered WWR. Finally, this paper shows that WWR above 35% result in increasing daylight quantity with higher glare issues, and in case of the adoption of floor to ceiling windows, WWR above 35% are not advantageous in terms of daylighting.

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Keywords: Daylighting; simulation; light shelves; Useful Daylight Illuminance (UDI); office buildings.

1. Introduction

Daylighting is an effective strategy to maintain a comfortable indoor environment and provides great opportunities for energy savings in buildings. The increasing trend for adopting large transparent envelopes often requires the integration of shading systems. These architectural elements reduce glare issues, provide better

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illumination distribution, and ideally can also increase the daylighting penetration into the spaces [1-4]. Light shelves are typically placed above the eye level and can be internal and/or external. The internal portion was designed to block direct sunlight from the window area above the shelf while the exterior portion shades the surface area closer to the window. Traditional approaches of lighting assessment focusing on horizontal illuminance are often inadequate to evaluate the daylighting quality. Performing daylighting analysis just for summer and winter solstices and equinox days and under certain sky conditions (mainly clear or overcast sky) has been proved insufficient [5,6]. The developments of lighting simulation provide new opportunities for studying daylighting based on new climate-based inputs. In this paper, the effects of light shelves with both interior and exterior parts on Useful Daylight Illuminance (UDI) levels in office buildings are investigated through daylighting simulations.

2. Background

The impacts of different shading devices on daylighting in office buildings have been investigated by different researchers. Ochoa and Capeluto evaluated illuminance and glare issues in three different daylighting scenarios for an office located in Israel [3]. Simulations were carried out in Radiance. Double glazing windows with clear glass were chosen and the internal surface reflectance for the ceiling, walls and floor were assumed to be 80%, 65%, and 20% respectively. The light shelf was considered to be 80% reflective. Simulations were performed on solstices and equinox days at 10am, 12pm, 2pm and 4pm. Results showed illuminance levels significantly decreased further than 6m from the window. However, the light shelf system improved the daylighting distribution through decreasing the contrast between areas close to the window and in back of the room [3]. Cantin and Dubois assessed the daylighting quality in two offices in Montreal, one facing South-West and the other North-West. Both offices had fully-glazed walls facing adjacent streets. Results showed that both offices received excessive daylighting with high risk of glare, and confirmed the importance of accurate shading devices [5]. Tzempelikos and Athienitis carried out an integrated thermal and daylighting study in perimeter spaces in office buildings in Montreal; double-glazed windows with clear glass were assumed. The Daylight Autonomy (DA) metric was used to assess yearly illuminance levels. Seven different WWR were investigated for the four orientations. Results showed that increasing WWR above 30% had a minor impact on DA levels [7]. Reinhart and Wienold proposed a hybrid definition for daylighting which comprises the usage of natural light, occupant visual satisfaction, and optimal thermal loads [6]. In their study, an office located in Boston with a WWR equal to 50% was simulated. It was assumed that windows were only located on the south façade. Double glazing windows with visual transmittance of 72% were selected; the ceiling, walls and floor were 80%, 50% and 30% reflective respectively. The space was modelled with and without controllable external venetian blinds. The results showed an over-lit area in the one-third of the space close to the windows while the back two-thirds of the room received adequate daylight [6]. Further analysis on a specific point in the middle of the over-lit area showed excessive daylighting occurred all year round, and during 39% of the office operating hours, the Daylight Glare Probability (DGP) was in the 'intolerable' range. The effects of the venetian blinds on enhancing the daylighting (and energy saving) greatly depended on occupant behavior [6].

