

THE DAYLIGHT PERFORMANCE OF CENTRAL ATRIUM BUILDING

Jatmika A Suryabrata*

ABSTRACT

A computer based simulation study was carried out to investigate daylight performance in a hypothetical four-sided atrium building (a typical commercial office). The analysis of the results was carried out in terms of daylight components, i.e. the Direct Component (DC), the Externally Reflected Component (ERC), and the Internally Reflected Component (IRC). By decomposing the daylight distribution into its components, the behavior of the daylight in the atrium space could be determined.

The results reveal relatively insignificant contribution of the DC from the sunlight and sky-vault despite the presence of the sun (clear sky condition). This is mainly due to the limited penetration of the DC into the lower floor and the deeper parts of the office spaces. Consequently, various atrium proportions and atrium axis orientations investigated in this study did not significantly modify the overall daylight performance. This suggests that geographical latitude may not have significant effect on the overall daylight performance in an atrium building. The results also reveal a potential energy saving by considering electric lighting as a supplemental system to the daylighting system.

INTRODUCTION

The Energy Conservation Issues

It is widely recognized that one of the most effective ways to increase energy efficiency in a commercial building is to minimize the lighting load (Selkowitz and Johnson 1980). In industrial countries, which their climates are predominantly "warm-humid", 40% of the annual energy consumption goes to lighting (Collins 1977; de Boer 1982; Jarmul 1980; Turiel 1981). In developing countries with constant warm-humid climatic conditions, such as Indonesia, HVAC system may consume more energy than electric lighting (Triyogo 1998). However, energy saving potential from electric lighting is still promising due to the much greater adaptation capability of the human visual system compared to that of thermal comfort system (Flynn et al. 1988).

Apart from state of the art design application which may moderately save energy (Suryabrata 1998), the direct alternative for energy saving is using highly efficient light sources (de Boer 1982). Another alternative, which currently regains its popularity, is daylighting systems. Results from various studies have shown that state of the art daylighting design could reduce electrical consumption for lighting by 35% -50% (Selkowitz and Johnson). In addition, due to the greater luminous efficacy of daylighting compared to that of most available lamps (Moore 1985), daylighting can be used as a strategy to reduce space cooling load leading to lower energy consumption for HVAC system (Chase 1977).

Energy Saving Potential of Atrium Buildings

The primary reasons for using atria in modern architectural design are their ability to save energy and improve the quality of the buildings (Bednar 1986; Saxon 1987). Atrium buildings are often considered energy efficient compared to similar conventional buildings (Treado and Gillete 1986). The basic concept, in terms of daylighting, is to reduce the non-daylit core area and increase the "perimeter" zone by providing a large-sized aperture in the building core. Thus, like the building perimeter zone, the core zone also has access to daylight as well as to a view of the atrium space. Daylighting design for energy conservation is most suitable for institutional and commercial buildings, where high illuminances are required during the day. Atria can also be utilized as a thermal buffer space to modify extreme climatic conditions. Many options for passive and hybrid cooling have been proposed to further enhance the energy savings (e.g. Cook 1989; Konya 1980; Nary 1981).

Daylighting Using Atria

In general, daylighting analysis in atrium buildings can be organized around three major considerations: admitting light into the atrium, distributing light within the atrium, and utilizing the light in the adjacent occupied spaces (Bednar 1986; Robbins 1986; Saxon 1987). Studies have been carried out using scale model and real buildings to investigate, for example, various fenestration (Navvab

* Ir. Jatmika A Suryabrata, MSc., Department of Architecture, Faculty of Engineering Gadjah Mada University

and Selkowitz 1984; Treado and Gillete 1986), atrium proportions (Aschehoug 1986; Kim and Boyer 1986; Liu et al. 1991), atrium surfaces' configurations (Aschehoug 1986; Kim and Boyer 1986), and climatic conditions (Treado and Gillete 1986).

However, to simplify the analysis most of these studies were carried out under overcast sky condition, which is not always the case. Under clear sky condition, the presence of the sun causes highly non-uniform luminance distribution depending on the position of the sun. The much intense and the highly directional of the sunlight may significantly modify the luminance distribution on the atrium surfaces, which in turn may considerably affect the daylight illuminances in the occupied spaces adjacent to the atrium.

Experimental Objectives

Two important factors that determine the daylight distribution in the atrium space are atrium geometry and its surface reflectance. These factors govern the "pressure" that can be achieved, and thus how much daylight can be delivered into the bottom atrium floor and lowest story of the building (Bednar 1986; Robbins 1986).

