


Article

A Study of Design Variables in Daylight and Energy Performance in Residential Buildings under Hot Climates

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Abstract: In Saudi Arabia, residential buildings are one of the major contributors to total energy consumption. Even though there are abundant natural resources, it is somewhat difficult to apply them to building designs, as design variables, due to slow progress and private issues in Saudi Arabia. Thus, the present study demonstrated the development of sustainable residential building design by examining the daylighting and energy performance with design variables. Focusing on the daylighting system, the design variables were chosen, including window-to-wall ratios (WWR), external shading devices, and types of glazing. The illuminance level by these design variables in a building was evaluated by using daylight metrics, such as spatial daylight autonomy and annual sunlight exposure. Moreover, the building energy consumption with these design variables was analyzed by using energy simulation. As a result, the daylighting was improved with the increase in WWRs and the tinted double glazing, while these design options can cause overheating in a residential building. Among types of glazing, the double pane windows with a low-E coating showed better energy performance. Based on the results, it is necessary to find the proper design variables that can balance the daylighting and energy performance in residential buildings in hot climates.

Keywords: daylighting; energy consumption; design variables; residential building; hot climates

1. Introduction

Energy has become a global concern in developed, as well as developing, countries. The International Energy Agency (IEA) indicated that 81% of the world's total energy was primarily supplied by fossil fuels, which are depletable resources [1]. Buildings have consumed a large share of global energy and they have contributed to about 33% of the greenhouse gas (GHG) emissions [2]. The GHGs emitted by buildings have a detrimental impact on the environment. Subsequently, this issue has attracted the attention of scientists as well as public attention [3,4]. Energy conservation has also received great attention in Saudi Arabia. The building industry in Saudi Arabia has experienced major developments with a rapidly escalating population [5]. In addition, a high level of economic growth in Saudi Arabia has caused a vigorous expansion of infrastructure, in that buildings, including residential, commercial, and governmental buildings over the last two decades, were highly demanded [6]. Eventually, Saudi Arabia needs to pay more attention to energy, both in terms of energy resources and energy usage in buildings.

In Saudi Arabia, the building sector comprised 79% of the total electricity consumption [7]. Specifically, about 50% of the total building energy was consumed by residential sectors [8]. As the main contributor to the total energy consumption in Saudi Arabia, the energy efficiency in residential buildings has become a main concern. Several studies have been conducted to improve energy efficiency

in buildings, in that a number of strategies have proposed. These strategies have mainly dealt with the different building systems, including envelope, HVAC (Heating, ventilation, and air-conditioning), and lighting. These were: (1) improvement of thermal resistance in building envelopes [9–11]; (2) application of advanced window systems [12,13]; (3) application of more efficient lighting bulbs [14,15]; (4) and the use of energy-efficient mechanical systems [16]. Other strategies included the utilization of renewable energy technology [17], daylight systems [18,19], and natural ventilation techniques [20]. Since most buildings in Saudi Arabia are heavily dependent on mechanical systems to maintain thermal comfort, as well as to provide lighting, it is necessary to find a proper strategy to reduce building energy consumption.

In addition to the strategies above, several studies have performed investigations to improve energy efficiency in residential buildings in Saudi Arabia. In a study by Taleb and Sharples, energy use patterns in apartment buildings were analyzed, and energy efficiency was improved by applying various measures, such as improved building thermal insulation and external shading devices [5]. In the case of the retrofitting project for villas by Mejjaoui and Alzahrani, they applied various types of mechanical systems and building envelope components as retrofitting measures to improve the energy efficiency of villas [21]. In addition, Waleed et al. performed experiments and simulations to investigate the thermal performance of building materials for walls of residential buildings [22]. A similar study was conducted by Alaidroos and Krarti [23]. In their study, the impact on energy consumption by various components of building envelopes, including thermal insulation, window shading, and glazing types, was investigated to develop an optimum building envelope system for residential buildings. Moreover, the advanced air-conditioning system was applied to residential buildings to reduce the energy consumed by mechanical systems [24]. As can be shown, most studies focused on the improvement of building envelopes or high energy-efficient mechanical systems for energy-efficient residential buildings. Considering the reduction of greenhouse gas emission, passive design solutions should be implemented more than active design strategies.

Among passive design strategies, daylighting is one of the effective design solutions for improving building energy efficiency. According to the study by Li and Liam, daylighting in a building can satisfy the human visual response, and it can make a more attractive and pleasing environment [25]. By installing daylight responsive control systems in an office building, considerable energy savings were achieved [26]. Furthermore, Do et al. proposed the use of semi-transparent solar cell window systems with daylight dimming systems for residential buildings to obtain the opportunity of energy saving [27]. A similar study for utilizing daylighting systems was conducted by Reffat and Ahmad [28]. In their study, energy performance by various daylighting systems in an office building was extensively investigated to reduce energy consumption for cooling. To summarize, the use of a daylighting system in buildings can provide benefits regarding visual comfort as well as potential for energy consumption reduction.

Daylighting is one of the most abundant natural resources in Saudi Arabia. If the admitted daylighting in the building is well-controlled, it can provide great potential for energy-saving by reducing energy consumption for artificial lighting, heating, etc., while uncontrolled daylighting can cause overheating and glare [29–31]. Considering the substantial advantage of daylighting, there were a few studies for the investigation of both daylighting and energy performance in residential buildings in Saudi Arabia. For the present study, the daylighting and energy performance by the design variables of residential buildings were investigated. The outcomes of the study were used to develop an energy-efficient residential building design considering daylighting performance.

