

CHAPTER 4

RESULTS AND DISCUSSION

This chapter reports the results of a series of experiments conducted to measure the interior daylight illuminance and its distribution in an atrium space in a tropical region. The results from a daylight simulation program are also presented together with the experimental results for the validation. Using the simulation program based on ray-tracing method, correlations between the daylight in the atrium and geometrical parameters i.e. light well index were investigated.

4.1 Experimental Study

A series of experiments was conducted to measure the daylight in the atrium model under a real sky. The interior daylight illuminances were measured on the ninth floor and on the third floor of the scale model. The measurements were taken for four points in the southern area of each floor (Figure 3.1 in Chapter 3). Exterior daylight illuminances were measured and recorded at the meteorological station at the same site. From a number of experiments were selected to illustrate the results in three different sky conditions.

4.1.1 Experiment on 28th Feb 2013

On the day of the experiment, the sky was rather clear and the daylight varied quite smoothly throughout the day. The global daylight illuminance was above 90 klux during 11:00-13:00. The beam illuminance also reached 60 klux. The values of sky ratio index, the ratio of diffuse horizontal to its corresponding global irradiances were lower than 0.5 for most of the time. Figure 4.1 exhibits a plot of the variations of beam normal (E_{bn}), diffuse horizontal (E_{hd}), and global (E_{hg}) daylight illuminance from 6.00-18.00, (28th Feb 2013).

Figure 4.2 illustrates the interior daylight values at the four measurement points on the ninth floor. For the measurement point #1, the illuminance values were higher than 2,000 lx for the whole day. The maximum daylight illuminance could reach 12,000 lx at noon, caused mostly by sunlight. This situation is depicted by the photographs in Fig. 4.3, which

were taken during the experiment. The penetration of the sunlight into the west zone of the floor in the morning (the sun stays east orientation) and to the east zone in the afternoon would increase extremely the illuminance in the zones which in turn increases the daylight illuminance in the measurement area by the internal light reflection.

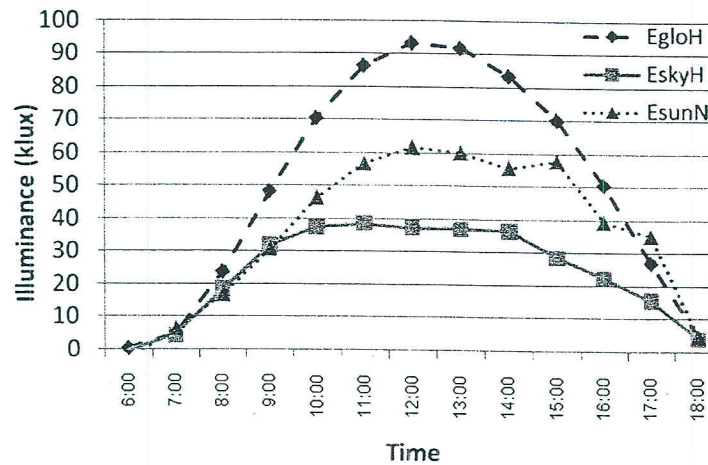


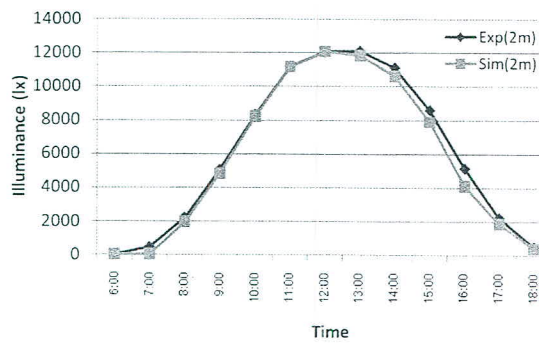
Figure 4.1 Exterior daylight illuminance on 28th February 2013

During the experiment, the sun stayed toward the south. The penetration of sunlight causes the interior daylight in the north zone of the adjoining space to be larger than that of the south zone. The plot in Figure 4.2 also shows the calculated values of the daylight from simulation software.

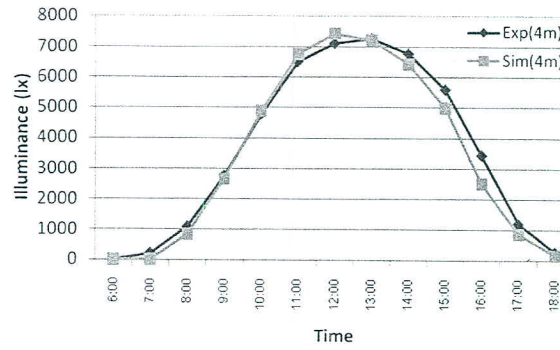
The illuminance measurements at Points #2, #3, and #4 are exhibited respectively in Figures 4.2(b), (c), and (d). The illuminance values at Points #2 were over 1,000 lx, Point#3 and #4 were over 500 lx during the whole day. The variations of illuminance at these points are similar to that at Point #1. The daylight on the upper floor of atrium can be higher than 500 lx throughout the day even if it is the deepest sensor position (Point#4) in the scale model. The results show that the illuminance decays exponentially from the light well to the rear walls. Figure 4.2 exhibits the well agreement between the illuminance data from measurement and from the software calculation.

Figure 4.4 exhibits similar plots with Figure 4.2 but for the third floor. From the plots, the simulation results quite agree with those from the experiment. The daylight levels on the

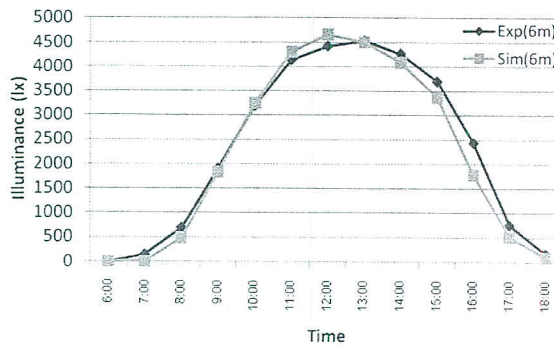
third floor are comparatively lower than that on the ninth floor because of the lower penetration of daylight from both the sun and the sky.



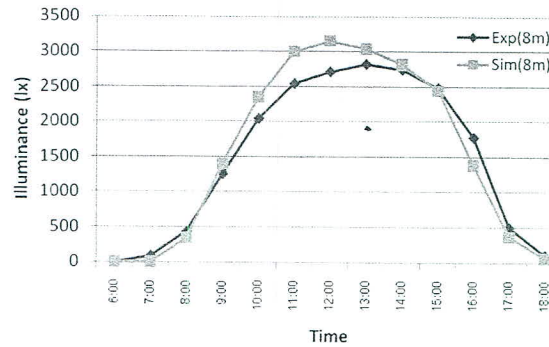
(a) Daylight illuminance at Point #1



(b) Daylight illuminance at Point #2



(c) Daylight illuminance at Point #3



(d) Daylight illuminance at Point #4

Figure 4.2 Experimental results on 28th February 2013 (9th Floor)

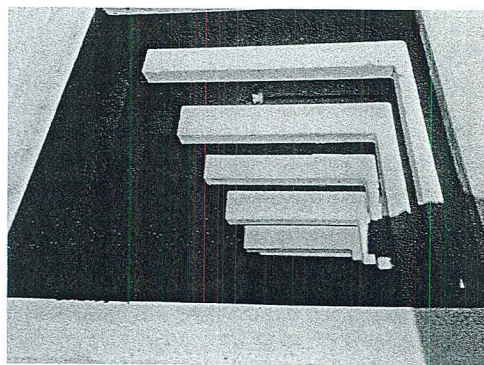
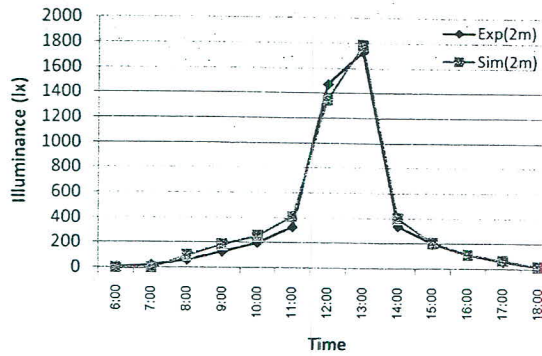
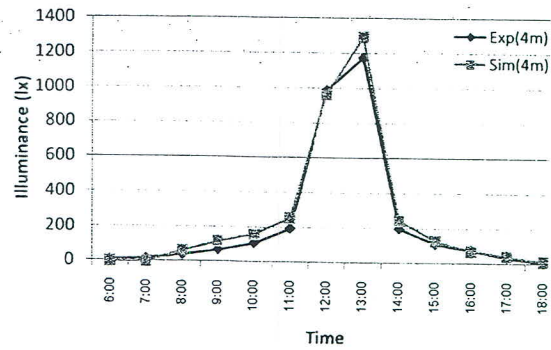


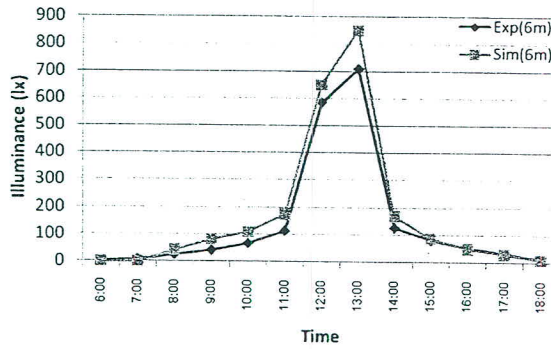
Figure 4.3 A photograph taken from the top of the model
(The top of the picture is the northern direction)



