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Journal of Asian Architecture and Building Engineering

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tabe20

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To cite this article: Feny Elsiana, Sri Nastiti N Ekasiwi & IGN Antaryama (2024) The impact of aspect ratio of buildings implementing Horizontal light pipe and shading systems on daylight performance, Journal of Asian Architecture and Building Engineering, 23:5, 1658-1676, DOI: 10.1080/13467581.2023.2278450

To link to this article: https://doi.org/10.1080/13467581.2023.2278450

JOURNAL OF ASIAN ARCHITECTURE AND BUILDING ENGINEERING
2024, VOL. 23, NO. 5, 1658–1676
https://doi.org/10.1080/13467581.2023.2278450

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The impact of aspect ratio of buildings implementing Horizontal light pipe and shading systems on daylight performance

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ABSTRACT

Deep-plan buildings limit daylight use in spaces far from the building perimeter, leading to uneven daylight distribution. Integrating a Horizontal Light Pipe (HLP) as an optical daylighting system, reflective light shelves, and blinds as shading systems can reduce excessive daylight levels at the perimeter area of a building and improve daylight uniformity. Earlier investigations of HLP daylight performance concentrated on fixed building geometries, but few studies focused on the building aspect ratio, one of the design variables of building geometry that greatly influences daylight performance. This study aims to investigate the impact of the aspect ratio of buildings implementing HLP and shading systems on daylight performance. The research method was experimental, using IES-VE simulation as a tool. The daylight factor (DF), uniformity daylight factor (UDF), and useful daylight illuminance (UDI) of various aspect ratios and depths of office buildings implementing HLP and shading systems were analyzed. The results show that increasing the building aspect ratio from 1:1 to 2.1:1 sequentially increased the average DF and UDF values by 18.47% and 17.2%, respectively. Improving the building aspect ratio from 1:1 to 2.1:1 along the east-west axis improved the UDI by 3%, whereas the north-south axis decreased it by 10.2%.

ARTICLE HISTORY
Received 9 August 2023
Accepted 27 October 2023

KEYWORDS
Building aspect ratio; daylight performance; horizontal light pipe; shading system; tropics

1. Introduction

Daylight use can reduce the energy consumption of a building and decrease the cooling load and peak demand. Proper daylighting use in buildings can decrease the energy used for electric lighting and the energy consumption of the entire building (Chen et al. 2014; Chi, Moreno, and Navarro 2018; Wong 2017). Natural daylight also reduces the sensible cooling load amount due to electric lighting (Li, Lam, and Wong 2005) and lowers the cooling load of buildings (Boubekri 2014). Proper daylighting design lowers the air-conditioning system's (Alrubaih et al. 2013) and the building's peak power demand (Li, Lam, and Wong 2005). Reducing peak demand is necessary for office buildings occupied in the daytime. Peak demand usually occurs when daylight is most abundant (Boubekri 2014).

Daylight also positively affects human comfort and health. Daylight is the best source of light and is the most probable equivalent to the human visual response (Alrubaih et al. 2013). It also makes the interior space appear livelier and more attractive. Building users prefer good daylighting in their working and living environments (Li and Lam 2003). Daylight is also associated with serotonin and melatonin hormone production, which regulate circadian rhythms. Inadequate daylight exposure and serotonin or melatonin cycle disturbances can cause seasonal affective disorder (SAD) (Boubekri 2014). Daylight has also become one of the most effective antidepressants available (Boubekri 2008). Therefore, buildings should provide human exposure to sunlight to facilitate cutaneous photosynthesis, which provides most or all human vitamin D needs (Boubekri 2008).

Other essential aspects of daylighting include user productivity and economic value. Daylighting improves productivity in workplaces (Ander 2003). Tenants spend 5–6% more on office areas with high daylight than those with low daylight presence (Turan et al. 2020). Spaces with high view and daylight access also have a 6% effective rent premium over areas with inadequate access to view and daylight (Turan et al. 2021).

The potential for daylight utilization in the tropics is high. Daylight is abundant in this area because of the high sun intensity and long illumination period during the daytime (Roshan and Salisu 2016). Studies of daylighting in the tropics need to consider inconsistent cloud formation of intermediate skies, which are neither clear nor overcast (Lim and Heng 2016). Global illuminance at noon reached 80 Klux in March and 60 Klux in December (Zain-Ahmed et al. 2002).

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From the architectural design standpoint, a building should have a narrow plan to optimize daylighting (G-Hansen 2006). Nevertheless, deep-plan buildings are commonly developed to maximize the net floor area (G-Hansen 2006; Mayhoub 2014). A deep-plan building design limits the daylight level in spaces far from side windows. The daylight intensity reduces as the distance from the side window increases (Urbano Gutiérrez et al. 2019), leading to uneven daylight distribution and glare problems (Heng, Lim, and Remaz Ossen 2020; Mayhoub 2014). A core daylighting system is required to bring daylight in spaces around the building perimeter (Friedrich, Wittkopf, and Louis Scartezzini 2010).

A Horizontal Light Pipe (HLP) is one of the core daylighting systems that can bring daylight further into a building's interiors. The HLP consists of an aperture, a pipe, and an opening distribution. The aperture collects, redirects, and occasionally concentrates or collimates the incoming light flux (Canziani, Peron, and Rossi 2004). Pipe transports and opening distribution distributes daylight to the deep area of the building. HLP is placed in the plenum above the ceiling (Canziani, Peron, and Rossi 2004). HLP increases the daylight factor (DF), and estimated indoor illuminance reaches 25% and 24%, sequentially, in deep office spaces (Heng, Lim, and Remaz Ossen 2020).

The aperture is located at the building façade, with a flat capturing system to minimize the protrusion of the building façade (Canziani, Peron, and Rossi 2004). The aperture is equipped with reflectors to redirect the incoming sunlight to minimize inter-reflections within the pipe and to maximize the system efficiency (Canziani, Peron, and Rossi 2004; G-Hansen 2006), especially the oblique sunbeam in cases of solar positions not in axis with the pipe (Canziani, Peron, and Rossi 2004). Material of reflectors is a highly reflective specular material, such as an aluminum sheet (Canziani, Peron, and Rossi 2004; Duc Hien and Chirarattananon 2009; Obradovic and Matusiak 2021), silver, mirror folium with a reflectivity of 99% (Obradovic and Matusiak 2021). The aperture is covered by clear glazing (Duc Hien and Chirarattananon 2009) with a visible transmittance of 88%.

The pipe transports the light with the principle of multiple specular reflections. The efficiency of a mirror Light Pipe depends on the area, the pipe's geometric form, the material's reflectivity, and the light sources' directional properties (Hansen and Edmonds 2003). The pipe materials are highly specular, such as specular reflective film with a reflectance of 95% (Beltran, Lee, and Selkowitz 1997; Canziani, Peron, and Rossi 2004), polished aluminum with a reflectivity of 85%, or silvered aluminum with a reflectivity of 95%. In cross-section, the pipe is tapered toward the rear of the room (Beltrán and Mogo 2007).

The opening distribution or diffuser transmits daylight to the deep area of the building. The opening distribution is located at the ceiling plane (Figure 1), at 4.5 m from the side window to the building depth, to optimize the light pipe efficiency (Beltran, Lee, and Selkowitz 1997). The material of opening distribution is translucent sheets (Chirarattananon, Chedsiri, and Renshen 2000), clear glass with egg-crate reflectors (Elsiana, Soehartono, and Kristanto 2020), clear glazing (Elsiana, Nastiti N Ekasiwi, and Gusti Ngurah Antaryama 2021), and laser-cut panels (Hansen and Edmonds 2003; Kwok and Chung 2008).

The HLP obtains daylight from half of the hemisphere in front of the aperture (Duc Hien and Chirarattananon 2009). HLP captures and utilizes direct sunlight. HLP can be installed on any building floor (Duc Hien and Chirarattananon 2009), supplement the daylight provided by a side window, and become the primary daylight source in deep areas of the building (Beltran, Lee, and Selkowitz 1997).

In the tropics, HLP should be combined with shading systems (Elsiana, Nastiti N Ekasiwi, and Gusti Ngurah Antaryama 2021) to reduce high daylight intensity adjacent to the perimeter window (Heng, Lim, and Remaz Ossen 2020; Kim et al. 2015) and improve daylight uniformity (Elsiana, Nastiti N Ekasiwi, and Gusti Ngurah Antaryama 2021). In addition to controlling excessive daylight (Lim and Heng 2016), shading systems can protect buildings from direct sunlight and reduce glare problems (Luca, Sepúlveda, and Varjas 2022). Internal shading consisting of reflective light shelves and blinds was used in this study. Reflective light shelves can redirect daylight to the ceiling and improve daylight distribution (Hashemi 2014), whereas blinds can reduce luminance contrast. The combination of LS and partial blinds at a height of 1.20 m is an effective shading design for office buildings in the tropics (Lim, Hamdan Ahmad, and Remaz Ossen 2013).

Figure 1 shows the design of an office room with an HLP, light shelves, and blinds. The aperture captures sunlight and daylight using a fixed mirror system. The pipe transports daylight through multiple specular reflections, and the opening distribution distributes daylight through the translucent glass. Internal shading consists of light shelves that redirect sunlight to the ceiling for better daylight distribution (Kontadakis, Tsangrassoulis, and Doulos 2018) and blinds that control direct sunlight (Gomes, Santos, and Calhau 2022).

