ISSN (Print) : 0974-6846
Indian Journal of Science and Technology, *Vol 9(33), DOI: 10.17485/ijst/2016/v9i33/86216, September 2016* ISSN (Online) : 0974-5645

Relationship between Window-to-Floor Area Ratio and Single-Point Daylight Factor in Varied Residential Rooms in Malaysia

Al-Tamimi Nedhal[1*], Fadzil Sharifah Fairuz Syed[2] and Abdullah Adel[3]

[1]Architectural Engineering Department, Faculty of Engineering, Najran University, 61441, KSA; naaltamimi@nu.edu.sa

[2]School of Housing Building and Planning, Universiti Sains Malaysia, 11800 Penang, Malaysia; sfsf@usm.my

[3]Architectural Department, Hadhramout University of Science and Technology, Republic of Yemen; adel077@gmail.com

Abstract

Objectives: Daylight studies on buildings are key aspects of environmental analysis, and can be conducted during early stages of design to ensure environmentally responsive building design. The Malaysian Uniform Building By-law states that rooms should be provided with natural lighting and natural ventilation through one or more windows with a total area of not less than 10% of the clear floor area. This requirement is depicted by the window-to-floor area ratio (WFR). **Methods:** The by-law is further investigated by determining the relationship between WFR and daylight levels in terms of percentage daylight factor (%DF). The WFR minimum stated in the by-law is assessed using two tests: (1) Determining whether a WFR less than 10% is indeed inadequate for lighting purposes, and (2) Whether a maximum WFR should be imposed to avoid over-lit spaces. Research was conducted in a condominium unit with varied room designs and WFR. Natural illumination data were collected at midpoints of four different rooms for comparison with simultaneous outdoor illumination over a span of several days to obtain average %DF values. **Findings:** A strong direct relationship exists between WFR and natural illumination levels (in terms of %DF). In a local context, a WFR less than 10% was found to provide sufficient daylight levels in typical rooms, whereas a WFR more than 25% could cause rooms to be over-lit.

Keywords: Daylight Factor (%DF), Uniform Building By-Law (UBBL), Window-to-Floor Ratio (WFR), Window-to-Wall Ratio (WWR)

1. Introduction

Building occupants can enjoy an aesthetically pleasing indoor environment with less lighting energy required if sufficient daylight is available. Effective use of daylight is essential in achieving a sustainable building design. The size of a glazed window is proportional to the level of daylight and depends on the proper integration of both window area and glass properties. Improperly designed windows could not only lead to poor illumination in building interiors, but may also cause fatigue, depression, and inefficient energy usage[1-3]. A naturally illuminated indoor environment is influenced by many design aspects, including opening and glazed parts of building envelopes, interior surfaces, and appropriate use of colours[4-6]. Window design depends on the optimization of the glazed area for visual comfort without glare. Window position also plays a vital role for indoor daylight levels and distribution[7-9]. Building code (or building regulation) requirements associated with ensuring adequate daylight have been introduced in New Zealand (habitable spaces only), Portugal, Germany, Sweden, Australia (for ventilation), France, China, Singapore, and Belgium (residential areas only). These requirements are generally based on average daylight factor (DF) and/or minimum window sizes as 'A' (percentage of floor area and/or wall area) or 'B' (%DF minimum). No minimum legal requirement associated with daylight exists in

** Author for correspondence*

Switzerland, Denmark, Ireland, the United Kingdom, the United States, and South Africa. Most countries have (as a minimum) informative codes and standards that require "sufficient" daylight or illumination, but mandatory levels are not defined[10].

In Malaysia, legislative requirements state that a minimum of 10% window-to-floor area ratio (WFR) be imposed on any room designed (residential, commercial, or others). This rule is similar to laws in Singapore. More specifically, the Uniform Building By-law 1984 (#39:1) states the following day lighting requirements in Malaysia[11] "Every room designed, adapted or used for residential, business or other purposes shall be provided with natural lighting and natural ventilation by means or one or more windows having a total area of not less than 10% of clear floor area of such room and shall have openings capable of allowing a free uninterrupted passage of air of not less than 5% of such floor area".