Cammarano et al. recently conducted a comprehensive parametric study about the impacts of different architectural features on daylighting [8]. They investigated the effects of orientation, room depth, and external obstruction on a 12m wide room with ceiling height of 3m in Turin. North, south and west facing windows with visual transmittance of 70% and different WWR from 30% to 60% were simulated. The ceiling, walls, and floor reflectance were assumed to be 70%, 50% and 30% respectively. Results were used to calculate some new daylighting metrics including UDI in order to evaluate the quality of daylight. For all WWR and different room depths, the north facing and south-facing windows with blinds showed the maximum average value of UDI. These two orientations were further analyzed and results showed that increasing the room depth from 3m to 10.5m constantly reduced the UDI levels, while changing WWR showed limited effects over UDI. Finally, the study showed that the presence of obstructions (simulated with angles from 0 to 75˚ in steps of 15˚) had a linear impact on the UDI average reduction [8]. Atzeri et al. assessed the performance of automated internal and external roller shades on thermal and visual comfort and energy consumption of an open-space office in Rome [9]. Different orientations, WWR of 45% and 75%, and four glazing types were considered. Results indicated that the roller shades eliminated visual discomfort close to the windows regardless of the internal or external position of the shades. Carletti et al. evaluated different shading devices and showed that these generally decrease the solar heat gains all year round; however, the authors also proved that both exterior and interior systems significantly improve the visual comfort and daylight quality [10].

3. Methodology

Numerous parameters affect the daylighting quality and quantity in an interior space. These parameters can be categorized under four major groups. Firstly the variables which are related to the architectural features of the space like dimensions (width, depth, and height), orientation and interior surfaces' reflectance. Secondly the ones that are related to the envelope geometry, such as the window area, glazing type, fenestration placement (i.e. windows sill and head height) and shading devices. Thirdly the parameters related to the site, like latitude, and local weather data. Lastly, the time-dependent variables like solar azimuth and altitude. As Cammarano et al. reported, the many variables that influence daylight prevents obtaining easy methods to generalize results [8].

In this study, an office with open space plan in Toronto is considered for the simulations. The building has a rectangular shape, 15m wide along east-west direction and 10m deep along north-south axis. Floor to ceiling height is assumed to be 3m. Typical interior reflectance for office spaces are picked based on the literature [1,3,6,11]: the reflectance of the ceiling, walls and floor is assumed to be 80%, 60%, and 20% respectively. WWR equal to 25%, 35%, 45% and 55% are chosen for the different simulations. Full-height 1m wide windows are considered; the area of each window is hence $3m^2$, which is 5% of the exterior wall area. Similarly, to other studies, windows are only located on the south façade [1,3,6,7,12], and are evenly distributed. Double pane clear low-e glazing is picked since it is a conventional glazing type, widely available in the market, and with a good light transmissibility.

The design then focused on the light shelves. Shading devices can be selected according to different criteria, such as to prevent overheating, enhance visual comfort, provide view to the exterior, and protect from atmospheric phenomena [14]. The main criterion in the design of the light shelves for the present study was to block the direct sunlight penetration above the work plane height (80cm above the floor) from 10am to 2pm for different time periods. A comparison among possible light shelf dimensions for fully block the sun in different period is reported in Table 1. Expanding the time span, resulted in larger shading devices. Light shelf area and full shading period of each alternative was compared as shown in Table 1. In terms of balancing solar heat gains and visual comfort, it was decided that was not advantageous to block the sun beyond the period of April 22nd to August 20th since an increase in the dimensions of the shading systems was considered inconvenient for construction reasons.

Table 1. Comparison between optimal light shelf area in different time spans respect to the minimum design for the period from June 11 to July 1.

Day period	11-Jun 1-Jul	1-Jun 11-Jul	22-May 21-Jul	12-May 31-Jul	2-May 10-Aug	22-Apr 20-Aug	12-Apr 30-Aug
Days with shading from 10am to 2pm	20	40	60	80	100	120	140
Light shelf area [m^2]	2.12	2.19	2.34	2.57	2.86	3.28	3.84
Light shelf area increase [%]	-	3.3%	6.9%	9.9%	11.1%	14.7%	17.1%