The primary objective of the study is to determine the impacts of atrium proportions in terms of Plan Aspect Ratio (PAR) and Section Aspect Ratio (SAR) on the daylight distribution in the atrium space as well as in the office spaces adjacent to it. Standard CIE clear-sky condition was employed instead of overcast sky, where the presence of the sun in the sky dome has a greater impact on the daylight distribution in the atrium. The illuminance distribution was analyzed in terms of daylight components, so that the relative performance of each component can be distinguished. By decomposing the daylight components, the contributions of each atrium wall in distributing the light into the adjacent spaces can also be determined. This experiment was a part of a much larger study investigating not only the daylight performance but also thermal performance of atrium buildings.

METHODOLOGY

This study was a computer simulation experiment utilizing the DOE-2 (Lawrence Berkeley Laboratory 1980) and SUPERLITE (Lawrence Berkeley Laboratory 1985) computer programs. Since the main purpose of the experiments was to determine the relative performances of the variables being

investigated, computer simulation best suits the objective of the study. Besides its cost effectiveness, computer simulation allowed investigating as many models as needed with a reasonable accuracy.

The DOE-2 was used to determine the average annual daylight performance and energy saving, while the SUPERLITE was employed to investigate the behavior of daylight in the atrium and interior spaces. The daylighting simulation results from both computer programs were cross-checked to determine the accuracy of the results.

The input process for the SUPERLITE computer program is quite simple, where each interior surfaces must be geometrically defined. In addition, the material properties of the interior surfaces, which can modify the behavior of the daylight distribution (e.g. reflectance, etc.), must also be defined in detail. On the other hand, input process for the DOE2 computer program is quite complicated since numerous factors must be defined simultaneously. However, as presented in Figure 1, the simulation process on DOE2 computer software can be roughly organized into four stages: loads, systems, plant and economics. Detail reports of building performance can be obtained at each simulation stage.

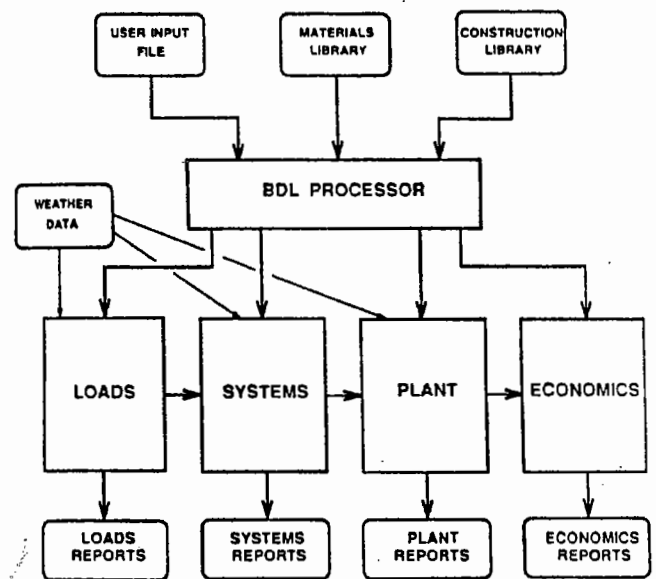


Figure 1. DOE2 Program Flow (reprinted from Lawrence Berkeley Laboratory 1980)

The Simulated Atrium

The simulated atrium building was perceived as a typical office building so that it met all of the standard requirements of office buildings, including building

materials and construction, indoor design temperature, lighting systems and building schedules. The building was simulated with six different thermal zones as shown in Figure 2. Thus, the results could be analyzed in terms of each space zone and total core zone (i.e. all spaces adjacent to the atrium) performances. The "base case" was assumed to have PAR and SAR of 1:1. Four different PARs (i.e. 1:1, 1:2, 1:3 and 1:4) with two orientations (i.e. south-north and east-west) and six SARs (i.e. 1:0.5, 1:1, 1:1.5, 1:2, 1:2.5, and 1:3) were simulated to investigate the effects of atrium proportions on daylight and thermal performances.

The measurements were taken at the center of each office space, 2.5 m from the windows. The results represent daylight performance near the window areas, which are highly influenced by sun positions and atrium surface geometry. The results show that illuminances across different space orientations (zones) were relatively similar. Higher illuminance fluctuations due to different orientations were found only on the top floor. This is readily understandable since the non-uniformity of the sky-dome (due to the presence of the sun) only affects areas that are exposed to it. The results also show that the illuminances drop off rapidly across different floor