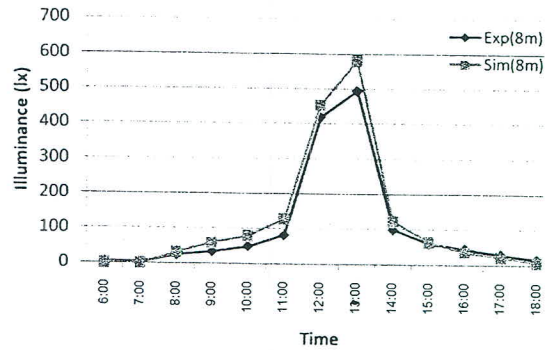
(a) Daylight illuminance at Point #1



(b) Daylight illuminance at Point #2



(c) Daylight illuminance at Point #3



(d) Daylight illuminance at Point #4

Figure 4.4 Experimental results on 28th February 2013 (3rd Floor)

The daylight illuminance on this floor began with a very low magnitude (close to zero) and then rose to reach its peak at noon time. On the third floor, the maximum daylight level measured at Point#1 was about 1,800 lx. The peak values decrease when the measurement points were located in deeper areas from the light well. It can be observed that the variation of the daylight on this floor is distinct from that of the ninth floor. The daylight values on this floor were high in a short period during noon when the sunlight penetrated to the base floor of the model. Again, the calculation results correspond well with the measurements.

4.1.2 Experiment on 21st February, 2013

On the day of the experiment, the sky was overcast sky this day and rained for a short period of time. The maximum beam illuminance was about 20 klux so it was also low on this day. Figure 4.5 exhibits a plot of the normal beam (E_{bn}), diffuse horizontal (E_{hd}), and global (E_{hg}) daylight illuminance from 6.00-18.00 in the day (21st February, 2013). The

approximated value of sky ratio index was higher than 0.85 during before- and after-noon and it was about 0.5 at noon time.

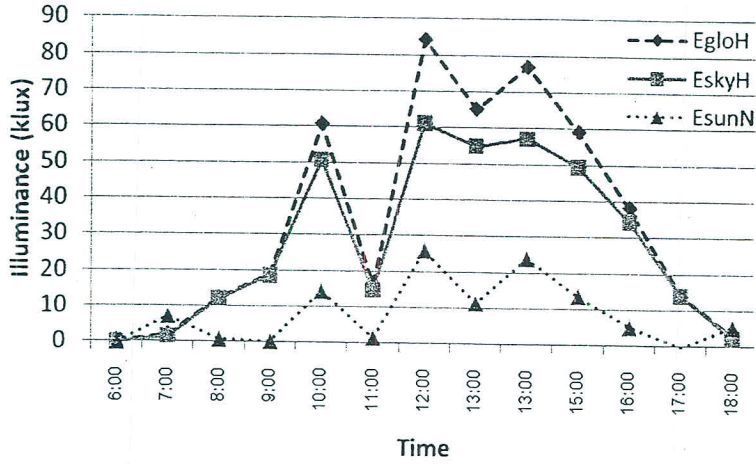
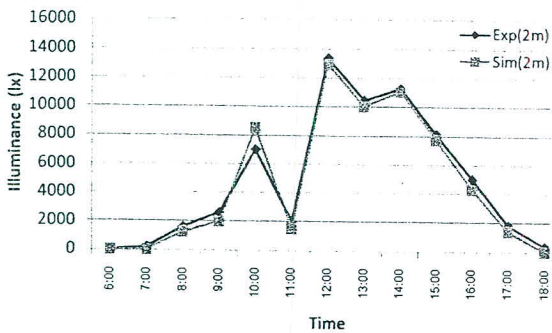
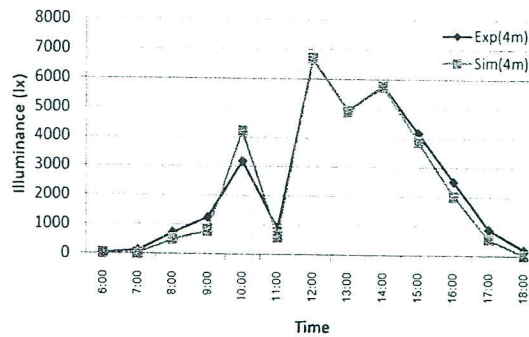


Figure 4.5 Exterior daylight illuminance on 21st February 2013

Figure 4.6(a) shows the variation of the daylight illuminance at the measurement Point #1 on the ninth floor of the model. The maximum illuminance value was about 13,000 lx at noon. In the plot, the illuminance values are slightly lower before- and after-noon. At 11.00 a.m. (during rain), the daylight reached 2,000 lx, caused by diffuse illuminance.

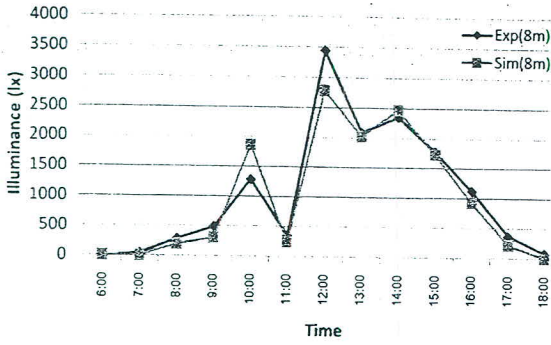


(a) Daylight illuminance at Point #1

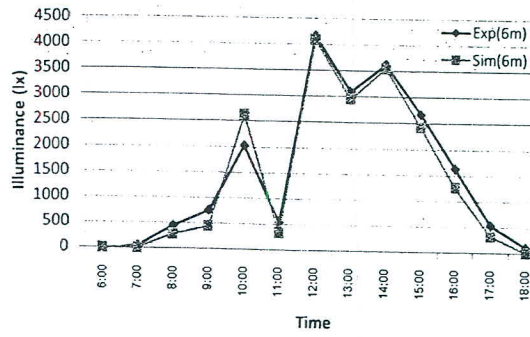


(b) Daylight illuminance at Point #2

Figure 4.6 Experimental results on 21st February 2013 (9th Floor)



(c) Daylight illuminance at Point #3

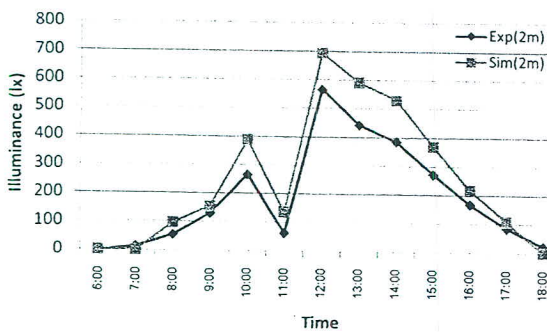


(d) Daylight illuminance at Point #4

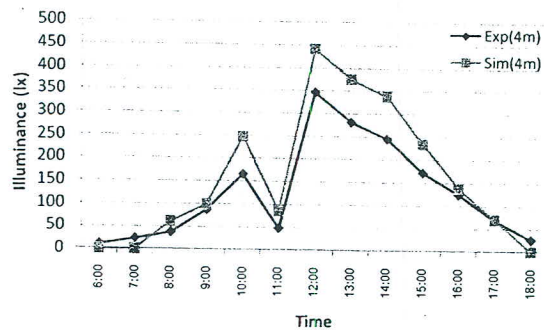
Figure 4.6 (Continued)

The results of the illuminance measurements at Points #2, #3, and #4 on the ninth floor of the scale model are illustrated respectively in Figures 4.6 (b), (c), and (d). The daylight illuminances close to noon at Point #2 varied between 4,000-7,000 lx, Point #3 between 2,500-4,000 lx and Point #4 between 1,800-3,500 lx. The variations of the illuminance at these points are similar to that at Point #1. At 11.00 AM. during rain, the minimum daylight illuminance at Point#4 (representing 8 m. for actual building) was about 400 lx. The results suggested that illuminance values on upper floor of the atria were sufficient illuminance levels even rain as a worst case scenario.

Figure 4.7 exhibits similar plots with Figure 4.6 but for the third floor. In the plots, the simulation results agree with that from the experiment. The daylight levels on the third floor are comparatively lower than that on the ninth floor.