2. Principal Design Variables for Daylighting in a Residential Building

There have been many design factors influencing daylighting performance in buildings. The daylighting performance is highly influenced by the geometries of buildings and rooms. One of the most important parameters is a window-to-wall ratio (WWR) that is designed to increase daylight admission. In general, higher WWRs can increase the quantity of daylight in the buildings, while it

can cause unwanted heat gains. According to the study by Abel et al., WWRs should be properly designed in the early design stage to prevent overheating in buildings [32]. In addition to their study, the function of WWRs can be varied by the shading design. A similar point was observed in the study of Li et al. [33]. In their study, daylighting and energy performance of key design variables, including shading devices, window areas, and glass types in a residential building, were investigated. Another study for the daylighting performance with a shading device, such as a solar screen, was conducted by Sherif et al. [30]. The illuminance levels by the solar screen were measured and some design suggestions were proposed. Based on the literature, the design variables, such as WWRs, shading devices, and windows, are the most influential key features of the daylighting system. Moreover, they can play a significant role in thermal behaviors in buildings. To prevent overheating through the daylighting system, as well as improve energy efficiency in a residential building under hot climate conditions, it was suggested to conduct both daylighting and energy simulations to optimize the design of WWRs, shadings, and the glazing types [34,35]. Thus, the daylighting and energy performance by design variables for the present study were evaluated by the simulation tools.

As mentioned above, it is imperative to mention the importance of the selection of glazing since the quality of daylighting and thermal behaviors in a building can be significantly altered by glazing types of window systems. In general, the application of energy-efficient glazing, such as double-pane windows, has been used in buildings under hot climate conditions, to reduce heat gain by about 15–20% [36]. In addition, a higher reduction for heat gain can be achieved by low-E coated glass. Focusing on daylighting and thermal performance, several glazing types were tested by Taleb and Antony [37]. Based on their results, tinted glazing can lower the cooling load by about 20%. Special gases, such as krypton and xenon between the layers of double glazing, can also lower the additional cooling load. In case of the study of Liu et al., thermal and daylight performance of triple glazing was also investigated [38]. Even though the energy consumption by triple pane windows is always lower than that by double glazing units, the triple-pane windows are not practically used due to the high initial costs. Thus, it is crucial to select the proper glazing for window systems, considering a balance between daylighting and energy aspects [12]. Based on the previous studies, various types of glazing were selected for the present study.

3. Methodology

3.1. Building Description

In Saudi Arabia, there are three types of residential buildings: apartments, villas, and traditional houses. Among these buildings, apartment buildings and villas have become the most popular residential buildings, accounting for about 80% of total residential buildings. For the present study, a typical villa was chosen as a reference building in the eastern region of Saud Arabia, in which the latitude and longitude are 26.2361° N and 50.0393° E, respectively. The highest temperature was observed in July (about 44 °C). In addition, the average global horizontal irradiance in the eastern area was 5874 W/m². For the reference building, the total floor area was 590 m² and the window-to-wall area ratio (WWR) was 15%. The floor to floor height was 3.5 m and the building area for the ground floor and the first floor were 300 m² and 290 m², respectively. Moreover, the reference building had 14 rooms and two kitchens. This reference building was occupied for a whole year, from 8 a.m. to 6 p.m. on all weekdays. The specification of the building envelopes is presented in Table 1. For the air conditioning system, a single packaged rooftop electric cooling unit was used to provide 15 tons of nominal cooling. For the building envelopes system, the lower thermal transmittance value was considered for the roof system than the wall system to reduce heat gain by the sun.

Table 1. The specification of building envelopes and the systems for the reference building.

Component and System	Specification
Walls	U-value: 0.54 W/m ² K
Roof	U-value: 0.24 W/m ² K
Window systems	Single clear glazing (U-value: 6.08 W/m ² K, SHGC:0.8, visible transmittance: 0.9)
Shading	No external shading
Air infiltration	0.57 ACH @ 50 PA
Internal heat gain	8 occupants Lighting: fluorescent lamps (lighting power density: 27.3 W/m ²) Equipment: 13 W/m ²
Design temperature	19 °C for cooling and 20 °C for heating
HVAC	Packaged unit air-conditioning system (Capacity: 15 tons, COP: 3.28)

3.2. Design Variables

Since the admitted sunlight is highly influenced by the design features of window systems, the design variables of window systems were chosen for the analysis of daylighting and energy performance in a residential building. Table 2 presents three different design variables of window systems. The first variable is the WWR. Since the WWR of the reference building was about 15%, three different WWRs (25%, 50%, and 70%) were used to assess the daylighting and energy performance. Another important design variable is a shading device. To admit sunlight effectively, it is imperative to use external shading devices. Focusing on external shadings, the impact on the daylighting and energy performance by overhangs and fins were investigated. As can be shown in Table 2, two different projection lengths of overhangs, and overhangs with fins, were designed for the analysis. For the reference building, a single clear glazing was used and the basic properties of the single clear glazing are presented in Table 1. The third design variable was the glazing types. To figure out the improvement of daylighting and energy use in a residential building, four different types of glazing were selected.

Table 2. The design variables.

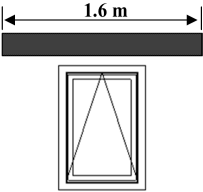
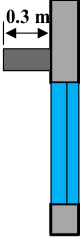
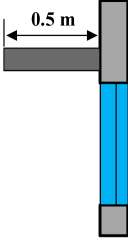
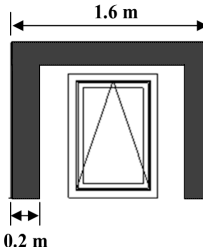
Design Variable	Specification		
WWR	(1) 25%, 	(2) 50%, 	(3) 70%, 
External shading device	Overhang 	a. Type A (Projection length: 0.3 m)	b. Type B (Projection length: 0.5 m)
		c. Type C (Projection length: 0.3 m)	d. Type D (Projection length: 0.5 m)

Table 2. Cont.