Previous research on HLP has mainly focused on improving its efficiency in capturing, transporting, and distributing daylight. This research includes modification of the HLP geometry and utilization of reflectors (Beltrán and Mogo 2007; Beltran, Lee, and Selkowitz 1997); laser cut panels at the aperture and opening distribution (Hansen and Edmonds 2003; Kwok and Chung 2008); anidolic daylighting systems (Heng, Lim, and Remaz Ossen 2020; Roshan and Salisu 2016), active reflectors (Canziani, Peron, and Rossi 2004), egg-crate reflectors (Elsiana, Soehartono, and

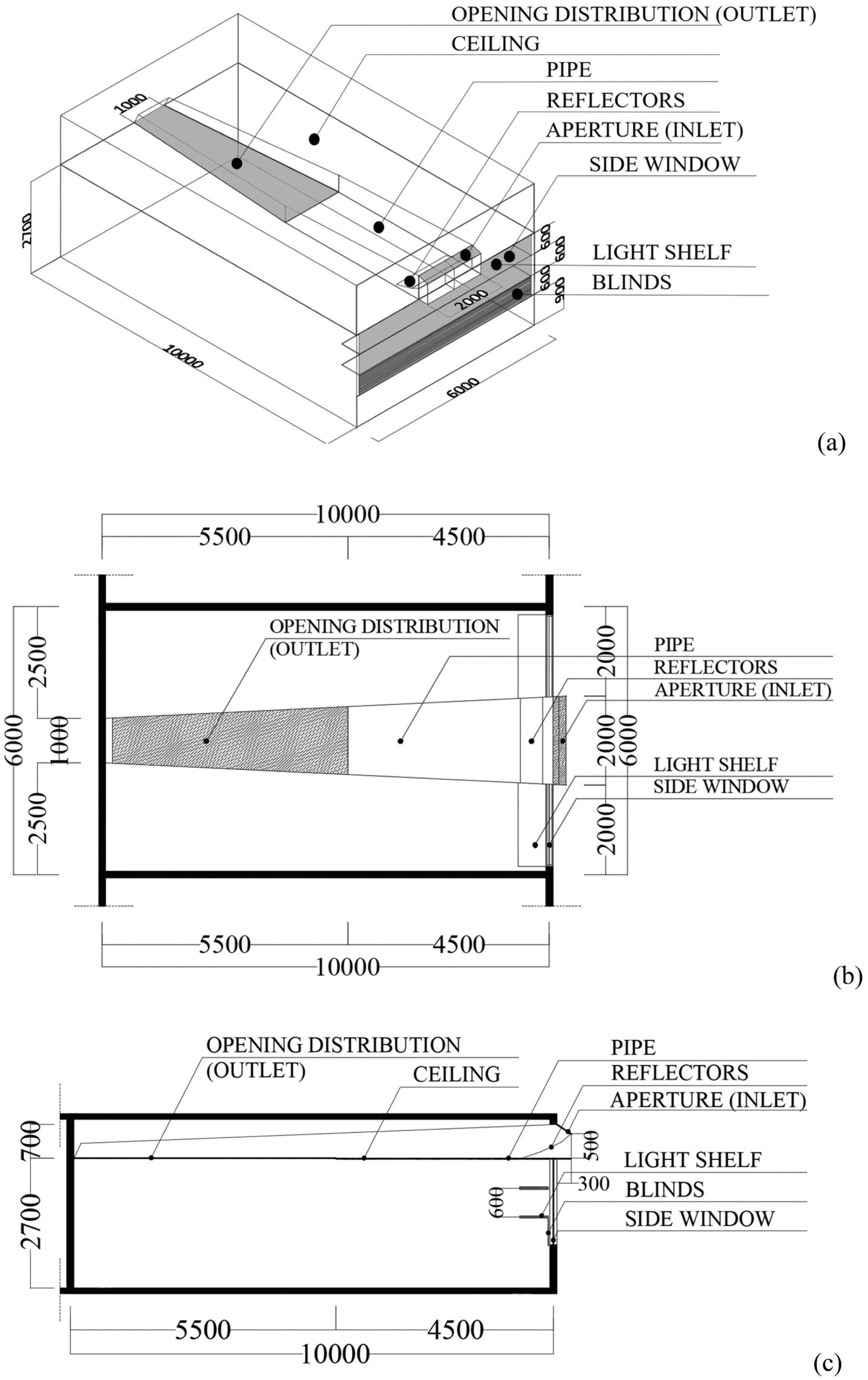


Figure 1. Office room with horizontal light pipe and shading systems (a) perspective (b) plan and (c) section (Elsiana, Nastiti N Ekasiwi, and Gusti Ngurah Antaryama 2021).

Kristanto 2020), and mirror systems (Duc Hien and Chirarattananon 2009). In this research, building geometry, which is one of the design aspects that significantly affects the daylight and energy performance of a building (Fang and Cho 2019), is studied.

Building geometry is one of the most essential architectural decisions made in the early design stage (Fang and Cho 2019). Exploring design possibilities in the early design stages, including building geometry, is important. Building geometry and fenestration selections significantly impact energy uses, making them a key area of attention for performance enhancements to reach low or zero-net energy buildings (Konis, Gamas, and Kensek 2016). Building geometry determines the quality of light distribution (Egan and Olgyay 2002).

Earlier studies on building geometry commonly focused on thermal performance (Inanici and Nur Demirbilek 2000; Jiayu et al. 2022; Yang et al. 2021) and energy performance (Chen, Janssen, and Schlueter 2018; Mckeen and Fung 2014). Earlier investigations concerning daylight performance concentrated on fixed building geometries. The design variables of these studies included the window-to-wall ratio, window orientation, wall reflectance (Mangkuto, Rohmah, and Dian Asri 2016), window type, and window-to-wall ratio (Lartigue, Lasternas, and Loftness 2014).

Previous studies on daylight performance evaluation and building geometry have focused on buildings with skylights (Fang and Cho 2019), side window strategies (Lee, Boubekri, and Liang 2019), and shading (Maltais and Gosselin 2017; Sepúlveda et al. 2020) in non-tropical areas. Building geometry influences daylight performance differently for different climate zones (Fang and Cho 2019). Studies on building geometry concerning daylight performance in the tropics are limited, particularly those integrating HLP as a light transport system.

This study focuses on building aspect ratio, the ratio between the building length and width (Inanici and Nur Demirbilek 2000), as one of the design variables of building geometry. Building aspect ratio is one of the most important factors influencing daylight performance (Fang and Cho 2019; Kibert 2008). The study location is Surabaya (7°21` S, 112°36′ E), a city in the Tropics. This study evaluates the impact of the aspect ratio of buildings implementing HLP and shading systems on daylight performance in the tropics. The optimum aspect ratio of buildings implementing HLP and shading systems in the tropics with the highest daylight performance was also presented. The findings will provide information for architects in designing the aspect ratio of buildings integrating HLP and shading systems in the early design stages.

2. Sky condition of Surabaya

Surabaya, Indonesia, is one of the cities in the Tropics. The tropical sky is predominant with the intermediate sky, which means it is neither overcast nor clear (Lim and Heng 2016; Roshan and Salisu 2016). The following section focuses on the determination and classification of three sky conditions: overcast, intermediate, and clear sky in Surabaya, using the sunshine duration method (Rahim and Mulyadi 2004).

Sunshine duration data from 2016–2020 measured at the Tanjung Perak II Station of Indonesia's Meteorological, Climatological, and Geophysical Agency in Surabaya were analyzed. Figure 2 shows Surabaya's solar radiation data profile from 2016–2020. The profile indicates that the shortest average sunshine duration occurred in December, as high as 49.3%. The longest average sunshine duration was observed in August, as high as 92%. The average sunshine duration in Surabaya from 2016–2020 was 72.3%.

Relative sunshine duration is the ratio of the sunshine duration to the maximum possible duration in a certain period (Rahim and Mulyadi 2004). The monthly mean value of the relative sunshine duration (σm) is employed to estimate the probability of

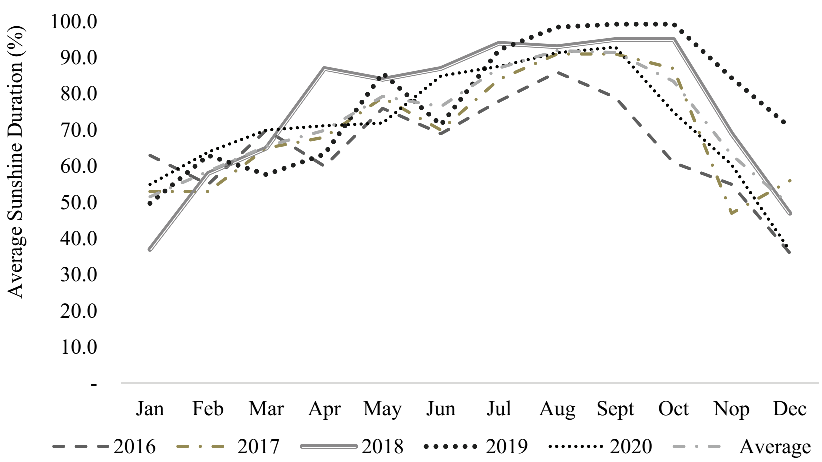


Figure 2. Average sunshine duration of Surabaya (Meteorological, Climatological, and Geophysical Agency of Surabaya).

