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Optimization of Envelope Heat Gain and Interior Daylight Illuminance in Building Facade Design Under Reflectance Limitations: A Case Study of Office Buildings in Thailand

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ABSTRACT

The popularity of using glass as the main building envelope material in commercial high-rise buildings has brought about numerous legal actions in recent years due to the widespread impact of the visible light reflectance of glass facades on the surrounding area. However, choosing suitable reflectance values for glazing the building facade remains a viable solution to lessen envelope heat gain and reduce cooling energy demand. Despite this, maximizing daylight is essential to maintaining healthy vision and the circadian rhythm of the building users. As a result, finding the optimal solution for envelope glass property selection to provide minimum heat gain through the building facade and maximum indoor daylight became a great challenge. The experimental research is conducted to identify the relationship between overall thermal transfer value (OTTV) and useful daylight illuminance (UDI) and to find suitable enveloped glass performance properties. Two typical high-rise office buildings in Thailand with a square-shaped and a rectangular-shaped floor plan are selected as case studies. BEC, a web-based program developed by Thailand’s Department of Energy Development and Efficiency, and Rhinoceros 6, along with Grasshopper, Ladybug, and Honeybee plugins, are used to calculate the OTTVs and transmitted visible light within the building, respectively. The results show that the maximum proportion of the building area that passes UDI requirements while in accordance with OTTV criteria is 23% and 26% in the square-shaped plan and the rectangular-shaped plan, respectively. These cases are with the WWR 80 and with glass performance values of SHGC 0.2, VLT 31%, and U-value 1.62 W/m2K.

Keywords: envelope heat gain, interior daylight illuminance, overall thermal transfer value, useful daylight illuminance, office building

INTRODUCTION

Due to the popularity of using glass as an external building material in high-rise buildings (e.g., offices, hotels, and condominiums), the design of these buildings using glass as a building facade has a direct impact on the habitants that live in the surrounding areas. Many lawsuits have been filed in terms of the undesirable amount of visible light reflectance that, especially between the months of November up to April in Thailand, adversely affects nearby individuals that live in the Sukhumvit area of Bangkok, for example. As a result, several court orders have been issued, requiring the building to compensate more than several thousands of baht to the affected individuals until a solution can be found (Anganapattarakajorn & Sreshthaputra, 2019). In response, government agencies issuing building and construction permits now impose more restrictions, including the requirements of a detailed Environmental Impact Assessment Report (EIA) to simulate visible light reflectance and assess its impact on the surrounding area. However, due to a shortage of experts, the EIA issuing agency in Thailand has set the visible light reflectance threshold at 15%, which is the same standard set for certified green buildings under TREES rating systems, the Thai Rating for Energy and Environmental Sustainability (Thai Green Building Institute, 2014). Despite being more effective in reducing energy consumption and the overall thermal transfer value (OTTV) of the building, according to the Thai Department of Energy (Royal Thai Government Gazette, 2009), using glass with reflectance values between 15-30% instead would still fail to meet EIA requirements. Nevertheless, building projects in Thailand are not required to follow the TREES building certification as buildings can use a glazing envelope up to a 30% threshold, as permitted by law (Office of the Council of State, 1997). Subsequently, glass materials have become limited in order to meet both the building energy code related to OTTV and reflectivity required by the EIA, especially when a building glazing envelope’s reflectivity is largely reduced. Heat-absorbing glass, also known as tinted glass, is commonly used to overcome these challenges. However, rather than using a glass material that reflects more sunlight that comes along with heat to minimize the cooling energy, the tinted glass reduces the amount of visible light waves of daylight within the building, which in turn negatively affects the vision and the circadian rhythms of the users. In order to achieve both building energy codes and EIA, the tinted glass must have a very dark color; therefore, it will provide an extremely negative impact on the indoor daylight requirement. Regarding the daylight requirement, The WELL Building Standard requires a minimum visible light transmittance value of 40% (International WELL Building Institute [IWBI], 2021), while LEED and related studies propose a natural daylight range between 300-3,000 lux to maintain visual comfort (Mardaljevic, 2017; Srisutapan, 2019; U.S. Green Building Council, 2014; VELUX, n.d.). The UDI (useful daylight illuminance) has become a widespread and useful indicator representing the annual indoor work plane illuminances caused by transmitted daylight (Nabil & Mardaljevic, 2005, 2006). As a result, while choosing building facade glass, special consideration and evaluation must be given to the EIA, building energy code, and daylight requirements.

Given the circumstances, a challenge remains in analyzing and evaluating glass materials with reflectance values between 5 and 30% in order to determine the optimal OTTV value and the optimal UDI value of the building. This study is being conducted in order to meet this challenge. Using a variety of simulation software programs like BEC, Rhinoceros 6 and Grasshopper can be very supportive in terms of the calculation and evaluation. In this study, typical office buildings in Thailand will be selected as case studies. This research contributes to new guidelines for architects to select proper glass specifications in order to comply with the related regulations along with indoor daylight quality.

LITERATURE REVIEW

The popularity of glass as a building envelope material in commercial high-rise buildings has been increasing over recent decades. The design of such buildings must use glass materials that are durable and safe to building users and surrounding residents. More importantly, this type of glass should allow enough daylight into a space without gaining excessive heat to avoid high energy consumption. Given the current technology, there are different types of glass which can function as thermal insulation materials while allowing natural light to pass through. Currently, there are five types of glass that are widely available for use in the construction of high-rise buildings in Thailand: (1) float glass (e.g., clear or tinted), (2) Heat treated glass (e.g., tempered or heat strengthened glass), (3) Surface coated glass (e.g., solar reflective glass, or low-e glass) (4) Processed glass (e.g., insulated glass or laminated safety glass), and (5) Application glass (e.g., pattern, wired, or fire-resistant glass) (Royal Thai Government Gazette, 2009). In Thailand according to the building regulation, high-rise buildings must use laminated glass which remains intact after breaking (Office of the Council of State, 1997). However, the reflectance rate of the glass may not be higher than 30%. This can be problematic, especially when another restriction is imposed on energy usage (Office of the Council of State, 1997). In an effort to promote energy conservation Thailand, OTTV legally permitted that commercial buildings cannot exceed 50 W/m^2 (Royal Thai Government Gazette, 2021a), which is required for buildings with a gloss floor area starting from 2,000 m^2. The calculation of OTTV comprises three types of heat transfer that occur in a building envelop, which can take place in the following three ways: (1) conduction through solid walls, (2) conduction through glass walls or windows, and (3) radiation through glass walls or windows. Regarding the conduction activity, the heat transfer coefficient or U-value (measured in W/m^{2}K) of the material, which is either opaque (e.g., concrete wall) or translucent (e.g., glass envelope), is dependent on the thickness of the material and the thermal conductivity of the wall materials (Royal Thai Government Gazette, 2009). On the other hand, the solar heat gain coefficient, or SHGC, is a ratio that indicates the degree of solar radiation that directly passes into the building through the material that is translucent with a range of 0-1 (Royal Thai Government Gazette, 2009). Despite the wide variety of building materials and legal restrictions to reduce the amount of heat transfer that occurs in commercial office buildings, a well-designed building must also allow sufficient natural daylight not only for optimal and healthy vision but also for the well-regulated circadian rhythms of the users.