Glazing	(1)	Tinted single glazing
	(2)	Air-filled double glazing
	(3)	Air-filled double glazing with a low-E coating
	(4)	Tinted double glazing

3.3. Assessment of Daylighting and Energy Performance

For the present study, the design variables were tested by using the building performance analysis software provided by AUTODESK (Version 2019, New York, NY, USA) for a residential building satisfying both daylighting and energy performance [39]. This software is a plug-in module for Revit, enabling the assessment of both daylighting and energy consumption in a building [39]. Figure 1 shows a model of the reference building created by Revit.

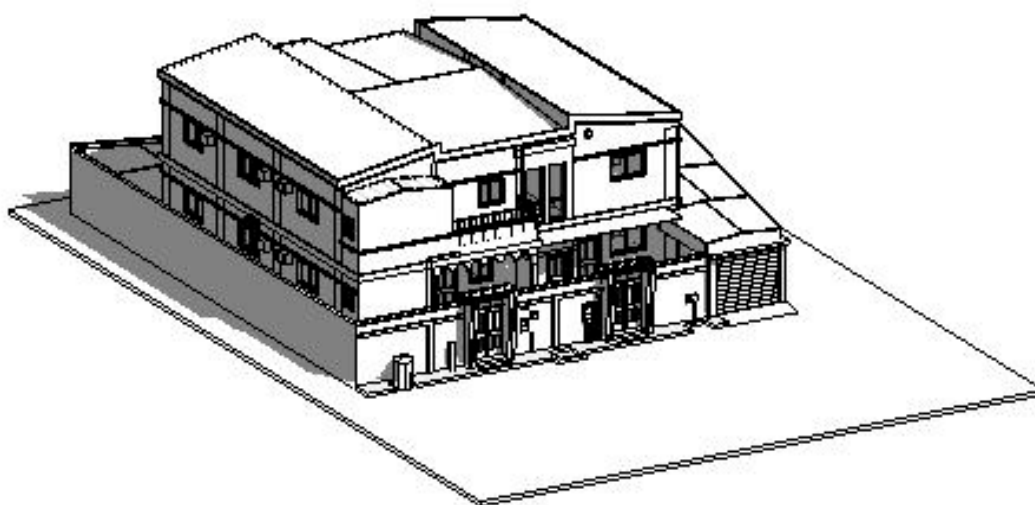


Figure 1. The reference building created by Revit.

To evaluate the daylighting performance, two daylighting metrics were implemented: annual Sunlight Exposure (aSE) and spatial Daylight Autonomy (sDA). Specifically, aSE is the percentage of the area in the space where the direct sunlight illuminance is greater than a specified level, while sDA is the percentage of the area in the space where the daylight illuminance is greater than the target level for more than a specified number of occupied hours in a year [40]. The illuminance threshold for the aSE was set to 1000 lux, while the number of annual operation hours exceeding 1000 lux should be lower than 250 h to prevent glare [41]. For the sDA metrics, the target illuminance was set to 300 lux, in which the value should be retained about 50% of the occupied hours (8 a.m. to 6 p.m.) from January 1 to December 31 [40]. For the present study, the simulation for the daylighting performance was evaluated by using these two measures. In addition, the suggested values for these two measures were presented in Table 3.

Table 3. The suggested values for aSE_{1000,250h} and sDA_{300/50%}.

Metrics	Value	Ref.
aSE _{1000,250h}	<10%: Accepted	[40–42]
	<7%: Neutrality	
	<3%: Preferred	
sDA _{300/50%}	>75%: Preferred 55–74%: Nominally accepted	[40,42,43]

For the evaluation of the energy performance by design variables, the energy analysis module of the Revit was employed. Before the analysis, it is essential to validate the computational conditions of energy simulation. Using the weather file of Saudi Arabia provided by EnergyPlus and the specified building condition in Table 1 [44], the energy simulation with the reference villa was conducted through the energy analysis module of Revit. The monthly energy consumption obtained from the simulation was compared with the energy consumption of the reference building by using the coefficient of variation of the root mean squared error (CV(RMSE)) provided by ASHRAE Guideline 14 [45]. The models will be declared calibrated if they produce CV(RMSE)s within $\pm 15\%$ with monthly energy data.

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (M_i - S_i)^2}{n}} \quad (1)$$

$$C_V(RMSE) = \frac{RMSE}{M_{avg}} \times 100 \quad (2)$$

where M_i is the energy consumption of the residential building, while S_i is the monthly energy consumption by energy simulation. N is the period and M_{avg} is the average for the energy consumption of the residential building. After the validation, the annual and artificial lighting energy consumption of each design variable was compared.

4. Result

4.1. Assessment of Daylighting Performance

Using the values for $aSE_{1000,250h}$ and $sDA_{300/50\%}$, the daylighting performance of design variables was assessed. For this assessment, three WWRs, four different external shading designs, and four different types of glazing were applied.

4.1.1. WWRs

The reference building had a WWR of 15% with a single pane glass. As with the WWR (15%) of the reference case, it was difficult to reach the preferred or accepted levels of daylight metrics, in which $sDA_{300/50\%}$ was less than 20%, while the value of $aSE_{1000,250h}$ was about 5% (Figure 2). When the WWR was increased by 25%, 50%, and 70%, the values of $sDA_{300/50\%}$ were increased to 38%, 58%, and 75%, respectively. Among them, only the WWR of 70% reached the preferred range of $sDA_{300/50\%}$. In addition, the WWR of 50% reached the nominally accepted range of $sDA_{300/50\%}$. For the values of $aSE_{1000,250h}$, it increased gradually, as with the increase in the WWRs. However, the WWR of 70% exceeded 10% of the value of $aSE_{1000,250h}$. Even though the WWR of 70% can provide a reliable daylight level, there is also a risk of glare or overheat due to the excessive admitted daylight in a building. Considering the results, the WWR of 50% can thus provide reliable daylight by preventing glare. While the increase in the WWRs showed improvement by satisfying with the accepted or preferred ranges of $sDA_{300/50\%}$, it also has potential for glare.