According to this requirement, openings for natural light may range from 10%–100% of the floor area. Studies need to be conducted to determine whether this minimum is sufficient for natural room lighting, and also whether a WFR less than 10% is indeed insufficient. A study by Syed Fadzil[12] suggested an upper limit because in the tropical context, too much light may not be desirable because it can introduce heat and glare problems. Therefore, for new buildings with a high percentage of glass, finding the right balance between exposure to the environment and protection from extreme conditions is a serious concern[13]. Aside from the required WFR ratios, another legislative requirement called "right to light" must be considered. The right to light legislation allows a building owner to preserve the amount of natural light received by the building. However, the owner must ensure that the building does not obstruct the daylight received by neighboring structures[14].

The daylight factor (%DF) is the percentage ratio between indoor illuminance on a working plane and external horizontal illuminance during overcast sky conditions[4-6]. This ratio is based on a relatively simple concept for measuring and analyzing the presence of daylight in buildings. The formula for %DF is derived as follows:

$$\%DF = E_i/E_o \times 100\%,$$

where E_i is the illuminance from daylight at a point on the indoor working plane, and E_o is the simultaneous outdoor illuminance on a horizontal plane from an unobstructed hemisphere of the sky[15]. Average daylight factor is probably the most widely used parameter for daylight design and performance evaluation[16-19]. The amount of daylight entering an interior space from an overcast sky is emphasized over its quality. As a result, a large value of the average %DF does not always imply good indoor daylight quality.

2. Previous Studies

Numerous studies have addressed the influence of window size on energy efficiency, thermal performance in buildings, and visual comfort. Most of these studies considered the size of windows with reference to wall area ratio. However, only a few studies focused on the effect of glazing area on illumination in indoor spaces. In the literature, an average daylight factor of 1% is generally described as the minimum level at which people experience daylight in actual[20,21]. If the average daylight factor in a workplace is lower, the user is more likely to be dissatisfied. When the daylight factor in the workplace is more than 3%, the workplace is considered as a daylight-oriented location. Dubois[20] presumes that a daylight factor higher than 5% might cause glare problems, especially for working with computer screens. Dietrich[21] found that heat problems occur at daylight factors over 10%. The minimal window size, found by [22]can be expressed as a percentage of the total wall area. The average window width chosen by the respondents was 2.42 m, which is 23% of the total wall area. The acceptable window size was further affected by several parameters such as view content, distance from window, window height, and visual angle. [23]Performed an optimized and comprehensive evaluation using building simulation and indoor CFD simulation to accurately predict the indoor thermal environment for naturally ventilated buildings in the hot-humid climate of Singapore. The window size in this coupled simulation was made to vary from a window-to-wall (WWR) ratio of WWR = 10% to WWR = 40% for all orientations. The optimum WWR in Singapore was determined to be 24%. This percentage of WWR was recommended based on the improvement of indoor thermal comfort.

In an investigation of 280 residential buildings in [24]observed that the WWR of living rooms and bedrooms ranged from 15% to 50%; and about 90% of buildings had WWRs between 25% and 35%. A study[25] optimized the relationship between window size, space dimensions, and daylight with regard to the energy consumption of the space. The ideal window area was found to be larger in orientations with lower energy consumption as a result of reduced solar radiation exposure. The larger the room and the smaller the façade, the larger the ideal window area. Although minimizing the window size ensures low energy load, it may fail to provide the required natural light. Another researchers[26] studied the impact of window size on the average natural daylight level received, wherein eight scenarios summarizing all possible alternatives of window positions in the room are investigated; the study concluded that using the minimum of 10% offers the best option for visual comfort in most scenarios. In another study[27] used a 1:12 scale model for their research. The preferred window size was found to be not a fixed percentage of the size of the wall, but it is influenced by the nature of the view and the size, shape, and function of the room.

This study has the following objectives:

- To investigate a method to determine single point %DF values in varied residential rooms in Malaysia,
- To investigate daylight pattern in varied room designs with varied WFR, and
- To determine the relationship between WFR to single point %DF and the measured natural illumination.