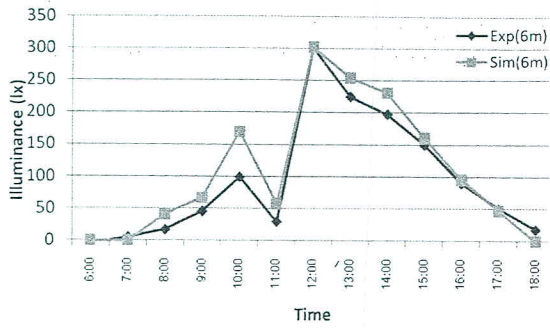


(a) Daylight illuminance at Point #1

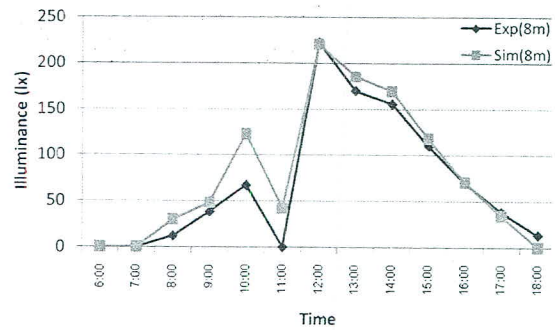


(b) Daylight illuminance at Point #2

Figure 4.7 Experimental results on 21st February 2013 (3rd Floor)



(c) Daylight illuminance at Point #3



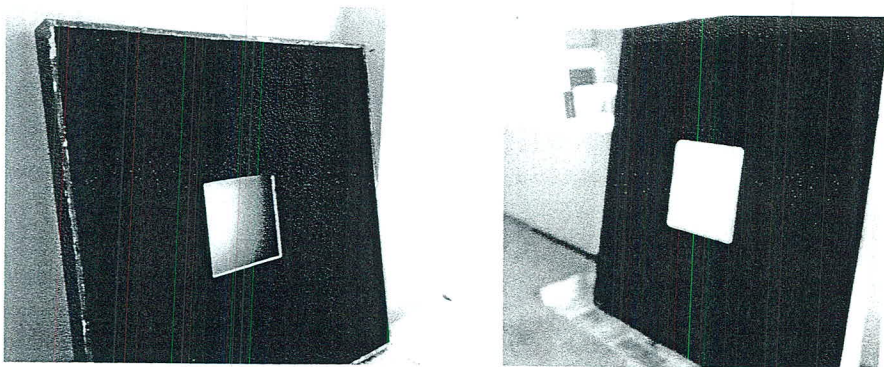
(d) Daylight illuminance at Point #4

Figure 4.7 (Continued)

On the third floor, the maximum daylight level measured at Point#1 was about 600 lx. The variations of the daylight illuminance on the third floor are similar to that of the ninth floor. It was different from the results of the third floor on the day with a clear sky because the overcast sky was not influenced by the beam illuminance on interior daylight illuminance on the lower floor.

4.1.3 Experiment on 4th April 2013

To demonstrate the effect of the interior surface reflectance, the experiment on this day measured the interior daylight with the reflectance close to zero. The eighth floor of the scale model was painted black and its surface reflectance about 0.1 (measurement value).

**Figure 4.8** Eighth floor of the scale model (painted black)

On the day of the experiment, the sky was partly cloudy. The global daylight illuminance was above 80 klux during 10:00-15:00. The values of sky ratio index were lower than 0.4 for most of the day. Figure 4.9 exhibits a plot of the variations of beam normal (E_{bn}),

diffuse horizontal (E_{hd}), and global (E_{hg}) daylight illuminance from 6.00-18.00 in the day (4th April 2013).

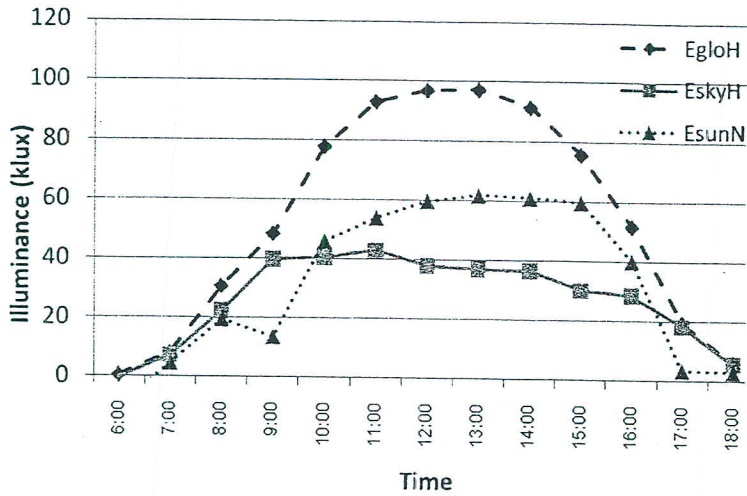
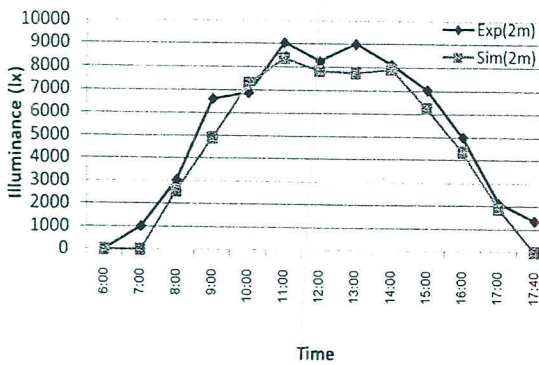
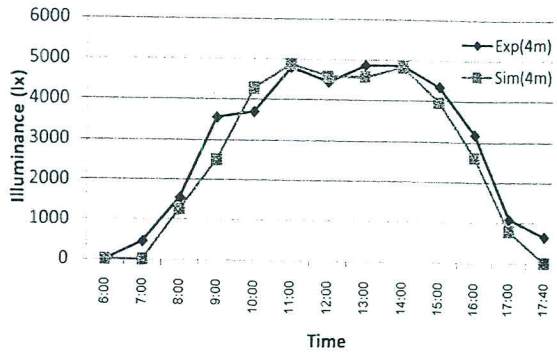


Figure 4.9 Exterior daylight illuminance on 4th April 2013

Figure 4.10 shows the variation of the daylight illuminance at measurement point #1 on the ninth floor of the model. The illuminance values were within 9,000 lx during before-and after-noon time. It demonstrated that at noon, most of the sunlight penetrates directly to the base floor, thus the illuminance is lower at this time.

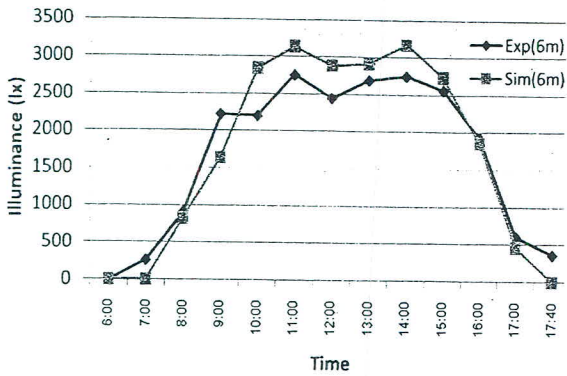


(a) Daylight illuminance at Point #1

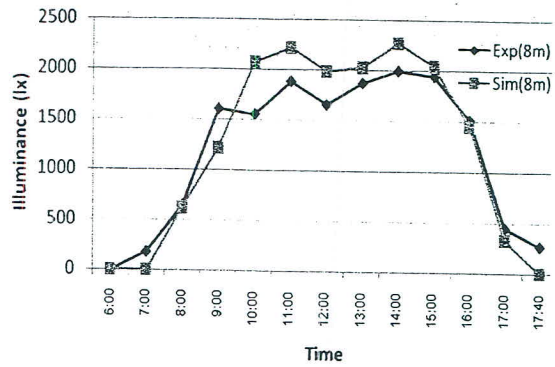


(b) Daylight illuminance at Point #2

Figure 4.10 Experimental results on 4th April 2013 (9th Floor)



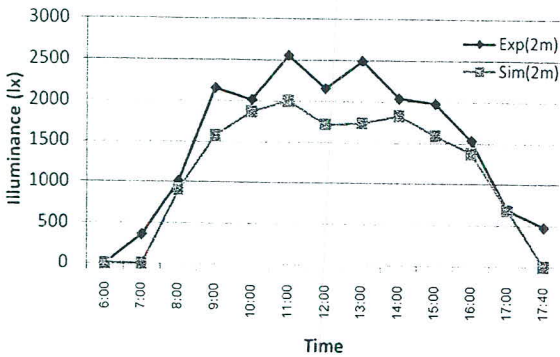
(c) Daylight illuminance at Point #3



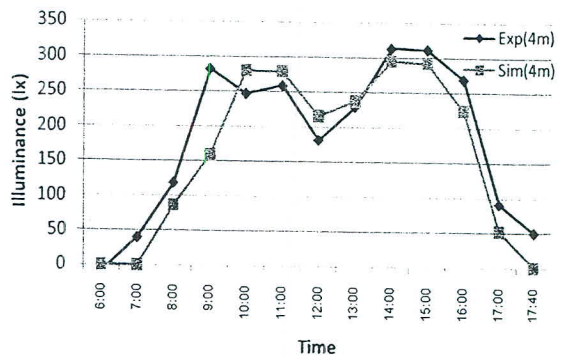
(d) Daylight illuminance at Point #4

Figure 4.10 (Continued)

Figure 4.11 exhibits interior illuminance on the eighth floor with surface reflectance 0.1. At Point #1, the maximum daylight was about 2,500 lx during, before and afternoon. The daylight illuminances at Point #2 was about 300 lx, Point #3; 130 lx and Point #4 ; 30 lx. From graphs, the illuminance values at Point #2, #3 and #4 decreased drastically because the measurement points were located in deeper areas from the light well and also without interior surface reflectance. It can be observed that the surface reflectance values have highly impact on interior daylight illuminance even if it was located as an upper floor of the physical model.