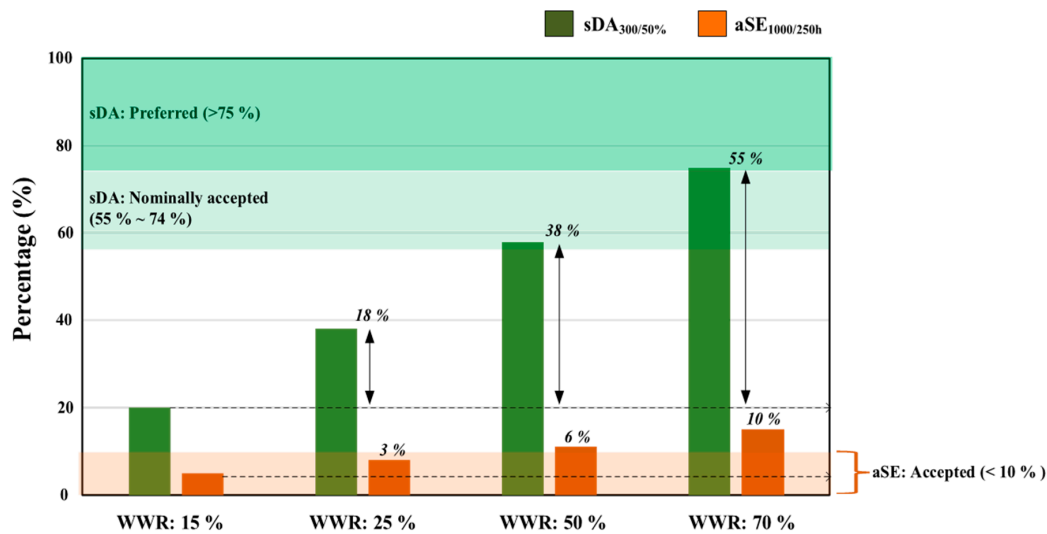


Figure 2. Daylighting performance by WWRs.

4.1.2. External Shadings

Generally, shading devices have been used to control daylighting in a building to prevent glare and overheat by blocking direct sunlight. It is designed externally for building design in the early design stage as an essential design variable. In this view, the daylighting performance of four different designs of external shading devices was evaluated, as shown in Figure 3. For this analysis, the WWR of 50% with a single pane glass was used as a reference case to figure out whether the daylighting level by the shading device was satisfied with the accepted values of $sDA_{300/50\%}$ and $aSE_{1000,250h}$. Largely, the values of $sDA_{300/50\%}$ were decreased when applying four shading devices. Consequently, all the cases were not satisfied with the accepted range of $sDA_{300/50\%}$. Specifically, about 8% to 10% of the decrease in $sDA_{300/50\%}$ was observed when two horizontal overhang designs were applied (Type A and Type B). When the overhang with fins was used, more than 15% of the $sDA_{300/50\%}$ was decreased compared with the reference case. For the $aSE_{1000,250h}$, all external shading designs showed that the illuminance level was within the accepted ranges. Moreover, the best performance regarding the $aSE_{1000,250h}$ was observed with the shading designs of Type C and Type D. Even though the use of external shading devices can decrease the illuminance level, it can prevent glare and overheat. Considering the results, Type A showed the best overall performance.

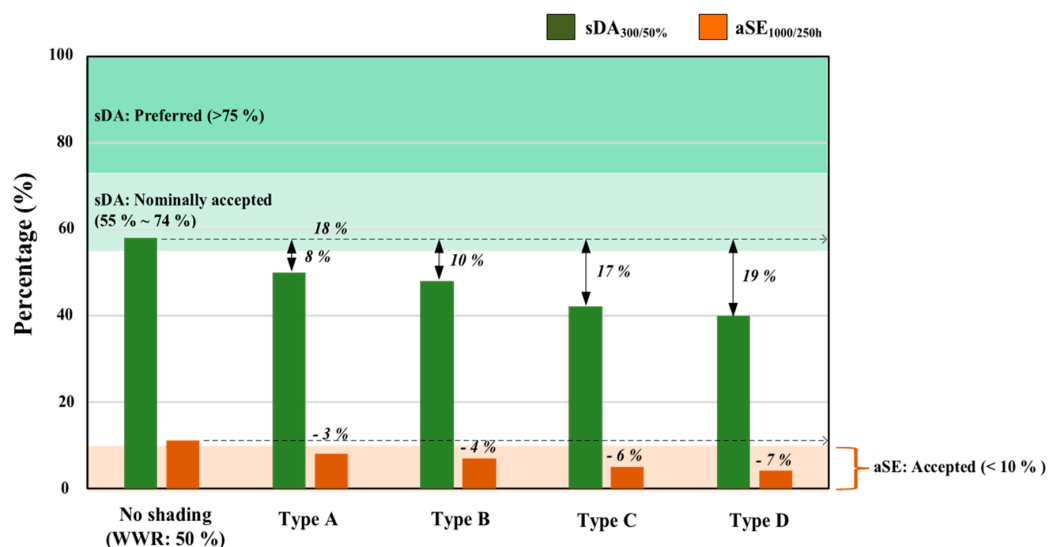


Figure 3. Daylighting performance by different designs of overhangs and overhangs with fins.

4.1.3. Types of Glazing

In general, the double-glazed windows with low-E coating have been applied to buildings to reject heat in buildings. However, most residential buildings in Saudi Arabia have equipped with a single pane of glass. For the present study, the daylighting performance of four different types of glazing was compared with that of a single pane glass in the reference villa, where the WWR was 50%.

