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Research paper

Effect of the Window Position in the Building Envelope on Energy Consumption

Neveen Y. Azmy[1]*, Rania E. Ashmawy[2],

[1] Faculty of Engineering, Tanta University, Tanta, Egypt
[2] Ph.D. student, Egypt-Japan University of Science and Technology (E-JUST)
**Corresponding author E-mail: neveenazmy@f-eng.tanta.edu.eg*

Abstract

Windows play a significant role as they largely influence the energy load. Although there are many studies on the energy-efficient windows design, there is still a lack in information about the mutual impact of windows' size, position and orientation on the energy loads. In this paper, the effect of different window positions and orientations on the energy consumption in a typical room in an administrative building that is located in the hot climatic conditions of Cairo city, Egypt is considered. This case study has been modeled and analyzed to achieve good environmental performance for architectural space, as well as assessing its impact on the amount of natural lighting required by using the Energy Plus program. The study concludes that the WWR (Window Wall Ratio) 20% square north-oriented upper opening consumes 25% lower energy than the rectangular 3:1 opening in the lower west-oriented façade. The upper openings are the highest in terms of light intensity, as they cover about 50% of the room area. The WWR 30% rectangular north-oriented upper 3:1 opening consumes 29% lower energy than the rectangular lower 3:1opening in the façade. Regarding light intensity, the upper openings are the best for natural lighting as the light covers more than 60% of the room area.

Keywords: *Energy efficient, window position, day lighting, Thermal comfort, Cairo, WWR (window wall ratio).*

1. Introduction

Energy consumption in buildings in Egypt is important, where the amount of energy consumed, whether (residential, commercial, or administrative) accounts for more than 60% of the total energy [1]. Energy efficiency in buildings is today's primary objective for energy policy on regional, national and international levels. The building's envelope always protects it from external factors. An important part of the shell is windows, which are considered the most important functional elements as they have a direct impact on the thermal behaviour of -the building, and hence, the amount of energy consumed within it.

The location, orientation, dimensions, area and shading of such openings, have an essential role in achieving the thermal comfort of the users of the space [2]. Windows perform many functions such as natural lighting and ventilation as well as outside visibility. They also play an essential function in the architectural appearance of the building [3]. However, they represent the weakest area in the building's enclosure because they ease the heat exchange between the inner space and the outer environment [4]. Therefore, windows have a significant impact on both the energy consumption and thermal comfort of a building.

Several studies were conducted on the impact of window design on energy load regarding various factors of windows, to reduce the energy loss by windows [5], [6]. It is noted that building and construction legislations always focus on the percentage of openings to the room space. In addition, the energy codes focus on the window wall ratio, without considering the position of the opening in the outer shell. This paper, therefore, addresses this gap by assessing the influence of window design in terms of its size, position and orientation on energy consumption, which is measured via indoor lighting and heating or cooling loads. The paper provides analysis of thermal performance by estimating the amount of energy consumed annually and its effect on the amount of lighting loads with changing orientation and size of the window and its proportion to the outer wall in an office building, Cairo, Egypt.

Objectives

The objective of this research is to assess the impact of window design and the amount of energy consumed in buildings according to the different possible positions of windows in the building envelope. Throughout this paper, the impact of the position of window with a fixed area and with different dimensions and positions in the building's envelope is assessed by calculating the amount of the annual energy consumed and the best natural lighting distribution within the administrative spaces to achieve the best environmental performance in accordance with the different basic orientations and the standards of passive design of energy-saving buildings.

Methodology

The following sections introduce a review of the previous efforts for studying the effect of window designs on the environmental performance of the buildings. Then, a simulation for standard room with a window opening in an administrative building is done using the "Energy plus" environmental simulator. The building is assumed to be located in a hot climate area which is the Great Cairo, Egypt. The window area is fixed, but the width to the height ratio is

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changed and also its position is varied. The orientation of the window is also varied to north, east, west or south. Another variable that is considered is the window wall ratio, which is 20% or 30% according to the energy codes in Egypt. The performance is measured via the annual energy consumption and the daylight intensity that enters the room through the window.

2. Effect of windows on the environmental performance of buildings and the amount of energy consumption

The characteristics of windows, in terms of their dimensions and direction in the external walls of the buildings, are the most important factors affecting their performance. The performance measures include improving the internal environmental performance of the architectural space, the natural lighting and ventilation in the building and the amount of energy consumed in the space. Several studies addressed these factors as illustrated below.

