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Original Contribution

The Impact of Clerestory Window Height on the Performance of Fixed Horizontal Lightshelf on Daylighting Classroom in Dhaka, Bangladesh

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This paper investigates the impact of clerestory window height on fixed horizontal light shelf performance regarding daylighting quality in classrooms. As a case study, a south-facing classroom of a university located in Dhaka was selected, and five alternative models of 3300 mm high case spaces were created with light shelves at the height of 2100mm above the floor finish. Varying heights of clerestory windows were used in the models to analyze the influence of clerestory windows on light shelves' performances. The three-dimensional models of the classrooms were first generated in Ecotect to investigate the interior illuminance level and uniformity distribution with static daylight performance metrics. The models were also imported to Radiance, a raytracing software, to create rendered images for crosschecking and validating Ecotect findings. Then, to compare the findings with dynamic daylight metrics, the results were verified and refined with DAYSIM. The result showed that a 750 mm high clerestory window with a fixed horizontal light shelf at the height of 2100mm above floor finish performed better for a classroom face south compared to other studied alternative clerestory window heights.

INTRODUCTION

Daylighting is an effective strategy to improve the learning environment in classrooms. It maintains comfortable indoor environments and boosts students' and teachers' mood, health and eyesight (Heschong Mahone Group, 1999). Previous studies showed that controlled full spectrum daylight in classrooms reduces absenteeism rates and promotes student academic performance (Surat, et al., 2013). Therefore, there is a need to control daylight in classrooms, which is possible by adopting shading systems.

Shading devices can increase daylighting penetration into the room and reduce glare and thermal issues (Ruck, et al., 2001; Berardi & Anaraki, 2018). One downside of installing shading devices is that these systems usually reduce daylight levels; however, a light shelf can solve this issue to a certain extent (Joarder, et al., 2009). Light shelves divide windows into clerestory areas above and the view areas below (Joarder, et al., 2009). This study analyses the effects of different clerestory window heights on light shelves performance in daylighting classrooms in Dhaka.

This paper is divided into three major parts. The first part presents the research methodology and the basic idea behind a light shelf and a clerestory window; the second part describes simulation analysis with dynamic and static metrics, and the final part compares findings that recommend the best possible height of clerestory windows for light shelves in classrooms.

LIGHT SHELVES AND CLERESTORY WINDOWS

A light shelf is an effective form of shading device typically placed above eye level. It functions as a reflector, directing light to deeper areas of any room while reducing

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light near windows; therefore, a light shelf helps create a balanced luminous environment in a room by reducing glare and contrast (Zakhour, 2015; Ali & Ahmed, 2012).

Although a rule of thumb is that a light shelf width should be the same as the height of a clerestory window, many researchers gave different recommendations based on different contexts and design parameters. According to Selkowitz, et al. (1983), exterior light shelf depth should not exceed 1.5 times the clerestory window's height. In addition, Place, et al. (1990) suggested that for south-facing façades, exterior light shelf depth should be 1.25–1.5 times the height of the vertical window above. On the other hand, the height of the vertical window above the light shelf should be the same as the depth of the interior light shelf, while the depth of an external light shelf width should be less than the distance between the light shelf's height above the floor level and the work plane, (Littlefair, 1995). However, light shelf depth and glazing height should be selected based on the specifics of climate and latitude (Ruck, et al., 2001).

Both clear and overcast conditions are observed each year in composite climates like Dhaka. As the two conditions are contrasting, designers face challenges in making design decisions (Ahmed, 1987). To tackle this condition in terms of daylighting, researchers recommended use a light shelf and found that it performs better at the height of 2000 mm or 2100 mm above floor level based on different design parameters in the context of Dhaka (Joarder, et al., 2009; Baten & Joarder, 2020; Sharmin, 2011). However, these investigations were confined to the height of the light shelf only. Hence, the different heights of clerestory windows are analyzed in this study to identify suitable clerestory window height for a standard horizontal light shelf placed at the height of 2100mm from the floor level. (Baten & Joarder, 2020).

METHODOLOGY

Site and Building Selection for Simulation

Dhaka city's physical and environmental characteristics are different from other cities because of its geographic location, built environment density, inadequate green space, and building types, heights and orientations.