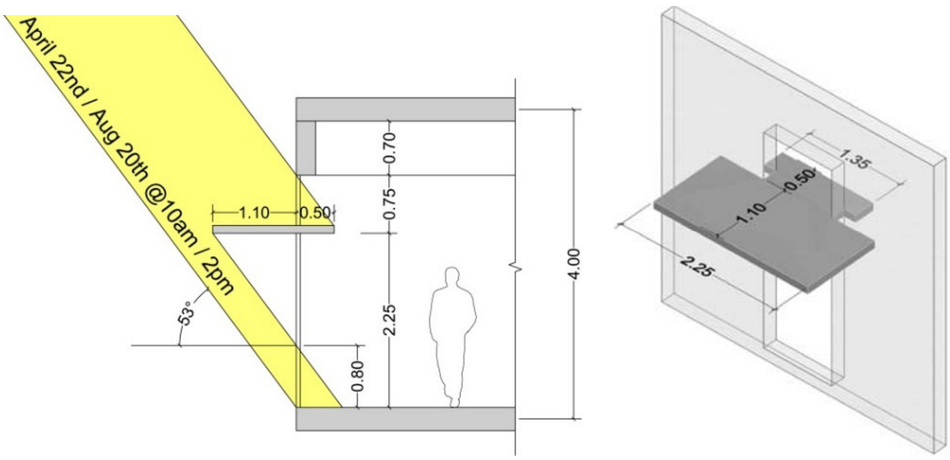

Figure 1. Cross section of the room (left) and axonometric view of the final design of the light shelf (right).

The final length and width of shading devices have been calculated based on other parameters such as windows head height, sill height (or required shading height from the floor), window width, light shelf height, wall thickness, solar altitude, and solar azimuth. In order to block the sunlight from the upper portion of window, light shelves also extend 50 cm into the interior space. The bottom of selected light shelf in Fig. 1 is 2.25m above the floor with a superior reflectance set to 80%.

Annual climate-based simulations at every hour from 9:00am to 4:00pm for each WWR, with and without light shelves were carried out in AGi32 software. The Perez All-Weather model was used for the sky. This model uses real data from weather stations all around the world to obtain the luminance distribution of the sky dome. For Toronto data from Pearson International Airport weather station were used (Table 2). A grid of 551 points with 0.5m spacing was hence defined to investigate the illuminance levels. The illuminance levels obtained for each point were then used to calculate the annual UDI levels. UDI is a dynamic (climate-based) metric which is derived from yearly illuminance levels under real sky conditions. For this study, UDI uses 100 lux and 2000 lux as the minimum and maximum limits for useful daylighting [15]. Illuminance levels above 2000 lux represent an oversupply of natural light which may lead to glare issues while below 100 lux threshold indicates insufficient daylighting. Many contrasting results are found in literature on illuminance optimal values, but on average, a point is considered to receive good daylighting if the illuminance level is between 100 lux and 2000 lux for at least 50% of the time [13].

Table 2. Summary of simulation parameters

Location	Toronto, ON (716240_CWEC weather file)	Glazing type	Double pane low-E (VT 70%)
Orientation	South facing	Light shelf height	2.25m above the floor
Dimension	15m x10m x 3m (W x D x H)	Light shelf design goal	Block direct sunlight from Apr 22 to Aug 20
Interior reflectance	Ceiling 80% - Walls 60% - Floor 20%	Light shelf reflectance	80%
Work plane height	0.8m	Sky condition	Perez All-Weather
Window dimension	1m x 3m (W x H)	Simulation time step	Hourly, from 9:00am to 4:00pm
Window to Wall Ratio	25%, 35%, 45%, 55% (w or w/o light shelf)	Illuminance grid spacing	0.5m x 0.5m

4. Results and Discussion

Figure 2 shows the average $UDI_{100\text{-}2000lux}$ as a function of the distance from the windows. This shows that increasing the WWR decreases the UDI levels in the first few meters in front of the window while enhances the daylighting in the back of the room. Except the 25% WWR, without light shelves the UDI falls below 50% within 3m from the windows. The maximum level of UDI for cases without light shelves occurs at 3m, 4m, 5.5m and 6m away from the windows for 25%, 35%, 45% and 55% WWR respectively.