3. Malaysia – Location, Climate, and Sky Characteristics

Malaysia is located in the equatorial region 1°–7° N, 100°–120° E. Most towns in Peninsular Malaysia experience high temperatures and humidity throughout the year without remarkable variations. The following are brief descriptions of the Malaysian climate[28]:

- Minimum diurnal temperature range is 23–27 °C,
- Maximum diurnal temperature range 30–34 °C,
- The average difference is 6.7–8.3 °C, and
- Annual RH value ranges from 74–90%.

Malaysian skies are in the category of very cloudy intermediate skies; neither overcast nor clear even though the skies are occasionally clear in the morning and overcast during rainy monsoon seasons. Average cloud cover, which is measured in oktas (0 okta being clear, and 8 okta being overcast), is 6.8 oktas, according to meteorological stations[29]. Another guideline for sky illuminance is provided by the Building Energy Efficiency Technical Guideline for Passive Design, which states the diffuse daylight availability for the Malaysian climate with maximum, minimum, and average values in klux (refer to Figure 1)[29].

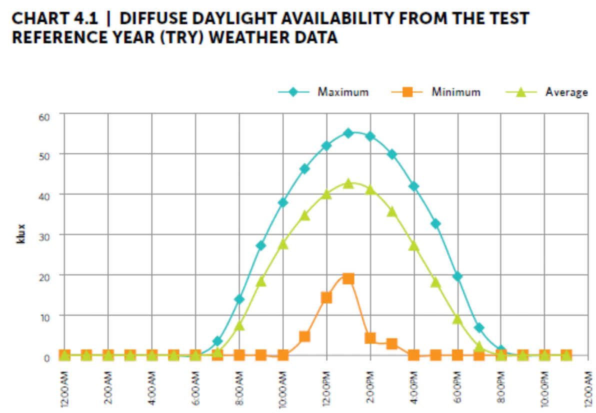


Figure 1. Diffuse daylight availability from weather data.

4. Baseline and Methodology

4.1 Baseline Configuration

The View condominium (also popularly known as Penang Twin Towers) was selected as the primary case study. This condominium was selected because of its modern and unique design, variety of room configurations and layouts, and different window shapes and glass areas, which give a wide range of calculated WFRs. This condominium is located at the Batu Uban area, with coordinates of 5.20° N, 100.18° E (Figure 2. Left), in Penang, Malaysia. The residential scheme consists of two towers (A and B, both 29-storey condominiums) with a total of 164 units; the towers are connected to each other via a skybridge on the 14th floor (Figure 2. Right). The building is oriented to the southeast (Tower A) and northeast (Tower B) directions as shown in (Figure 3. Left). Each floor consists of 3 residential units with an approximate floor area of 530 square meters. One unit in Tower A (Unit 1A) was chosen for study. Details of other rooms (labeled R1, R2, R3, and R4 in Figure 3. Right) are presented in Table 1.

Figure 2. (Left) The View building (Case Study) Location in Penang, Malaysia; (Right) The View building: General Views.

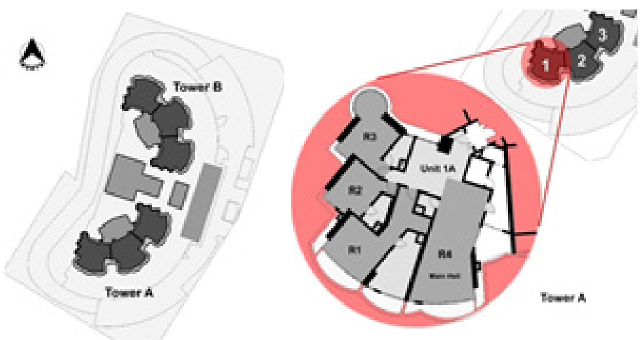


Figure 3. (Left) Typical floor of The View, Units 1A and 1B at Towers A and B; (Right) Typical floorplan of The View, Unit 1A at Tower A.Location in Penang, Malaysia; (Right) The View building: General Views.