The following is a brief review of some metrics that have been invented over the years to evaluate the amount of natural light and the efficiency of the design in terms of illuminance. In the early 1900s, Daylight Factor or DF was developed in the United Kingdom as a metric which became a standard metric commonly used by 1960 (Mardaljevic et al., 2009). Expressed as a percentage, the luminance inside a given space is compared to the light received from the cloudy sky according to CIE standards (Kaufman, 1966). By 2006, Climate-based Annual Daylight Performance Metrics (also known as Climate-based Daylight Metrics), or CBDM, was developed using annual weather files (Mardaljevic et al., 2009; Brembilla & Mardaljevic, 2019) to simulate illuminance hourly based on a year of real weather data, which contains a detailed record of sky conditions and sun paths from weather stations close to the building used in the simulation model. CBDM uses Spatial Daylight Autonomy (sDA) in conjunction with Annual Sunlight Exposure (ASE) as indicators. The sDA describes the percentage of the indoor space area that receives sufficient illuminance level, whereas the ASE indicates the percentage of the indoor floor area that does not exceed a specified direct sunlight illuminance level. The simulation commonly pulls weather data from Typical Meteorological Year (TMY) weather files (Ashdown, 2014). Similarly, Useful Daylight Illuminance or UDI emerged around the same time (Nabil & Mardaljevic, 2005, 2006), presenting the useful indoor illuminance level predicted under realistic climate conditions. This indicator not only takes indoor illuminance into consideration but also visual comfort. As a result, this study applies UDI as an indicator for the daylight performance of building facades. The definition of achieved UDI is the annual occurrence of illuminances across the work plane when all illuminances fall within the specified range (Nabil & Mardaljevic, 2005). The useful illuminance limits will be reviewed and discussed in detail in the following paragraphs.

The amount of daylight in a given amount introduced into a space is considered useful when it does not cause glare or disrupt the visual environment and is sufficient for indoor activities. The indoor illuminance range which is considered useful has been studied for decades using occupant survey for preferences and behaviors in daylit offices with user-operated interior and/or external shading devices. As Nabil and Mardaljevic (2005) explored with previous research by Vine et al. (1998) and Lee et al. (1999), it can be concluded that the user feels more satisfied using a space in an office building that is filled with natural daylight and with an outside view where glare is minimal or non-existent. According to the UK Charter Institute of Building Services Engineers, the amount of illuminance at the indoor working plane should be 500 lux, which is a common and mandatory lighting practice in many countries globally (Nabil & Mardaljevic, 2005). Nevertheless, this amount of illuminance is solely achieved by artificial lighting, leaving room for natural daylight to be integrated. While the desirable illuminance can be achieved by daylight in such areas, it is possible to reduce the use of artificial lights by turning them off manually or installing an automatic power-off system. Based on a field study conducted by Lawrence Berkeley National Laboratory (USA) in 1998, Baker (2000) points out that building users can tolerate working under conditions with lower levels of illuminance whenever natural light rather than artificial light is present. In office buildings where users can adjust the lighting conditions individually, whether it is opening and closing curtains, blinds or adjusting the brightness of the lamp, building occupants can work in areas with higher illuminance values than are required in the design range between 510 lux – 700 lux (Vine et al., 1998). Furthermore, Nabil and Mardaljevic (2005) finds that many research studies have conclusive findings that many users in office buildings prefer natural light to artificial light with illuminance levels over 500 lux if the natural light does not lead to glare or visual discomfort (Lee et al., 1999; Littlefair, 2000; Roche et al., 2000). In an office environment where a user may interact with a computer screen, Roche (2002) finds that illuminance levels between 700 - 1,800 lux are fairly acceptable whether the user is staring at a screen or physical sheets of paper (Department of the Environment, Transport and the Regions, 1999; Roche, 2002). Overall, Nabil and Mardaljevic (2005, 2006) conclude that useful daylight illuminance levels are between the range of 100 - 2,000 lux in open-plan office buildings, which can replace daylight factor as the traditionally used metric. Around the same time, Mardaljevic (2006) uses the proposed metric in publishing “Example of Climate-Based Daylight Modeling” in CIBES National Conference in 2006 and a collaborative study with Reinhart et al. (2006) named “Dynamic Daylight Performance Metrics for Sustainable Building.” Another collaborative study conducted by Mardaljevic et al. (2009) expanded the useful range of illuminance to up to 2,500 lux for users in residential buildings due to the fact that many of the activities done at home involve more movement than sitting for long periods of time at work. Regardless, more conclusive results are still needed to understand the needs of users in residential buildings. In a large office, computer glare is commonly found on computer screens. Mardaljevic (2017) defines illuminance levels as useful based on a satisfaction survey of visual comfort of the users interacting with computer screens. Based on this study, the UDI levels can be summarized as follow:

1. UDI not achieved (UDI-n); natural light is not sufficient ~ below 100 lux
2. UDI supplementary (UDI-s); natural light is somewhat sufficient (there is some natural light but not enough, therefore, additional artificial lighting is required) ~ between 100 lux - 300 lux
3. UDI autonomous (UDI-a), natural light is optimal ~ between 300 lux - 3,000 lux
4. UDI exceeded (UDI-x), natural light is superfluous and disruptive ~ over 3,000 lux

In a research study of daylight metrics for buildings in Thailand by Srisutapan (2019), UDI has been found to have both quantitative and qualitative potential when compared to other metrics like DF, sDA, or ASE. The range of illuminance considered to be useful in this study is 300 lux – 3,000 lux. In light of the literature review mentioned above, UDI with an illuminance range between 300 and 3,000 lux will be used as the metric for daylight analysis along with OTTV as the metric for heat transfer in this study.