2.1. Window Orientation

The direction of the opening in the outer shell of the building affects the amount of ventilation and light entering the architectural space, as well as the amount of exposure to the sun and hence, the thermal performance of the building and the amount of energy consumed. Some studies have examined the impact of building orientation on the amount of energy consumed, according to the loads of heating, cooling and lighting [7]. Some studies have also examined the effect of window design on energy loads, with respect to only one or two influential design factors such as orientation and/or window size [8],[6]. These factors vary according to the different latitude, longitude and climatic considerations of the different regions as well as the seasons of the year. They also vary according to the function of the building and its performance. No constant orientation can achieve the best thermal performance or lower energy consumption in all regions and circumstances [9].

2.2. Window wall ratio (WWR).

The earlier studies dealt with the impact of the window-wall ratio (WWR) on the thermal performance of the architectural space. Some studies have related the WWR and its impact on the environmental performance and the lighting of the building [10].

In [11], a the proportionality between the WWR and the amount of natural lighting in the architectural space is studied. It is found that the increase in WWR for the outer wall reduces the dependence on artificial lighting. Some researchers have also studied the WWR versus the characteristics of the glass versus the position of the window in the wall [10], [12], [13].

Other studies also examined the relationship between the WWR and the amount of energy consumed [14] [15]. It is found that in the different climates and orientations there are optimum WWRs that result in a reduced annual energy consumption. Most of these optimal values of WWR are from 30% to 40% [15].

Glazing

The stuff and thermal characteristics of the window material affect its thermal performance as they affect the amount of heat gained and lost through the window. A window loses heat five times faster than the wall itself. So, some studies have analyzed the types of glass (one layer and two layers) and have studied its impact on the environmental performance of the building. It was found that the single glass, which is common in the Middle East because it is cheap, has low thermal resistance compared to the double glass, which contributes to reducing heat and sound transmission, as well as reducing cooling loads [16], [17].

The type of glass panel itself affects the amount of heat absorption and thus the amount of energy consumed. Some research has dealt with the different types of processed glass such as heat-absorbing glass, heat-reflecting glass, and low radiation glass. Thermal exchange and solar radiation treatment are studied for these glass types to find the extent of energy consumption saving [18].

2.3. Window position

The position of the window aperture in the external wall of the building is one of the considerations that affect the amount of lighting and natural ventilation, according to its direction, proportion and dimensions Previous studies measured the effect of the different positions of the aperture on the amount of natural lighting inside the room. One of these studies showed that the openings, whose center on the vertical wall axis with WWR of 10-20%, result in almost the same amount of natural lighting in the room, while openings, whose center lay on the wall's horizontal axis, produce more consistent lighting and more efficient than other window positions, especially with the increase of the aperture ratio [14]

Some studies show that when the opening in the wall has a WWR of about 20%, the effect of the opening becomes more evident [19].

2.4. Research Motivation

However, studies on the window's size, position and orientation, and studies on energy loads are still limited and are in different climatic regions .They do not cover these factors on energy consumption in the dry hot regions. As building designs become increasingly complex, a more detailed and comprehensive analysis of the various design factors of windows should be undertaken. Therefore, this paper aims to find the best suitable positions for windows with WWR ranging from 20% to 30% in the Greater Cairo region of Egypt. This range has been chosen as it is dominant and influential in the openings as described in the energy code of buildings in Egypt.

3. Case study

3.1. The study model

This research is based on the study of annual energy consumption and the daylight intensity in the administrative buildings in Egypt, which consume a great amount of energy needed for daylighting and achieving thermal balance. The case study model is an administrative room in a multi-storey building with a brick exterior. The room geometry is illustrated in (Fig. 1) and its dimensions are as follows: (3.6 m) width, (5.4 m) length, and (3.5 m) total height. The window in the room is placed in one side only and is of double glass thickness of 3 mm for one sheet with a metal frame.

The research changes the position of the aperture and its proportion in the outer wall of the room, while its area is kept fixed. For the case of WWR 20%, the window area is 2.52 square meters with different dimensions and positions as shown in Table (1).

In the case of WWR 30%, the area of the opening shall be 3.78 square meters with different positions and elongation ratios are as shown in Table (2). The direction of the wall, including the window, is varied to north, east, south and west

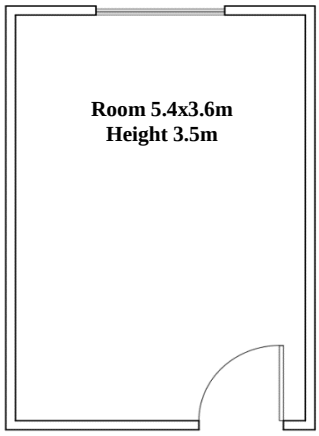


Fig 1: model under study

Table 1: The shape and position of openings used in the study model and its different dimensions for WWR 20%