The selection of the case building ensured that it is used for educational purposes and located in Dhaka city (Figure 1). In addition, it was ensured that the building façade is suitable for installing light shelf and the internal layout can allow ample daylight penetration and distribution.

A critical case sampling technique was used to select the case building. This entails selecting samples appropriate for research and evaluating them (Etikan, et al., 2016). After surveying twelve university campuses, the North South University permanent campus was selected based on the criteria mentioned.

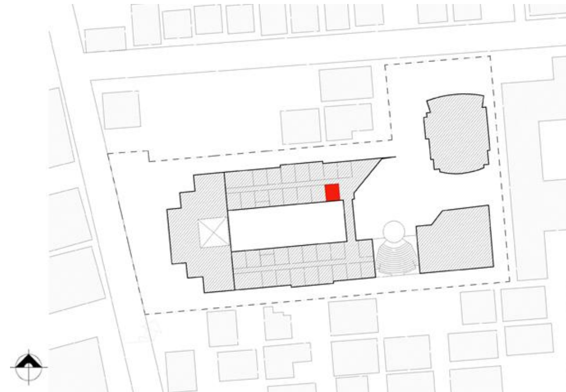

Figure 1: Location of the case classroom (shaded Red) and its surroundings.

The campus is located at Bashundhara R/A, Dhaka, which encompasses 5.5 acres of land and consists of three main buildings: the Administration Building, the South Academic Building, and the North Academic Building (Murshed, 2020). It has nine-storeyed academic buildings and 1.2 million square feet of floor space that contains 291 faculty rooms, 112 classrooms, and other facilities (Murshed, 2020). In order to simulate, a classroom located on the 4th floor of the North Academic building is selected (Figure 2), and during the physical survey, the following classroom features were found.

- Classroom orientation: South
- Classroom dimension: (9025x 8020) mm
- Classroom height: 3300 mm
- Window direction: South
- Work plane height: 750mm
- Window to floor ratio: 0.13

Figure 2: Image of the case classroom (marked red)

Simulation Study

Although it is challenging to identify the impact of one architectural feature physically, simulation helps investigate the effects of a single factor while keeping other aspects constant. Hence, the impact of different clerestory window heights on daylight penetration and quality was analyzed by daylight simulation in this study.

During daytime simulation, this study used two types of performance metrics: static and dynamic. The Daylight Factor (DF) method, which uses a single sky model (overcast sky), was used to calculate the static performance measurements. On the other hand, the Daylight Coefficient (DC) method was used for dynamic performance measurements, and it takes into account the surrounding environment as well as the different climate characteristics of the building site independently (Nabil & Mardaljevic, 2006).

Three simulation programs were used in this study in order to analyze the effect of clerestory window heights on the light shelf performance regarding the amount of daylight at the height desk plane, aiming to identify the best clerestory window height. First of all, Ecotect v5.20 was used, which is a powerful architectural, visualization, and analysis tool; it can analyze lighting, shading, thermal, energy, and acoustic performance (Crawley, et al., 2005; Osaji & Price, 2009). Second, RADIANCE 2.0 Beta was used to compare visual images to analyze illuminance levels. Finally, DAYSIM 2.1.P4 was used to assess the impacts of various design factors on annual interior illumination situations (Reinhart, et al., 2006).

Simulation Parameters

The following parameters were used to assess the qualitative and quantitative aspects of design strategies:

- Location: Dhaka, Bangladesh (90.40 E, 23.80 N)
- Time: April 01, 12 pm
- Calculation Settings: Full Daylight Analysis
- Precision: High
- Local Terrain: Urban
- Window (dirt on glass): Average
- Sky Illumination Model: CIE Overcast
- Design sky Illuminance: 16,500 Lux (Khan, 2005)

Study space

The interior space was kept vacant in the models to avoid reflecting and blocking daylight and hiding the actual effects of clerestory windows and light shelves. Other floors were kept hidden to avoid unnecessary processing time and make simulation faster because they have no contribution to simulation results during the trial simulation study (Joarder, et al., 2009). During the daylight simulation, the following parameters were used:

- Glazing: Single glazed Low-E aluminum frame (Visible transmittance: 0.9)
- Floor: Ceramic tile finish (reflectance 0.3)
- Wall: White painted plaster (reflectance: 0.5)
- Ceiling: White painted plaster (reflectance: 0.8)

Simulation evaluation process

The case classroom was divided into 1000 mm X 1000 mm grids (Figure 3), and 56 intersecting points were chosen to determine the amount of daylight on ECOTECT at the height 750mm above the floor level, representing the desk height of the classroom. In addition, XX' axis was created through the center of the case classroom to show the fluctuation of luminance from the glazing area towards the deeper area (Figure 3). These calculations consider DF concepts considered valid under the overcast sky (Koenigsberger, et al., 1997).