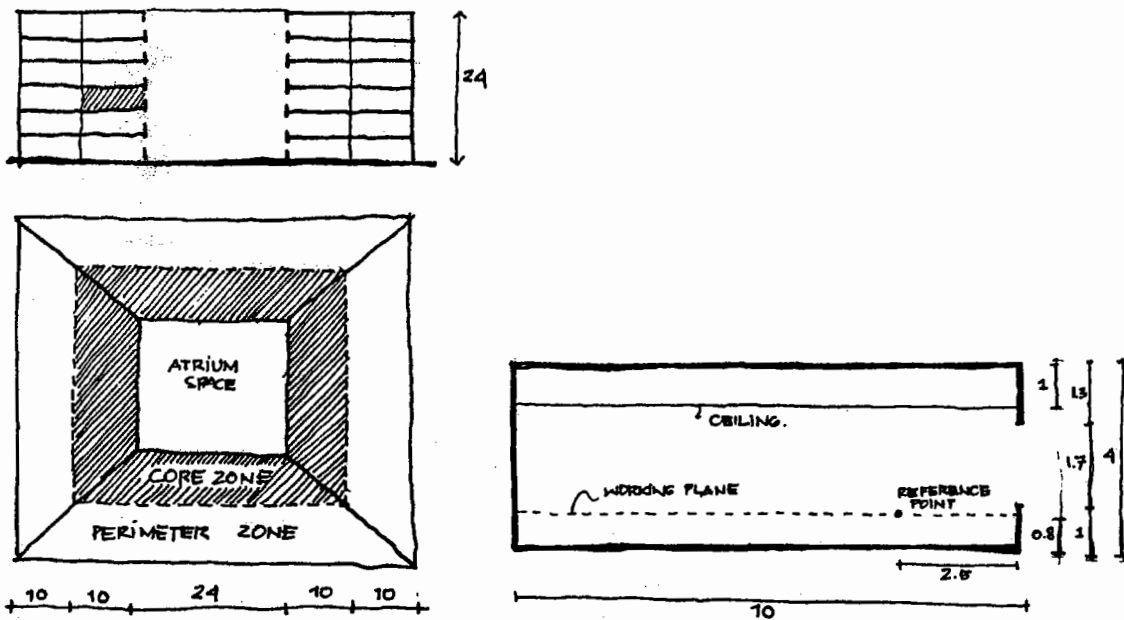


Figure 2. The atrium and typical office space geometry in the core zone

Various sun positions were investigated as part of the initial simulation to investigate the effects of daily and seasonal changes of the sun that commonly occurs in Indonesia. For the base case, however, the sun was simulated at a fixed 75° altitude and 10° west of north. This sun position was selected to represent high sun altitude angle around noon in Indonesia, where deep penetration of the daylight into the atrium space may enhance the effects of atrium geometry being investigated.

RESULTS AND ANALYSIS

The total daylight illuminances (lux) in each floor level and space zone are presented in Figure 3.

levels. The total illuminances at the 1st floor were found only about 50% that of the 6th floor. However, even for the lowest case, the daylight illuminances were found much higher than that of recommendations for general office spaces. IESNA recommends maintained illuminance of 500-lux (Kaufman and Haynes 1993) while that of Australian Standard suggests 400 lux for general office tasks (Australian Standard 1990). This suggests a potential energy saving through proper utilization of daylight in offices by considering the electric lighting system as a supplemental system. Automatic switching can be employed to activate the electric lighting only when the daylight illuminance fall below the specified level.

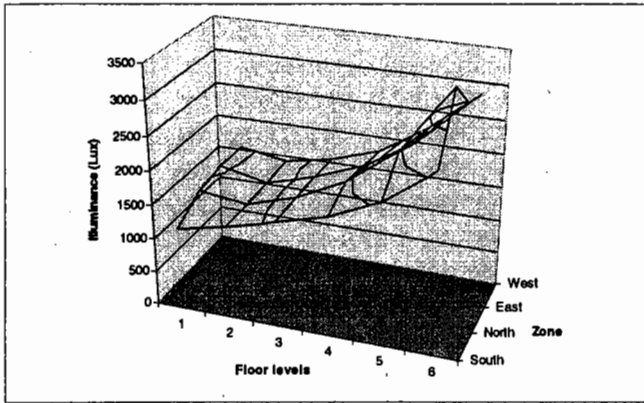


Figure 3. Total daylight illuminances near the windows' areas

The Daylight Component Distributions

To further analyze how the atrium delivers daylight into the office spaces, daylighting analysis can be broken down into its separate components, namely: Direct Component (DC), Externally Reflected Component (ERC), and Internally Reflected Component (IRC) (Robbins 1986). DC is daylight component that reaches the reference point (e.g. the working

plane in the office space where the measurement is taken) consisting of diffused sky component and direct solar illuminance. ERC is defined as daylight component that is reflected off the atrium walls before it reaches the reference point while the IRC is the one that is reflected off the interior office surfaces before it reaches the reference point.