	Window size	center	under	Above	right	left
1:1	The square window 1.6*1.6					
2:1	Horizontal window 2.24*1.12					
1:2	Vertical window 1.12*2.24					
3:1	Horizontal window 2.8*0.9					
1:3	Vertical window 0.9*2.8					

Table 2: The shape and position of openings used in the study model and its different dimensions for WWR of 30%

	Window size	center	Under	Above	right	left
1:1	The square window 1.9*1.9					
2:1	Horizontal window 2.7*1.35					
1:2	Vertical window 1.35*2.7					
3:1	Horizontal window 3.3*1.1					
1:3	Vertical window 1.1*3.3					

As for the structural components of the selected room and the basic parameters of the elements used, which are installed within the energy plus simulation software, are as shown in Table (3). The layers of structural elements are arranged from the inside to outside, and the room is ventilated naturally except in critical days of the year in which the air conditioners are employed.

Table 3: Research sample characteristics

Room dimension				**5.4 *3.6 m²**
Lighting energy			***Intensity of illumination***	**300 lux**
			Control type	**Suspended**
HVAC			***Mechanical ventilation***	**min fresh air (sum -4 (per person+ per area**
			Type	**Split + Separate Mechanical Ventilation**
			Natural ventilation	**3ac /h**
Layers of the building envelope	***(U-value ?wlm2-k***	**External wall**	**0.704**	**Whites perlite plaster board 2 cm + Cement \plaster\mortar-cement 2 cm + brick wall thickness of 25 cm + Cement \plaster\mortar-cement 2 cm + Plastic paint white color 2 cm.**
		Internal wall	**0.662**	**Whites perlite plaster board 2 cm + Cement \plaster\mortar-cement 2 cm + brick wall thickness of 12 cm + Cement \plaster\mortar-cement 2 cm + Plastic paint white color 2 cm.**
		Floor	**0.658**	**Carpets 1 cm + Ceramics Port Celine 2 cm + mortar thickness of 2 cm + Sand settlement 4 cm + reinforced concrete 12 cm + 3 cm thickness of the epithelium layer + Plastic paint white color 2 cm**
		Roof	**0.658**	**Slanting slab 2 cm + mortar 2 cm + Sand settlement 4 cm + Concrete 7 cm + isolate moisture 2 cm + heat isolating 2 cm + reinforced concrete 12 cm + Plastic paint white color 2 cm.**
Glass type				**Double Clear glass 3mm/13mm Air**
Window wall ratio				**30% ،20%**
Room - Painting color				**White**

3.2. Climatic characteristics of the study area

The study focuses on the Greater Cairo area, which is located at the longitude of 30^{o} 59" 32′and the latitude of 30^{o} 36" 36′ . It is about 23 meters above the sea level.

The dry hot climate of this region is characterized by high temperatures during the summer months and cold temperatures during the winter months. The average daily temperature in July ranges between 37 ° C (high) and 21° C (low), while the average daily temperature in January (winter) ranges between 17 ° C and 6 ° C. The region is also characterized by the dominance of the northern winds in all directions. The relative humidity ranges from 50-70%, and the solar glare in Cairo reaches a maximum of 95% in summer, while winter glare rates are around 60% [20].

3.3. Simulation Tool Description

The EnergyPlus™ simulator is an energy simulation program for building to model both energy consumption for heating, cooling, ventilation, lighting and plug and process loads—and water use in buildings [21].

The developers of EnergyPlus test it using industry standard methods. The goal is to assure as reliable and accurate results as possible. EnergyPlus is subject to analytical tests such as HVAC tests, based on ASHRAE Research Project 865 and building fabric tests, and it is based on ASHRAE Research Project 1052. It is also subject to comparative tests such as ANSI/ASHRAE Standard 140-2011, EnergyPlus HVAC Component Comparative tests and EnergyPlus Global Heat Balance tests [21].

Overall, the results of EnergyPlus are very closely compared to the analytical results obtained from the ASHRAE 1052-RP Toolkit [22]. An experimental validation test for EnergyPlus shows that simulation results are very close to the measurements in the experiment proposed throughout it. Hence, the EnergyPlus can be considered as a reliable simulation tool.

4. Results and analysis

Through the environmental simulation of the administrative room under study, the research results in the amount of energy consumed

annually in the room, as well as the distribution of light intensity with different window positions with window-wall-ratio (WWR) 20% in the basic trends as well as different window positions with window-wall-ratio (WWR) 30%.