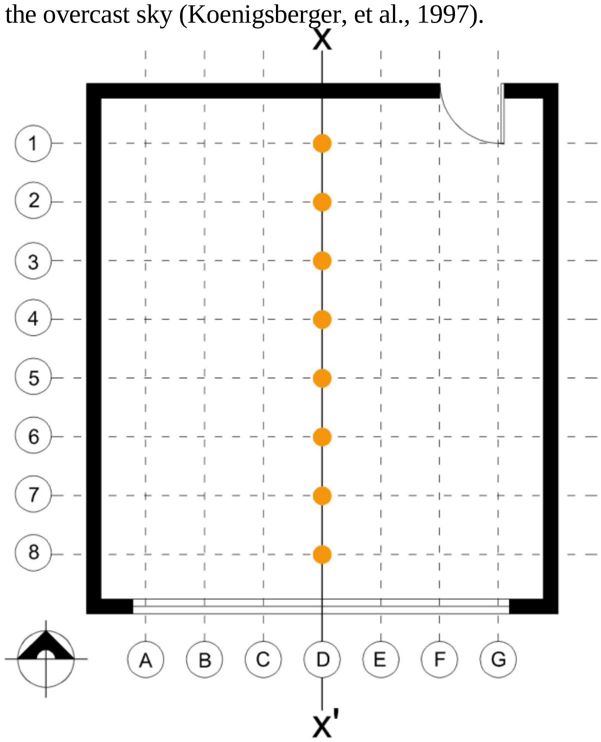

Figure 3: Plan showing core desk plane sensors and all grid points

The Ecotect program was first used to generate 3D models and determine the amount of light on each grid point of the desk plane. Then, the models were used in Radiance to generate realistic lighting level images and show daylight contour maps. Finally, DAYSIM was used to create a comprehensive annual picture. The following criteria were used to evaluate the simulation results.

- The average amount of daylight at the desk plane's height
- The number of points that can be considered as an acceptable amount of light (300-900 lux)
- Comparing rendered images of the case space
- Evaluating various annual performance metrics

Simulation of clerestory windows and light shelves

Custom light shelves (U value: 7.14 W/m2K; metal deck, reflectance: 0.88) were used during daylight simulation in Ecotect software. Five different models of the classroom were generated for alternative clerestory window heights with horizontal light shelf at 2100mm height above the floor finish extended 500mm outside and to the same depth inside the classroom (Figure 3).

The clerestory window heights above the fixed light shelves are 300mm, 500mm, 750mm, 1000mm and 1200mm (Table 1 and Figure 4).

Table 1: Clerestory window heights and types

Clerestory window height	Types
None	Type 0
300 mm	Type A
500 mm	Type B
750 mm	Type C
1000 mm	Type D
1200 mm	Type E

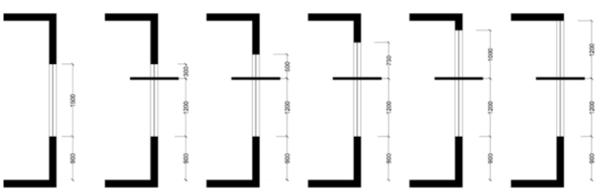

Figure 4: Schematic representation of the cases investigated in this study

RESULTS

Static simulation results

The recommended daylighting level for a desk and blackboard is 300 lux (BNBC, 2006). Hence, some variables such as daylighting level below 300 lux (under light), within 300-900 lux (effective light), and above 900 lux (glare) were compared to identify the best possible clerestory window height (Joarder, et al., 2009; Zakhour, 2015).