Summary of the results concerning the relative contributions of each daylight component (in percent) on the total daylight distribution in each floor level is presented in Figure 4. As can be seen in Figure 4, the DC (which is greatly influenced by the sky luminances) had a relatively high contribution in fifth and sixth floors. The DC illuminances drop off rapidly in the lower levels and its contribution were negligible in the first and second floor. The relative contributions of the ERC and IRC components, on the other hand, were greater at lower floor levels. Overall, the Direct Component contributed only 31% of the total illuminances received in the office spaces near the windows. Most of the DC was distributed in the fifth and sixth floor. The Internally Reflected Component contributed 48%, and the Externally Reflected Component delivered the remaining 21%.

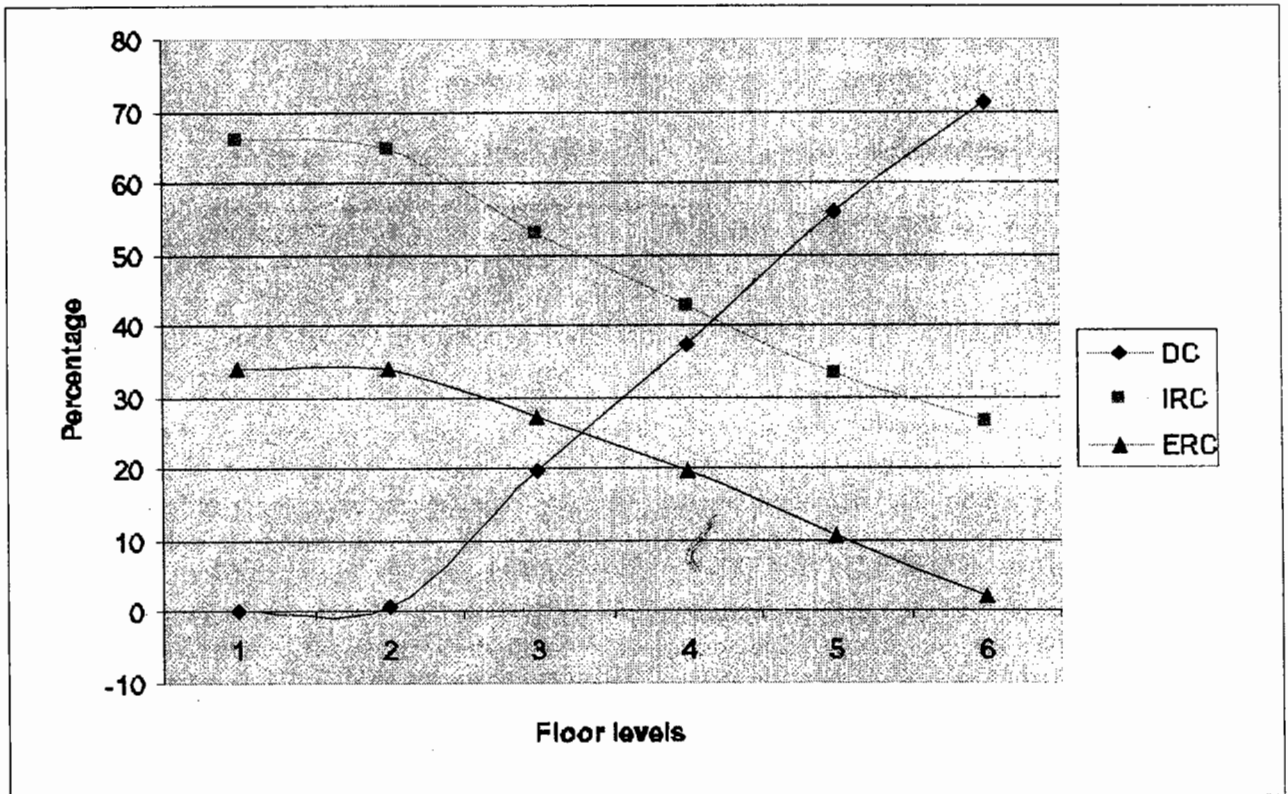


Figure 4. Relative contribution of the daylight components on the overall daylight illuminances in each floor level.

The above results signify the importance of the atrium and office space geometry and reflectance in modifying the daylight performance in atrium buildings. To further investigate the contribution of each atrium surfaces in distributing daylight into the office spaces, the IRC was broken down into its separate components (i.e. daylight reflected by each atrium wall and floor). The results show that contributions of each atrium wall in delivering the light into the office surfaces were relatively similar. On the other hand, the importance of atrium floor in distributing the light into the different levels of office spaces was inversely proportional to that of atrium walls. As presented in Figure 5, the IRC component from the atrium walls had much higher percentage in the upper floors, while that of atrium floors delivered daylight mostly in the lower floors. This is hardly surprising, since the most important interior surfaces in distributing daylight into the office spaces is the ceiling (Moore 1985; Robbins 1986). Thus, the ceilings in the lower floor levels received daylight

mostly from the atrium floor, while that of higher floor levels received daylight mostly from the atrium walls.