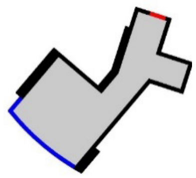
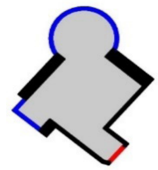
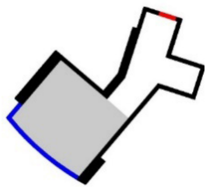
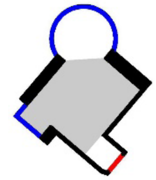
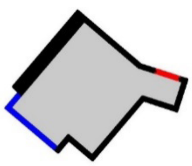
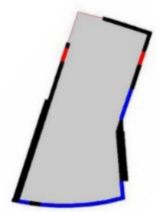
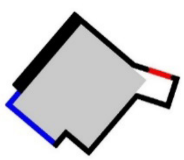
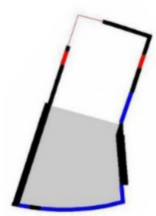
4.2 Methodology

Field work and data collection were conducted using a Babuc/A data logger connected to an indoor luxmeter probe (E_i) with a maximum reading of 20,000 lux and an outdoor luxmeter probe (E_o) with a maximum reading of 100,000 lux. The indoor lux meter probe was placed at the approximate center of each test room (R1–R4) at 1 m above floor level for Unit 1A. Readings were continuously collected every 10 minutes in each room from April to July. Due to varied orientations and extensive glass areas per room, the influence of direct sunlight on the E_i data (indoor illumination) entry was confirmed. This condition was particularly true when Unit 1A was located at level 9 with no external obstructions that might affect the daylight pattern inside. The direct sunlight penetration is countered by excluding from the collected data all data with direct sunlight influence and by considering only the data taken at higher sun altitude. These time periods with no direct sunlight entry in all rooms were observed to be from 1030 AM to 330 PM. All data from the average natural illumination levels and %DF calculated were graphed and analyzed by taking the averages of measurements from several consecutive days. All rooms were emptied of any furniture or curtains/blinds to avoid the influence of internally reflective components. The reflectance factors of walls, floors, and ceilings were kept as originally specified: white for the walls and ceiling, and light yellow for the floor tiles. Results of the case study are shown in Tables (1., 2.) and Figures (4., 5.). Measurements had to be taken room by room because of limitations in equipment, and 6 days of average data were used for each room. Measured %DF data from Unit 1A assumes the formula %DF = SC+IRC. Due to the location of the unit on the 9th floor, approximately 40 m from ground, no externally reflected component (ERC) of the time data was collected. Unit 1A has the sky component (SC) and internally reflected component (IRC) as the two components comprising the %DF.

4.3 Determining WFR Ratios for the Case Study Rooms

In this study, only one data point for %DF was measured per room because of limitations in available equipment.

Table 1. Total and effective floor area for WFR calculation of typical rooms in Towers A and B

Layout		WFR	Layout		WFR
R1			R3		
Case 1		F = 26.6 m^2 W = 10.4 m^2 WFR = 39%	Case 1		F (all) = 18 m^2 W = 14.7 m^2 WFR = 81%
Case 2		Case 2 (effective) F = 16.6 m^2 W = 10.4 m^2 WFR = 62.65%	Case 2		Case 2 (effective) F = 13 m^2 W = 7.36 m^2 WFR = 56.6%
R2			R4		
Case 1		F = 14.5 m^2 W = 3.8 m^2 WFR = 26.2%	Case 1		F = 42.6 m^2 W = 15.4 m^2 WFR = 36%
Case 2		Case 2 (effective) F = 13.4 m^2 W = 3.8 m^2 WFR = 28.4%	Case 2		Case 2 (effective) F = 23.6 m^2 W = 11.8 m^2 WFR = 50%

With the irregularities of room shapes and forms, determining the WFR ratios required correction factors. Window and floor areas need to be the effective WFR influenced by the single %DF point in the middle and not the overall WFR of the entire room. The calculation of WFR for R3 for example, can be as high as 81% (ratio of the total glass area of 14.7 m^2 to the total floor area of 18 m^2). However, not all the light from the circular window is reflected to the single point. The appropriate calculation for the single-point %DF of the rooms involves only the effective floor area (shaded) of each room, wherein the %DF is located at the middle. Thus, this effective area method was used in calculating the WFR for rooms R1 to R4 in Unit 1A. However, the overall WFR as depicted in the UBBL is also noted and provided. As shown in Table 1., all rooms (R1–R4) have the overall WFR given as Case 1, whereas the effective WFR is given as Case 2.