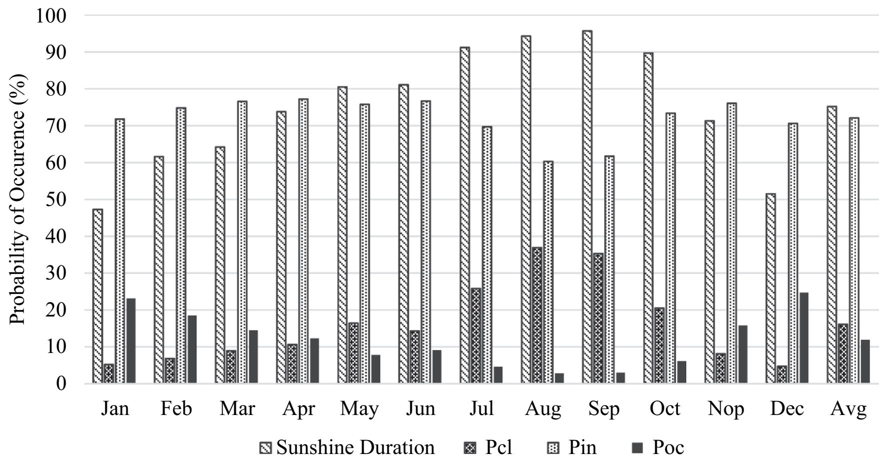


Figure 3. The average sunshine duration and the estimated probability of occurrence of clear, intermediate, and overcast sky conditions.

occurrence of the clear (Pcl), intermediate (Pin), and overcast sky (Poc). The equations for the monthly probabilities of the occurrence of clear, intermediate, and overcast skies are:

$$Pcl = \frac{5.689}{1.054 - \frac{\sigma m}{100}} - 5.397 \quad (1)$$

$$Pin = \frac{100 - 5.689}{1.054 - \sigma m/100} - \frac{78.629}{0.551 + \frac{\sigma m}{100}} \quad (2)$$

$$Poc = \frac{78.629}{0.551 + \sigma m/100} - 50.649 \quad (3)$$

where:

Pcl (%) = monthly probability of occurrence of clear sky

Pin (%) = monthly probability of occurrence of intermediate sky

Poc (%) = monthly probability of occurrence of overcast sky

σm (%) = monthly mean value of relative sunshine duration

Figure 3 shows the average sunshine duration and the estimated probability of occurrence of clear, intermediate, and overcast sky conditions. The yearly relative frequency of occurrence of overcast (Poc), intermediate (Pin), and clear sky (Pcl), corresponding to the working period in Surabaya, were 11.9%, 72.1%, and 16.1%, respectively. The intermediate sky had the highest probability of occurrence of sky conditions in Surabaya. These results align with the previous study about sky conditions in the Tropics (Lim and Heng 2016).

3. Methodology

The method of the research was experimental, using simulation as a tool. Building performance simulation is a useful tool for evaluating design options and their environmental performance (Brembilla, Drosou, and Mardaljevic 2022). Integrated Environment Solution-Virtual Environment (IES-VE) daylight simulation was used to study the daylight performance of various aspect ratios of buildings implementing HLP and shading systems. The IES-VE is based on radiance, which uses a raytracing calculation method and considers surface transmission, reflection, and refraction values (Heng, Lim, and Remaz Ossen 2020; Lim and Heng 2016). Radiance has been extensively validated and is an unbiased daylight simulation tool (Ayoub 2020). IES-VE is stable, tested, and based on validated Building Performance Simulation results (Negendahl 2015). IES-VE is widely used worldwide and can simulate various daylighting systems and lighting design features.

IES-VE has been validated in previous research on HLP (Heng, Lim, and Remaz Ossen 2020), dynamic internal light shelves (Lim and Heng 2016), light shelves, anidolic systems, translucent materials, light shelves with external reflectors (Freewan and Al Dalala 2020), light shelves, external horizontal louvers, internal horizontal blinds (Reffat and Ahmad 2020), and anidolic daylighting system (Roshan and Salisu 2016). The correlation of the daylight factor and daylight ratio of IES-VE simulation results and physical scaled model 1:10 measurements results focusing on HLP, and dynamic internal light shelves were in the range of 0.92 to 0.95 (Heng, Lim, and Remaz Ossen 2020) and 0.83–0.99 (Lim and Heng 2016), sequentially. The root mean square error of real measurements and IES-VE simulation was less than 10% (Freewan and Al Dalala 2020). Validation studies showed that the IES-VE software is reliable for calculating daylight performance from various daylighting systems such as light pipes, light shelves, and anidolic daylighting systems in tropical areas using daylight ratio and daylight factor.

3.1. Experimental with simulation as a tool

Experimental with IES-VE simulation was employed to study the impact of geometry of building implementing HLP and shading system on daylight performance. The daylight performance of the base case, an office building implementing HLP and shading systems with an aspect ratio of 1:1, was compared with various aspect ratios of office buildings implementing HLP and shading systems. The evaluated daylight performance consisted of average daylight factor (DFav), uniformity daylight factor (UDF), and useful daylight illuminance (UDI).

Table 1. Radiance parameters in IES-VE simulations.

Parameters	Values
Ambient bounces (–ab)	5
Ambient divisions (–ad)	2048
Ambient accuracy (–aa)	0.2
Ambient resolution (–ar)	64
Ambient super-samples (–as)	512

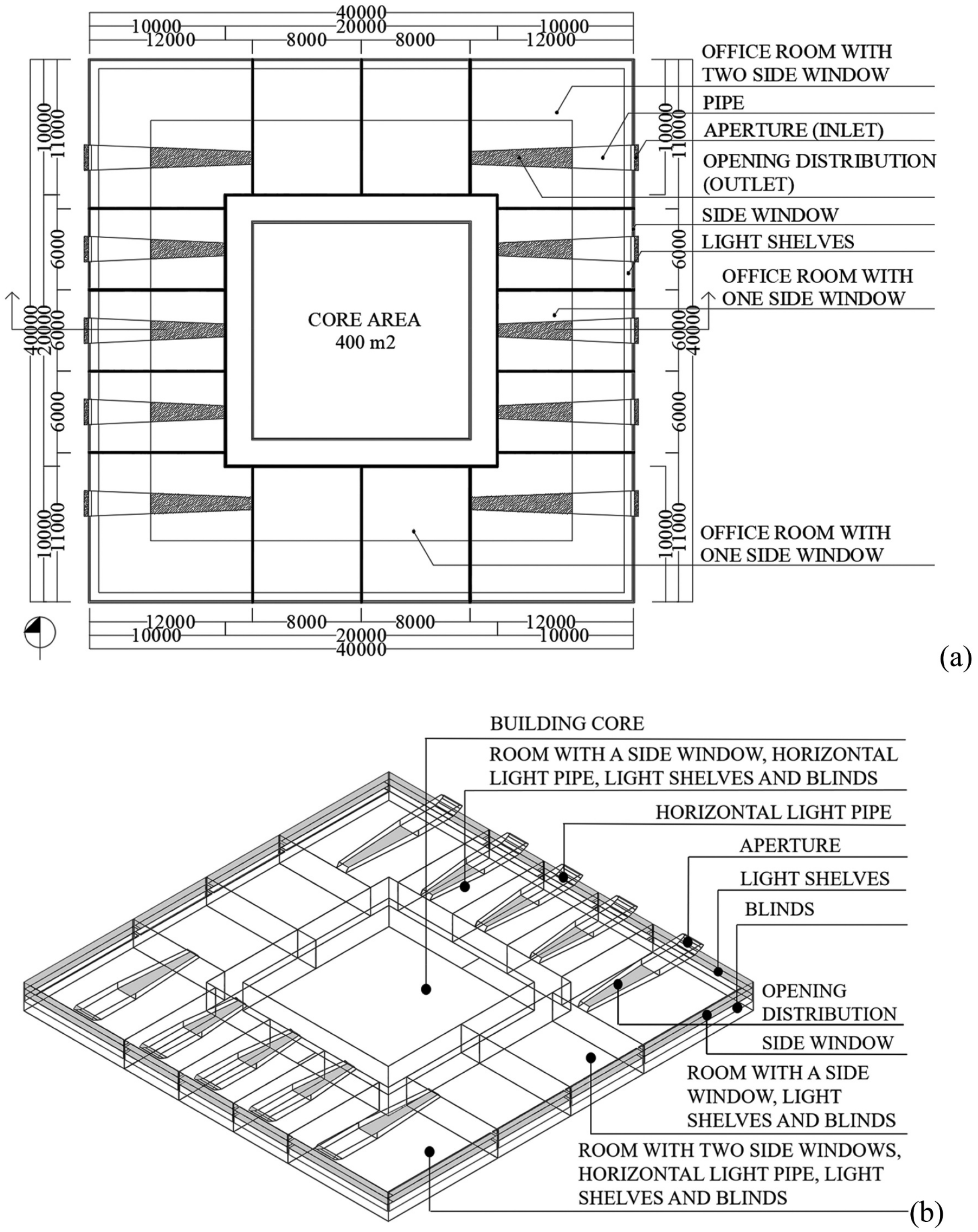


Figure 4. Configuration of the base-case office building implementing horizontal light pipe and shading systems.

The simulation employed the weather file of Juanda International Airport and used the radiance parameters, as displayed in Table 1.

Figure 4 shows the office building configuration that implements HLP and shading systems. The base case was rectangular in the floor plan and had an area of 1.600 m^2. The building length and leasing depth span were 40 m and 10 m, respectively, representing a typical office building with medium-depth space (Gero and Fay 1998). The floor-to-ceiling height was 2.7 m, based on the office floor-to-floor height consideration of Kohn and Katz (Kohn and Katz 2002). The office building had a single zone, a central core area of 400 m^2, and an open-plan work area of 1200 m^2. The office building was oriented to the north.

A typical office building floor was divided into smaller rentable units for different tenants, consistent with previous research on high-rise offices (Lim and Ahmad 2013). The smallest office room had an area of 60 m^2 and employed 10 workers with a minimum floor area per workstation of 6 m^2 (Meel, Martens, and Jan 2010). The building core functions as a service and circulation area and was excluded from the daylight performance analysis.

There are three types of office rooms in terms of daylighting access: an office room with a side window, HLP, and shading systems; an office room with two side windows, HLP, and shading systems; and an office room with a side window and shading systems (Figure 4). The office room with a side window, HLP, and shading systems facing the east or west, whereas the office room with two side windows and shading systems facing the north or south.

The side window in the office building had a window-to-wall ratio of 67%. The window glazing material was clear glass with a visible transmittance (VT) of 0.76. Shading systems consisting of two refective light shelves with 0.6 m in width and partial blinds (Figure 5) were integrated into office buildings as effective internal shading in the tropics (Lim, Hamdan Ahmad, and Remaz Ossen 2013). Following previous study results from Lim et al (Lim et al. 2012), modifying tinted glazing to clear glass VT 0.75, external shading devices, light shelves, and blinds can significantly increase the daylight quantity and quality in office buildings in the tropics.