Average illumination comparison showed that 1200mm clerestory window has the highest average illumination level (Figure 5) and the number of points between 300-900 lux (Figure 6); however, it has also the highest numbers of points above 900 lux (15points) which means it creates glare and discomfort. On the other hand, among the studied clerestory windows, type A, B and C have the lowest number of points (11 points) above 900 lux. In addition, Figure 7 shows that illumination level drop becomes sharper with decreasing the heights of clerestory window.

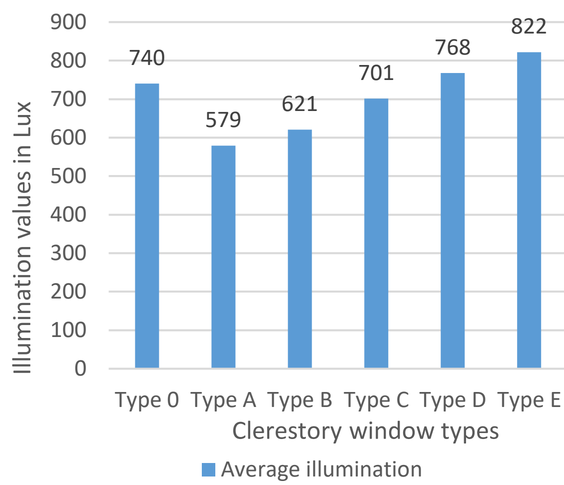

Figure 5: Average illumination level with clerestory window heights and no clerestory area

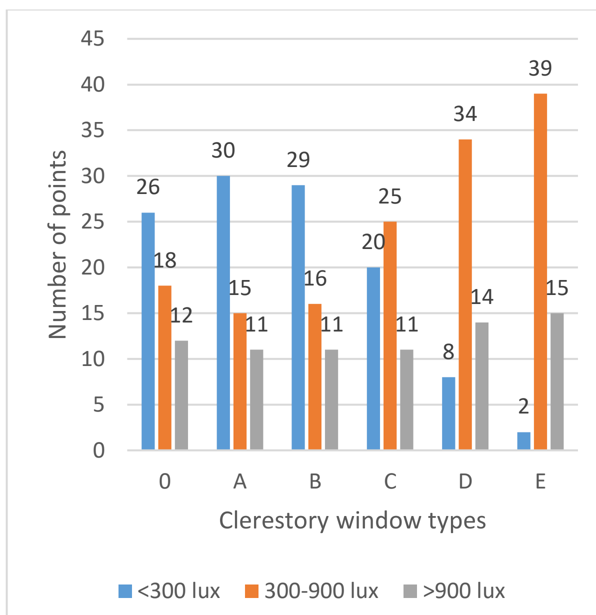

Figure 6: Number of points having an illuminance level of less than 300 lux, between 300 and 900 lux, and greater than 900 lux

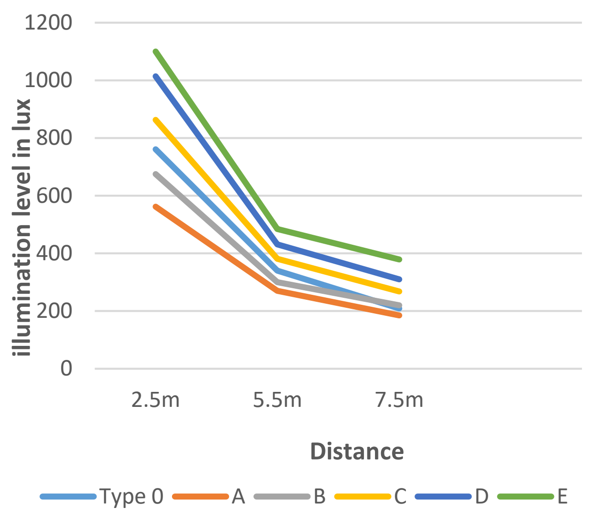

Figure 7: Drop of light along XX' axis with five alternative clerestory window heights and no clerestory area

The RADIANCE images (Appendix 1) indicate that the daylight intensity is higher near the windows and gradually falls towards the deeper areas. The case room is brightest for the 1200mm high clerestory window (Type E) whereas, it is darkest for the 300 mm high clerestory window (Type A).