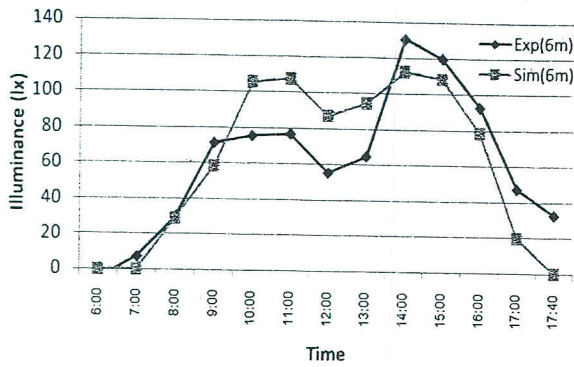


(a) Daylight illuminance at Point #1

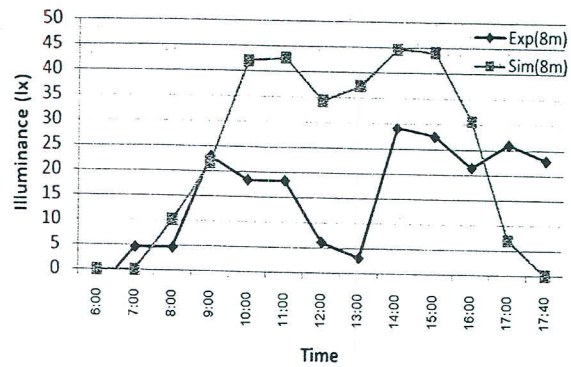


(b) Daylight illuminance at Point #2

Figure 4.11 Experimental results on 4th April 2013 (8th Floor)



(c) Daylight illuminance at Point #3



(d) Daylight illuminance at Point #4

Figure 4.11 (Continued)

4.2 Simulation study

The simulation study was performed to assess the daylight illuminance and its distribution in the atrium space. The simulations were made for two atrium configurations. Figure 4.12 exhibits the building configurations.

The first one is a square light well building. The dimensions of the building were 40 m wide by 40 m long by 40 m high (the floor-to-floor height was 4.0 m, and the floor-to-ceiling height was 3.2 m.). The 10m.×10m. light well was located at the center of the building. The second atrium building had a ten-story rectangular light well building. The dimension of the building was 40m. wide by 50m. long by 40m. high. The dimensions of the light well were 10m.×20m.

The openings in all models were unglazed because this study aimed to analyze the varying trend of average daylight level and its distribution, but not to achieve absolute values for a range of glazing types. To be more practical and realistic, the reflectance of the floor, the wall and the ceiling surfaces of the two buildings were changed into 0.3, 0.5 and 0.7 respectively.

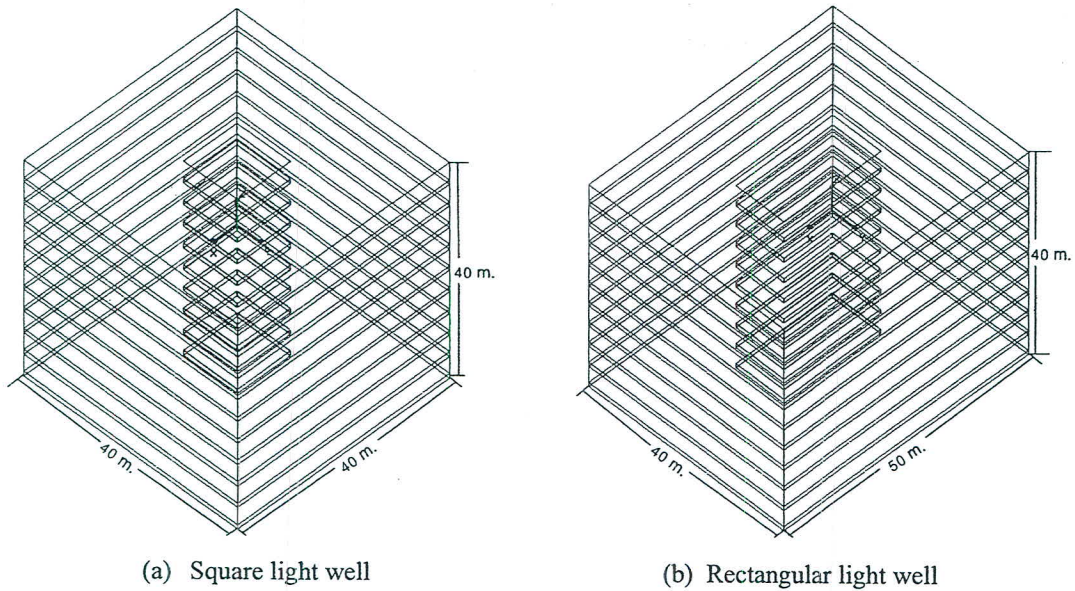


Figure 4.12 Atrium model used in simulation software

The simulation was performed to determine the daylight illuminance on a work plane level at points 2 m., 4 m., 6 m., 8 m., and 10 m. apart from the light well edge. The work plane was 0.75 m. above the room floor. The results also illustrated the illuminances for the four zones of the atrium floor (north, east, west and south zones). It also assumed that each floor has an opening balcony. Figure 4.13 illustrates the floor plan of the two atrium buildings and the points of the daylight illuminance to be calculated.

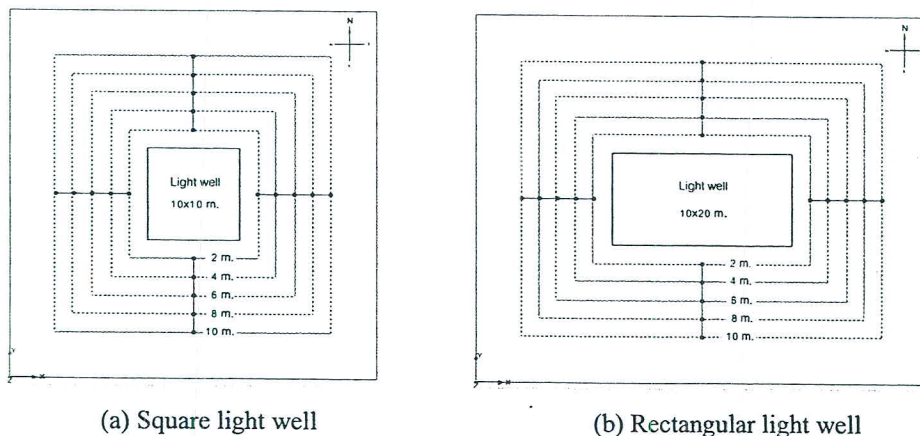


Figure 4.13 Floor plan atrium building and the calculation points

In Thailand, the sun transverses toward the south for eight months (September to April) thus the north zone of the atrium upper floor would largely influence the sunlight as

compared to the other zones. Daylight illuminance and its distribution were reported by divided into four areas of square-shape atrium building (north, south, east and west zones).

4.2.1 Daylight in North Zone

Figure 4.14(a) illustrates the plots of average daylight illuminance on each floor of the square light well atrium when the sun stays in the northern hemisphere. The results show that the total illuminance on the topmost floor (10th fl.) at 2 m. apart from the well edge is about 3,500 lx. Its illuminance values then decrease exponentially to about 130 lx at 10m. apart from the well edge. No direct sunlight penetrates into the zone.

During this period is about four months a year (from May to August), the total illuminance in the north zone of the atrium are only diffuse daylight from the sky (confirmed by Figure 4.14(b)). Large variations of the daylight over the space can be observed for the upper floors of the atrium (8th -10th fl.)

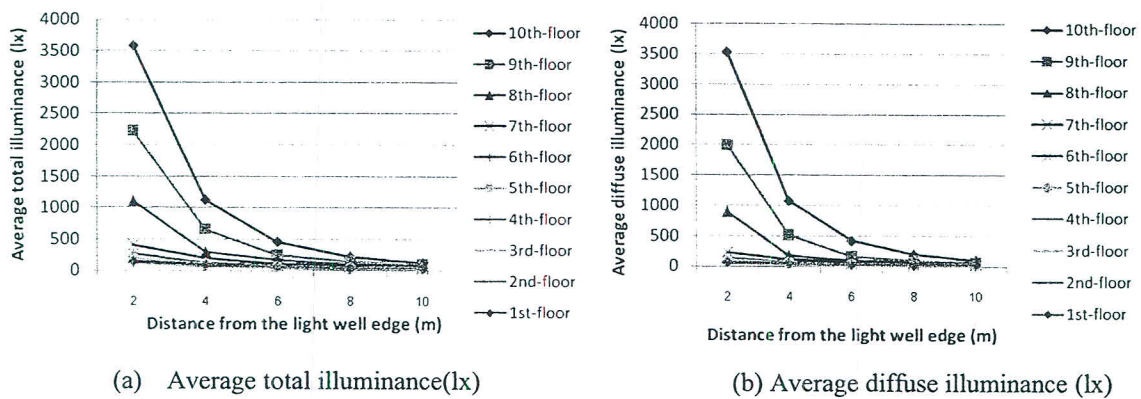


Figure 4.14 Average illuminance on the north zone (the sun stays in the northern hemisphere)

In the figure, it can be observed that for the lower floors (1st-6th fl), daylight distributions are more uniform. The average total illuminance on the lower floors at 2 m. apart from the well edge is not over 500 lx for year-round.