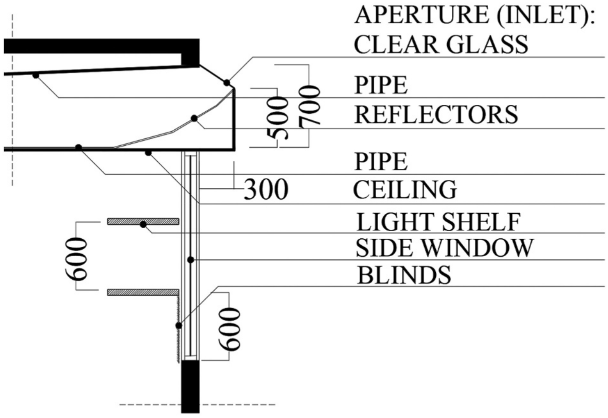


Figure 5. The aperture of horizontal light pipe and shading systems.

HLP was integrated into the building with an aperture-oriented east or west, following its best orientation in the tropics (G-Hansen 2006). The width, length, and height of HLP were 2 m, 10 m, and 0.7 m, respectively. The aperture of HLP collects sunlight from the building façade (Figure 5) and transfers it through the pipe with a highly specular material on its inner surface. The aperture is equipped with reflectors to redirect the incoming sunlight to minimize inter-reflections within the pipe and to maximize the system efficiency (Canziani, Peron, and Rossi 2004; G-Hansen 2006). The opening distribution emits daylight through a transparent glass. No daylight is distributed through the HLP at a distance of 0 to 4.5 m from the side window to maximize its efficiency and daylight distribution within the space. The HLPs were placed every 6 m to uniformly illuminate the open-plan office space, in line with previous research by Beltran (Beltran, Lee, and Selkowitz 1997).

For the same building, core, and work area, the building aspect ratio varied from 1:1 to 2.1:1 (Table 2). The maximum aspect ratio was 2.1:1, considering the maximum lease span for office function without a single tenant group (Sev and Özgen 2009) and daylight attenuation by increasing HLP length with a static reflector (Roshan and Salisu 2016). Cases AR 1.1:1 to AR 2.1:1 were buildings with an increased aspect ratio along the east-west axis, whereas cases AR 1:1.1 to 1:2.04 were buildings with an increased aspect ratio along the north-south axis (Figure 6).

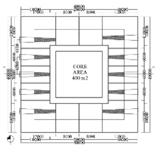
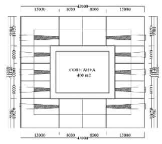
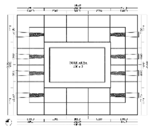
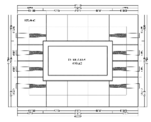
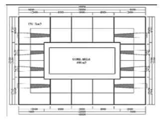
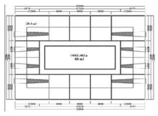
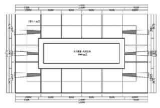
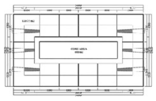
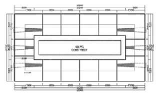
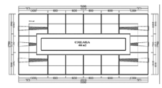
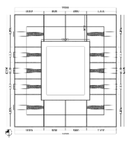
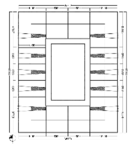
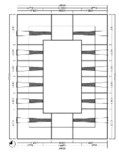
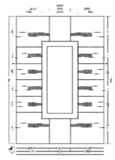
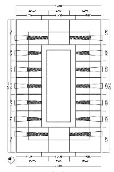
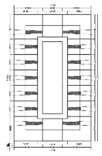
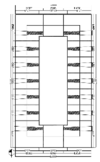
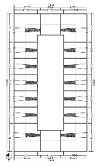
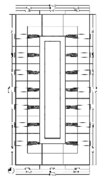
Figure 7 shows the location of sensor points in the building plan. The height of sensor points is 0.8 m above the floor (work plane) with a grid of 1 m × 1 m. UDI is based on work-plane illuminances (Nabil and Mardaljevic 2006) and considers daylight "useful" if all work-plane sensor points are simultaneously within the 100–2000 lx range (Nabil and Mardaljevic 2006). The occupancy hours used are 3650 for the period of 8:00–18:00 for the entire year.

The materials and surface properties of the office room, side window, HLP, and shading systems are summarized in Table 3. The impact of the aspect ratio of building implementing HLP and shading system on daylight performance was then analyzed using regression analysis through SPSS software.

3.2. Daylight metrics

Three daylight metrics were evaluated to study the impact of the aspect ratio of buildings implementing HLP and shading systems. The daylight performance analysis included the average daylight factor (DFav), uniformity daylight factor (UDF), and useful daylight illuminance (UDI). DFav was used to evaluate the

Table 2. The configuration of base case and cases.

Building parameters	Base Case	AR 1.1:1	AR 1.2:1	AR 1.3:1	AR 1.4:1
					
length (m)	40	42	44	46	48
width (m)	40	38.1	36.4	35	33.3
aspect ratio	1:1	1.1:1	1.2:1	1.3:1	1.4:1
	AR 1.56:1	AR1.68:1	AR 1.8:1	AR 1.96:1	AR 2.1:1
					
length (m)	50	52	54	56	58
width (m)	32	30.8	29.6	28.6	27.6
aspect ratio	1.56:1	1.68:1	1.8:1	1.96:1	2.1:1
	AR1:1.1	AR1:1.2	AR 1:1.3	AR 1:1.47	AR 1:1.56
					
length (m)	38	36	34	33	32
width (m)	42.1	44.4	47	49	50
aspect ratio	1:1.1	1:1.2	1:1.3	1:1.47	1:1.56
	AR 1:1.67	AR 1:1.79	AR 1:1.89	AR1:2.04	
					
length (m)	31	30	29	28	
width (m)	52	53	55	57	
aspect ratio	1:1.67	1:1.79	1:1.89	1:2.04	

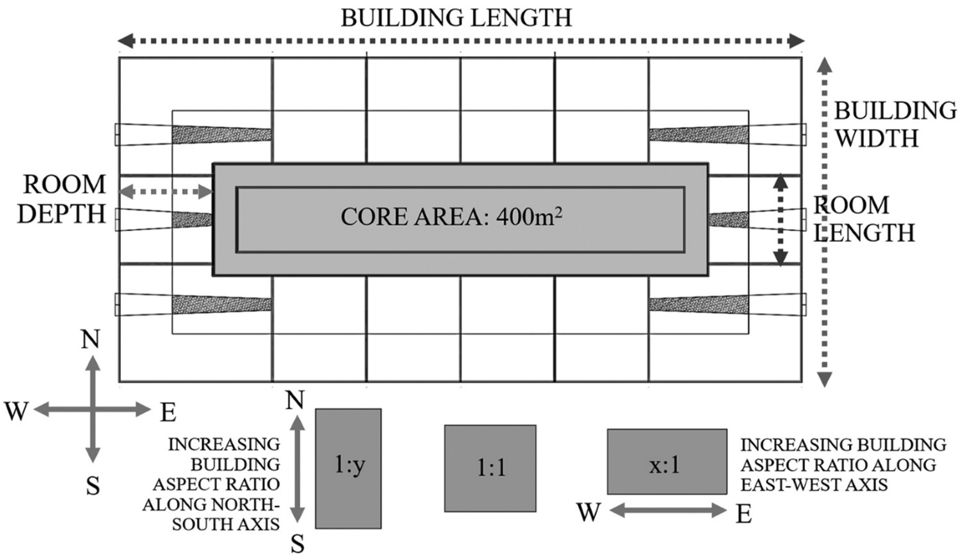


Figure 6. Increasing building aspect ratio along specific axis.

daylight quantity. Building aspect ratio, one of the building geometry parameters, impacts DF (Reinhart, Mardaljevic, and Rogers 2006). In an office building, the evaluation of daylight distribution, which has a strong relationship with visual comfort and describes daylight quality (Galatioto and Beccali 2016), is essential. The daylight distribution was assessed by using the uniformity of light. UDI, one of the dynamic daylight

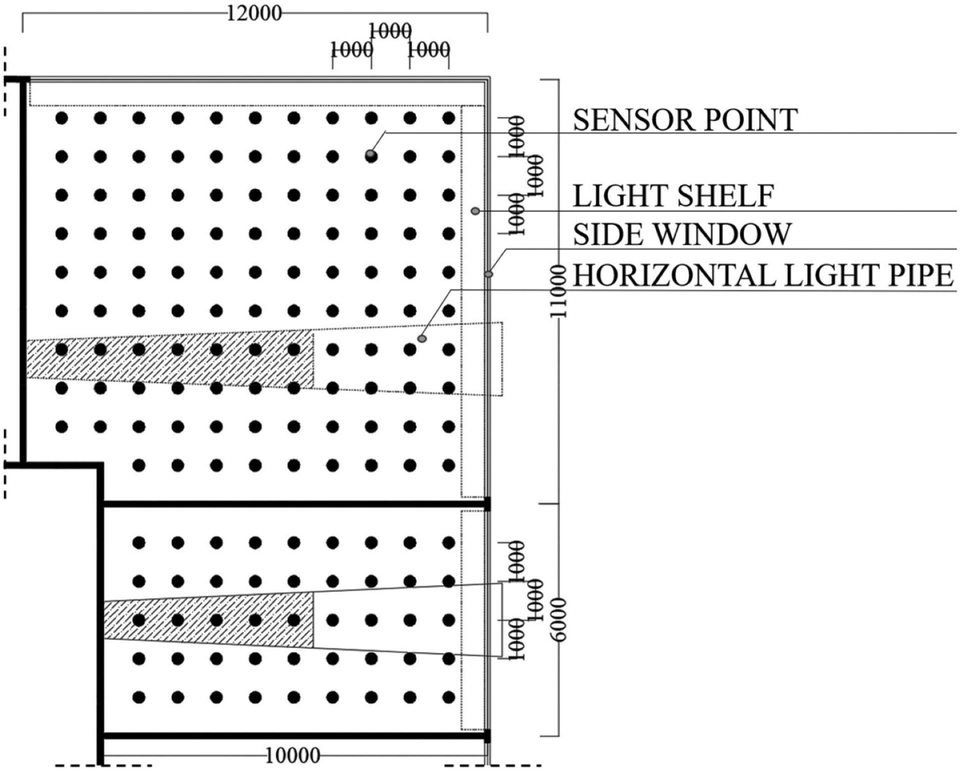


Figure 7. Sensor points location in the building plan.