5. Results and Discussions

Based on natural illumination levels at midpoints of all rooms (R1–R4) in lux, all rooms in Unit 1A were found to be sufficiently illuminated. Table 2. shows the average %DF from R1 to R4 at Unit 1A, along with their respective maximum, minimum, and average %DF, as well as illumination levels in lux. These were six-day averages per room (not on similar six days because of lack of equipment); however, the selected days were observed to be typical bright sunny days in March. Data excluded direct sunlight influence as discussed, and were taken only from 1030 AM to330 PM. Natural illumination levels were generally observed to be on the high scale compared with standards for illumination in bedrooms, which is usually around 100–200 lux. To analyze further the relationship between WFR and %DF or absolute illumination levels,

Table 2. Tower A WFR, daylight factor, and illumination according to the effective floor area

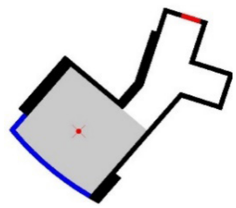
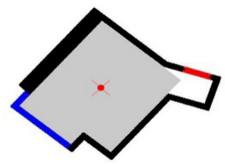
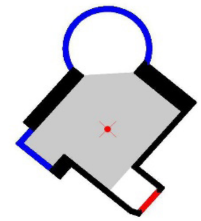
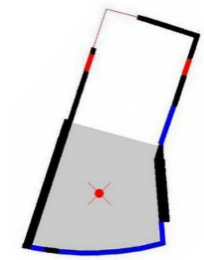
Rooms	R1			R2			R3			R4		
WFR effective floor area (shaded area)												
WFR	63%			28%			57%			50%		
DF (%)	Ave.	Min	Max	Ave.	Min	Max	Ave.	Min	Max	Ave.	Min	Max
	7.3%	5.7%	8.9%	4.5%	3.5%	7.2%	7.1%	5.4%	12.2%	5.9%	5.1%	6.8%
Average illumination (lux) at mid-point	1248	765	1794	815	441	1258	1337	944	1810	1051	753	1186

Figure 4. ranks the rooms according to effective WFR from smallest to largest. This ranking identifies R2 as the smallest effective WFR at 28%, followed by R4 at 50%, R3 at 57%, and R1 at 63%. All rooms satisfy UBBL #39 (1) because all of them have WFR ratios (effective or overall) of 10% or more. From Figure 4. it can deduce that with lower WFR, the average single point %DF also decreases. For example, at Unit 1A, R2 had the lowest WFR at 28% and also the lowest average %DF at 4.5%. R1, with the highest WFR at 63%, also had the highest average %DF at 7.3%. The WFR for R4 and R3, including their respective average midpoint %DFs, is between that of the two other rooms.

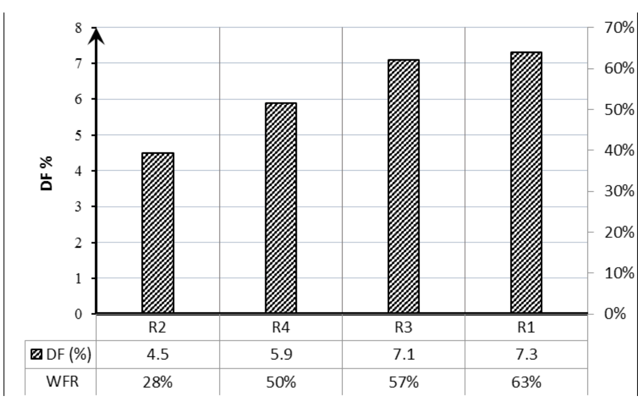


Figure 4. Tower A Rooms Ranking according to WFR.