As shown in Figure 4, each glazing showed different values of $sDA_{300/50\%}$ and $aSE_{1000,250h}$. Among them, about 5% of the decrease in $sDA_{300/50\%}$ was observed, when a tinted single glazing was used. In addition, a similar trend was observed, when a low-E coated double glazing was used. In the case of the air-filled double-glazed clear windows, there was a little impact on $sDA_{300/50\%}$. The lowest illuminance level was observed by the air-filled tinted double glazing among all the cases, which was about 10% decrease in $sDA_{300/50\%}$. A similar trend was observed among all the cases regarding the values of $aSE_{1000,250h}$. In sum, a single tinted glass and the double-glazed clear windows provided a somewhat accepted illuminance level for the $sDA_{300/50\%}$, while the illuminance by all the cases was within the accepted range of the $aSE_{1000,250h}$.

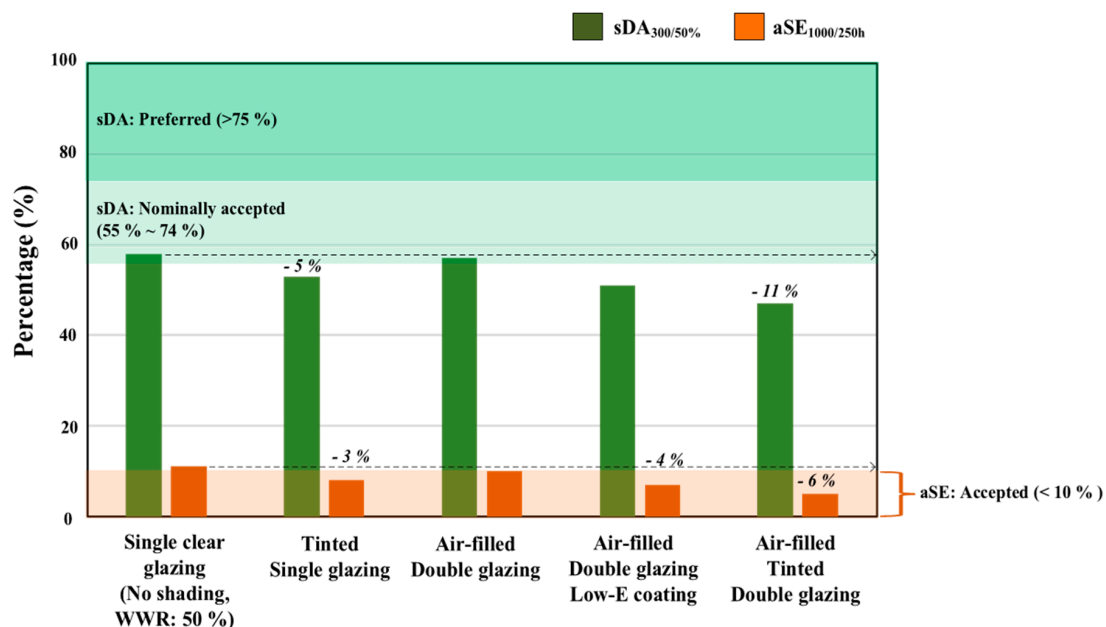


Figure 4. Daylighting performance by different types of glazing.

4.2. Energy Performance Assessment of Design Variables

4.2.1. The Monthly Energy Consumption Comparison between the Data of the Reference Villa and Energy Simulation

Before the energy performance assessment of the design variables, the computational conditions of energy simulation should be validated. For the validation, the monthly energy consumption of the reference villa was compared with the energy consumption prediction by the simulation. The total energy consumption of the residential building was about 76.2 MWh, while about 84 MWh of the energy consumption was predicted by the energy simulation, in which the difference between them was about 9%. As shown in Table 4, the largest difference was observed in the winter from November to February, and the root-mean-squared errors (CV(RMSEs)) ranged from 0.46 to 3.64. Since these results were within the acceptable range, the predicted results by the simulation met the requirement by ASHRAE Guideline 14 [45].

Table 4. The monthly energy consumption comparison.

Month	Energy Consumption (MWh)			CV(RMSE) (%)
	The Reference Villa, 2019	Energy Simulation	Difference	
January	4.1	5.0	−0.9	2.05
February	3.9	5.5	−1.6	3.64
March	4.9	5.7	−0.8	1.82
April	6.0	6.5	−0.5	1.14
May	7.6	7.4	0.2	0.46
June	7.7	7.9	−0.2	0.46
July	8.6	8.3	0.3	0.68
August	8.9	8.6	0.3	0.68
September	7.8	8.4	−0.6	1.46
October	7.2	7.9	−0.7	1.59
November	5.1	6.5	−1.4	3.19
December	4.4	6.0	−1.6	3.64

4.2.2. The Energy Performance of Design Variables

One of the most important considerations for the design features of the daylighting system is to control thermal performance in buildings. Considering this point, energy consumption for the annual energy consumption, artificial lighting, and the HVAC system were presented.

As shown in Figure 5, the energy consumption in the reference residential building for each WWR was presented. The reference building was equipped with a single pane window without external shading devices and the WWR was 15%. The other conditions were specified in Table 1. As the WWR increased, the energy consumption for the HVAC system operation increased due to the increase in cooling demand. With the WWR of 75%, about 30% of energy for the HVAC system increased compared with the energy consumption of the reference building. Consequently, the total energy consumption also increased with the WWR increase. However, some energy consumption was offset by the energy consumption reduction of artificial lighting due to daylight. Comparing the artificial lighting energy consumption for the reference case, the energy consumption for artificial lighting was decreased to 30% and 40% for the WWR of 50% and 70%, respectively. Even though the annual energy consumption increased with the increase of the WWRs, the smallest increase in the annual energy consumption was about 5% with the WWR of 25%. In addition, only a 2% difference in the annual energy consumption was observed between the WWR of 25% and 50%.