Table 3. Materials and surface properties in IES-VE simulation.

Elements	Materials	Reflectance (%)	Specularity	Roughness	Visible Transmittance
Interior wall	Plastic: white paint	0.75	0.00	0.02	N/A
Interior ceiling	Plastic: white paint	0.75	0.00	0.00	N/A
Interior floor	Plastic: light grey	0.45	0.00	0.03	N/A
Light pipe inner surfaces	Metal: mirror acrylic	0.85	0.90	0.02	N/A
Light pipe's aperture	Clear glass	N/A	N/A	N/A	0.88
Light pipe's opening distribution	Clear glass	N/A	N/A	N/A	0.85
Light shelf	Metal: mirror acrylic	0.85	0.90	0.02	N/A
Blinds	Plastic	0.40	0.04	0.03	N/A
Side window	Clear glass	N/A	N/A	N/A	0.76

performance metrics, was then used to evaluate daylight sufficiency during occupied hours in the year.

The DF (Equation (4)) is the ratio between indoor (Ei) and exterior illuminance (Eo) in an unshaded area under CIE standard overcast sky conditions (Reinhart and Weissman 2012). The average daylight factor (DFav) is the mean DF at all sensor points placed on the work plane height, 0.8 m above the floor. The recommended DF range for workspaces is 2–5% (British Council for Offices Guide in 6). Rooms with an average DF of less than 2% will look gloomy, and a room with a DF of more than 5% appear very bright (Mcmullan 2007).

$$DF = \frac{Ei}{Eo} x100\% \quad (4)$$

The uniformity DF (Equation (5)) shows the degree of homogeneity in the light distribution (Michael, Gregoriou, and Kalogirou 2018). UDF value is determined by dividing the minimum DF value (DF min) by the average DF value for the entire room (DFav). The UDF required for the working environment should be a minimum of 0.4 (BREEAM 2023).

$$UDF = \frac{DF\ min}{DF\ avg} \quad (5)$$

Useful Daylight Illuminance $(UDI)_{100\text{-}2000\ lx}$ is the percentage of occupied hours in the year with daylight illuminance within the range of 100-2000 lx (Equation (6)) (Nabil and Mardaljevic 2006). UDI is a climate-based daylight analysis based on daylight due to multiple sky conditions in the occupied hours of the year in specific geographical locations (Mangkuto, Siregar, and Handina 2018).

$$UDI100 - 2000lx = \frac{t100lx \leq E \leq 2000lx}{T} x100\% \quad (6)$$

where t is the duration of daylight illuminance (E) ranging from 100-2000 lx, and T is the total number of occupied hours in the year.

Daylight illuminances higher than 2000 lx (UDI exceed) tend to produce thermal or visual discomfort,

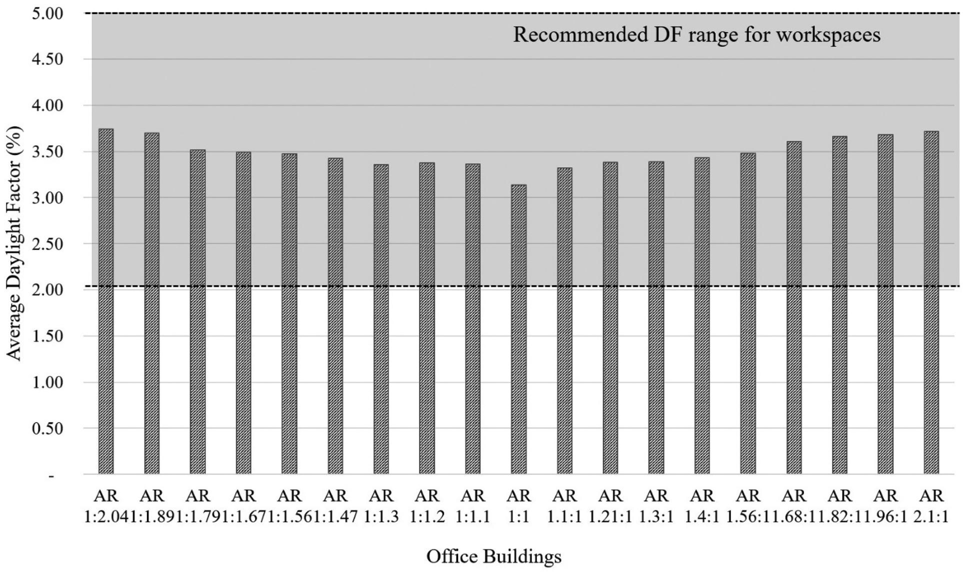


Figure 8. Average daylight factor of office buildings with various building aspect ratio.

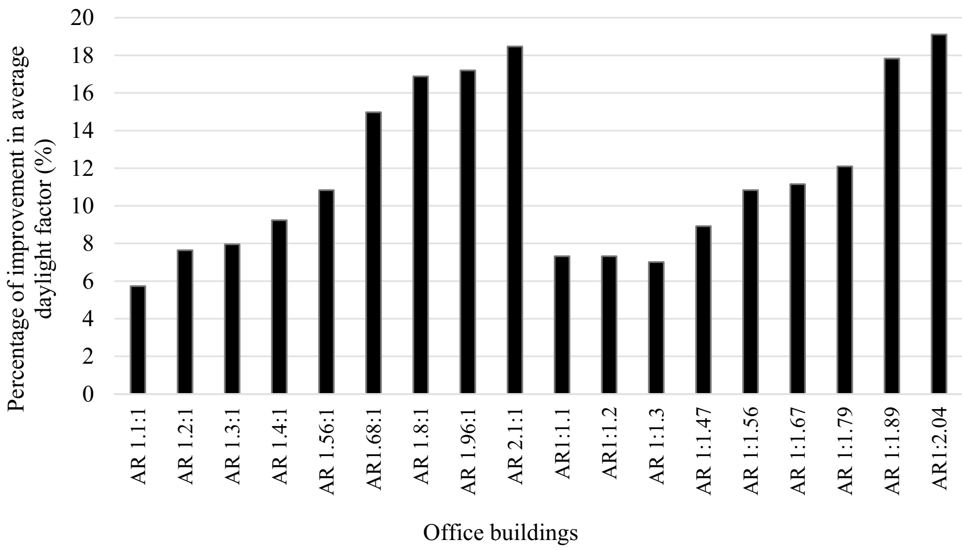


Figure 9. Percentages of average daylight factor improvement of office buildings with a different aspect ratio.

whereas illuminances lower than 100 lx are considered insufficient as the only source of illumination (Boubekri 2014). Daylight illuminances in the range of 100-500 lx (UDI supplementary) and 500-2000 lx (UDI autonomous) are considered effective in complementing electric lighting and are sufficient as a main source of illumination, sequentially (Reinhart, Mardaljevic, and Rogers 2006). The minimum criteria of $UDI_{100\text{-}2000\ lx}$ are 50% (Berardi and Anaraki 2015; Mangkuto, Rohmah, and Dian Asri 2016).

4. Results and discussion

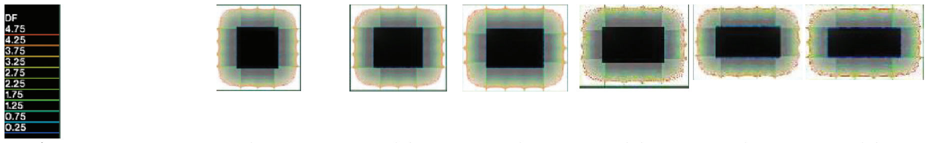
4.1. Daylight performance results and analysis

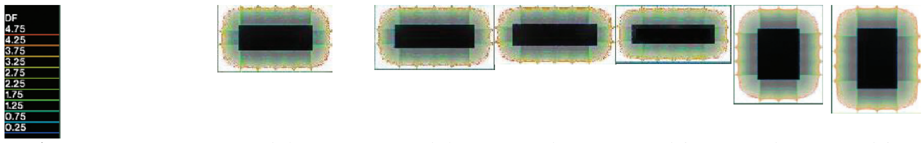
4.1.1. Average daylight factor analysis

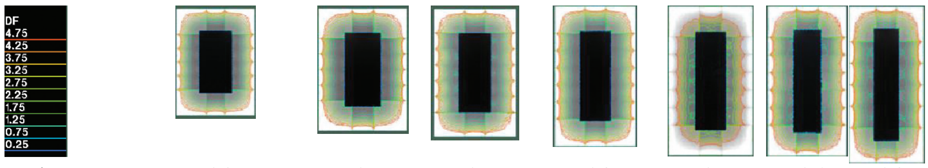
The simulation results showed that all cases had a DFav level of 3.14% to 3.74%. The base case, with a building aspect ratio of 1:1, exhibited the lowest average DF level of 3.14%. Office building AR 1:2.04 had the highest average DF level of 3.74% (Figure 8). The average DF level of all cases was within the recommended DF range for workspaces of 2–5%.