It is stated earlier that the differences between atrium walls in distributing IRC in the office spaces are practically negligible. This is quite surprising since the presence of the sun in the sky dome should cause non-uniform luminance distribution on the atrium walls. However, further investigation concerning the behavior of the daylight in the atrium space indicated that much of the daylight did not directly distributed into the office spaces. In other words, a large portion of the daylight was inter-reflected in the atrium spaces before distributed into the office spaces. It was found that inter-reflection of daylight in the atrium space contributed 33% of the ERC. This has led to the negligible differences between atrium walls in distributing daylight into the office spaces, although some portion of the atrium walls received direct sunlight (hence, non-uniform atrium-surface luminances).

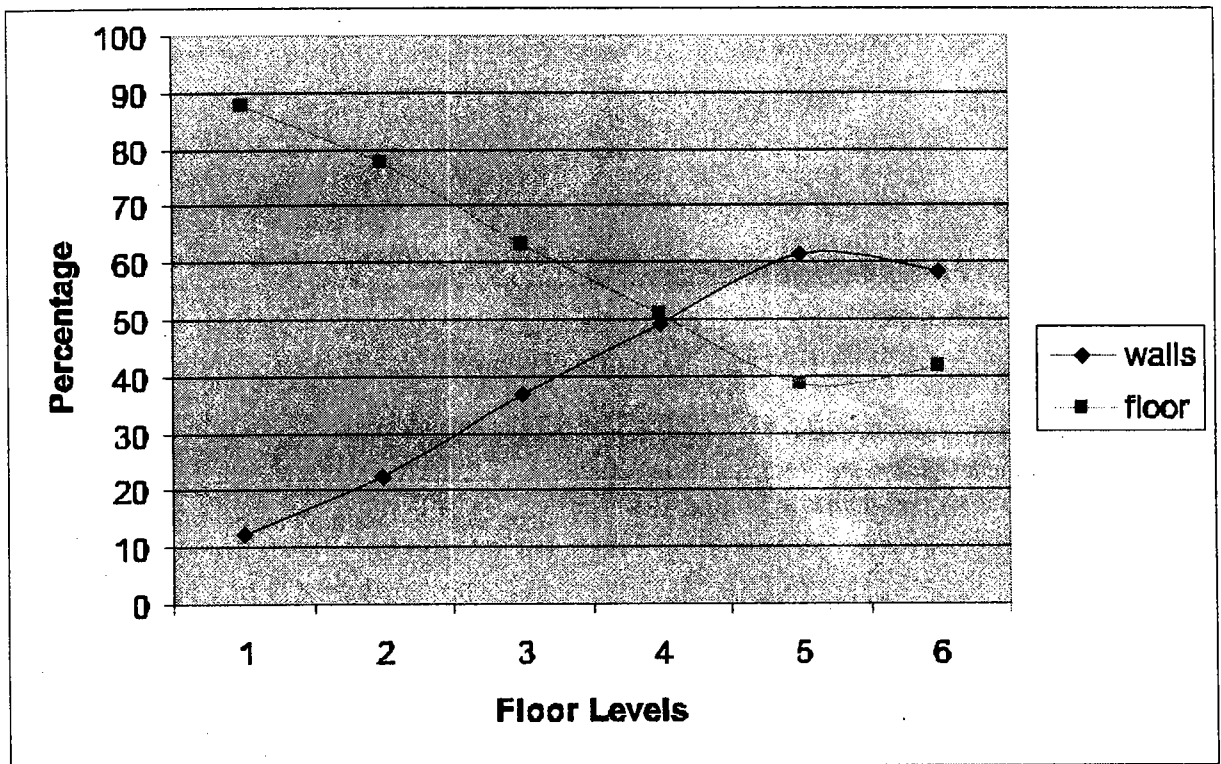


Figure 5. Relative contribution (percent) of the atrium surfaces in distributing IRC in the office spaces.

Daylight Distribution in the Office Spaces

To determine daylight performance in the office spaces, the daylight distribution component distribution across the office spaces were examined. Similar to that of illuminances near the windows, the differences of the daylight penetration into the deeper parts of the office spaces between different zones were found negligible. Therefore, only the average daylight illuminances from different floor levels (i.e. 1st, 4th and 6th) are presented in Figure 6.