Figure 4.15 is similar to Figure 4.14 but presented for which the sun stays in the southern hemisphere. The figure demonstrates that the average total illuminance at 2 m. on the top floor apart from the well edge is about 8,500 lx and decrease exponentially to about 250 lx

at 10 m. deep. During this period is about eight months a year (from September to March), the direct sunlight contributes to the total interior daylight in the north area in the atrium. It causes higher total illuminance almost two times compared with previous case (especially for the upper floor of atrium).

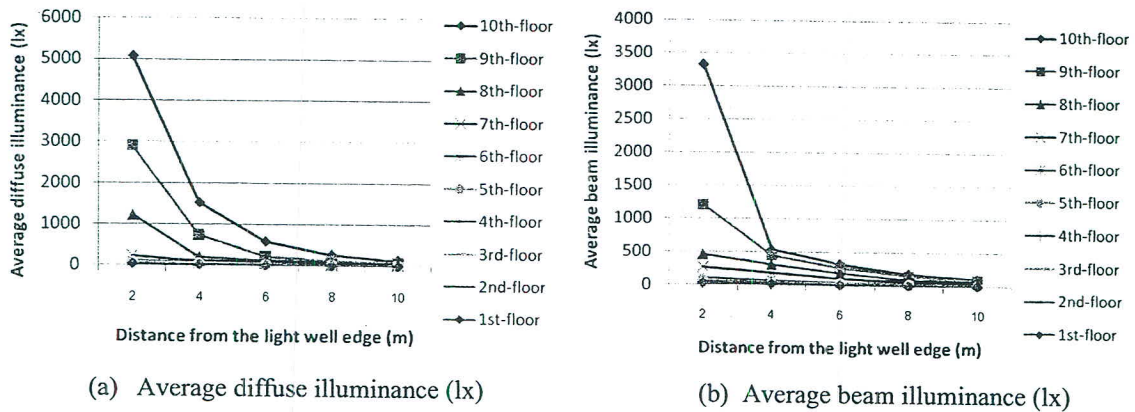


Figure 4.15 Average illuminance on the north zone (the sun stays in the southern hemisphere)

Both of the beam and diffuse illuminance have highly effect on interior daylight illuminance on the upper floors (8th fl.-10th fl.), causing their illuminance high accordingly. For the middle floors (4th fl.-7th fl.) to the lower floors (1st fl.-3rd fl.), the diffuse and beam illuminance values of the daylight are within a range of 10-120 lx and seems to decay linearly from the well edge to the rear walls of the space. It is observed clearly that the average daylight illuminance values are different and are influenced highly by the transverse of the sun and the anisotropic luminance distributions of the apparent skies.

The daylight in the zone was also evaluated in terms of the useful daylight illuminance (UDI). The UDI is defined as the percentage of occurrence of the daylight within a useful range of 100-2000 lx. UDI values were calculated for each measurement points in the zone.

Figure 4.16(a) exhibits UDI values when the sun stays toward the north. The UDI values of the point close to the light well edge (at 2 m.) on the top floor are much lower (14%) due to the excessive daylight. For points further away e.g. 4 m. and 6 m. respectively from the edge, the UDI values are higher than 90% on the ninth and eighth floors. The UDI values

at 8 m. and 10 m. of the tenth floor is about 95% and 70% respectively and that of the ninth and eighth floors become lower to 75% and 60%, respectively. The upper floors of the building (eighth to tenth floor) demonstrate the effective daylighting zone. Because of daylight penetration, the UDI values of the lower floor (the first to fourth floors) at 2 m. from the light well edge is about 30-40% but for deeper point (4 m, 6 m, 8 m and 10 m) show UDI values less than 20% thought out a year. Thus, ineffective areas need to add artificial lamps in order to meet daylight requirements.

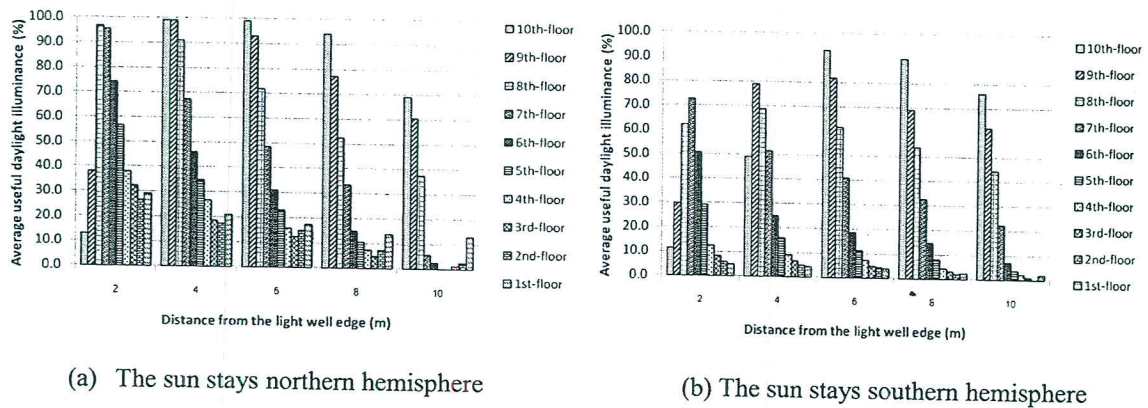


Figure 4.16 UDI in the north zone

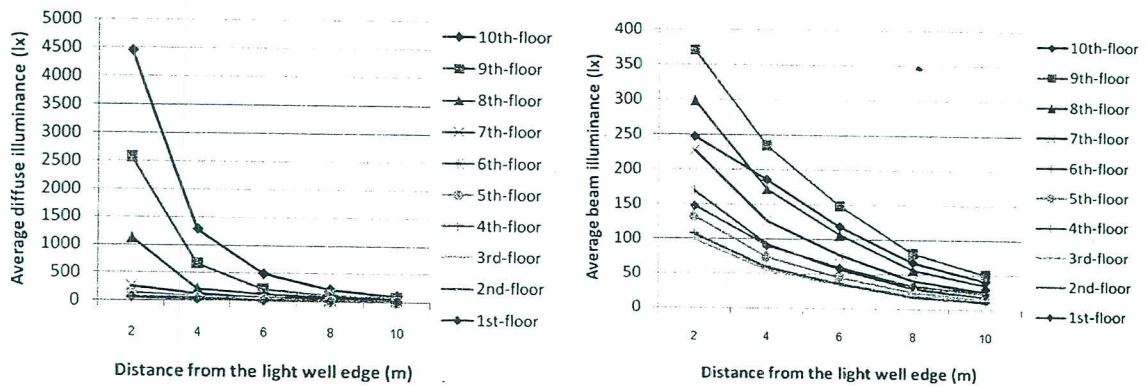
The UDI values when the sun stays in the southern hemisphere are shown in Fig. 4.16(b). It shows lower UDI values than when the sun stays in the northern hemisphere because the northern area of building is impacted by direct sunlight caused excessive daylight illuminance during that period. The upper zone of building also received better quality of daylight illuminance, in range 50-90% UDI, more than lower zone which less than 10% UDI for all calculation points. From the observation, the UDI values of the lower floor become higher when the sun stays northern hemisphere because the direct sunlight can penetrate deeper than it stays southern hemisphere. Overall, UDI vales in this zone are higher when the sun stays in the northern hemisphere.

4.2.2 Daylight in South Zone

Figure 4.17 illustrates the plot of average daylight illuminance in the south zone when the sun stays in the northern hemisphere. The plot shows that the daylight in the zone is dominated by the diffuse light from the sky. On the 10th floor, the diffuse daylight is high

upto 4,500 lx near the well edge. The diffuse light near the well edge drops dramatically for the lower floors (1st-7th floor). Figure 4.17(b) show the contribution of the sunlight in the south zone. The maximum average sunlight is just 370 lx.

Figure 4.18 illustrates the daylight in the south zone when the sun stays in the southern hemisphere. The daylight in the zone during this period is just slightly lower than the previous. This is because the sunlight does not influence much in the zone. It should be noted that the illuminance in figure 4.18 is the total interior daylight illuminance. For middle to lower floor (1st -7th fl.), the illuminance and its distribution on the north and south zones are similar throughout the year (comparing Fig. 4.18 and Fig. 4.15) shows that the total daylight illuminances are not over 500lx.