Figure 9 shows the percentage of the DFav improvement in the cases compared to the base case. The results showed that buildings implementing HLP and shading systems with higher aspect ratios had a higher DFav level. A higher building aspect ratio implies that the building perimeter form is extended, allowing daylight to reach most building spaces and increasing the total daylighting area. These results align with previous research (Fang and Cho 2019), showing that larger building aspect ratios have a higher daylight performance in a hot climate. Following a previous study (Roshan and Salisu 2016), the increase in the building aspect ratio also indicates

Table 4. Daylight factor comparison between the base case and all cases.

		Base Case	AR 1.1:1	AR 1.2:1	AR 1.3:1	AR 1.4:1	AR 1.56:1
							
Daylight Factor (DF)	maximum	9.7	10.2	10	9.9	10.7	10.2
	minimum	0.8	0.8	0.8	0.8	0.9	0.9
	average	3.14	3.32	3.38	3.39	3.43	3.48
	uniformity	0.36	0.35	0.35	0.35	0.39	0.38
Percentage of changes in DF	maximum	0	5.15	3.09	2.06	10.31	5.15
	minimum	0	0	0	0	12.5	12.5
	average	0	5.73	7.64	7.96	9.24	10.83
	uniformity	0	−2.78	−2.78	−2.78	8.33	5.56
Percentage of sensor points with DF level 2–5%		45.6	44.2	42.9	44	44.1	45.34

		AR1.68:1	AR 1.8:1	AR 1.96:1	AR 2.1:1	AR1:1.1	AR1:1.2
							
Daylight Factor (DF)	maximum	10.6	10.6	10.5	10.3	10.5	10.3
	minimum	0.9	0.9	0.9	1	0.8	0.8
	average	3.61	3.67	3.68	3.72	3.37	3.37
	uniformity	0.38	0.41	0.40	0.41	0.33	0.34
Percentage of changes in DF	maximum	9.28	9.28	8.25	6.19	8.25	6.19
	minimum	12.5	12.5	12.5	25	0	0
	average	14.97	16.88	17.20	18.47	7.32	7.32
	uniformity	5.56	13.89	11.11	13.89	−8.33	−5.56
Percentage of sensor points with DF level 2–5%		46.9	49.24	50.1	50.3	43.61	45.12

		AR 1:1.3	AR 1:1.47	AR 1:1.56	AR 1:1.67	AR 1:1.79	AR 1:1.89	AR1:2.04
								
Daylight Factor (DF)	maximum	10.2	10.7	10.1	10.3	10.1	10.6	10.8
	minimum	0.8	0.8	1	0.9	0.9	1	1
	average	3.36	3.42	3.48	3.49	3.52	3.70	3.74
	uniformity	0.35	0.37	0.38	0.38	0.38	0.40	0.40
Percentage of changes in DF	maximum	5.15	10.31	4.12	6.19	4.12	9.28	11.34
	minimum	0	0	25	12.5	12.5	25	25
	average	7.01	8.92	10.83	11.15	12.10	17.83	19.11
	uniformity	−2.78	2.78	5.56	5.56	5.56	11.1	11.11
Percentage of sensor points with DF level 2–5%		45.05	45	45.2	46.8	48.7	49.8	47.9

a reduction in the HLP length in rooms oriented east and west, improving daylight levels within the space.

Increasing the aspect ratio of the building implementing HLP and shading systems along the north-south axis resulted in a more significant improvement in DFav than that along the east-west axis. The percentage of DFav improvement ranged from 5.73% to 18.47% in buildings elongated along the east-west axis and from 7.32% to 19.11% in buildings elongated along the north-south axis. Building AR 1:2.04, which was elongated along the north-south axis, significantly improved the DFav more than building AR 1.96:1, which was elongated along the east-west axis. The improvements in the DFav of buildings AR 1:2.04 and AR 1.96:1 were as high as 19.11% and 17.2%, respectively. With a similar building aspect ratio, building AR 1:2.04 has a higher perimeter area that receives daylight from the east and west and a higher HLP integrated into buildings than building AR 1.96:1.

Table 4 summarizes the DF comparison between the base case and cases. Office building AR 2.1:1, which had an aspect ratio of 2.1:1, had the highest percentage of sensor points with a DF level of 2–5%, which reached as high as 50.3%. The lowest percentage of sensor points with a DF level of 2–5% was in the base case, which reached 31.34%.

The increase in the building aspect ratio along the east-west axis results in a slightly higher percentage of sensor points with a DF level of 2–5% than along the north-south axis. With a similar building aspect ratio, office building AR 1:2.04, which was elongated along the north-south axis, had a lower percentage of sensor points with a DF level of 2–5% than building AR 1.96:1, which was elongated along the east-west axis. The percentage of sensor points with a DF level of 2–5% for buildings AR 1:2.04 and AR 1.96:1 were 47.9% and 50.1%, respectively. With a similar building aspect ratio,

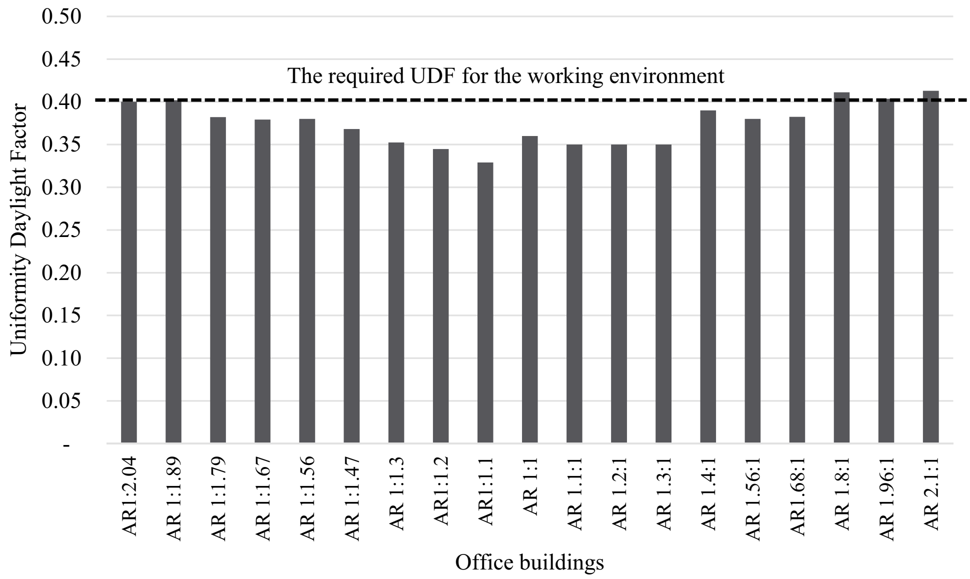


Figure 10. Uniformity daylight factor of office buildings with different aspect ratio.

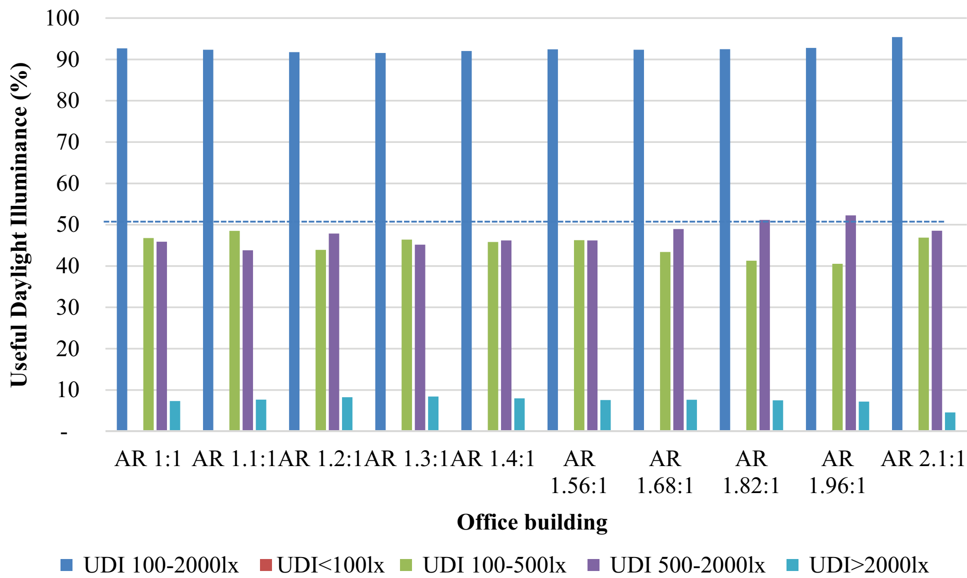


Figure 11. Useful daylight illuminance of office buildings elongated to the east-west axis.

building AR 1:1.96 has a higher perimeter area that receives daylight from the north and south than building AR 1:2.04.

4.1.2. Uniformity daylight factor analysis

Figure 10 shows the UDF values of office buildings with different aspect ratios. The results showed that the base case had a UDF value of 0.36, below the required UDF for the working environment, which should be at least 0.4. Only five buildings had UDF ≥ 0.4, ie, buildings AR 1.8:1, AR 1.96:1, AR 2.1:1, AR 1:1.89, and AR1:2.04.

Buildings implementing HLP and shading systems with UDF ≥ 0.4 had a high building aspect ratio. A high building aspect ratio results in a higher daylight level (Lee, Boubekri, and Liang 2019). The contrast between the daylight level in the area far from the side window and the area near the side window decreased, reducing the visual problem.