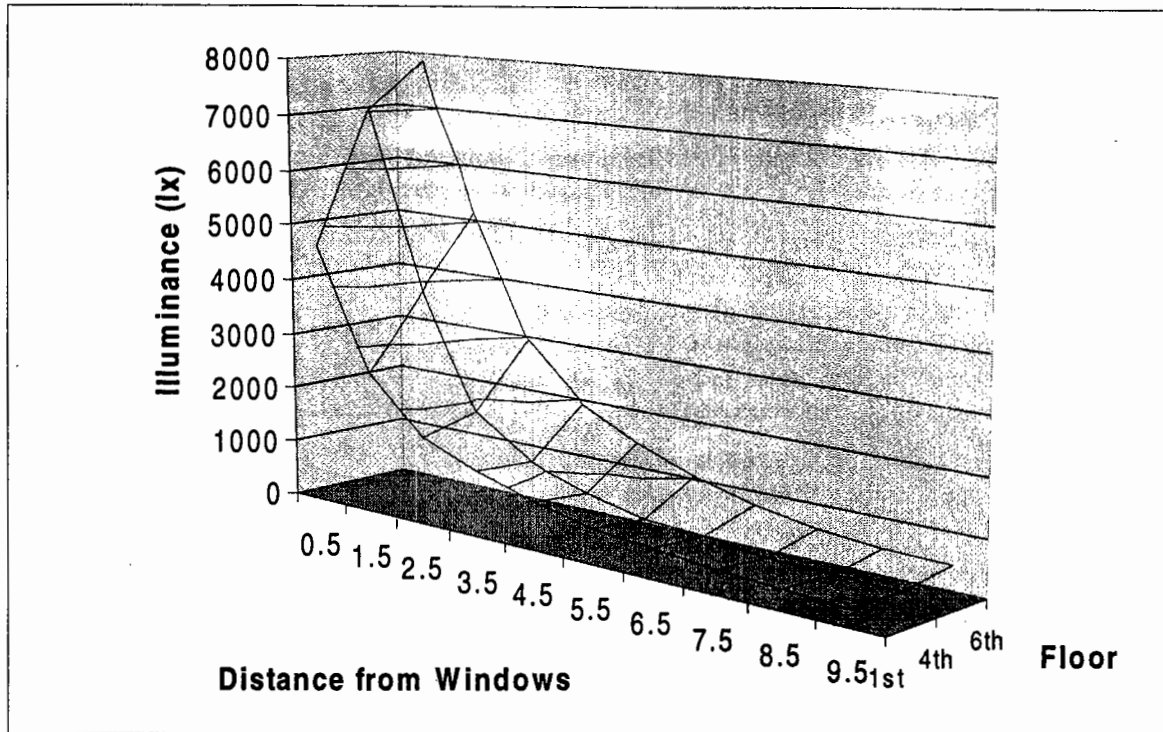


Figure 6. Average total daylight illuminance (lux) across the office spaces

The results reveal that the conventional atrium and office space geometry (see Figure 1) could not effectively distribute the available daylight into the deeper parts of the office spaces. This is obvious from Figure 5 revealing the sharply decline of the daylight illuminances further away from the windows. The results demonstrate a classic example of the main problem in a conventional sidelighting system where daylight illuminance uniformity can hardly be achieved (American Institute of Architect 1982; Robbins 1986). The illuminance ratios between the highest to the lowest were 1:17 in the sixth floor and 1:14 in the first floor, which clearly are much higher than some recommendations. It is suggested that to ensure comfortable luminous environment, the permissible horizontal illuminance ratio between working area and non-working area should be less than 1:3 (CIBS 1984; CIBSE 1993).

The problems of non-uniform distribution of the daylight were much more significant in the office spaces where DC could penetrate into the spaces (e.g. in the upper floors and areas near the windows). This suggests that DC may become a liability in daylighting design. The excessive illuminances and non-uniformity due to DC may cause discomfort glare, veiling reflection and other visual discomfort problems. In addition, admitting sunlight into the interior spaces may cause thermal discomfort and significantly increase the cooling load.

To further analyze the daylight distribution in the office spaces, the results are presented in terms of average daylight components, which graphically is shown in Figure 6. It is clearly seen in Figure 7 that the DC contributed greatly only in the areas near the windows, and most of these were located at the upper floors. The overall daylight performance in the lower floors and at the deeper parts of the office spaces, conversely, depended mainly on the IRC and ERC. Overall, the DC delivered 50% of the total daylight in the areas near the windows (e.g. up to 3.5 m from the windows). However, it can only contributed an average of 19% at the areas further from the windows. In other words, the overall daylight performance in the core zone was largely depending on the effective distribution of the ERC and IRC.