Based on previous research studies concerning OTTV, creating energy-efficient designs by reducing the amount of heat transfer through the building envelope is established as the common goal. Attempts are made to select suitable materials that are both opaque as well as translucent to achieve energy efficiency. Comparing different translucent materials such as window glazing while adjusting the WWR ratios of the glass window to the total wall area is one of the most well-known methods in finding effective designs that are also cost-effective. According to a study conducted by Daoprakaimongkok (2009), buildings with a WWR of less than 20% may use commonly used glass (e.g., tinted glass) which does not cause OTTV to exceed the requirements set by the Thai Department of Energy. By comparing different OTTV parameters from different case study buildings when different glass materials are used, the blue-green laminate insulated glass treated with Low – E substance is found to have the most suitable properties (Daoprakaimongkok, 2009). Oupala and Puthipiroj (2020) propose setting the WWR ratio to no more than 40% in designing buildings so to not exceed the established OTTV for all building types. For the opaque wall parameters, low density concrete or red clay bricks must not exceed a U-value of 1.20 W/m^2K or 1.50 W/m^2K, respectively. However, density specific heat value (DSH) must be higher than 181.92 kJ/m^2K. Looking at these two studies, it can be noted that buildings that can maintain their OTTV typically have a low WWR, which is not found in commercial high-rise buildings that exhibit more translucent rather than opaque wall areas. By looking at related OTTV studies that examine types of glass and solid materials that are used in building envelopes, there have been studies on the heat transfer into the building along with the study of the ratio of transparent windows to total opacity of the building envelope known as WWR. As a result, WWR should be considered as another key variable in understanding the dynamics of OTTV, in addition to the U-value and solar heat gain coefficient (SHGC) of each type of glass with different reflectance rates since it can directly impact the overall heat transfer. As such, buildings with different WWR attributes should be selected and investigated as case studies. As for the properties of glass related to heat transfer that directly affects the amount of natural light inside the building, there are no relevant concrete studies conducted in Thailand. As a result, in this study, the goal is to investigate and evaluate the amount of natural light and visual comfort in the context of UDI by identifying the types of translucent glass materials that must also maintain OTTV requirements set by building energy laws in Thailand.

METHODOLOGY

Building Base Cases as Office Buildings

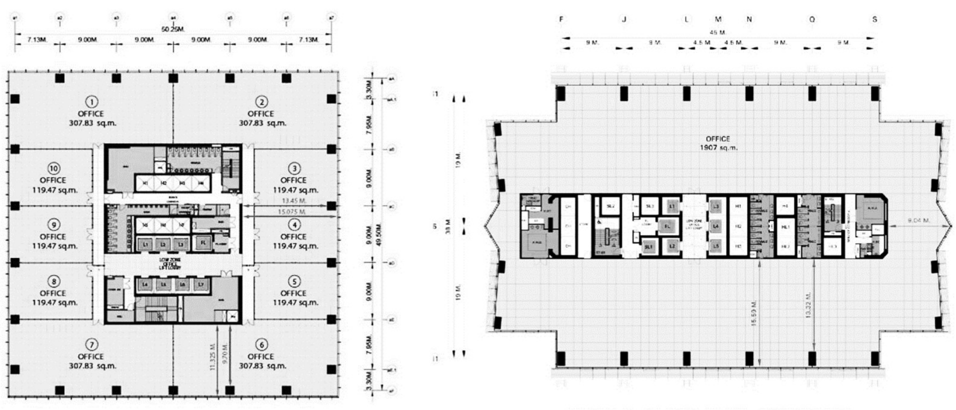
In this investigation, it was discovered that high-rise office buildings have had the most current facade reflectivity issues in Thailand. The characteristics of typical Thai office buildings have been identified after reviewing numerous prior relevant studies.

In the context of a study of office buildings by Chirarattananon and Taveekun (2004), which aims to improve the formulars for calculating OTTV and whole building energy consumption, the design of typical office buildings in Thailand is found to exhibit the following characteristics: the building (1) must be a high-rise 12-story building, (2) must be built on a square-shaped area of 40 m^2, and (3) has a core area of 20 m^2 in the center that is unconditioned space. In another research (Jiaranaipanich, 2012), which investigates the impact of the shape and orientation of high-rise office buildings on the efficacy of energy conservation according to ASHARE 90.1 2007, various building shapes with a varied shape factor (SF) have been identified as case studies. This study has found that there are two popular building floor plans in Thailand: a square-shaped plan (SF 1:1) and a rectangular-shaped plan (SF 1:2) with an unconditioned building core placed in the middle of the building. These buildings are 12-story tall with an area per floor of approximately 1,600 m^2 and a floor-to-floor height of 4.00 m. In light of the research conducted by Jiaranaipanich (2012), the square-shaped and rectangular-shaped office buildings have been selected as typical floor plans for Thai office buildings. As the previous research mentions above, in order to define the current typical floor plan for Thai office buildings as case studies, further consideration has been given to two particular office building floor plans with the square-shaped plan (SF 1:1) and the rectangular-shaped plan (SF 1:2). Therefore, Samyan Mitrtown and the Park Ventures Ecoplex, two well-known square and rectangular floor plan offices in Bangkok with comparable floor area sizes, have been selected as representatives for two building floor plan types (shown in Figure 1). Using computational simulation software programs, building dimensions are adjusted as input for calculations for each office building.

For the square-shaped office building type (as shown in Figure 2a) with SF of 1:1, the calculation model is configured per floor to have a gross floor area of 2,500 m^2: (50 x 50 m^2) with a central core area of 484 m^2: (22 x 22 m^2) with a salable area of 2,016 m^2 (approximately 80.64%) with a floor-to-ceiling height of 3.00 m. For the rectangle-shaped building type (as shown in Figure 2b), with SF of 1:1.68 the calculation model is configured per floor to have a gross floor area of 2,432 m^2 (38 x 64 m^2) with a central core area of 480 m^2: (48 x 10 m^2) with a salable area of 1,952 m^2 (approximately 80.26%) with a floor-to-ceiling height of 3.00 m. For the purpose of this study, the ratios of the area of the translucent wall area to the total wall area (WWR) are defined as 0.4, 0.6, 0.8, 1.0.

Figure 1

Office Buildings Currently Being Constructed and Occupied in Thailand: (a) Square-Shaped Floor Plan of Samyan Mitrtown Office Building (b) Rectangle-Shaped Floor Plan of Park Ventures Ecoplex Office Building

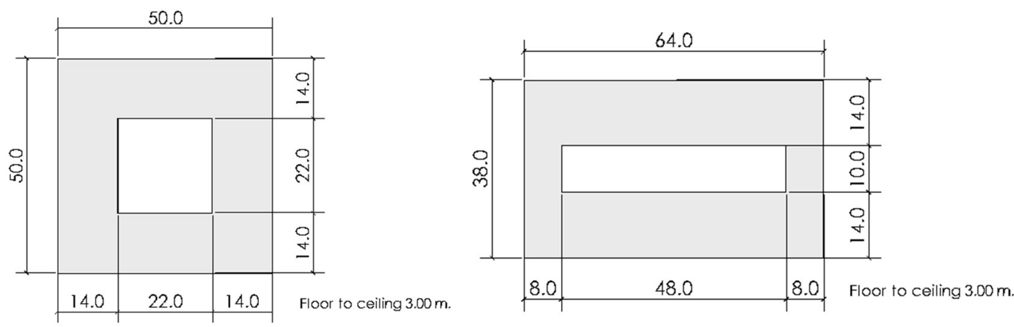


(a) (b)

Note. (a) from *Mitrtown Office Tower nungnai office thi smart thisutkongthai* [Mitrtown office tower, one of the smartest offices in Thailand], by Boonyarit, 2018 (https://thelist.group/realist/blog/samyan-mitrtown/). Copyright 2023 by Realist Solution, and (b) from *Park Ventures Ecoplex*, by Jones Lang LaSalle, 2022, (https://property.jll.co.th/office-lease/bangkok/pathum-wan/park-ventures-ecoplex-tha-p-00163s). Copyright 2022 by Jones Lang LaSalle.