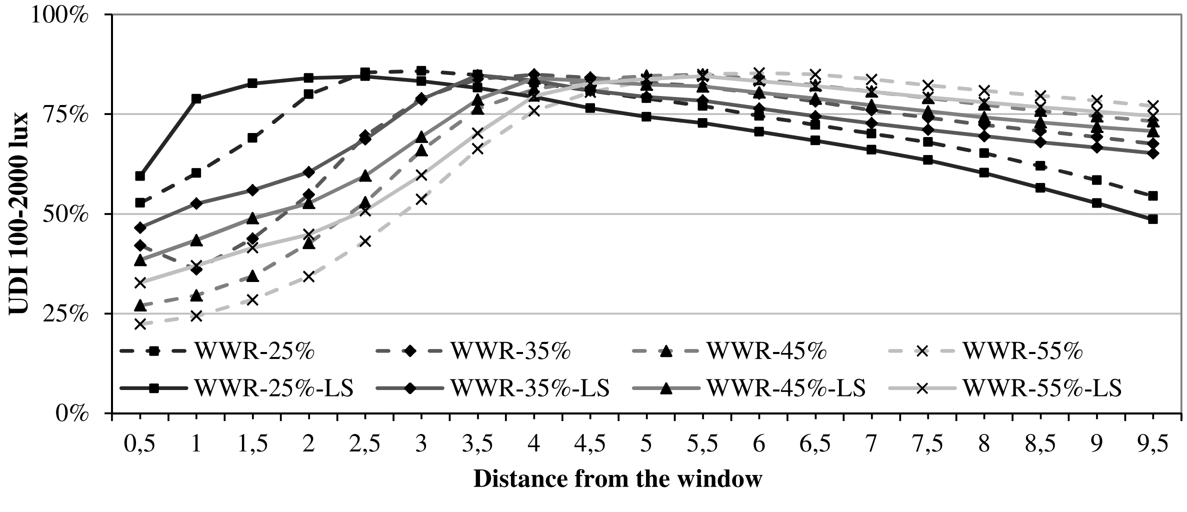

Figure 2. Average $UDI_{100\text{-}2000lux}$ for each row at equal distance from the windows for different WWR.

Figure 2 also shows that the integration of light shelves improves the daylighting quality closer to the windows, while in the back of the room the UDI level diminishes slightly. The depth of the area with improved daylighting is consistent with the increase in the WWR. Among the iterations with light shelves, UDI for WWR25%-LS and WWR35%-LS is almost always above 50%. The distance between the windows and the point where the UDI exceeds 50% reduces from approximately 2.35m to 1.75m for WWR45%-LS and from 2.85m to 2.5m for WWR55%-LS compared to the options with the same WWR but without shading. The maximum UDI occurs at 2.5m, 3.5m, 4m and 5.5m from the windows for the cases with light shelves from 25% to 55% WWR respectively. The comparison between the cases that have the same WWR with and without light shelves indicates that shading devices reduce the magnitude of the maximum UDI, but allow a more homogenous distribution.

Table 3 reports percentage of the office area within different UDI intervals. This shows that increasing the WWR without integrating light shelves consistently raises the office area with UDI levels above 75% from 48.5% to 59.7%. On the contrary, it decreases the area with UDI between 50% and 75% from 43.9% to 13.1%. The overall impact of WWR on the office area within the good daylighting range reduces from 92.4% to 72.8%. Adding light shelves in all cases brings down the area with UDI above 75%, while increases the area where UDI is the range between 50% and 75%. Comparing cases with and without light shelves with the same WWR shows an overall increase in the area within the good daylighting range. The maximum improvement is achieved by adding light shelves to the case with 35% WWR which raises the area with good daylighting from 84% to 93.5%.

Table 3. Percentage of the office area with different UDI intervals.

	UDI100-2000lux	25%	25%-LS	35%	35%-LS	45%	45%-LS	55%	55%-LS
Good daylighting	75%<	48.5%	43.2%	51.4%	38.1%	58.6%	47.7%	59.7%	57.2%
	50%-75%	43.9%	50.6%	32.7%	55.4%	19.4%	37.2%	13.1%	20.7%
	Total	92.4%	93.8%	84.0%	93.5%	78.0%	84.9%	72.8%	77.9%
Poor daylighting	25%-50%	6.7%	5.6%	14.7%	6.5%	17.8%	15.1%	17.8%	22.1%
	<25%	0.9%	0.5%	1.3%	0.0%	4.2%	0.0%	9.4%	0.0%
	Total	7.6%	6.2%	16.0%	6.5%	22.0%	15.1%	27.2%	22.1%

A WWR above 35% increases the area with UDI levels between 25%-50% and below 25%; this shows that higher WWR increase the glare risks and deteriorate the overall daylighting quality. Adding light shelves reduced the area with poor daylighting for all cases. The only exception is the increase from 17.8% to 22.1% for the case without and with light shelves for the 55% WWR; however, in this case, it is also important to notice that the light shelves eliminates the areas with UDI below 25% of the time.