Figure 6 showed the energy consumption comparisons in the reference building with the application of four different shading devices. For the reference building, no shading device was equipped. As can be shown, the annual energy consumption and energy consumed by artificial lighting and HVAC systems were reduced as the projection lengths of the overhang was increased. In addition, better energy performance was observed when the overhang with fins was applied (Type C and Type D), which was about a 30% decrease in annual energy consumption. Among the cases, Type D showed the best overall energy performance, in which about 25% of the HVAC system load was reduced, compared with the reference case. Moreover, the highest reduction for the annual energy consumption was observed. For all of the cases, a slight energy consumption difference was observed for artificial lighting energy consumption.

Moreover, the energy performance by the different types of glazing was also investigated as shown in Figure 7. For this analysis, the reference building equipped a single pane glass with a WWR of 15%. With the use of the double-glazed windows with low-E coating, the annual energy consumption decreased by about 35%, which was the lowest annual energy consumption among the cases. The second-lowest annual energy consumption was observed when the tinted double glazing was used (about 27% decrease). However, only a 5% difference in the annual energy consumption was observed between the tinted double glazing and the air-filled double glazing. Considering this point,

it can be seen that the low-E coating has a significant impact on thermal performance. A similar trend was observed for HVAC energy consumption by different types of glazing. In addition, there was little difference in artificial lighting energy consumption among the cases.

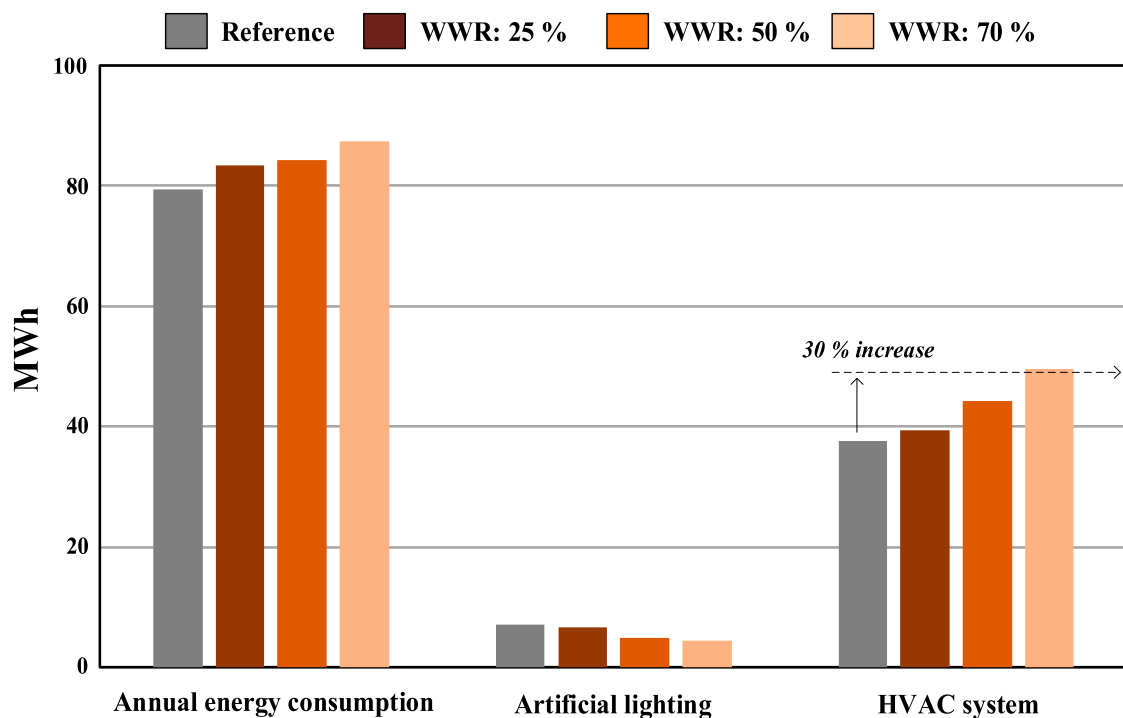


Figure 5. The energy consumption by different WWRs.

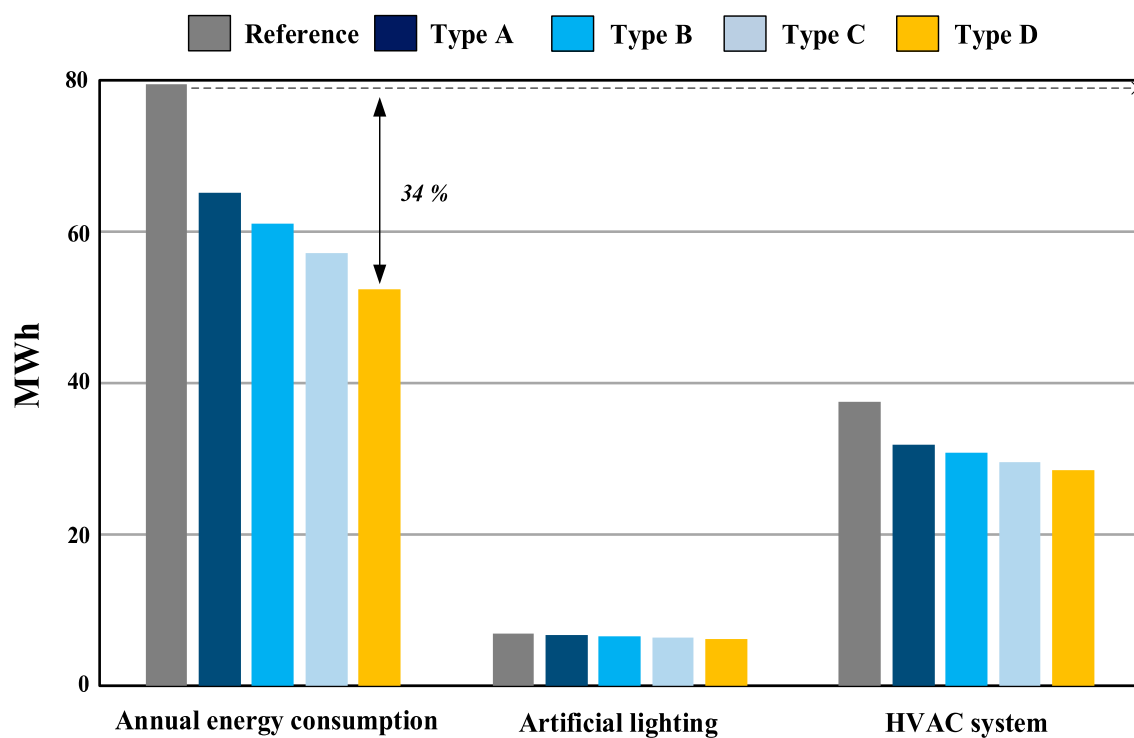


Figure 6. The energy consumption by different designs of external shadings.