Figure 2

Office Building Plans as Simulation Models With (a) A Square-Shaped Floor Plan and (b) A Rectangle-Shaped Floor Plan



(a) (b)

Types of Glass Materials and their Properties

In this study, six types of visible light reflectance (VLR) values of the glass material used in computational simulation for each type of the model office building have been identified as: 5%, 10%, 15%, 20%, 25%, and 30%. The U-value values in each VLR value will be namely: high (more than 3.50 W/m^{2}K), medium (from 2.00 to less than 3.50 W/m^{2}K), and low (less than 2 W/m^{2}K). In addition to the VLR and U-value of the glass material, visible light transmittance (VLT) and solar heat gain coefficient (SHGC) values are also considered, which further differentiates the glass materials into four subsets. The VLT values range between 10–85%, while SHGC values range between 0.10-0.85. Considering these related parameters within the affected ranges, a total of 72 types of glass material, named GL1-GL72, will be used in the simulation for this study. The 72 glass materials are classified into four main types, which are: clear glass (3), tinted glass (34), reflective glass (27), and low-e glass (8).

After configuring the appropriate values to simulate the model office buildings, specifications for the glass material that are commercially available have been identified and chosen from three different local suppliers and manufacturers: (1) AGC Flat Glass Thailand, PCL; (2) Thai-German Specialty Class Company Limited; and (3) Guardian Glass Company Limited (see Tables 1–3). However, after carefully searching for the glass materials from suppliers and manufacturers in Thailand, 30 out of 72 glass specifications could not be found on the market. In order to encompass all possible options in the simulation, the research assumes a set of hypothetical values.

Table 1

Glass Material With 5% and 10% VLR Specifications

NAME	VLR%	U value	SHGC	VLT%
GL1	7.9	5.04	0.73	85.3
GL2	6.9	5.04	0.57	70.8
GL3	5.8	5.04	0.56	55.7
GL4	5	5.04	0.15	15.0
GL5	5	2.72	0.85	85.0
GL6	5	2.72	0.70	70.0
GL7	7	2.72	0.44	53.0
GL8	5	2.72	0.15	15.0
GL9	5	1.55	0.85	85.0
GL10	5	1.55	0.70	70.0
GL11	5	1.55	0.50	50.0
GL12	5	1.55	0.15	15.0
GL13	9	4.13	0.62	70.0
GL14	9	5.51	0.46	50.0
GL15	10	5.51	0.25	25.0

Table 1 (Continued)

NAME	VLR%	U value	SHGC	VLT%
GL16	10	5.51	0.15	15.0
GL17	10	2.73	0.63	79.0
GL18	9	2.7	0.48	51.0
GL19	12	2.85	0.27	18.0
GL20	11	2.57	0.24	12.0
GL21	10	1.5	0.70	70.0
GL22	9	1.5	0.36	41.0
GL23	12.8	1.6	0.23	31.2
GL24	10.2	1.6	0.16	14.2

Table 2

Glass Material With 15% and 20% VLR Specifications

NAME	VLR%	U value	SHGC	VLT%
GL25	14.5	5.04	0.55	51.3
GL26	16.4	4.77	0.41	32.4
GL27	15	4.56	0.30	30.0
GL28	14	4.56	0.27	9.0
GL29	14	2.76	0.46	54.0
GL30	17	2.8	0.48	46.0
GL31	15	2.38	0.30	30.0
GL32	16	2.38	0.2	11.0
GL33	15	1.64	0.50	50.0
GL34	16	1.64	0.25	41.0
GL35	16.5	1.62	0.2	30.5
GL36	15	1.64	0.23	38.1
GL37	20	5.04	0.60	60.0
GL38	19.3	5.04	0.44	33.0
GL39	19	4.61	0.32	18.0
GL40	22	4.61	0.28	13.0
GL41	20	2.75	0.60	60.0
GL42	20	2.75	0.41	36.0
GL43	20	2.53	0.36	30.0

Table 2 (Continued)

NAME	VLR%	U value	SHGC	VLT%
GL44	19	2.4	0.22	16.0
GL45	20	1.8	0.60	60.0
GL46	20	1.8	0.40	40.0
GL47	19	1.8	0.27	33.0
GL48	20.3	1.6	0.22	28.9

Table 3

Glass Material With 25% and 30% VLR Specifications

NAME	VLR%	U value	SHGC	VLT%
GL49	25	4.62	0.55	55.0
GL50	24	4.62	0.45	36.0
GL51	25	4.25	0.35	22.0
GL52	25	4.25	0.15	15.0
GL53	25	2.54	0.55	55.0
GL54	25	2.54	0.40	40.0
GL55	23	2.54	0.32	34.0
GL56	23	2.32	0.19	12.0
GL57	25	1.63	0.55	55.0
GL58	26	1.63	0.32	48.0
GL59	23	1.74	0.3	39.0
GL60	26.8	1.6	0.21	28.0
GL61	30	5.04	0.40	40.0
GL62	27.1	5.04	0.36	22.2
GL63	30	5.04	0.20	20.0
GL64	30	5.04	0.10	10.0
GL65	30	2.69	0.40	40.0
GL66	28	2.69	0.37	30.0
GL67	31	2.32	0.23	19.0
GL68	30	2.32	0.10	10.0
GL69	30	1.64	0.40	40.0

Table 3 (Continued)

NAME	VLR%	U value	SHGC	VLT%
GL70	32	1.64	0.27	39.0
GL71	28	1.6	0.21	29.0
GL72	30	1.6	0.10	10.0

Calculation of OTTV and UDI

Simulation Input Data and Software Calculations for OTTV

Developed by Thailand's Ministry of Energy, the Building Energy Code (BEC) software program is used to perform OTTV calculations per building energy codes (Ministry of Energy, 2017; Royal Thai Government Gazette, 2021b). In accordance with Energy 4.0, a framework on energy efficiency with technology and innovation, a web-based BEC program was developed to be accessible via http://bec.energy.in.th (Ministry of Energy, n.d.).