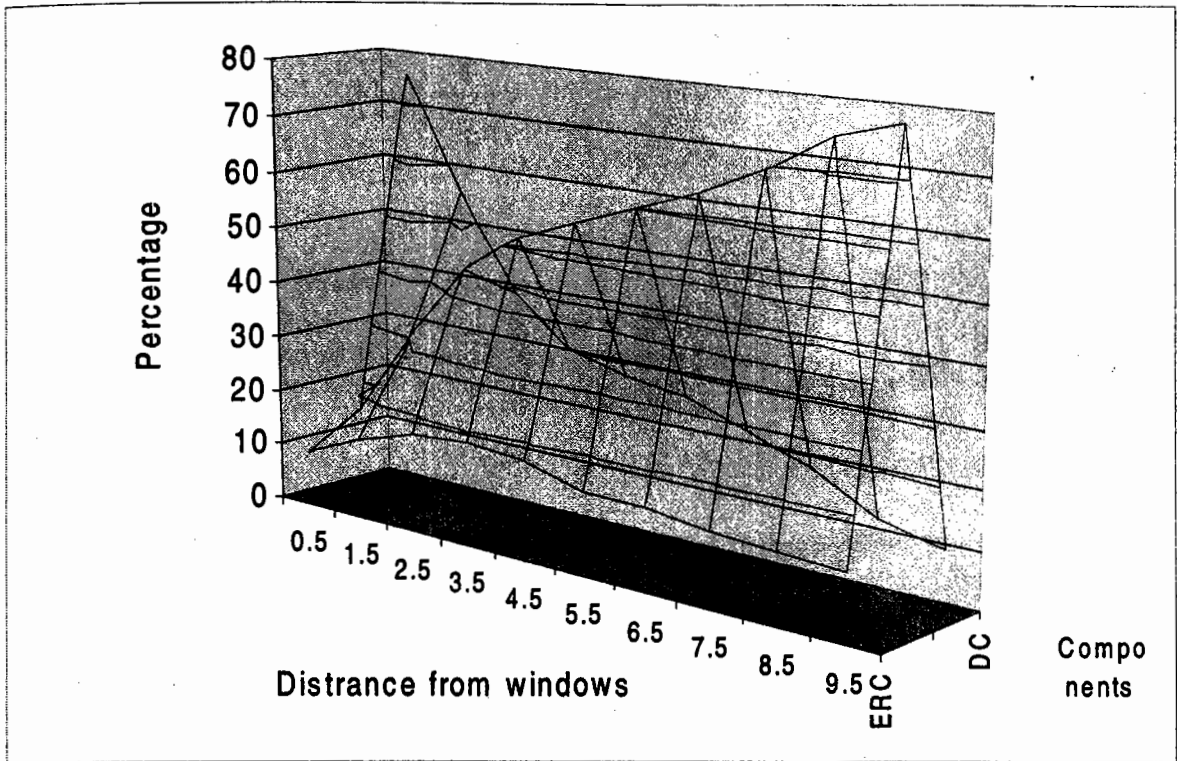


Figure 7. Average daylight component contributions (percent) across the office space

The Effects of Atrium Proportions

Limited space does not allow for a detail discussion of the results regarding the effects of various PARs and SARs. Therefore, the results are presented in terms of total daylight illuminance in the core zone. The results suggest that the effects of various PARs and atrium's axis orientations (i.e. north-south and east-west) on the overall daylight illuminances in the core zone were practically negligible. This, somehow, "unexpected results" can be explained from the findings concerning the behavior of each daylight components discussed previously.

It was expected that various PARs and atrium orientation would greatly modify the daylight penetration into the atrium space (thus, modify the atrium space luminances) leading to different daylight illuminances in the core zones. However, due to the limited contribution of the DC, the overall daylight

illuminances were not greatly modified by various PARs and atrium orientations. The inter-reflection of daylight in the atrium space, further reduce the effects of non-uniformity of the atrium surfaces on the daylight distribution in the core zone.

As expected, the taller the building is the lower the daylight illuminance that can be utilized in the core zone. This is readily understandable since taller atrium space limits the penetration of the daylight into the lower floors. The results show that increasing SAR from 1:1 to 1:2 reduced the total daylight illuminance by 33%. A further increased ratio to 1:3, brought about an additional 19% reduction in the average illuminances. As presented in Figure 8, the daylight illuminance reduction due to various SARs was mainly due to significant decreased of DC, while ERC was relatively constant. Overall, the results suggest that for maximum utilization of daylight, the Section Aspect Ratio should be lower than 1:1.