4.1. The amount of energy consumed for basic directions, when windows ratios are (1:1, 2:1, 1:2, 3:1, 1:3) in the positions (Center, Upper, Bottom, Left, and Right)

4.2. Total energy consumption in window wall ratio 20%.

- Total energy consumption in different window position - in the northern direction (WWR20%) is shown in (fig 2)

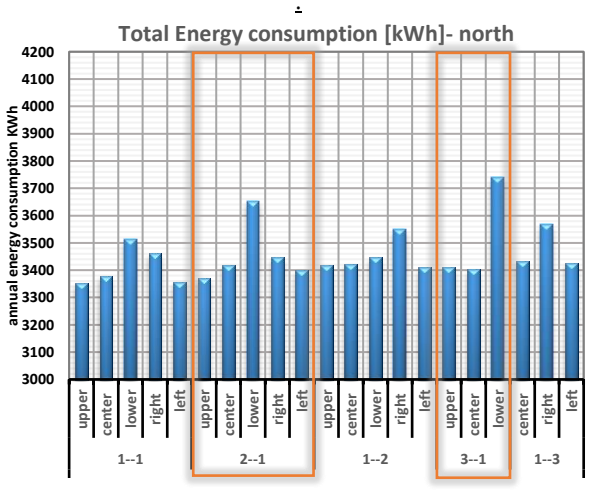


Fig 2: the annual energy consumption in the different window position – in north –WWR 20%

- Total energy consumption in different window position - in the eastern direction (WWR20%) is shown in (fig 3.)

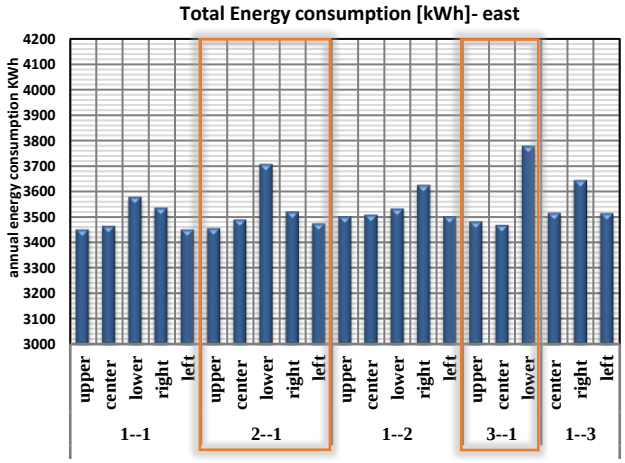


Fig 3: the annual energy consumption in the different window position – in east –WWR 20%

- Total energy consumption in different window position-in the southern direction (WWR20%) is shown in (fig 4)

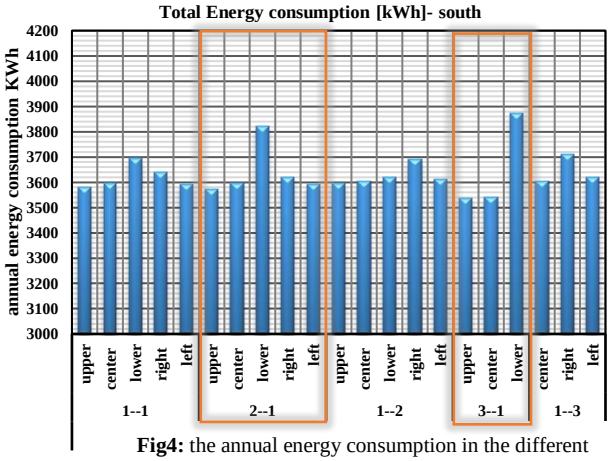
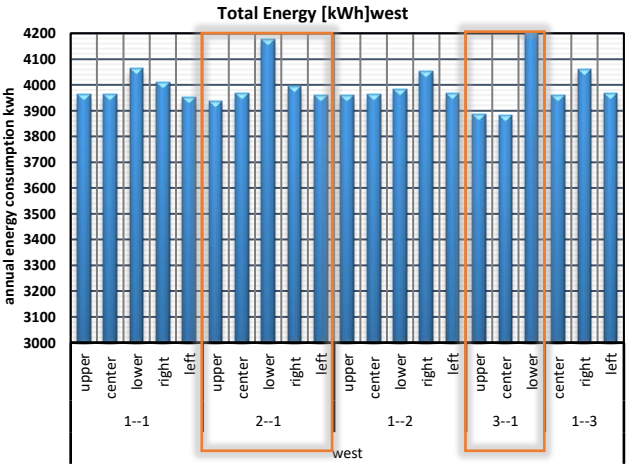


Fig4: the annual energy consumption in the different window position – in south –WWR 20%

- Total energy consumption in different window position-in the western direction (WWR20%) is shown in (fig 5)



From Figure (2) through Figure (5), many notable results can be reported.