Increasing the building aspect ratio along the east-west axis resulted in a more significant improvement in UDF than the north-south axis. The UDF improvement in buildings elongated along the east-west axis was 8.33% to 13.89% for buildings AR 1.4:1 to AR 2.1:1, respectively. The percentages of UDF improvement of buildings elongated along the north-south axis were 2.78% to 11.11% for buildings AR 1:1.47 to AR1:2.04, repectively. The building elongated along the east-west axis has a larger perimeter area that receives daylight from the north and south. Following previous research (Lim and Ahmad 2013), diffused illuminance was the primary daylight source

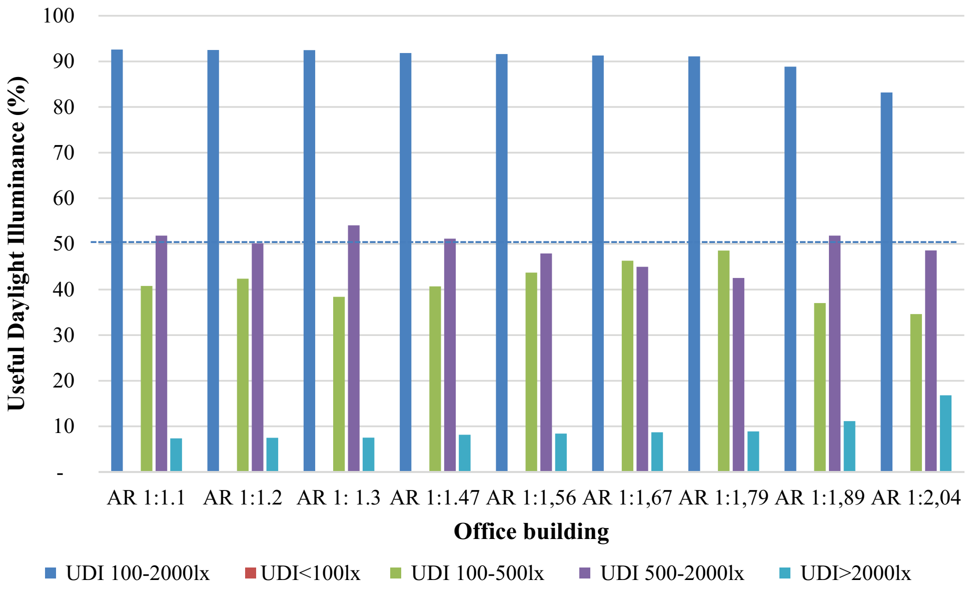


Figure 12. Useful daylight illuminance of office buildings elongated to the north-south axis.

for the north and south-facing side windows, resulting in a more uniform daylight distribution.

4.1.3. Useful daylight illuminance analysis

Figure 11 shows the UDI of office buildings extended along the east-west axis. Figure 12 shows the UDI of office buildings elongated along the north-south axis. All office buildings with different aspect ratios had a $UDI_{100\text{-}2000\ lx}$ in the 83–95% range and were above the minimum criteria of $UDI_{100\text{-}2000\ lx}$. These results showed the reliability of HLP and shading systems in maintaining room lighting with $UDI_{100\text{-}2000\ lx}$ for over 50% of occupied hours in a year. The simulation results also showed that all buildings had no percentages of UDI fell-short (<100 lx) of the working year.

Office building AR 1: 2.04 elongated along the north-south axis had the lowest $UDI_{100\text{-}2000\ lx}$ value, as high as 83% of the work year. Office building AR 2.1:1 elongated along the east-west axis had the highest $UDI_{100\text{-}2000\ lx}$ value, which reached up to 95% of the working year. With a similar aspect ratio, office buildings elongated along the east-west axis had a higher $UDI_{100\text{-}2000\ lx}$ value than those elongated along the north-south axis. The reason is that office building AR 1: 2.04, elongated along the north-south axis, had a larger opening area facing east and west than office building AR 2.1:1, elongated along the east-west axis.

With a similar building aspect ratio, office building AR 1:2.04 elongated along the north-south axis had a higher UDI exceed (>2000 lx) than office building AR 2.1:1 elongated along the east-west axis, as high as 16.8% and 4.6% of the working year, respectively. The office building elongated along the north-south axis had a larger opening area facing east and west than the office building AR 2.1:1, which elongated along the east-west axis.

Office buildings implementing HLP and shading systems had $UDI_{100\text{-}500\ lx}$ in the range of 35–49% of the working year. At those times, daylight illuminance is considered adequate as the primary source of room illumination or in combination with electric lighting (Nabil and Mardaljevic 2006). Office building AR 1:2.04 elongated along the North-South axis had the lowest $UDI_{100\text{-}500\ lx}$, which reached up to 35% of the working year. Office building AR 1.1:1 and AR 1:1.79 had the highest $UDI_{100\text{-}500\ lx}$, as high as 49% of the work year.

Office buildings implementing HLP and shading systems had UDI autonomous (500-2000 lx) in 43–54% of the working year. These results indicated that daylight illuminance was perceived as desirable or at least tolerable at 43–54% of the occupied hours in a year. Office building AR 1:1.3 had the highest $UDI_{500\text{-}2000\ lx}$, which reached up to 54% of the work year. Office building AR 1:1.79 had the lowest $UDI_{500\text{-}2000\ lx}$, as high as 43% of the working year.

4.2. The impact of building aspect ratio on daylight performance

The impact of the building aspect ratio on DFav, UDF, and $UDI_{100\text{-}2000\ lx}$ was analyzed using regression analysis. Figure 13 shows a regression analysis plot of the building aspect ratio and daylight performance. Figure 13 shows the DFav and UDF as a function of the building aspect ratio.

The regression analysis of the building aspect ratio with the DFav shows that the building aspect ratio strongly influences the DFav, with the coefficient of determination as high as 0.9089 (Figure 13). A linear relationship between the DFav and building aspect ratio can be obtained, as follows:

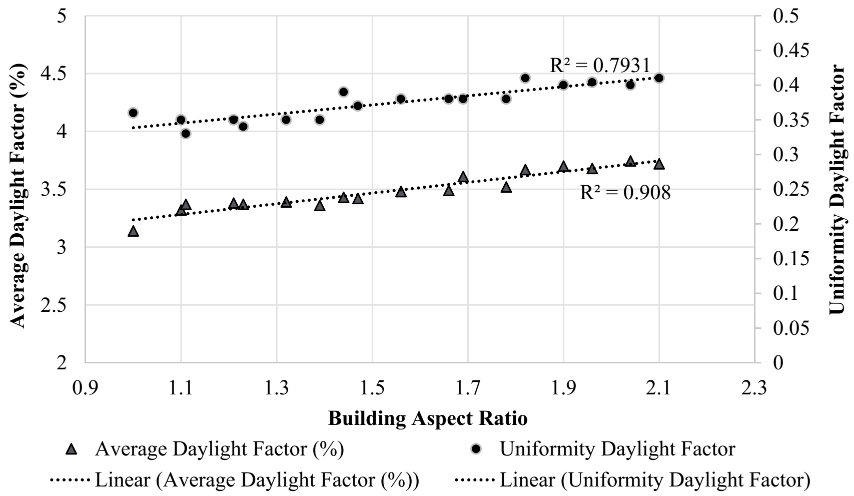


Figure 13. The relationship of building aspect ratio with average daylight factor and uniformity daylight factor.

$$DFav = 0,463x + 2,7731 \quad (7)$$

With every 0.1 increase in the building aspect ratio, the average DF is expected to increase by a linear difference of 2.82%. This equation is valid only in this case, a building that implements HLP and shading systems.

The analysis also indicated that the building aspect ratio strongly influences the UDF, with a coefficient of determination as high as 0.7973. A linear relationship between the uniformity DF and building aspect ratio can be obtained as follows:

$$UDF = 0,0656x + 0,2731 \quad (8)$$

With every 0.1 increase in the building aspect ratio, the uniformity DF is expected to increase by a linear difference of 0.28. This equation is valid only in this case, which is a building that implements HLP and shading systems.

As one may expect, the results indicated that the higher the building aspect ratio, the higher the DFav of the entire building (Figure 13). The higher the building aspect ratio, the larger perimeter receives daylight. These results align with Lee et al (Lee, Boubekri, and Liang 2019). that the longer the building length compared to the building width, the higher the daylight availability. In office buildings with integrated HLP and shading systems, increasing the building aspect ratio from 1:1 to 2.1:1 will increase the average DF of the entire building by 18.47%.

The regression analysis also showed that the higher the aspect ratio of the building integrating HLP and shading systems, the higher the UDF value. Office building with an aspect ratio of 2.1:1 has a higher UDF than office building with an aspect ratio of 1:1. The UDF improvement of office buildings with an aspect ratio of 2.1:1 reached 17.2% compared to office buildings with an aspect ratio of 1:1.

The higher aspect ratio means the building becomes narrower in plan and reduces room depth. The increase in the UDF level as the building aspect ratio increases aligns with previous research by Lee et al (Lee, Boubekri, and Liang 2019), that the smaller the room depth, the more daylight intensity enters the room. A higher building aspect ratio results in a higher daylight level (Lee, Boubekri, and Liang 2019). The contrast between the daylight level in the area far from the side window and the area near the side window then decreased, resulting in a more uniform daylight distribution, which, in this research, is characterized by an increase in UDF value.

Figure 14 shows the $UDI_{100\text{-}2000\ lx}$ as a function of the building aspect ratio. The regression analysis for the aspect ratio of the building elongated along the east-west axis (Figure 14(a)) with $UDI_{100\text{-}2000\ lx}$ shows that the building aspect ratio has a weak influence on the $UDI_{100\text{-}2000\ lx}$, with a coefficient of determination of 0.4052 (Figure 14(a)). A linear relationship between the building aspect ratio and $UDI_{100\text{-}2000\ lx}$ can be obtained as follows:

$$UDI_{100-2000lx} = 1.8164x + 89.832 \quad (9)$$

With every 0.1 increase in the building aspect ratio, $UDI_{100\text{-}2000\ lx}$ is expected to increase by a linear difference of 90.01. This equation is valid only in this case, a building that implements HLP and shading systems.