In sum, more than 30% of the annual energy consumption was reduced by applying the overhang with fins and the air-filled double low-E glazing. For the WWRs, the annual energy consumption

was increased as with the increase in the WWRs. Based on the result of the daylighting performance analysis, the WWR of 50% provided the acceptable range of both sDA and aSE. Thus, the WWR of 50% was chosen. By applying the selected design variables, the energy consumption was compared with that of the reference building (Figure 8). As a result, about 35% of annual energy consumption was reduced compared with that of the reference villa. In addition, 17–20% of the energy consumption was reduced for the artificial lighting and HVAC system.

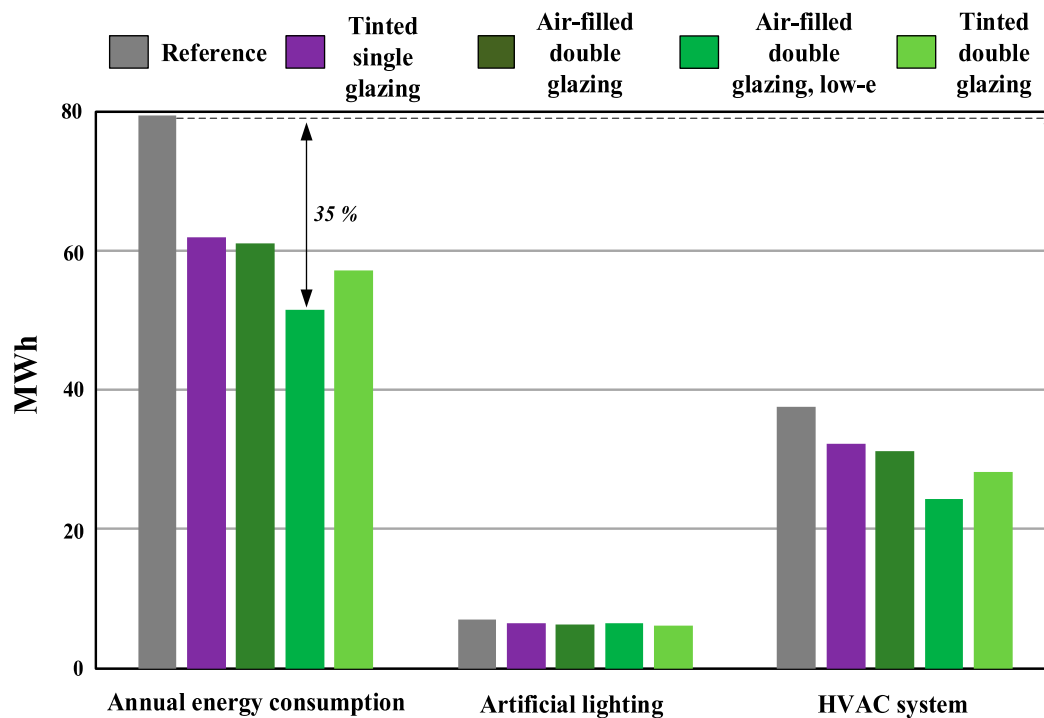


Figure 7. The energy consumption by different types of glazing.

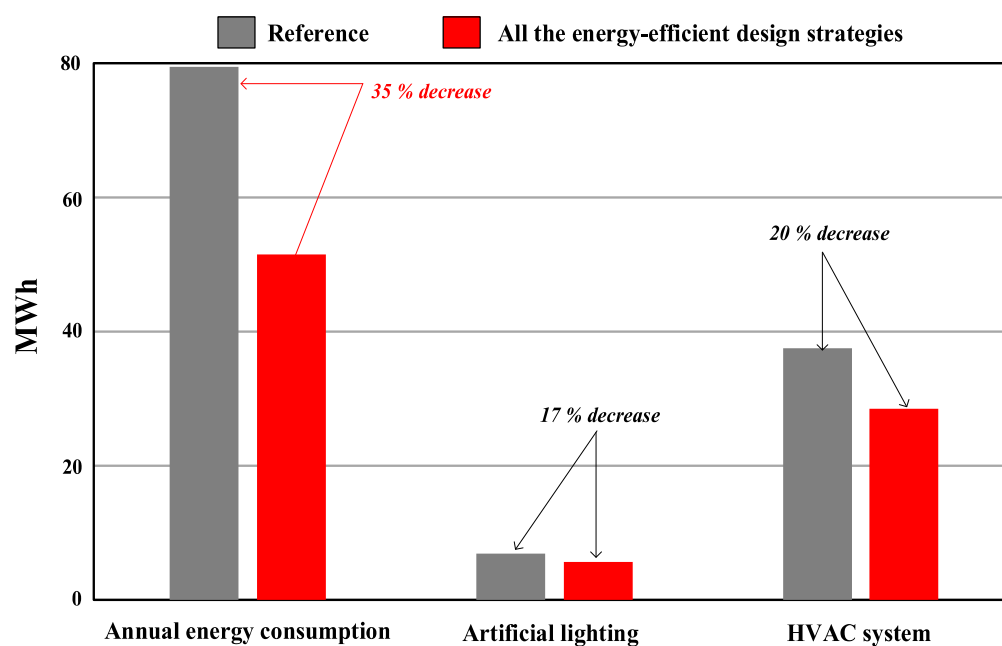


Figure 8. The energy consumption comparison between the reference villa and the villa with energy-efficient design strategies.