The minimum amount of energy consumed per year is in the **northern facade** as in Figure (2); and in the case of the square window in the upper part of the wall as it reaches (3350 kWh per year) followed by the square opening in the left of the wall, then the 2:1 window and finally the 3:1 window. It is also clear that the position of the window at the bottom of the wall increases the energy consumed with 1: 1 window and this is less than the 2:1 window. The maximum consumed energy is found in the rectangular rectangle 3:1 window, (3750 kWh), with an increase of about 400 kWh for the least value in this direction.

In Figure (3), it is clear that the amount of energy consumed in **the eastern facade** is reduced when using the upper 1:1 square window. The square opening in the center of the wall causes relatively high-energy consumption and the 2:1 opening and 3:1 in the wall cause higher consumption than the former. The lower openings cause high increase in energy consumption. It is also noted that the greater the width of the aperture with respect to its height, the higher the energy consumption. It is found that the ratio of 3:1 is higher than 2:1 and 1:1, which causes energy consumption (3800 kWh).

In case of **the southern façade**, the amount of energy consumed is notably greater than that calculated for the northern and eastern facades as shown in Figure (4). The amount of energy consumption for the case of rectangular widow with

ratio 3:1 that is located at the upper of the wall results in the least consumption for that façade, followed by the window in the center of the wall and the upper of the wall with 2:1 and 1:1. The 1:2 and 1:3 windows cause nearly the same energy consumption for the center and left positions in the wall. The highest energy consumption for this façade is caused by the bottom windows with ratios 1:1, 2:1 and 3:1. These ratios are ordered ascendingly with respect to energy consumption.

The western façade causes the highest annual energy consumption as compared to other facades as shown in Figure (5). The upper and center rectangular 3:1 window causes the lowest consumption for this façade (about 3850 KWh), while the bottom rectangular 3:1 window causes the highest consumption for this façade (about 4250 KWh). A vertical rectangular window causes nearly the same energy consumption irrespective of the façade direction and its position except the right position, which causes an increase of about 100 KWh annually.

4.2.1. Total energy consumption in window wall ratio 30%.

- **Total energy consumption in different window position - in the northern direction 30% as shown in figure (6).**

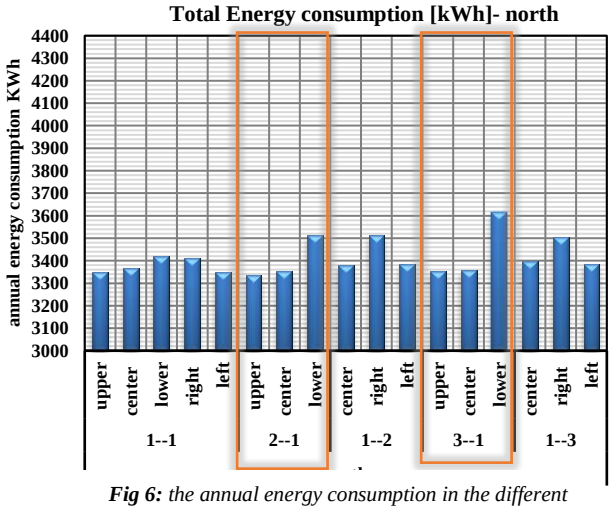


Fig 6: *the annual energy consumption in the different window position – in north –WWR 30%*

- **Total energy consumption in different window position - in the eastern direction 30% as shown in figure (7).**

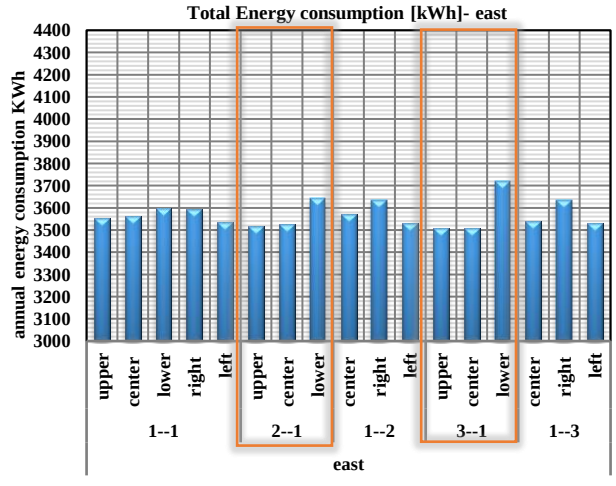


Fig7: the annual energy consumption in the different window position – in east –WWR 30%

- **Total energy consumption in different window position - in the southern direction 30% as shown in figure (8).**