Table 2: Static performance of varying clerestory window types

Clerestory Window Types	Value and Rating points (RP)	Average Illumination	Points below 300 lux	Points above 900 lux	Points between 300 to 900 lux	Total rating points	**Ranks**
Type 0	*Value*	739.88	26	12	18	11	6th
	RP	4	3	3	1		
Type A	*Value*	579.08	30	11	15	10	5th
	RP	1	1	6	2		
Type B	*Value*	620.84	29	11	16	13	4th
	RP	2	2	6	3		
Type C	*Value*	701.05	20	11	25	17	2nd
	RP	3	4	6	4		
Type D	*Value*	767.86	8	14	34	17	2nd
	RP	5	5	2	5		
Type E	*Value*	822.17	2	15	39	19	**1st**
	RP	6	6	1	6		

Static simulation results are ranked based on their performance (Table 2). Rating points are given between one to six in this study; the lowest points indicate the worst performance, whereas the highest point means the best performance among all options. The total rating points for each type are then added together to finalize the score. By comparing these individual total scores, ranking is done to identify the best possible option.

1200mm clerestory window (Type E) received the most points and was ranked first, followed by Type D, C, B, A, and 0. Therefore, Type E is a feasible option based on the static simulation result. Figure 8 shows the distribution daylight distribution on node points for Type E.

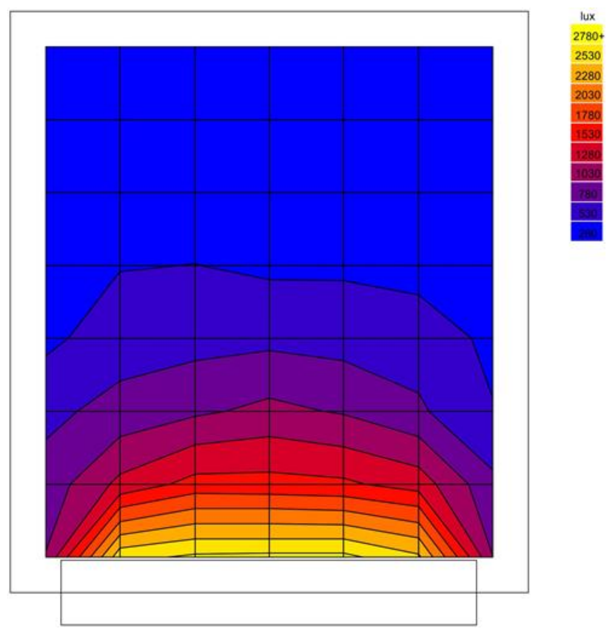

Figure 8: Distributions of daylight on node points with 1200mm clerestory window height

Dynamic simulation results

While overcast sky represents the more critical condition, the clerestory windows performance in other sky conditions is also necessary to get a complete picture and make design decisions (Joarder, et al., 2009). Therefore, simulations were run by DAYSIM, and clerestory windows performance are compared with different dynamic metrics, such as UDI, DA and DAmax. Then, using rating points, the outcomes are analyzed and ranked (Appendix 2).

Type E is superior to the other types based on the rating points in DA, DAcon and UDI<100; However, it scored the lowest points in DAmax, UDI100-2000 and UDI>2000 metrics (Table 3). This indicates that a 1200mm window will allow more than the recommended amount of daylight in the classroom, and therefore it will create glare and discomfort, and students will draw the curtains and turn on artificial lights most of the days. On the other hand, Type A scored highest in DAmax, UDI100-2000, and UDI>2000 metrics; however, it scored the lowest rating points in DA, DAcon and UDI<100 (Appendix 2). This indicates that it will allow the recommended amount of daylight in a specific part of the room, and the rest of the room will not get enough daylight all over the year, and therefore some students will depend on artificial light.

Although Type C did not score highest in any dynamic metrics, it scored four points in six out of seven dynamic metrics and scored the highest total rating points among all the options. This result indicates that the 750mm height clerestory window performs better than other clerestory window heights based on dynamic performance metrics.