Using SPSS, a regression studies by[30,31] were conducted to determine the relationship between %DF to WFR, and natural illumination levels (E_i) to WFR. This task was performed in the same graph with respect to the View condominium in March, which has the following condition:

$$\%DF = SC + IRC.$$

As shown in the graphs, both charts have high reliability and validity with R values above 0.95[32-34]. WFR significantly influences the single point %DF and illumination levels. The higher the WFR, the higher the single point average %DF. A general guide to predict the approximate value of midpoint %DF, given the WFR percentage, may be derived from this chart. However, this condition is not necessarily true for absolute illumination levels because the average illumination level for R1 with the highest WFR was found to be lower than R3 as a result of the changing variability of outdoor sky illuminance, which varies in terms of brightness. %DF values are more reliable in depicting daylight performance in the rooms. In Figure 5, lines depicting a strong relationship can be extended as shown by the red lines.

We consider the blue lines, for example, which pertain to the View units at topmost floors where SC predominates. If designers require a 3%DF at the midpoints, the required WFR is only at 10%WFR (Figure 5). Designers for high-rise residential buildings with daylighting situations where SC predominates should therefore be more cautious of having excessively high WFR percentages, which would result in over-lit spaces. These over-lit spaces are likely to have other problems, such as glare and heat gains[35-37]. In terms of absolute natural illuminance level in lux, all rooms were found to be over-lit because of extensive glass areas and high WFR. These rooms had very bright sky conditions, with average readings from as low as 815 lux for R2 and as high as 1337 lux for R3. High luminance causes heat gains and glare problems, but with curtains and furniture, the values are expected to decrease slightly. However, based on the graphs and illumination standards for typical rooms around 100–200 lux, a WFR of 5% was shown to be sufficient when values of 500 lux were predicted from the graph.

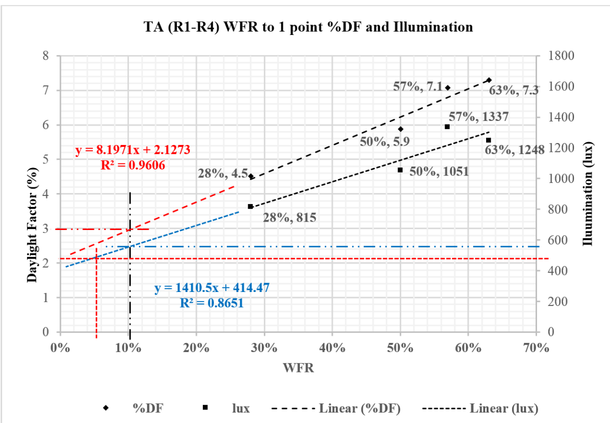


Figure 5. Relationship between %DF and WFR to illumination level for TA from fieldwork data of R1–R4.

Interestingly, according to the graph, the dotted line does not seem to converge to zero. Logically, when WFR approaches zero, the room is implied to have no window area at all. Thus, the resulting %DF should approach zero as well. However, this does not seem to be the case in Figure 5. A strong 2%DF was obtained at an WFR of zero. This occurrence may be attributed to the following:

- The rooms (R1–R4) are not in isolation. They are linked together via doors to adjacent spaces.
- Leakage of light from other linked spaces can occur through voids (i.e., beneath doors and through joints).
- Leakage of light can occur when doors are opened.

Limiting the passage of light only to the window area as calculated in the WFR is impossible, especially in a typical building with connected spaces.

6. Conclusions

The relationship between WFR and daylight factor was investigated in several residential rooms in Malaysia. Based on the graphs and the level of natural illumination upon collection of field work data, the following conclusions can be derived:

- %DF is a valid and reliable assessment of daylight in spaces. However, it is limited to the sky illuminance conditions in Malaysian.
- %DF recommendations (a minimum of 2%DF in countries with temperate climates) are not applicable in the hot-humid climate of Malaysia and need be adjusted accordingly.
- In cases where %DF is mostly determined by the SC and IRC, an average %DF of 1% to 2% can be considered sufficient.
- A WFR of 25% is suggested as the upper limit to avoid over-lit spaces.

7. Acknowledgment

The authors are grateful for the support of the Malaysian government and the University Science Malaysia through the Fundamental Research Grant Scheme. Cooperation from the management of the View Condominiums is sincerely acknowledged.

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