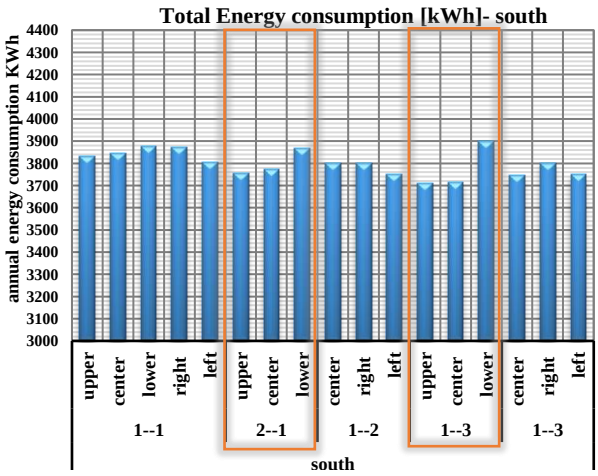


Fig 8: *the annual energy consumption in the different window position – in south –WWR 30%*

- **Total energy consumption in different window position-in the western direction 30% as shown in figure (9).**

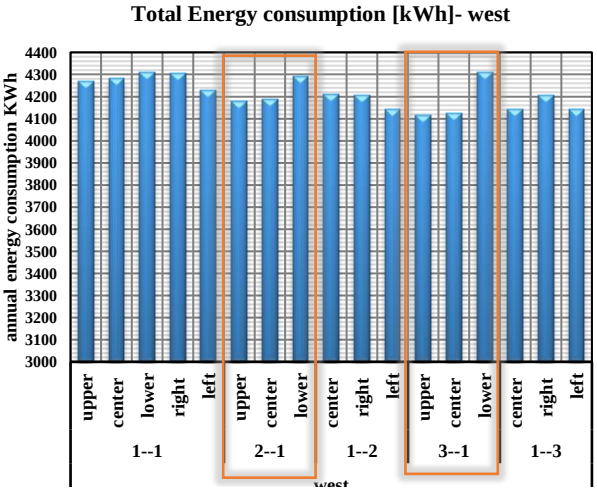


Fig9: the annual energy consumption in the different window position – in west–WWR 30%

Figure (6) through Figure (9) show the results for annual energy consumption for the 30% WWR case. Many notable results can be reported.

the least amount of energy consumption is obtained in **the northern facades** with the 1:1, 2:1 and 3:1 windows that are located in the upper position, and followed by the 1:1, 2:1 and 3:1 windows in the wall center, as show in Figure (6). The 2:1 and 3:1 windows cause an increased consumption when they are located at the bottom of the wall. This can be explained by the increase of the annual required lighting energy needed. Vertical windows that are in the right part of the wall can cause nearly the same phenomenon that leads to consumption increase.

In **the eastern façade**, as shown in Figure (7), the wide rectangular aperture in the upper of the wall with a ratio of 3:1 represents the window position for the lowest annual energy consumption. The top and the middle positions of the wall, for the 2:1 and 1:1 window lead to a slightly greater consumption than the left and the middle positions, respectively. The

3:1 and 2:1 wide rectangular window at the bottom of the wall results in the highest energy consumption per year by about 250 kWh.

In **the southern façade**, the amount of energy consumed annually exceeds the northern facade by about 400 kWh for most of window positions, as in Figure (8). The amount of energy consumed in the case of a 1:1 square window is evident in its different positions. The rectangular window opening with the 3:1 ratio in the center or the upper part of the wall is the reason for the lowest energy consumed annually with respect to other positions, followed by the rectangular opening by 2:1 in the upper and center of the wall. The rectangular openings in the bottom of the wall are still resulting in the highest annual consumption of energy by about 200 kWh as compared to the lowest value in the southern façade.

The western façade represents the highest annual energy consumption as depicted in Figure (9). It is preferable not to use square openings as well as rectangular openings in the lower part of the wall. The rectangular aperture with a ratio of 3:1, in the center of the wall and the upper part of it, represents the positions for the lowest consumption of energy in this direction followed by the upper rectangular 2:1 opening and the middle 2:1 opening and then the rectangular 1:3 openings in the center and left of the wall.