Figure 3 shows the impacts of light shelves on different UDI ranges for all WWR. The comparison between the cases with and without light shelf shows that shadings resulted in an evident improvement in the daylight quality in the areas closer to the windows. The light shelves allow a more uniform and deeper penetration of good daylight. Adding light shelves in all cases reduced UDI levels in the middle and back of the room. The only anomaly is for the cases with 55% WWR in which UDI level in the middle of the room remains unchanged after adding the light shelves. The effect of shading devices on the cases with 25% and 35% WWR is reversed compared to higher WWR in the first 4 meters. Shading devices enhance the daylighting in the first two meters for 25% and 35% WWR but slightly deteriorates the situation for the same cases between 2m and 4m. The impact of WWR and light shelves in the middle part is negligible for all cases.

Obviously, it is important to mention also some limits of the present study. The selection as minimum illuminance value of 100 lux in the calculation of the UDI seems to have affected the result significantly because led to consider a sufficient daylight quantity also particularly far from the windows. Performing simulations with unobstructed windows and the lack of furniture in the offices also allowed to obtain higher than typical lighting levels

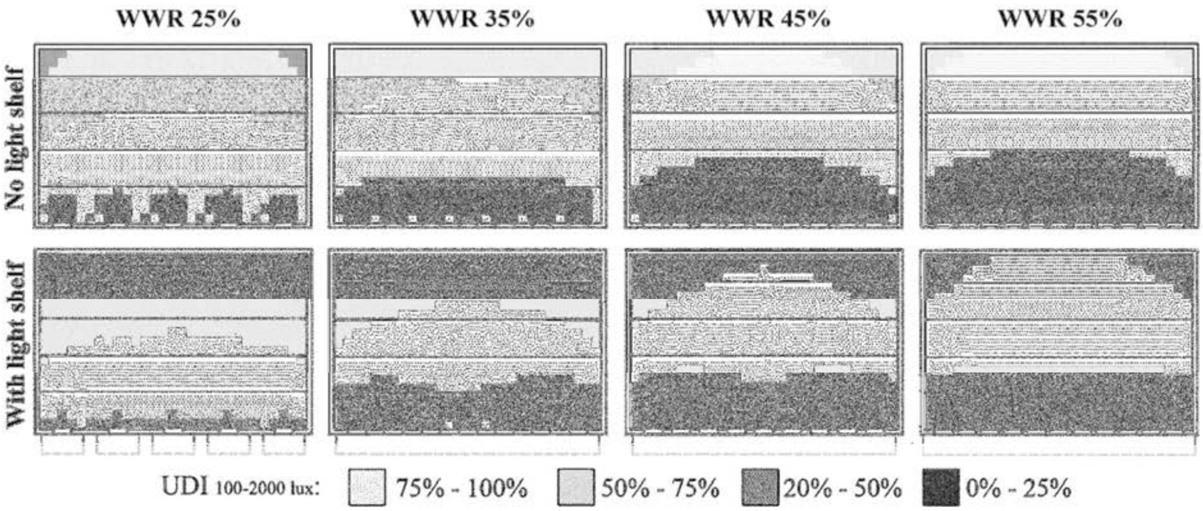

Figure 3. Comparison between UDI maps for all WWR with/without light shelves.

5. Conclusions

This study shows that in the modelled office in Toronto increasing the WWR constantly reduces the UDI levels for the points closer to the windows (longer periods with illuminance above 2000lux) while increasing the UDI in the back of the room. However, the integration of light shelves improves the UDI in the front zone, with reduced effects away from the windows. Moreover, the designed shading devices have minimal affects over the UDI in the middle of the room. The paper also shows that full-height windows allow deep penetration of light, with UDI always above 50% in the back zone for all cases (even for 25% WWR). WWR above 35% are never advantageous for daylighting quality. Future studies will focus on different orientations and obstruction scenarios, as well as parameters other than UDI.

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