In this study, the focus of the research is placed on the building envelope. In order to evaluate the OTTV of the building envelope in this study, the web-based BEC program is deployed as a calculation tool (Ministry of Energy, n.d.). Firstly, the location of the selected model office buildings is set to Bangkok, Thailand. The models are assigned a variety of metrics according to the type of building materials that are either opaque or translucent (i.e., concrete vs. glass). For opaque materials (specifically, concrete walls with a thickness of 15 cm.), parameters for thermal conductivity (k), specific heat (Cp) and density are assigned the values of 1.442 W/m^{2}K, 0.62 kJ/kgK, and 2400 kg/m^3, respectively. On the other hand, for translucent materials (specifically, glass), parameters for VLT, SHGC and U-value are assigned the values as shown in Tables 1-3. There are two zones in each model, which are: (1) the core zone, which measures 484 m^2. for the square-shaped floor plan and 480 m^2. for the rectangular-shaped floor plan, and (2) the salable area zone, which measures 2,016 m^2. for the square-shaped floor plan and 1,952 m^2. for the rectangular-shaped floor plan. The wall inclination value is 90°. The WWR setting in the calculation model is required for all cardinal directions of the entire building envelope of all cases. For example, the south-facing section envelope, which has an area of 150 m^2. (Width 50.00 m. X Height 3.00 m.), is assigned the WWR 60 in which the transparent area (glass envelope) has an area of 90 m^2. And the opaque area (concrete wall) has an area of 60 m^2.

Simulation Input Data and Software Calculations for UDI

The software programs used for UDI evaluation in this study include Rhinoceros 6 along with plug-ins such as Grasshopper and Ladybug 0.0.69 and Honeybee 0.0.66. Known for their high accuracy and flexibility in working in numerous fields of study including environmental building design, Rhinoceros 3D (developed by Robert McNeel & Associates) and Grasshopper 3D (developed by Ladybug Tools LLC) along with free and open-source plugins like Ladybug and Honeybee are some of the leading computer-aided design programs used in evaluating and simulating UDI and other related metrics concerning natural light (McNeel Wiki, 2020). In one approach to the design process, using Grasshopper 3D along with Rhinoceros 3D aims to make "environmentally responsive design decisions," by analyzing the impact of weather data on building design in terms of thermal comfort, the effect of solar radiation on building orientations, the quality of indoor illuminance and building energy consumption (Roudsari & Pak, 2013).

Following the development of Ladybug, Honeybee was developed in 2013 to connect Grasshopper to simulation engines like Radiance (Ladybug Tools LLC., n.d.-a, n.d.-b), a program suite developed by Greg Ward at the Lawrence Berkeley National Laboratory for the visualization and analysis of lighting in design (RFritz & AMcneil, 2019). First used in 1985, Radiance has gained popularity over the decades for its reliability and accuracy when checked against other programs in laboratory settings as well as in situ settings (AMcneil & RChadwell, 2020; Grynberg, 1989).

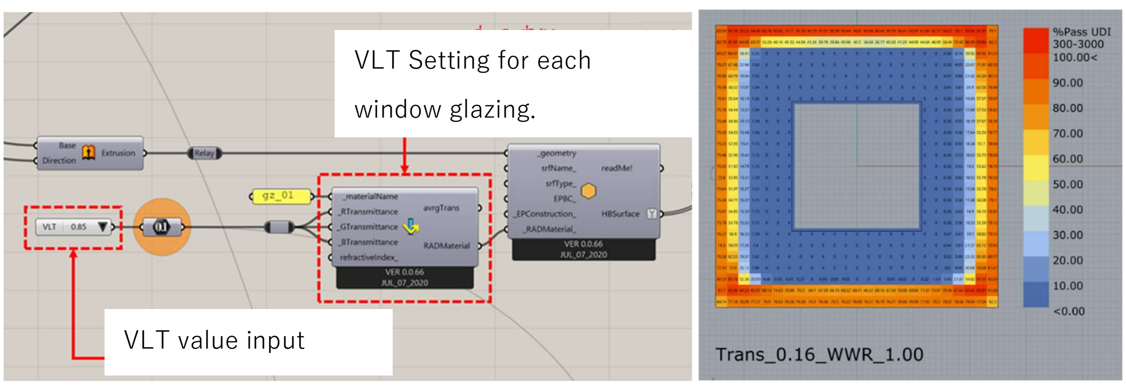
In order to generate daylight simulation data to evaluate UDI, Rhinoceros 6 along with plug-ins named Grasshopper software together with Ladybug 0.0.69 and Honeybee 0.0.66 were used in this study. Referring to LEED V4 Reference Guide for Building Design and Construction (U.S. Green Building Council, 2014), the reflectance parameters of the floor, wall and ceiling are 0.20, 0.50 and 0.80, respectively. The VLT parameters are set in Grasshopper 3D (see Figure 3) according to the type of glass material presented in Tables 1-3. Using the .epw weather file for Bangkok (Climate.Onebuilding, n.d.), illuminance is simulated for every 2 m^2. at the plane up to a height of 0.75 m. from the floor. UDI levels ranging between 300 - 3,000 lux for 80% of occupancy hours (Mardaljevic, 2017; Srisutapan, 2019; U.S. Green Building Council, 2014; VELUX, n.d.) are compiled in this study. The UDI simulations are conducted during the hours of 8:00 AM - 18:00 PM for a total of 10 hours per day (including a lunch break between 12:00 PM - 13:00 PM), 365 days for one simulated year for a total of 3,650 hours (Srisutapan, 2019; U.S. Green Building Council, 2014).

Indicators for Evaluation and Analysis of OTTV

According to the building energy code set by Ministry of Energy in 2564 B.E. (2021 AD), OTTV must not exceed a certain threshold set for the following specific building types (see Table 4) in order for building permits to be issued for construction. Specifically for office buildings, the OTTV must not exceed 50 W/m^2 (Royal Thai Government Gazette, 2021b).

Figure 3

Input Parameter Settings in Grasshopper (a) and (b) a Sample Illuminance Result From the Rhinoceros Program



(a) (b)

Table 4

OTTV Threshold Set for the Following Specific Building Types According to Building Energy Code (BEC) in 2563 B.E.

Building Types	OTTV (W/m^2)	Building Types	OTTV (W/m^2)
1) performance theaters	40	6) office buildings	50
2) hotels	30	7) shopping centers	40
3) retail services	40	8) residential buildings	30
4) hospitals	30	9) convention centers	40
5) academic institutions	50		

Note. Adapted from *Prakatkrasuangphalangng an ruangkamnot khamattrathankan okbap akhanpuawkan anurakphalangngan phosor 2564* [Announcements from the Ministry of Energy on building design standards for energy conservation 2564 B.E.], vol.138 (pp. 2–8), by Royal Thai Government Gazette, 2021. Copyright 2021 by The Secretariat of Cabinet.