From the above discussion, it can be concluded that:

- The direction of the window is an important factor that affects the total amount of energy consumption. Throughout the experiment, it is found that the northern façade of different positions results in the lowest energy consumption, for the administrative room, which is naturally ventilated during the days of the year, and air conditioned on the critical days.
- The energy consumed annually in case of 20% WWR is about 15% lower for northern facades than the western facades, which are the highest in the annual consumption of energy by its various window positions, while it is lower by about 20% in the case of WWR 30% with respect to the southern façades.
- In the case of 20% WWR windows, it is found that the 1:1 window at the top or the center of the façade leads to the least energy consumption in the northern and eastern facades. This was followed by the wide rectangular windows with 2:1 and 3:1 dimensions at the top or center of the eastern or northern façades. Those configurations can reduce the energy consumption by about 12% as compared to the other windows dimensions and positions in these two facades.
- For the western and southern façades, the least consumption is caused by 2:1 and 3:1 wide rectangular windows in the top and center of that façade. This consumption is less than the 3:1 wide rectangular window at the bottom of the wall by 10-11%.
- Generally, the least energy consumption for the WWR 30% windows is obtained by the 3:1 then by 2:1 that are in the top or the center of the façade in the four main directions (North, East, South, West). The reduction in annual energy consumption is found to be 7-9% with respect to the wide rectangular windows that are located at the bottom of the facades.
- The least energy consumption for the 20% WWR is achieved by the 1:1 window in the northern façade, which is less than the energy consumption obtained by the rectangular 3:1 window at the bottom of a western wall by about 25%. The western façade leads to the highest energy consumption as reported throughout the results of the experiments.
- For the energy consumed in the WWR 30% case, the lowest configurations in total consumption are obtained in the rectangular aperture at the top and the center of the northern facade, which is about 29% lower than the annual energy consumed by the wide rectangular aperture of 3:1 at the bottom of the western facade, which is configuration of the highest energy consumption.

4.3. The distribution of light intensity, when windows ratios are (1:1, 2:1, 1:2, 3:1, 1:3) at the positions (Center, Upper, Bottom, Left, and Right) in WWR 20%, 30%

- The distribution of the natural light intensity of the different window positions and dimensions is analysed using EnergyPlus program to determine the best lighting in the administrative rooms of the study area. The results for the ratio of WWR 20% are in Figure (10) and for the WWR ratio of 30% can be found in Figure (11).
- In the case of the rectangular aperture of 3:1 at WWR 20% and 30%, the shape of the lighting distribution is almost identical when moving the aperture to left and right on the horizontal axis with the position in the middle of the wall. In the case of a 1:3 opening in WWR 20% and 30%, the distribution of lighting is also very similar when moving on the central vertical axis towards the top and bottom of the wall.

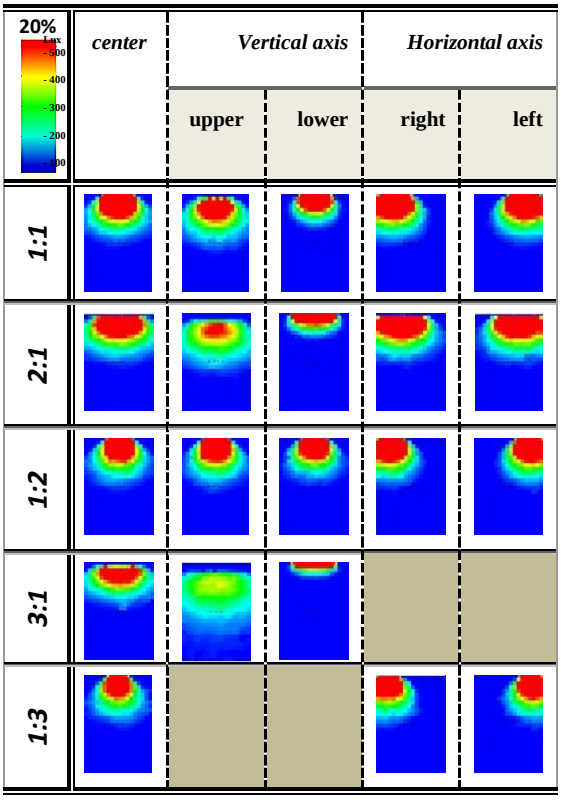


Fig10: the distribution of light intensity in the different window position – in west–WWR 20%