5. Discussion

For the present study, the daylighting and energy performance of design variables for residential buildings under hot climates were investigated. Contrary to typical residential buildings in other countries, the residential buildings in Saudi Arabia have relatively small WWRs to reduce cooling loads, and for other reasons, such as cultural characteristics [46]. Subsequently, it is, thus, difficult to find out daylighting systems in current residential buildings. As mentioned previously, the important functions of daylighting systems are to control the quality of admitted daylight as well as reduce heat gain in buildings. In this view, the daylighting performance of various sizes of WWRs, shading devices, and types of glazing was examined by using daylighting metrics. In addition, the energy performance of these design variables was evaluated. Among these design variables, windows with higher WWR can provide more illuminance and more daylighting distribution in the room [47]. Thus, higher WWRs have shown more acceptable daylighting performance, while the potential for glare or overheating was also increased. Similarly, the result of the present study showed that the daylighting performance was improved as the WWR increased. However, the energy consumption also increased. A similar result was observed in the study of Alghoul [48] et al. An increase in WWRs can cause significant cooling loads. In the case of the study of Xue et al., they investigated the cooling energy performance by increasing WWRs [49]. Their result showed that the cooling load was increased as with the increase in WWRs. According to the study of Mangkuto et al., larger WWR can cause increasing cooling loads and rising glare in a building [50]. They pointed out that different energy consumption and daylighting performance can be caused by the same WWR through different window configurations. For the present study, a similar trend was observed that there was a difference in daylighting and energy performance by same design variables. For example, the annual energy consumption increased as the WWR increased, while the increased WWR can provide better daylighting performance. It can be seen that the evaluation result of either daylighting or energy performance can cause visual or thermal discomfort for occupants. The daylighting performance in the current study was only analyzed by two daylighting metrics: sDA and aSE. Due to insufficient information on daylighting performance, it is difficult to find the proper design variables satisfying both energy and daylighting performance. Moreover, the other difficulty was from the limitation of the range of design variables. Based on the obtained results, the daylighting and energy performance was sensitive to the design variables. Therefore, it is necessary to apply various daylighting metrics into the daylighting analysis. It also requires to have more configurations of design variables for further study to design more proper daylight systems.

Regarding the assessment results for various types of glazing, the windows with low-E coating showed better performance for preventing heat gain than other windows. This was also investigated by the study of Huang et al. [36]. In their study, low-E glazing was the best design option for reducing cooling loads, while maintaining a satisfactory daylighting level compared with double-pane clear glazing. According to the study of Leung et al., the aerogel glazing showed better performance than the windows with low-E coating regarding the thermal performance in buildings [51]. Moreover, krypton or xenon gas-filled double-glazing systems can improve lighting performance in building under hot climate conditions [37]. Some studies mentioned the importance of the selection of the color of the glazing since it affects significantly overall comfort in buildings [52]. According to the study by Chen et al., the color of the tinted glazing had an impact on occupant behavior and green glazing can improve working performance [53]. For the present study, only bronze glazing and double low-E glazing were used. Considering the current building industry in Saudi Arabia, it is still difficult to apply advanced glazing systems for residential buildings. Based on the obtained results, the tinted double glazing has shown the second-best performance in energy consumption. For more accurate analysis, it is thus imperative to analyze the economic impact of the tinted and the low-E coated double glazing.

6. Conclusions

In Saudi Arabia, residential buildings account for more than half of total buildings, and the energy consumed by residential buildings has become one of the most significant concerns. To improve energy efficiency in residential buildings, several studies have mainly investigated the performance of mechanical systems, because of high cooling demand due to hot climates in Saudi Arabia. In addition, privacy issues in Saudi Arabia have caused small WWRs in residential buildings. Even though there are abundant natural resources in Saudi Arabia, it is still difficult to apply passive design strategies for residential buildings. Focusing on the use of natural resources, such as daylight, the present study has investigated the daylight and energy performance of design variables for developing energy-efficient residential buildings.

For the design variables, three different WWRs, four designs of the external shading device, and four types of glazing were selected. By using two different simulations, the daylighting and energy performance of these design variables in a typical villa were examined. Moreover, two daylight metrics—sDA and aSE—were used to evaluate the daylighting performance of design variables. As a result, the daylighting performance was satisfied with the accepted ranges of sDA_{300/50%} and aSE_{1000,250h}, when the WWR of 50% and the double-glazed clear windows were applied into the reference building. The illuminance levels by two overhang designs (Type A and B) were somewhat satisfied with the accepted values of sDA and aSE, while the other shading designs were not.

For the energy performance assessment, the annual, artificial, and HVAC energy consumption were analyzed. While the daylighting performance was improved with the increased WWRs, the energy consumption also increased as the WWR increased. This was caused by the increase in cooling demand by the excessive sunlight through the increased WWRs. Similar to the daylighting performance, the energy consumption decreased, as with the increase of the projection lengths and fins for the external shading devices. A villa with the double-pane windows with a low-E coating showed a better energy performance. In summary, the lowest energy consumption was achieved by using the external shading device.

Based on the results, the energy-saving potential for residential buildings under hot climates with the implementation of daylighting was observed. In addition, the daylighting performance can be improved by using the proper design variables. However, the design variables for the present study seemed to be insufficient to draw out more valuable outcomes. Thus, it is necessary to examine the performance of more various design variables, such as triple-glazed windows with various inert gases, and various types of internal/external shading devices for further study. For the present study, the daylighting performance by design variables was evaluated by only using simulation tools. To figure out the illuminance level practically, it requires further field measurements.

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