The regression analysis for the aspect ratio of a building elongated along the north-south axis (Figure 14(b)) with $UDI_{100\text{-}2000\ lx}$ shows that the building aspect ratio moderately influences $UDI_{100\text{-}2000\ lx}$, with a coefficient of determination of 0.6373 (Figure 14(b)). A linear relationship between the building aspect ratio and $UDI_{100\text{-}2000\ lx}$ is obtained as follows:

$$UDI_{100-2000lx} = -7.4997x + 102.28 \quad (10)$$

With every 0.1 increase in the building aspect ratio, $UDI_{100\text{-}2000\ lx}$ is expected to decrease by a linear difference of 101.53. This equation is valid only in this case, buildings that implement HLP and shading systems.

Unlike the DF trends, improving the aspect ratio of buildings elongated along the north-south axis

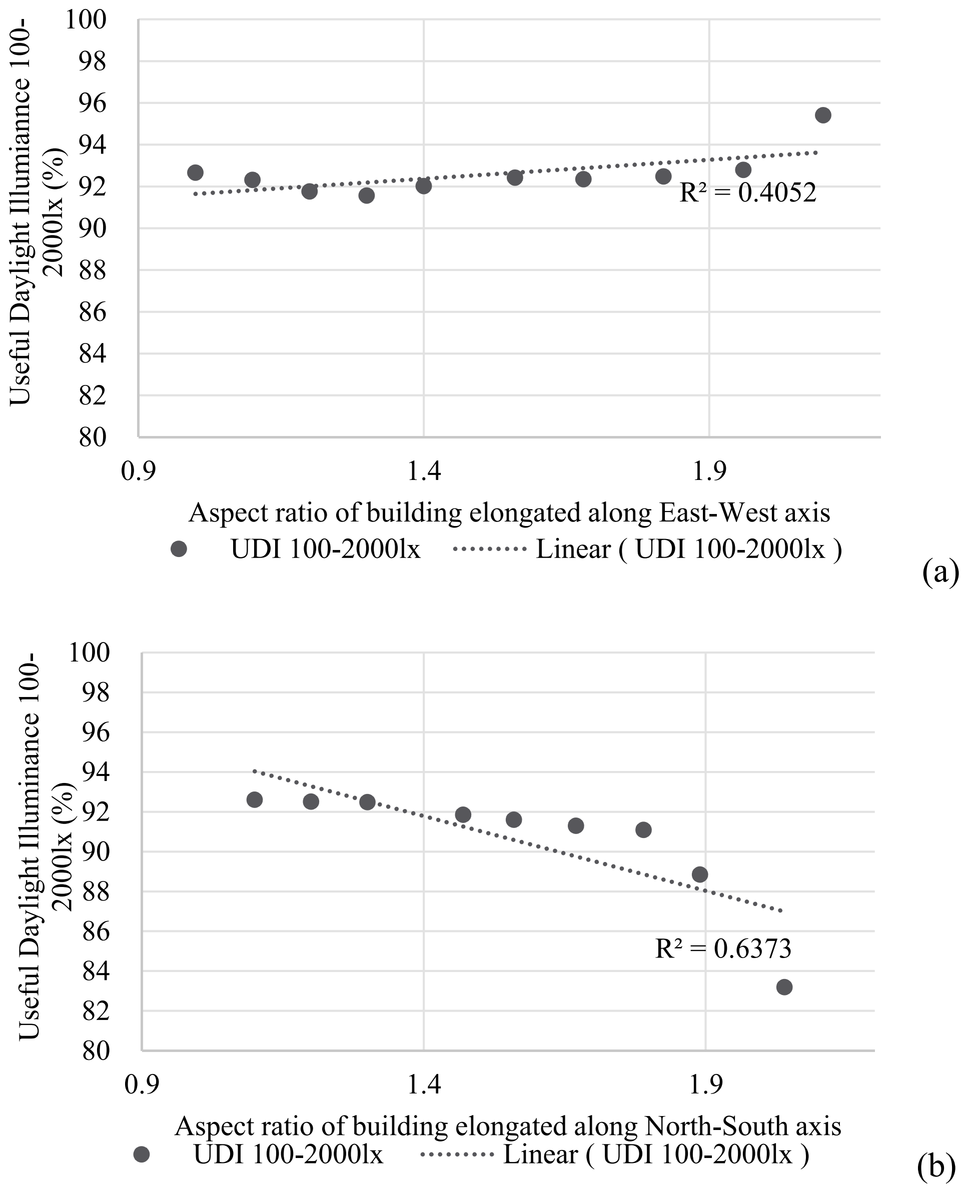


Figure 14. The relationship of building aspect ratio elongated along (a) east-west axis and (b) north-south axis with $UDI_{100\text{-}2000lx}$.

decreases the $UDI_{100\text{-}2000\ lx}$. The improvement in the aspect ratio of buildings elongated along the north-south axis increases the building area's side window facing west, which causes an increase in the UDI exceed (>2000 l×) and a decrease in the $UDI_{100\text{-}2000\ lx}$. In contrast, improving the aspect ratio of buildings elongated along the east-west axis slightly improves $UDI_{100\text{-}2000\ lx}$, caused by the reduction of the building area's side window facing west.

For daylight to be "useful," UDI has lower and upper illuminance thresholds of 100lux and 2000lux (Reinhart and Weissman 2012). In this research, the $UDI_{100\text{-}2000\ lx}$ trends are influenced more by the percentages of $UDI_{>2000\ lx}$, where all office buildings had no percentage of occupied hours in the year with daylight illuminance <100 l×. Area with an illuminance level of more than 2000 lx is located on office rooms facing West. In line with previous research (Boubekri and Lee 2017), a large portion of illuminance values of more than 2000 lx are excluded from the $UDI_{100\text{-}2000\ lx}$ calculation and makes the building that has a larger façade area facing sunlight; in this research, the West has a lower UDI.

Using linear regression, the building aspect ratio has a relatively weak and moderate influence on $UDI_{100\text{-}2000\ lx}$. $UDI_{100\text{-}2000\ lx}$ trends are influenced by the percentages of $UDI_{>2000\ lx}$, where daylight illuminances higher than 2000 lx tend to produce thermal or visual discomfort and closely correlate with the Daylight Glare Probability (Boubekri and Lee 2017). These results align with previous research using the Annual Glaring Index, which showed that building aspect ratios have a minor impact on glaring using linear regression (Maltais and Gosselin 2017).

In this research, the impact of building aspect ratio elongated East-West and North-South axes on $UDI_{100\text{-}2000\ lx}$ is weak and moderate sequentially. The length of the shading systems in this study changes simultaneously with changes in side window length at different building aspect ratios. Unlike DF and UDF, which took only overcast sky conditions, UDI involves the (hourly) sun and sky conditions from annual climate datasets (Nabil and Mardaljevic 2006). Under different sky conditions, the role of light shelves and blinds as shading systems in reducing $UDI_{>2000\ lx}$ appeared more, diminishing the impact of building aspect ratio on $UDI_{100\text{-}2000\ lx}$, which makes the correlation coefficient relatively low.

Determination of the optimum building aspect ratio involving DFav, UDF, and $UDI_{100\text{-}2000\ lx}$ showed that the optimum building aspect ratio is AR 2.1:1, which has a narrow plan and is elongated to the East-West axis. The building is 58 m in length and 27.6 m in width. The building has DFav, UDF, and $UDI_{100\text{-}2000\ lx}$ as high as 3.72 lx; 0.413 and 95% of the working year, sequentially. With a similar building aspect ratio, building AR1:2.04, elongated to the North-South axis, has a lower $UDI_{100\text{-}2000\ lx}$, as high as 83% of the working year. Building elongated along the North-South axis is not selected for the optimum building aspect ratio because although it has the highest DFav and UDF of 0.4, it has a lower $UDI_{100\text{-}2000\ lx}$. Considering the daylighting design in tropical climates emphasizes controlling solar radiation entering the buildings, building elongated to the East-West axis with a higher $UDI_{100\text{-}2000\ lx}$ than the North-South axis is selected as the optimum building aspect ratio.

These results can give insight to building designers in designing the aspect ratio of buildings integrating HLP and shading systems for daylight performances in early design stages. Observing various daylight metrics in this research, DF, UDF, and $UDI_{100\text{-}2000\ lx}$, is important in the design phase. Observing various daylight metrics in the design phase is essential since they influence the design variables differently.

Consideration of other aspects, such as thermal and energy performances, should be elaborated in future studies. The relationship between building aspect ratio and design variables such as window-to-wall ratio and building orientation should be studied. User perceptions of buildings implementing HLP and shading systems can also be included, considering the importance of users' psychological aspects.

5. Conclusion

The impact of the aspect ratio of buildings with HLP and shading systems on daylight performance was studied. The results indicated that office buildings integrating HLP and shading systems with an aspect ratio of 1.1:1 to 1:2.04 had an average daylight factor (DFav) in the range of 2–5% and $UDI_{100\text{-}2000\ lx}$ of 83–95%. Only five office buildings had UDF ≥ 0.4, ie, buildings with an aspect ratio of 1.82:1, 1.96:1, 2.1:1, 1:1.89, and 1:2.04, sequentially.

The results indicated that improving the building aspect ratio increased the average daylight factor and uniformity daylight factor. Increasing the building aspect ratio along the north-south axis improved the DFav more than along the east-west axis. Increasing the building aspect ratio along the north-south axis reduced the $UDI_{100\text{-}2000\ lx}$, while increasing the building aspect ratio along the east-west axis improved the $UDI_{100\text{-}2000\ lx}$ slightly. The optimum building aspect ratio involving DFav, UDF, and $UDI_{100\text{-}2000\ lx}$ showed that the optimum building aspect ratio is AR 2.1:1, which has a narrow plan and is elongated to the east-west axis.

Future research can involve other design variables, such as building orientation and window-to-floor ratio. Future studies should also focus on the energy and thermal performance of buildings integrating HLP and shading systems. The daylight and energy optimization of buildings implementing HLP and shading systems can also be investigated. Considering the importance of users' psychological aspects, user perceptions of buildings implementing HLP and shading systems can also be included.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

The authors report no funding.

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