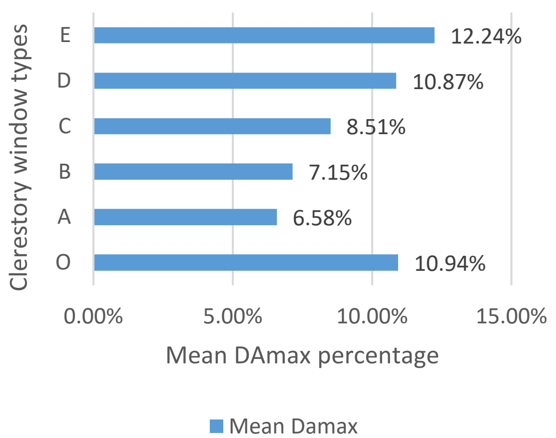

Figure 9: Performance analysis of the mean DAmax metric for various Clerestory window types

Table 3: Comparison between static and dynamic simulation result

Ranks	0	A	B	C	D	E
Dynamic simulation	6th	5th	*2nd*	**1st**	*2nd*	*2nd*
Static simulation	6th	5th	4th	2nd	2nd	**1st**

While static simulation results show that a 1200mm high clerestory window (Type E) performs better than other clerestory window heights, dynamic simulation results indicate that a 750mm high clerestory window (Type C) is the most feasible option among all the studied options (Table 3).

If type E is suggested, students will get more than 300 lux in most parts of a classroom under overcast sky conditions, which means that ample daylight will penetrate the classroom under other sky conditions. In reality, this is only suitable for overcast conditions because type E performs the worst in terms of glare and effective daylight level among all studied options based on dynamic simulation results. On the other hand, if type C is selected as the best possible option, adequate and uniform daylight will penetrate the classroom in all the sky conditions, and it will also reduce glare issues. Therefore, 750mm (Type C) clerestory window height for a fixed horizontal light shelf at the height of 2100mm above floor level is recommended in this research.

CONCLUSION

This simulation study is performed to determine the impact of clerestory window height above the light shelf in the south-faced classrooms in a tropical location. The result shows that increasing the height of clerestory window as high as possible above light shelf allows deep penetration of daylight in a classroom, and it is advantageous for a specific timeframe, such as overcast condition; however, after a certain height of an increase, clerestory window start creating glare and discomfort under other sky conditions.

This paper shows that a 750 mm high clerestory window with a light shelf extending 500mm on both sides of the windows at the height of 2100mm above the floor performs better to improve the quality of daylighting compared to other studied options.

Finally, it can be concluded that the clerestory areas significantly affect light shelves' performance in terms of enhancing daylight quality in tropical classrooms. Although only clerestory window height was analyzed in this study, structure, shape, angle, and properties of clerestory windows also significantly impact the luminous environment in a classroom.

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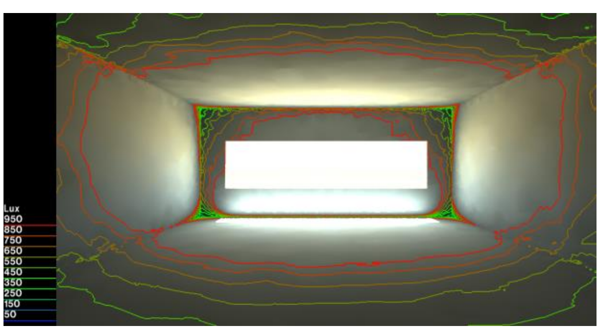
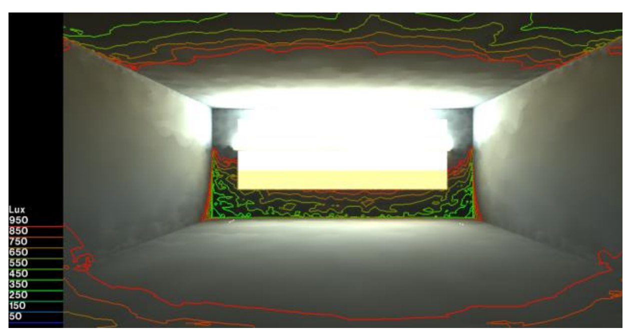
APPENDICES

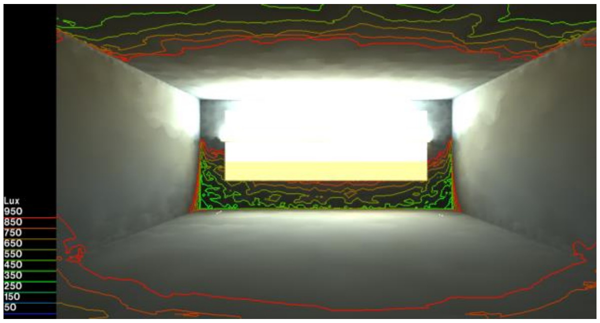
Appendix 1: Distribution of Daylight contour with different clerestory heights and without clerestory area