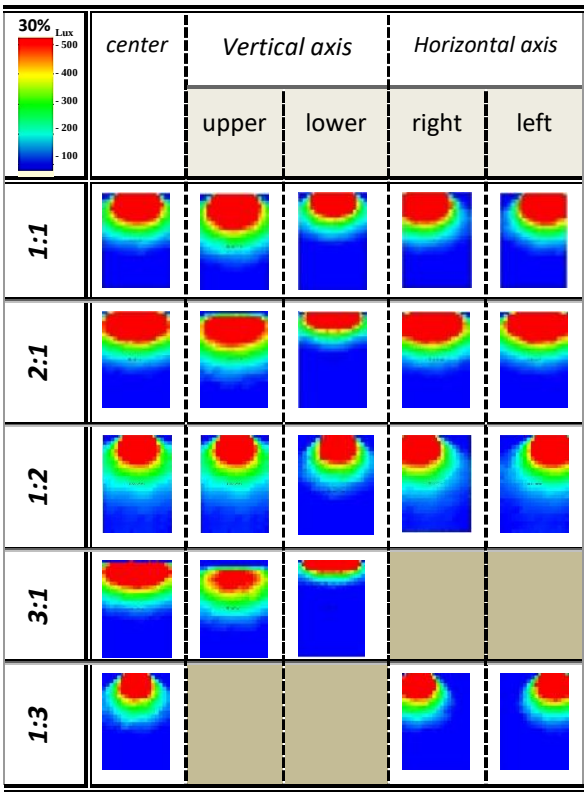


Fig 11: the distribution of light intensity in the different window position – in west–WWR 30%

By analyzing the distribution of lighting in both the 20% and 30% WWR characteristics illustrated the following:

- It is clear that the distribution of light intensity in each ratio of WWR almost converges in the main directions (north - east - south - west) with the identical positions, where it is found that the position of the opening and its ratio to the wall is the main ruler in the form of lighting entering and its distribution in the space of the room. The distribution of light intensity in the study sample is displayed by the different windows' positions, irrespective of façade direction.

- The top window in the wall with the WWR 20% or 30% represents the best configuration for distributing the natural light intensity. The WWR 20% with windows dimensions of 2:1, 3:1 and 1:1 at the top of the façade are slightly better than rectangular openings with 2:1 and 3:1 in the center of the wall, where the position for the best distribution of lighting inside the room covers about 50% of the room space.

- In case of the 30% WWR, it is found that the case of 1:1 window in the façade center results in the highest light intensity. It is notably reduced for bottom openings, where the light is found only near the aperture. For the wide rectangular window of 2:1 and 3:1, it is found that the light intensity is nearly the same for different locations on the central horizontal axis of the wall (left or right). The light intensity increases as the window location varies toward the top of the wall. It decreases by moving the opening toward the bottom of the wall. The best light distribution inside the room is obtained by the top windows with 2:1 and 3:1, which covers up to 60% of the room area.

- The vertical 1:2 and 1:3 windows lead to a nearly constant distribution as the window location changes along the vertical axis due to the short span for such opening ratio. Moving these windows along the horizontal axis results in moving the light pattern with the same distribution. This finding is noted for both the 20% and 30% WWR.

- Increasing the WWR from 20% to 30% leads to an increase in light pattern coverage especially for the 1:2 vertical window for its different tested locations. The more the WWR is, the more light spreads within the room. This explains the increase of light distribution coverage from (30% to 50%) of the room area.

5. Conclusion

- In this paper, it is concluded that the northern façade leads to the least energy consumption for a naturally ventilated administrative room over the whole year except in the critical days. Both window wall ratios (20% and 30%) lead to that conclusion. The annual energy consumption in northern facades is less than other directions by 15% to 25%.

- For the 20% opening ratio, the highest annual energy consumption difference for the administrative room reaches 400 KWh between the different window positions for every façade direction. It represents about 10-11% of the total energy consumed for a façade direction with different window positions.

- For the 30% window-wall ratio, the energy consumption notably increases over that of the 20% ratio. The highest annual energy consumption difference for the administrative room ranges between 250 to 300 KWh between the different window positions for every façade direction, which represents about 7-9% of the total energy consumed for a façade direction with different window positions.

- The direction of the window affects the performance of it in the different positions especially in the 30% case. The squared window in a northern or eastern façade, leads to the least yearly energy consumption. For the western or the southern facades, the squared window leads to higher energy consumption when compared to the rectangular windows with height to width ratios 1:2 and 1:3.

- The least energy consumption for the 20% WWR is achieved by the 1:1 window in the northern façade, which is less than the energy consumption obtained for the rectangular 3:1 windows at the bottom of a western wall by about 25%. In the window wall ratio 30% case, the lowest configurations in total consumption are obtained in the rectangular aperture at the top and the center of the northern facade 3:1, which is about 29% lower than the annual energy consumed by the wide rectangular aperture of 3:1 at the bottom of the western façade. Itis the configuration of the highest energy consumption.

- The WWR 20% with windows dimensions of 2:1, 3:1 and 1:1 at the top of the façade are the best for the distribution of lighting inside the room that leads to covering about 50% of the room space. In case of the 30% WWR, the best light distribution inside the room is obtained by the top windows with 2:1 and 3:1, which lead to covering up to 60% of the room area.

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