(a) Average diffuse illuminance (lx)

(b) Average beam illuminance (lx)

Figure 4.17 Average illuminance on the south zone (the sun stays in the northern hemisphere)

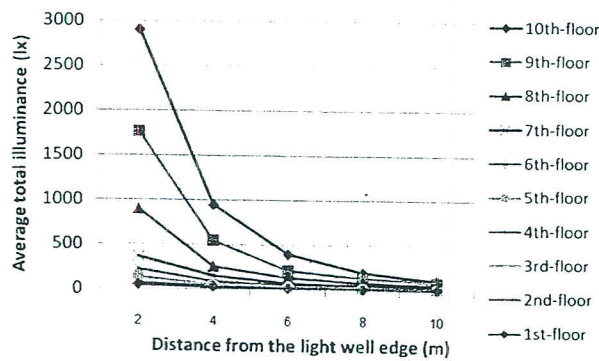
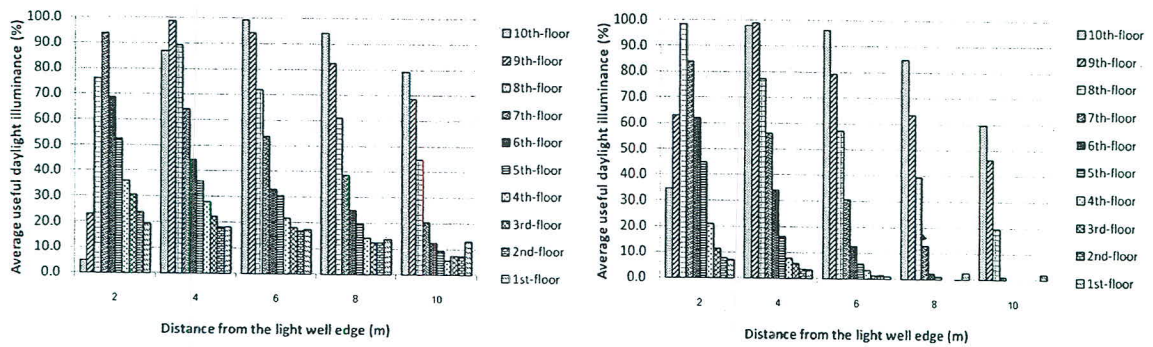


Figure 4.18 Average total illuminance on the south zone (the sun stays in the southern hemisphere)

The south zone of the atrium floors shows higher UDI values when the sun heads towards the north as shown in Fig. 4.19. Near the light well edge (2 m.), the UDI values of the fifth to eighth floors vary from 50% to 90%, except the ninth and tenth floors receiving excessive illuminance from direct sunlight. For points further away 4 m. and 6 m. respectively from the edge, the UDI values of upper floor zone (seventh to tenth floors) are in range of 55%-100%. At 8 m. and 10 m., the upper floor zone also shows high UDI values. The UDI values when the sun stays northern hemisphere close to that when the sun stays southern hemisphere. On the other hand, Fig. 4.19 also suggests clearly that the UDI values of lower floor zone (the sun towards north) become higher.



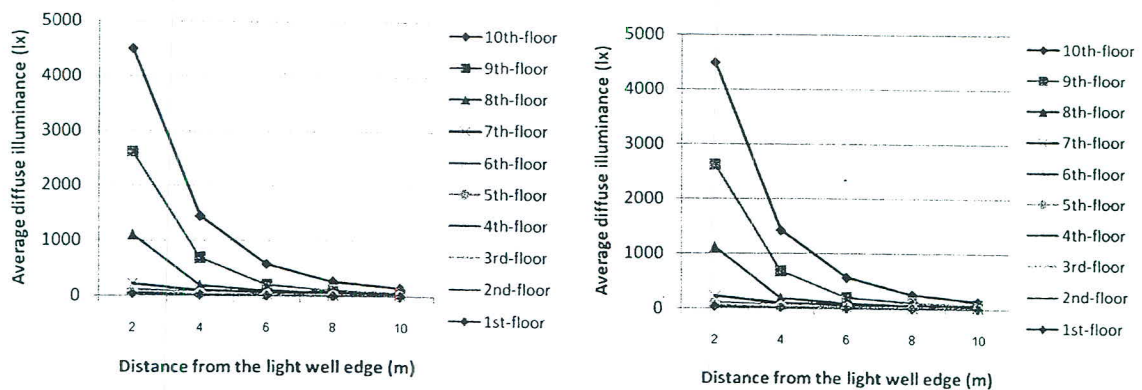
(a) The sun stays northern hemisphere

(b) The sun stays southern hemisphere

Figure 4.19 UDI in the south zone

4.2.3 Daylight in East and West Zone

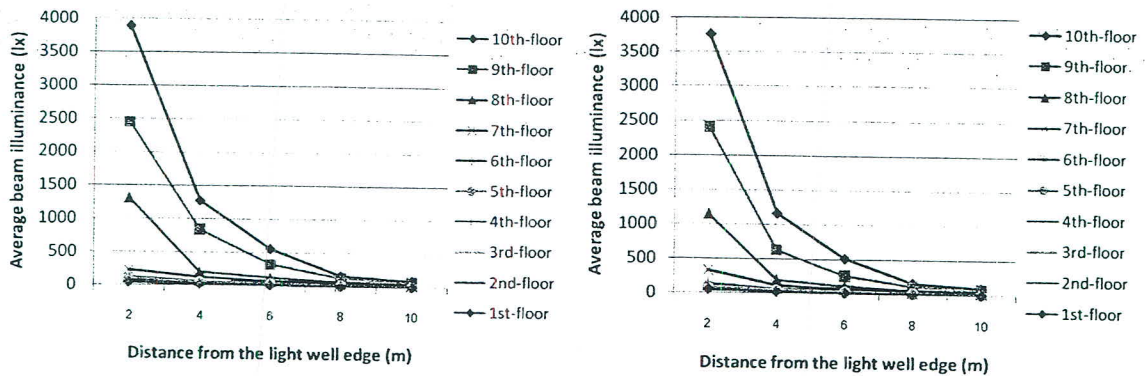
Whether the sun stays in the north or the south, daylight in the east and the west zones are influenced by both the diffuse and beam daylight for any day. Figures 4.20 and 4.21 illustrate the diffuse illuminance and the beam illuminances in the east and west zones, respectively.



(a) East Zone

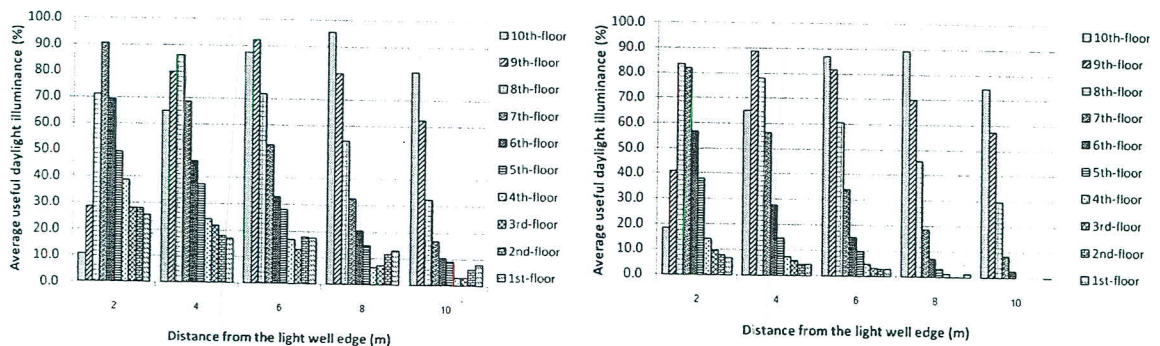
(b) West Zone

Figure 4.20 Average diffuse illuminance on different floors



(a) East zone (b) West zone
Figure 4.21 Average beam illuminance on different floors

The plot shows that the contributions of the two daylight components are quite comparable. It can be expected that the maximum day illuminance on both areas at 2 m. on the top floor is approximately 8,500 lx (the sum of the diffuse and the beam components). Figure 4.22 exhibits the UDI values of the east zone. The UDI in the west zone is quite comparable.



(a) The sun stays northern in the hemisphere (b) The sun stays in the southern hemisphere
Figure 4.22 UDI in the east zone

In the figure, on the upper floor, the UDI values of zone also show similar UDI levels as northern and southern areas for entire year. In conclusion, the quality of daylight for the lower floor zone is quite low especially when the sun stays southern hemisphere. During that period about eight months for a year, the sun cannot penetrate deeply to the lower zone of building so artificial lamps need to be required to increase illuminance levels. To achieve effective daylight use in east and west zones, the floor area should be higher than 7th floor.

The results of the daylight distribution of the rectangular light well of the atrium building (shown in Appendix E) also shows the same distribution patterns for both the sun stays in the northern and the southern hemispheres. Figure 4.23 to Figure 4.25 illustrate the yearly average illuminance by comparing two types of light well; rectangular and square light well. The results show that the total illuminance of rectangular light well on the topmost floor (10th fl.) at 2 m. apart from the well edge is about 8,600 lx. Its illuminance values then decrease exponentially to about 500 lx at 10m. apart from the well edge. For the base floor, the total illuminance level at 2 m. from the light well. The comparable results of daylight distribution suggest that the more size of light well increases, the higher daylight illuminance levels gain. According to the plot of rectangular light well, the total illuminance levels of base floor could reach to 260 lx and 160 lx far away 2m. and 4m., respectively from the light well edge. Both effects of beam and diffuse illuminance have an influence on total daylight illuminance on the base floor or lower floor.