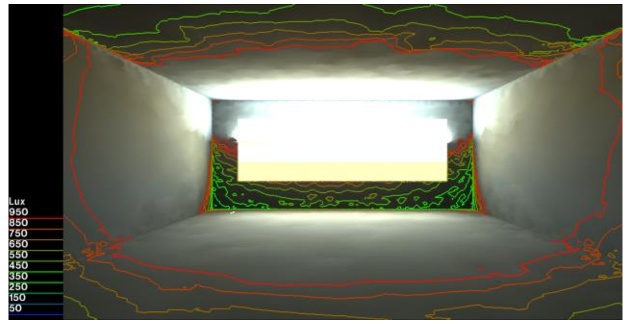
Type O- No Light shelf and clerestory window



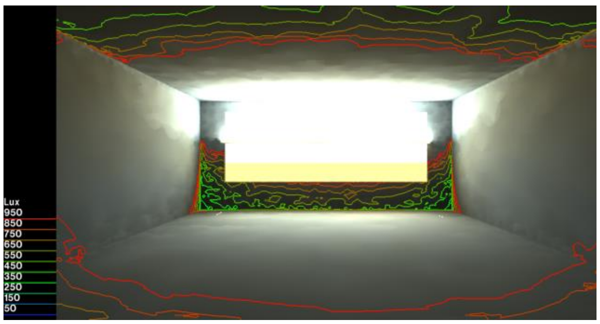
Type A- 300mm high clerestory



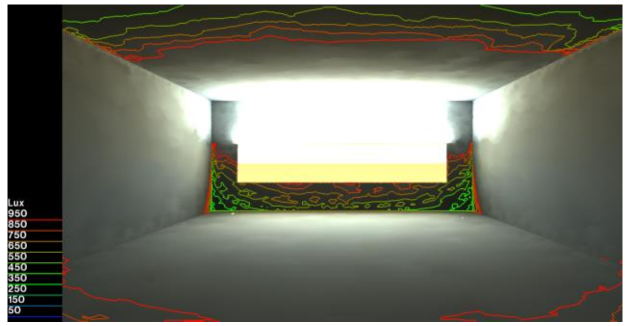
Type B- 600mm high clerestory window



Type C- 750mm high clerestory window



Type D- 1000mm high clerestory window



Type E- 1200mm high clerestory window

Appendix 2: Dynamic performance of varying clerestory window types

Clerestory window types	Value and Rating points (RP)	Daylight Factor (DF) [%]	Daylight Autonomy (DA) [%]	Continuous Daylight Autonomy (DAcon) [%]	Maximum Daylight Autonomy (DAmax) [%]	Useful Daylight Index (UDI) 100-2000[%]	Useful Daylight Index (UDI)<100 [%]	Useful Daylight Index (UDI)>2000[%]	Total rating points	**Ranks**
Type 0	*Value*	*4.55*	*61.48*	*82.03*	*10.94*	*72.22*	*1.69*	24.15	20	6th
	RP	*6*	*2*	*2*	*2*	*3*	*2*	*3*		
Type A	*Value*	*2.84*	*52.43*	*76.51*	*6.58*	*77.79*	*3.10*	17.20	22	5th
	RP	*1*	*1*	*1*	*6*	*6*	*1*	*6*		
Type B	*Value*	3.10	62.25	*83.22*	*7.15*	*76.38*	*1.33*	*20.37*	26	2nd
	RP	*2*	*3*	*3*	*5*	*5*	*3*	*5*		
Type C	*Value*	3.48	69.14	*87.12*	*8.51*	*73.39*	*.82*	*23.83*	27	**1st**
		3	4	*4*	*4*	*4*	*4*	*4*		
Type D	*Value*	3.97	76.02	*90.17*	*10.87*	*69.69*	*.64*	*27.87*	26	2nd
	RP	4	5	*5*	*3*	*2*	*5*	*2*		
Type E	*Value*	*4.50*	*81.79*	*92.55*	*12.24*	*65.83*	*.44*	31.80	26	2nd
	RP	*5*	*6*	*6*	*1*	*1*	*6*	1		