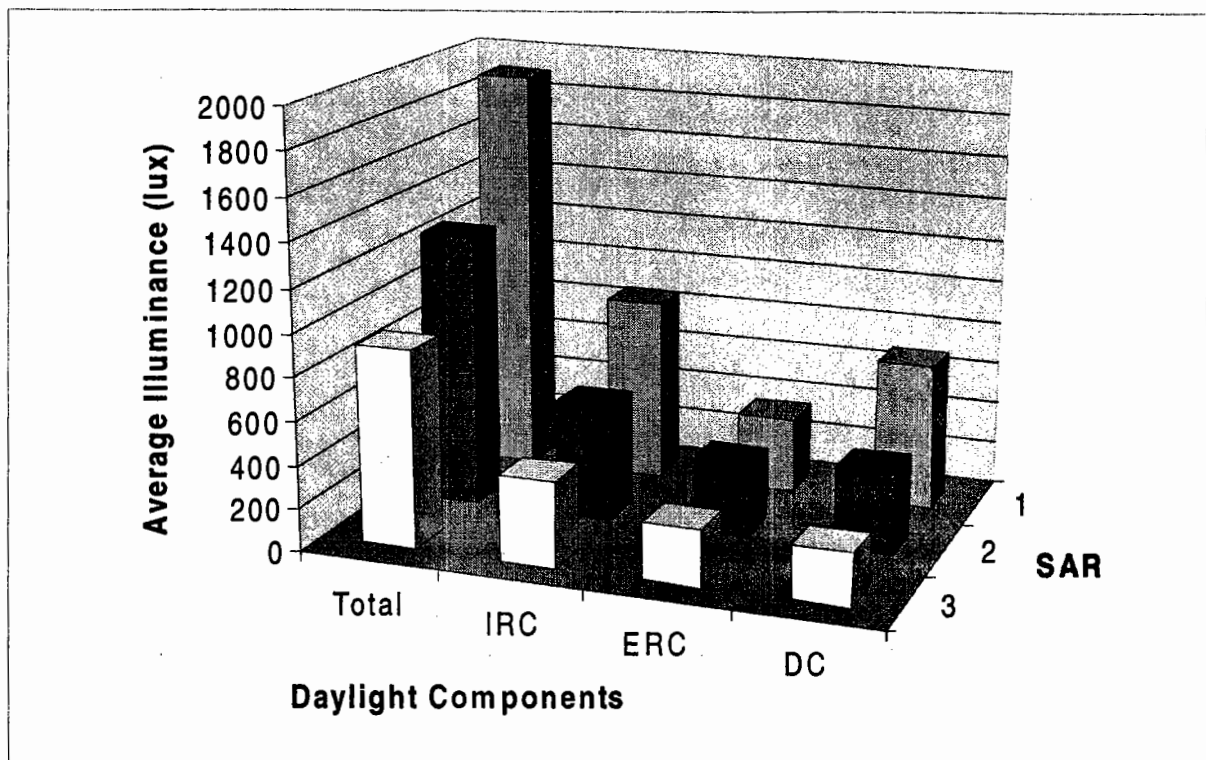


Figure 8. The effects of SARs on the average daylight components in the core zone.

Conclusion

A computer based simulation experiment was carried out to investigate the behavior of the daylight components in the atrium space as well as in the occupied adjacent spaces. The results show that DC from the sunlight and sky-dome has limited contribution to the overall daylight performance in the core zone. This partly explains the findings from previous studies that reveal the insignificant effects of geographical latitudes on the daylight performance in real atrium buildings (Treado and Gillete 1986).

However, the simulation results presented in this paper are strictly valid for the atrium geometry being investigated. For example, the atrium roof was assumed flat (see Figure 2) for simplification. Actual atrium buildings may use different types of roof geometry, which may alter the distribution of the daylight into the atrium space. Similarly, roof structures needed to support atrium aperture may considerably reduce the transmittance values of the atrium aperture, which in turn reduce the overall daylight performance in the office spaces.

The results also signify the importance of atrium surface geometry and reflectance in distributing daylight into the office spaces. For example, the findings from the present study show that a 20% increased in atrium surface reflectance value brought

about an additional annual energy saving of 8% due to the lower use of electric lighting. The effects of greater reflectance were much greater at the deeper parts of the office spaces.

Although the results indicate the energy saving potential, daylighting system using atrium faces many practical problems. The highly reflective atrium surfaces to increase atrium's "well pressure" may cause discomfort glare. The excessive illuminance non-uniformity in the office spaces may also create unpleasant visual environment. This may force the occupants to turn on the electric lighting although the daylight illuminances are adequate, and therefore, may lead to energy inefficiency (Julian 1988; Julian 1996a; Julian 1996b). Several practical design solutions can be found elsewhere to ameliorate the problems (American Institute of Architect 1982; Chauvel et al. 1982; Moore 1985; Suryabrata 1991). In addition, if not properly controlled, excessive heat gain from daylight may offset energy saving from electric lighting. The overall daylight energy saving and thermal load was part of the simulation objectives. This will be presented in a separate paper.

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