Indicators for Evaluation and Analysis of UDI

The achieved UDI in this study is defined as the indoor area percentage of the building salable area, which have annual indoor illuminances at the work plane level when illuminances fall within the specified range (300 - 3,000 lux) for 80% of occupancy hours (Nabil & Mardaljevic, 2005; VELUX, n.d.) to be used along with OTTV as the metric for heat transfer. The focus range of the achieved UDI area percentage is specified into three ranges: (1) greater than or equal to 10% but less than 20%; (2) greater than or equal to 20% but less than 30%; and (3) greater than 30%. The achieved UDI area which is less than 10% will not be considered in this study.

RESULTS AND DISCUSSION

The relationship between OTTV and UDI values of glazed buildings according to their properties in each case study

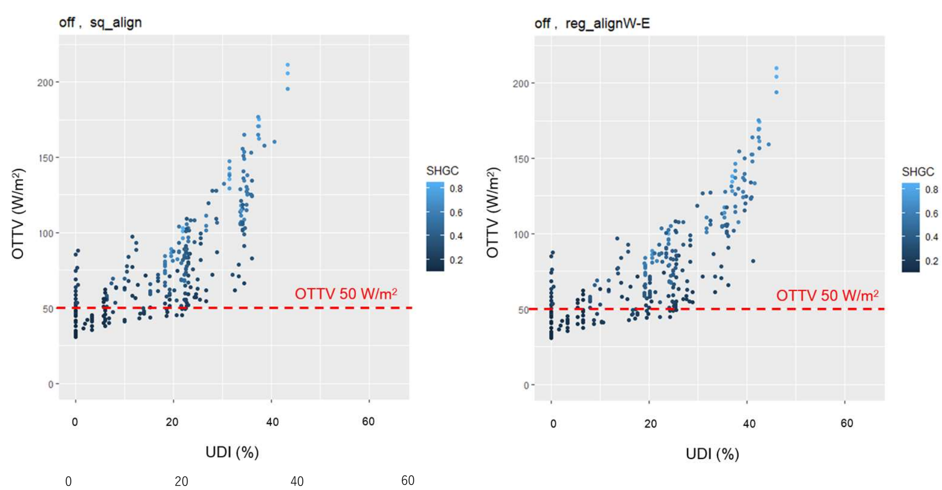
There are a total of 72 types of glass studied with the two shapes of floor plan: (1) the square-floor plan, positioned perpendicular to the north-south direction, and (2) the rectangular-floor plan with the long side, aligned along the east-west direction. Each case was assigned a different value of WWR, i.e., WWR 0.4, 0.6, 0.8, and 1.0. The results are shown in Figure 4 and Table 5.

Figure 4 shows that the cases with high UDI values result in high OTTV values, increasing the possibility of violating the building energy code (equal to or less than 50 W/m^2). In addition, the building glass cases with a high SHGC leads to high OTTV values, which are the opposite effects of the UDI. The highest number of glass types for which the OTTV criteria and the UDI criteria from 10% of the building area onwards can be achieved includes the building with WWR 0.4, followed by WWR 0.6 and 0.8, respectively. This trend runs contrary to the WWR proportion, which influences the percentage of building areas that meet UDI requirements. Regarding each floor plan type, there are only 18 cases (out of 288 cases) with all WWRs which comply with OTTV regulation and achieved UDI more than and equal to 10% of the area (shown in Figure 4). With the two-building floor plans the maximum percentage of the indoor area achieving UDI complying with the OTTV regulation are: (1) 21–22% of area achieving UDI, the WWR 0.4 buildings presenting OTTV values of 31.0–49.9

W/m², (2) 22–25% of area achieving UDI in the WWR 0.6 building presenting OTTV values of 31.1–49.8 W/m², and (3) 26% of area achieving UDI in the WWR 0.8 building presenting OTTV values of 32.1–49.9 W/m² (shown in Table 5). According to these results presented in Table 5, the largest percentage of a square-shaped building's area that satisfies the UDI is 26%, with a calculated OTTV value of 49.6 W/m². The largest percentage of a rectangular-shaped building's area that satisfies the UDI is 23%, with a calculated OTTV value of 49.9 W/m². Regarding the case of WWR 1.0 in both two floor plan shapes, there are six cases that passed OTTV requirements, with the OTTV value between 31.3 and 48.5 W/m². However, none of them can reach the 10% of the area that achieves UDI.

Figure 4

The Relationship Between the OTTV and UDI Results for (a) the Square-Shaped Floor Plan and (b) The Rectangular-Shaped Floor Plan Presenting the SHGC Values of All Cases



(a) (b)

Table 5

OTTVs of the Typical Buildings Designed With Various Glass Types That Comply With BEC and Its Corresponding UDI

GL	VLR	U	SHGC	VLT	LSG	WWR 0.4		WWR 0.6		WWR 0.8		WWR 1.0	
						OTTV	UDI	OTTV	UDI	OTTV	UDI	OTTV	UDI
(a) The OTTV and UDI results for the square-shaped floor plan													
GL19	12	2.85	0.27	18	0.67	49.3	19	58.6	19	67.9	11	77.1	12
GL23	12.8	1.6	0.23	31	1.35	43.1	7	49.2	22	55.4	23	61.6	27
GL34	16	1.64	0.25	41	1.64	45.0	21	52.2	23	59.3	23	66.4	35
GL35	16.5	1.62	0.2	31	1.55	40.3	7	45.1	22	49.9	23	54.7	27
GL36	15	1.64	0.23	38	1.65	43.2	13	49.4	22	55.6	25	61.8	33
GL44	19	2.4	0.22	16	0.73	43.7	15	50.2	15	56.7	12	63.2	10

Table 5 (Continued)