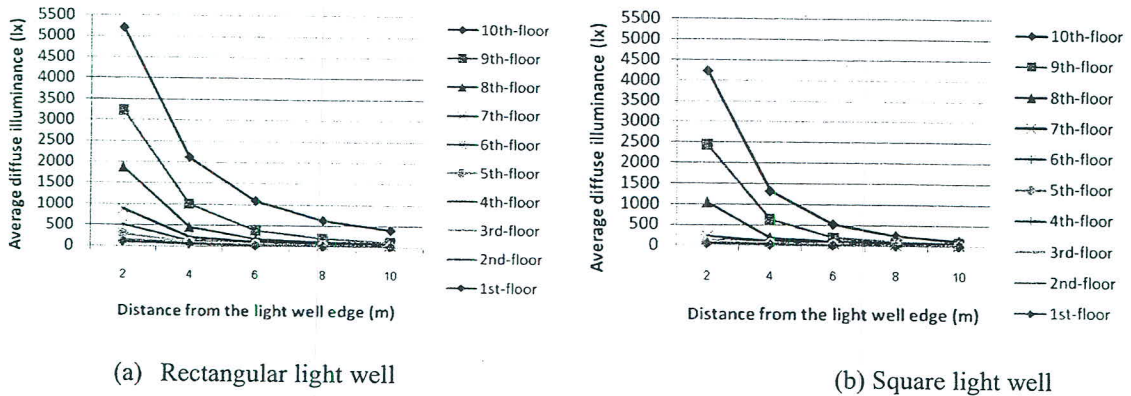


Figure 4.23 Yearly average diffuse illuminance

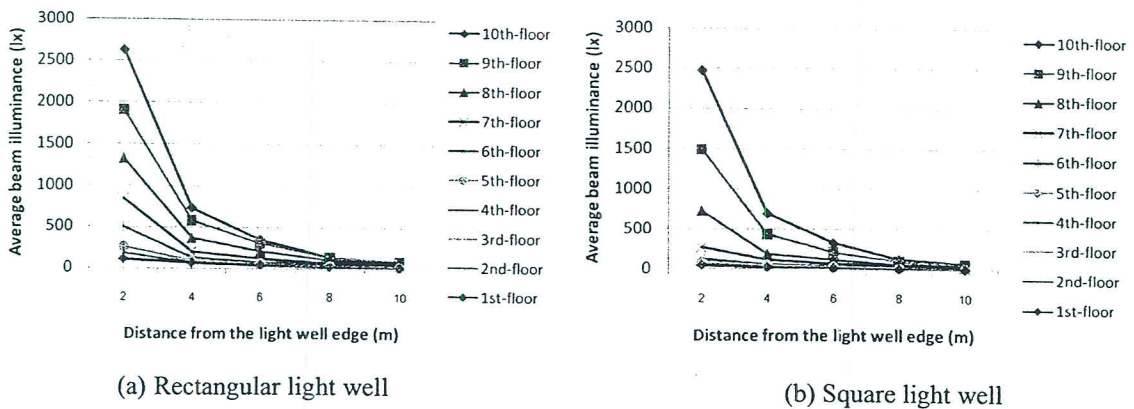


Figure 4.24 Yearly average beam illuminance

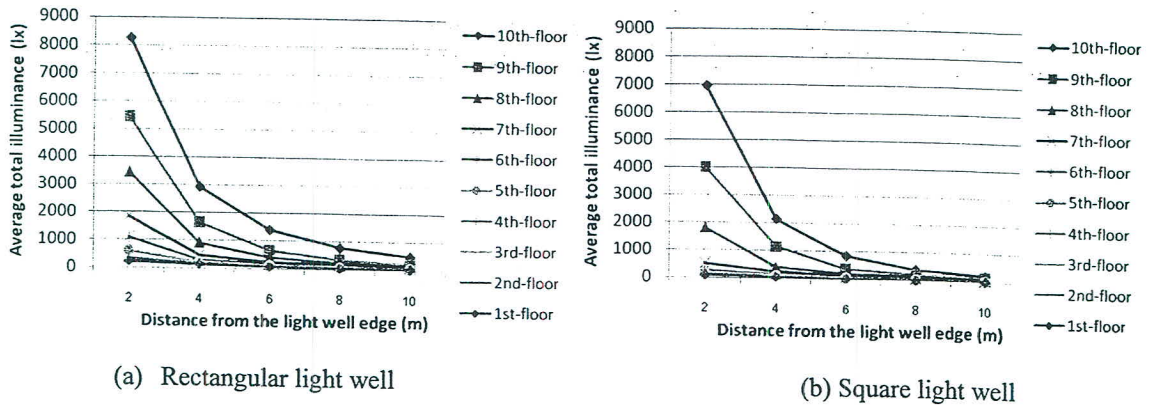


Figure 4.25 Yearly average daylight illuminance

Figure 4.25(a) exhibits the corresponding average values of useful daylight illuminance (UDI) over the floor area of rectangular light well. It shows the similar trend of percentage of UDI as square light well but higher values of illuminance.

On the top floor or upper floors (7th fl.-10th fl.), the UDI values of the points close to the light well edge (2 m.) are much low (10-20%) due to the excessive daylight. For deeper points (4 m, 6 m, 8 m, and 10 m) from the light well edge, the UDI values are higher than 80% indicating the effective daylighting zone. The UDI values of rectangular light well becomes higher than square light well for every point of the lower floor (1st fl.-3rd fl.). The results suggest that the size of light well have a highly effect on daylight illuminance level and its distribution.

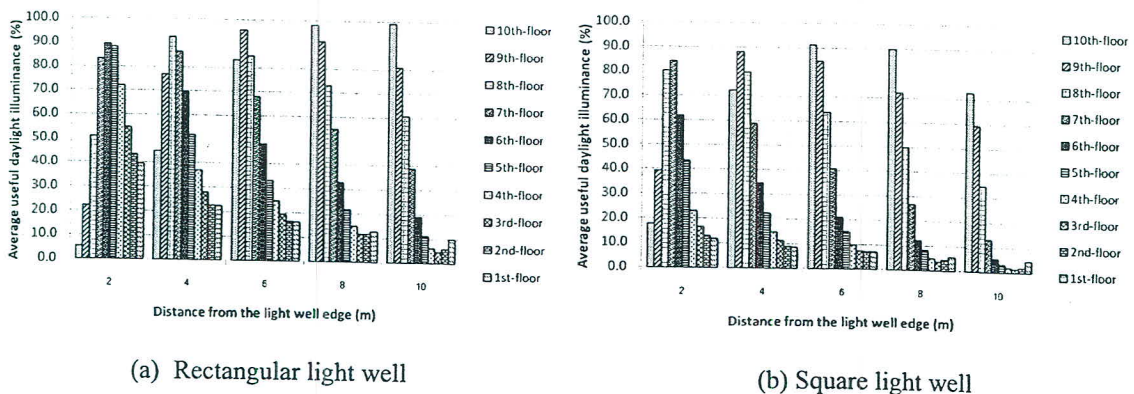


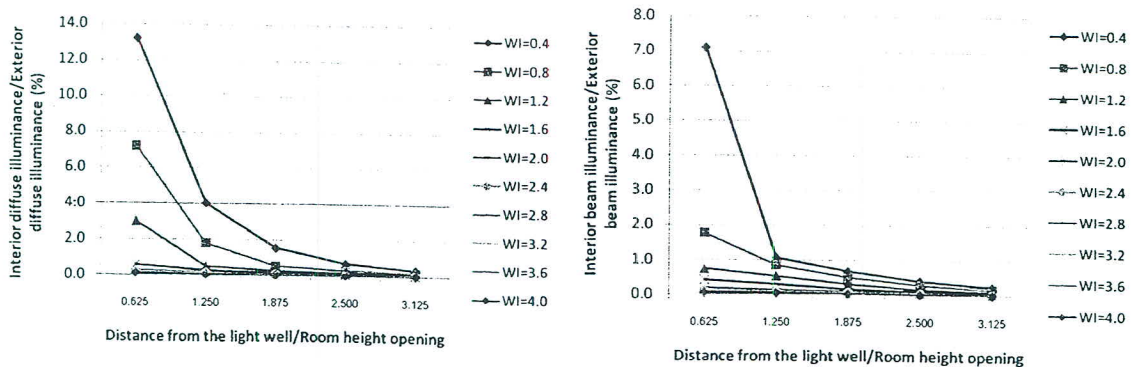
Figure 4.26 Average useful daylight illuminance

4.3 Relationship of Interior to Exterior Daylight Illuminance

In this section, relationships between interior daylight illuminance (E_i) and its corresponding exterior daylight illuminance (E_o) were examined. The analysis was made for each of the zone. The results from this section are expected to be used to facilitate the prediction of the illuminance in the atrium.

Figure 4.27(a) exhibits the ratio of interior diffuse illuminance (E_{di}) to exterior diffuse illuminance (E_{do}) as functions of the well index and the ratio of distance from the well edge to the floor-to-ceiling height for the north zone. The values of E_{di}/E_{do} were presented for the whole year (not separate for which the sun stays either north or south). In the figure, it is observed that for shallow atrium ($WI=0.4$), the diffuse daylight at the well edge is approximately 13% of the exterior diffuse daylight. For the atrium with WI exceeding 1.6, the interior diffuse illuminance should not be greater than 1% of its corresponding exterior diffuse illuminance.

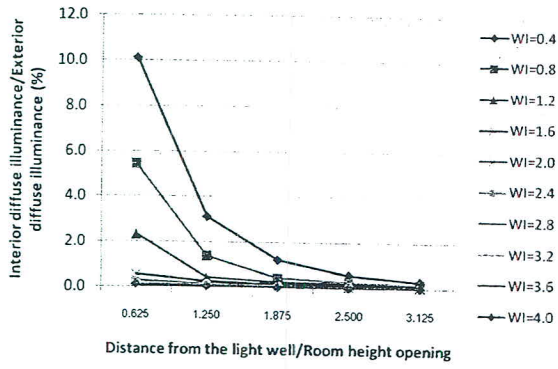
Figure 4.27(b) exhibits the ratio of interior to exterior beam horizontal component of the daylight in the atrium. It can be seen from the plot that for shallow atrium building ($WI=0.4$), the beam daylight contribute significantly to the interior daylight in the north zone near the well edge. The ratio of E_{bi}/E_{bo} values can be high upto 7%. For atrium with WI greater than 1.2, values of the ratio E_{bi}/E_{bo} are less than 1%. Figures 4.27(c)-(h) exhibit the illuminance ratio for the south, east and west zones, respectively.



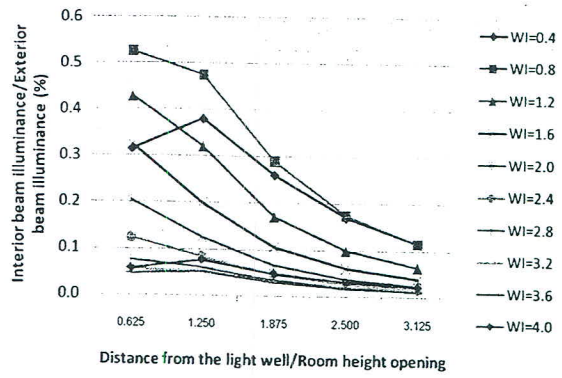
(a) Diffuse component (North)

(b) Beam component (North)

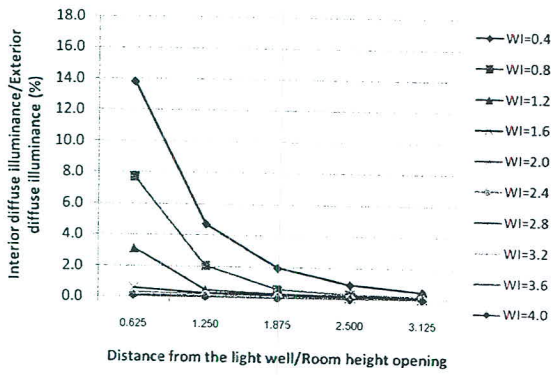
Figure 4.27 Ratio of interior to exterior daylight illuminance of square light well



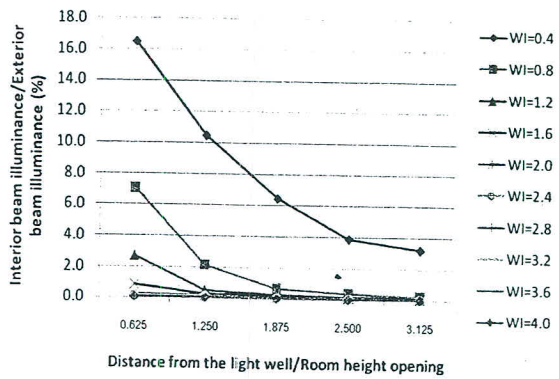
(c) Diffuse component (South)



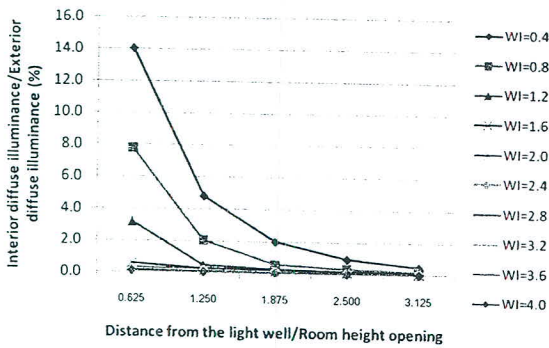
(d) Beam component (South)



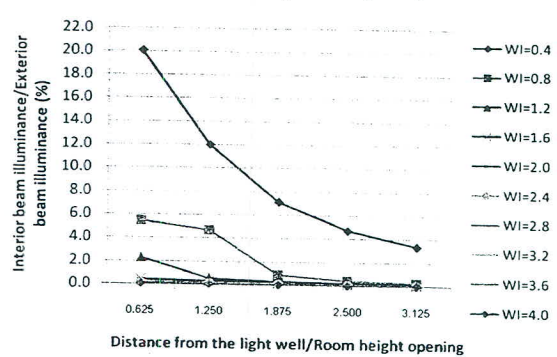
(e) Diffuse component (East)



(f) Beam component (East)



(g) Diffuse component (West)



(h) Beam component (West)

Figure 4.27 (Continued)

4.4 Relationship of Well Index and Skylight Transmittance and UDI

Figure 4.28 exhibits the relationship between average total illuminance and well index (WI) at transmittance value equal to one for different distances from the light well edge. The average total illuminance values in the graph were derived by averaging the total illuminance values of all four zones (north, south, east and west). The maximum average

interior daylight illuminance can be determined when the dimensions of the light well and distance are known.

Figure 4.29 exhibits the relationship between skylight transmittance and WI at the maximum UDI. With the graph, it is possible to determine the proper skylight transmittance at the maximum UDI value for every point of the buildings. At maximum UDI, the points near the light well require very low skylight transmittance in order to reduce excessive daylight. On the contrary, the deeper points and higher WI need high skylight transmittance value. Both graphs produced rapid evaluation of interior daylight illuminance for different WI in order to take advantage of the natural light as much as possible.

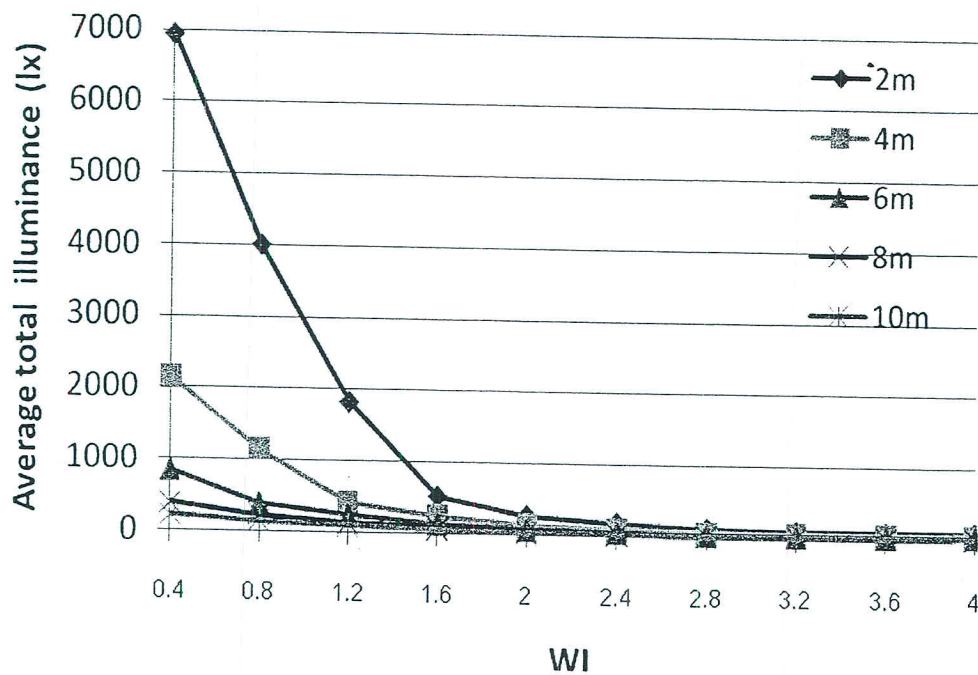


Figure 4.28 Relationship between average total illuminance and WI at T=1

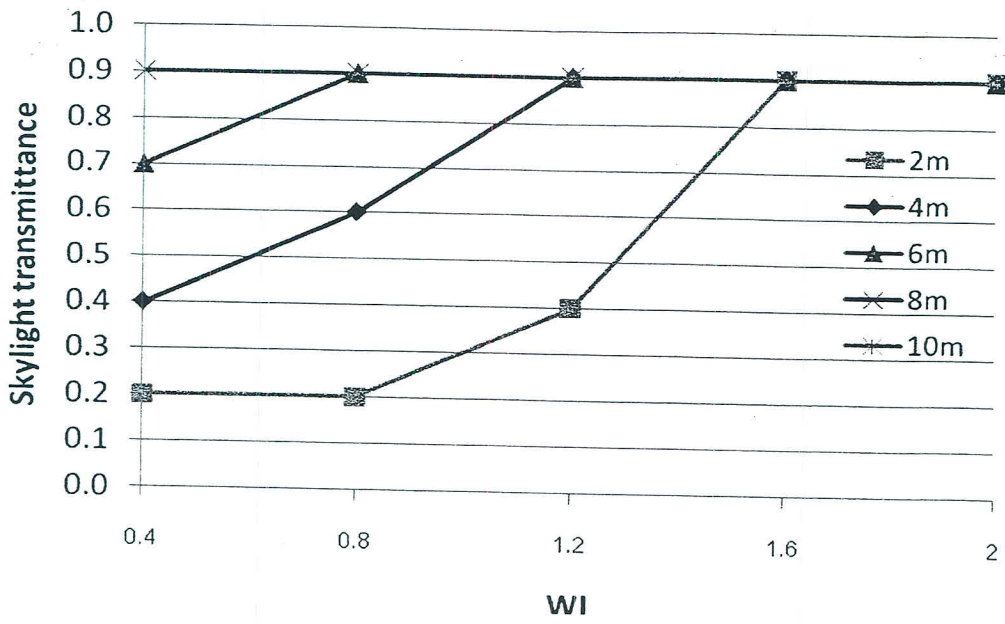


Figure 4.29 Relationship between skylight transmittance and WI at maximum UDI