GL	VLR	U	SHGC	VLT	LSG	WWR 0.4		WWR 0.6		WWR 0.8		WWR 1.0	
						OTTV	UDI	OTTV	UDI	OTTV	UDI	OTTV	UDI
GL48	20.3	1.6	0.22	29	1.32	42.1	10	47.8	14	53.5	23	59.2	25
GL59	23	1.74	0.3	39	1.30	49.9	14	59.4	22	69.0	25	78.6	33
GL60	26.8	1.6	0.21	28	1.33	41.2	10	46.4	13	51.7	23	56.9	24
GL63	30	5.04	0.2	20	1.00	47.2	19	55.4	19	63.6	8	71.8	14
GL67	31	2.32	0.23	19	0.83	44.5	19	51.4	19	58.3	12	65.2	13
GL70	32	1.64	0.27	39	1.44	46.9	14	55.0	22	63.0	25	71.1	33
GL71	28	1.6	0.21	29	1.38	41.2	10	46.4	14	51.7	23	56.9	25
(b) The OTTV and UDI results for the rectangular-shaped floor plan													
GL19	12	2.85	0.27	18	0.67	49.0	20	58.2	20	67.5	14	76.7	14
GL23	12.8	1.6	0.23	31	1.35	42.8	9	48.9	24	55.1	26	61.2	29
GL34	16	1.64	0.25	41	1.64	44.7	22	51.8	25	58.9	24	66.0	36
GL35	16.5	1.62	0.2	31	1.55	40.1	9	44.8	24	49.6	26	54.3	29
GL36	15	1.64	0.23	38	1.65	42.9	16	49.0	25	55.2	28	61.4	34
GL44	19	2.4	0.22	16	0.73	43.5	17	49.9	17	56.4	16	62.9	12
GL48	20.3	1.6	0.22	29	1.32	41.9	10	47.5	18	53.2	25	58.9	28
GL59	23	1.74	0.3	39	1.30	49.5	17	59.1	25	68.6	28	78.1	35
GL60	26.8	1.6	0.21	28	1.33	40.9	11	46.1	17	51.3	25	56.5	27
GL63	30	5.04	0.2	20	1.00	46.9	20	55.1	20	63.3	10	71.4	18
GL67	31	2.32	0.23	19	0.83	44.2	20	51.1	20	57.9	15	64.8	16
GL70	32	1.64	0.27	39	1.44	46.6	17	54.6	25	62.6	28	70.6	35
GL71	28	1.6	0.21	29	1.38	40.9	10	46.1	18	51.4	25	56.6	28

Note. The definitions of each color bar are specified as follows*:*

- OTTV passed @ 50 W/m^2 or less*.*
- OTTV not passed and UDI not passed *(*less than 10*%).*
- UDI passed @ greater than and equal to 10*%* but less than 20*%.*
- UDI passed @ greater than and equal to 20*%* but less than 30*%.*
- UDI passed @ greater than and equal to 30*%.*

Note. Adapted from *Prakatkrasuangphalangngan ruanglakken withikankhamnuan laekanraprongphonkantruatpramoēnnaikan okbap akhan puaekan anurakphalangngan taelarabop K anchaiphalangng andoiruamkhong akhan laekanchaiphalangnganmunwian nairaboptangtang khong akhan phosor 2564* [Announcements from the Ministry of Energy on criteria, calculation methods and building design certification for energy conservation in building systems, total building energy consumption, and the use of renewable energy in various building systems 2564 B.E.] (vol.138, pp. 9–36), by Royal Thai Government Gazette, 2021. Copyright 2021 by The Secretariat of Cabinet.

The relationship between SHGC and VLT of glazing in each case study, as well as OTTV values and percentage of area achieving UDI

The relationships between SHGC and VLT of glazing, as well as OTTV values and the percentage of area achieving UDI, are shown in Figure 5a (square-shaped floor plan and 5b (rectangular-shaped floor plan). The glass performances used in each case of building floor plan type and facade WWR are presented as a glass selection guideline in Tables 6–8.

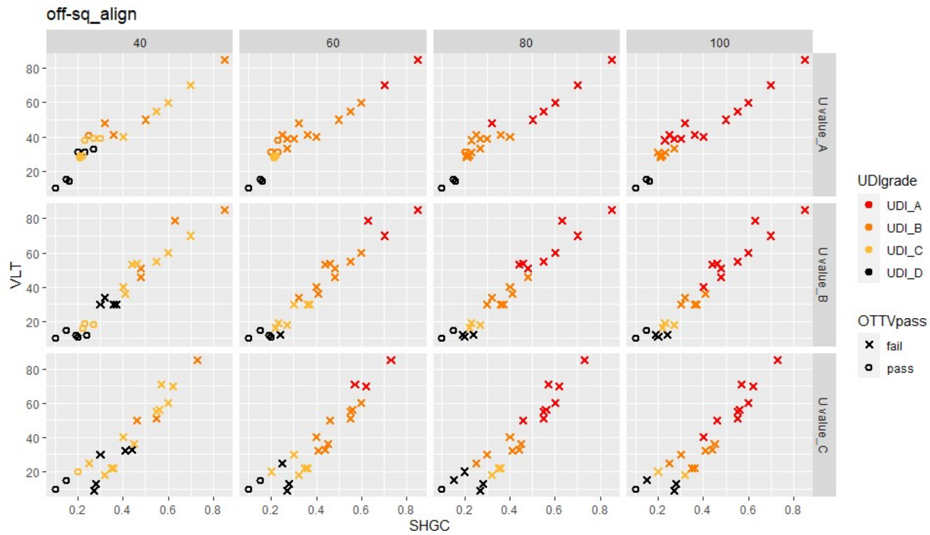
As shown in Figure 5, for all cases of either a square or rectangular floor plan, higher WWRs lead to higher OTTVs for every U-value. Lowering the glass U-values helps the building pass the OTTV criteria more easily. Regarding square floor plan buildings, the cases where the proportion of area that meets the UDI criteria is greater than or equal to 10% and the OTTV value passes the criteria occur with buildings with a WWR value of 0.4 for all U-value ranges of glass and buildings with a WWR value of 0.6 and a WWR value of 0.8 of a low U-value range. In contrast, it is possible to accomplish OTTV and UDI in the office's rectangular floor layout with a WWR of 0.6 with a medium range U-value. In the cases of buildings with WWR 0.4, the glass performance values which are suggested to achieve OTTV regulation and earn sufficient useful daylight (the percentage area, achieving UDI, starting from 10%), are SHGC 0.20–0.30, VLT 28–41% and U-values 1.6–1.8 W/m^{2}K. In the cases of buildings with WWR 0.6 the glass performance values which is suggested are SHGC 0.20-0.23, VLT 16–41% and U-values 1.6–2.4 W/m^{2}K. While the case of the WWR 0.8 building suggests glass performances with SHGC 0.20, VLT 31% and U-values 1.62 W/m^{2}K, which is the case that brings the highest quality of daylight. With the two floor plan case studies the maximum percentage of the indoor areas achieving UDI complying with the OTTV regulations are with the glass performances as follows (see Tables 6–8):

1. 21–22% in the WWR 0.4 buildings with the VLT 41% and SHGC 0.20–0.21 with the low U-value glass
2. 22–25% in the WWR 0.6 building with the VLT 38% and SHGC 0.2 with the low U-value glass
3. 26% in the WWR 0.8 building with the VLT 31% and SHGC 0.2 with the low U-value glass

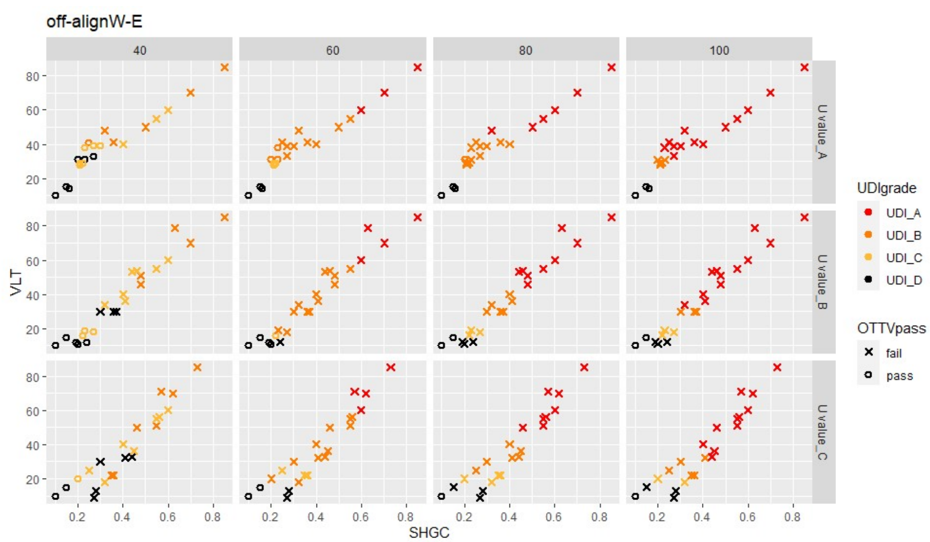
To comply with the Thai building energy code and enhance the indoor daylight quality, typical floor plans with 40–80% WWR, 31.41% VLT, and 0.20 SHGC insulating glass facade (IGU) are recommended. The GL35 glass type (31% VLT, 16.5% VLR, 0.2 SHGC, and 1.62 W/m2K U-value) allows the best performance in terms of energy savings and daylight quality. This corresponds to dark-tinted IGU applied to a facade with 0.8 WWR, which will allow the building to pass both OTTV regulations and adequate daylight.

Figure 5

The Relationship Between SHGC and VLT of Each Glass Material Used in (a) the Square-Shaped Floor Plan and (b) the Rectangular-Shaped Floor Plan With Different WWRs and U-Values



(a)



(b)

Note. UDI_A is the case that contains the percentage of area achieving a UDI of greater than 30% (labeled as red). UDI_B is the case that contains the percentage of area achieving a UDI of greater than or equal to 20% but less than 30% (labeled as orange), while UDI_C is of greater than or equal to 10% but less than 20% (labeled as yellow).

Table 6

The Glass Performance Values Which Meet the OTTV Requirements and Showing the Area Percentage Achieving UDI for (a) Square-Shaped Plan and (b) Rectangular-Shaped Plan With WWR 0.4

(a) square-shaped plan						
WWR 0.4	VLR (%)	U	SHGC	VLT (%)	OTTV	%area, UDI
Low U-value	15 - 30	1.60 - 1.74	0.21 - 0.30	28 - 41	40.9 - 49.5	10 - 22
Medium U-value	12 - 30	2.32 - 2.85	0.22 - 0.27	16 - 19	43.5 - 49.0	17 - 20
High U-value	30	5.04	0.20	20	46.9	20
(b) rectangular-shaped plan						
WWR 0.6	VLR (%)	U	SHGC	VLT (%)	OTTV	%area, UDI
Low U-value	12.8 - 28	1.60 - 1.64	0.20 - 0.23	28 - 38	44.8 - 49.0	17 - 25
Medium U-value	19	2.40	0.22	16	49.9	17

Table 7

The Glass Performance Values Which Meet the OTTV Requirements and the Area Percentage Achieving UDI for (a) Square-Shaped Plan and (b) Rectangular-Shaped Plan with WWR 0.6

(a) square-shaped plan						
WWR 0.6	VLR (%)	U	SHGC	VLT (%)	OTTV	%area, UDI
Low U-value	12.8 - 28	1.60 - 1.64	0.20 - 0.23	28 - 38	45.1 - 49.4	13 - 22
(b) rectangular-shaped plan						
WWR 0.6	VLR (%)	U	SHGC	VLT (%)	OTTV	%area, UDI
Low U-value	12.8 - 28	1.60 - 1.64	0.20 - 0.23	28 - 38	44.8 - 49.0	17 - 25
Medium U-value	19	2.40	0.22	16	49.9	17

Table 8

The Glass Performance Values Which Meet the OTTV Requirements and the Area Percentage Achieving UDI for a Square-Shaped Plan and a Rectangular-Shaped Plan With WWR 0.8

WWR 0.8	VLR (%)	U	SHGC	VLT (%)	OTTV	%area, UDI
Low U-value	16.5	1.62	0.20	31	49.6	26

CONCLUSION

We present the results of the OTTV calculation and UDI simulation (percentage of the indoor area achieving UDI) showing the building performance in overall heat transfer through the building facade and solar visible light (daylight) transmitted within the building, indicating the desirable illuminance on the working plane. The typical office buildings with a square-shaped floor plan and a rectangular-shaped floor plan were selected as case studies with 72 glass facade types with various SHGCs, U-values, and VLTs and varying WWRs of 0.4, 0.6, 0.8, and 1.0. The main findings of the study may be summarized as follows:

1. The highest number of glass types for which the OTTV criteria and the UDI criteria from 10% of the building area onwards can be achieved includes the building with WWR 0.4, followed by WWR 0.6 and 0.8, respectively. This trend runs contrary to the WWR proportion, which influences the percentage of building areas that meet the UDI requirements. However, none of the floor plans with WWR 1.0 can reach the 10% of the area that achieves UDI.
2. The two floor plan cases achieving the greatest daylight quality (23–26% area achieving UDI) and complying with OTTV regulations use the same glass type, which is GL35, with the performance values including SHGC 0.2, VLT 31%, VLR 16.5%, and U-value 1.62 W/m^{2}K. This finding indicates that the glass specification and the facade design used in the office building must be an IGU dark tinted glass with VLR 16.5% and VLT 31% with the facade design of WWR 0.8 in order to achieve the building energy code and create sufficient indoor useful daylight.
3. To comply with the Thai building energy code and support indoor useful daylight, for typical office floor plans with the variation of WWR between 0.4–0.8, the building glass performance specification must be between 31–41% of VLT, 0.20–0.21 of SHGC, and low U-value (referring as IGU).
4. There are some limitations to the study including the limit building glass performance specifications and office building floor plan types. The floor plan depth is found to be a significant factor impacting the percentage of the indoor area achieving UDI, which is highly suggested to be addressed in future studies.
5. To avoid lawsuits filed and to comply with OTTV regulations while receiving sufficient daylight, the design recommendations for the office high-rise building in Thailand are: (1) using an IGU with dark tinted glass (SHGC around 0.2) with VLR around 15% and VLT around 30% with an appropriate WWR (0.4–0.6); and (2) the floorplan depth is not deeper than 14 meters. The shorter the depth of the floor plan, the higher the percentage of the area receiving sufficient daylight.

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