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The Effect of Window to Wall Ratio on Energy Performance of High-Rise Office Buildings Across the Egyptian Climate Regions

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Keywords
High-rise office buildings, Window to wall ratio, Energy performance, Egyptian climate regions

Abstract

Due to innovations in construction technology and increasing land prices, the number of high-rise buildings has increased dramatically. These buildings are known for their high energy consumption, which caused by many factors including architectural and operational factors. Heating, ventilation, and air conditioning systems (HVAC) is one of the operational factors which led to intensive energy consumption. In the light of the global energy crises along with advanced simulation tools, architects have been motivated to improve the energy performance of buildings through controlling design parameters. This research discusses the impact of Window to Wall Ratio (WWR), as an important parameter of building's envelope design, on the total annual energy consumption of high-rise office buildings. It aims to determine the optimal WWR in terms of energy performance across the Egyptian different climatic regions. Many related previous works, in different climates, have been reviewed to theoretically extract the variables employed in this work. According to the review, nine WWR ranging from 10% to 90% in two shapes, square and rectangular, were adopted to be modelled using the Design Builder simulation tool. The proposed models were simulated within seven Egyptian cities (Alexandria, Cairo, Minya, Assiut, Hurghada, El-Kharga, and Aswan) representing the seven classified climatic regions in Egypt. The findings revealed that the optimal WWR is (20%) for the rectangular shape and (20-30%) for the square shape across all Egyptian cities. The energy conservation ranged between (53.3- 60.8%) and (41-49%) in the rectangular and square models, respectively, in comparison to the worst case.

1. Introduction

High-rise buildings have contributed to the high rate of energy consumption of buildings around the world [1]. After the global energy crisis, engineers and architects intensified their efforts to reduce energy consumption in buildings in general, especially in high-rise buildings [2]. Egypt has the same situation, as it suffers from a shortage of energy resources. According to a report issued by the

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Egyptian Electricity Holding Company, electricity use increased by 22.5% between (2017/2018) [3] and (2016/2017) [4]. The construction sector represents about 62% of the total electricity consumption in Egypt (Fig. 1) [5].

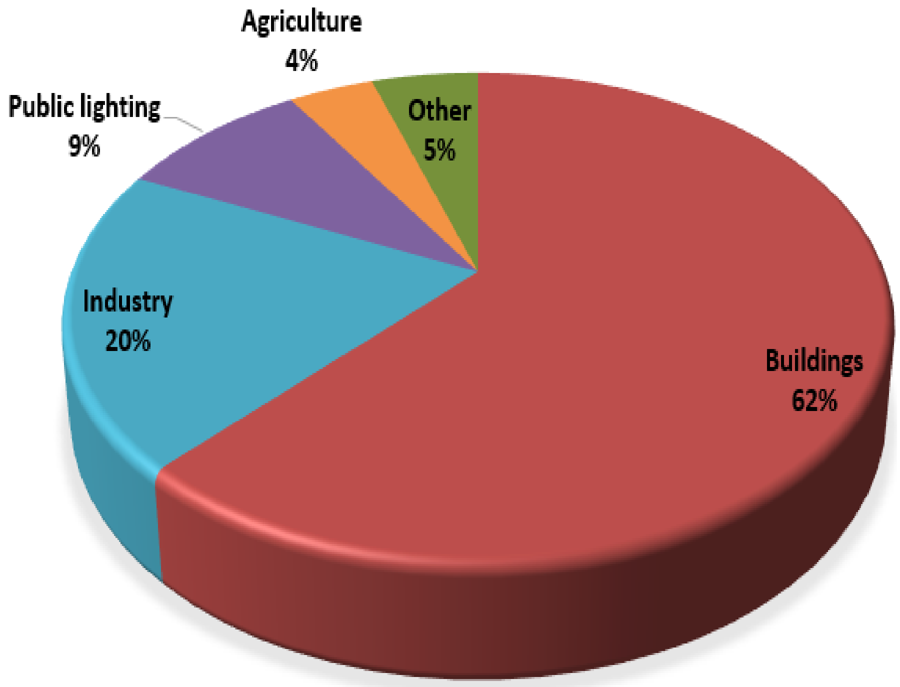
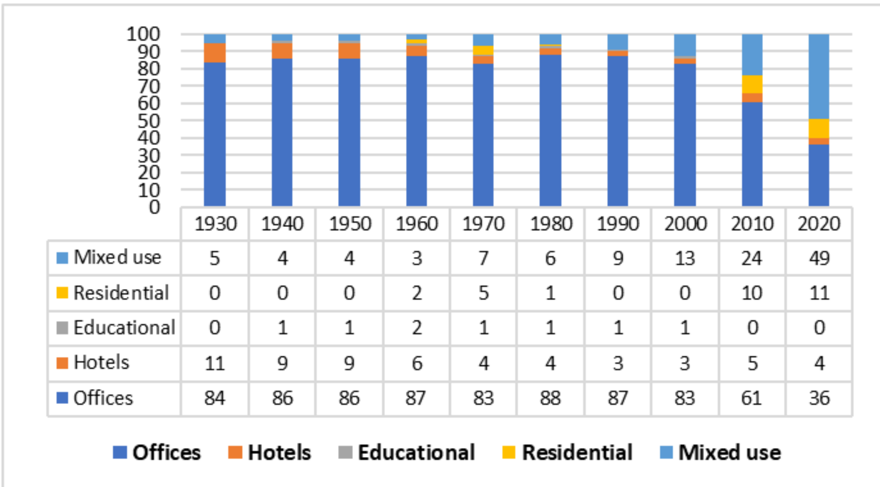


Fig1. Electricity consumption in Egypt by sector [7]

During operation phase, which represent the longest phase in the building life cycle [6], the building consumes about 80% of its lifelong total energy [7]. This is due to the density of users and the dependence mainly on air conditioning and artificial lighting systems, especially in office buildings during working hours [8]. Office buildings are the most prevalent type of high-rise building in the world [9, 10], (Fig. 2), which consume more than half of the energy consumption of the non-residential buildings [11].



	1930	1940	1950	1960	1970	1980	1990	2000	2010	2020
Mixed use	5	4	4	3	7	6	9	13	24	49
Residential	0	0	0	2	5	1	0	0	10	11
Educational	0	1	1	2	1	1	1	1	0	0
Hotels	11	9	9	6	4	4	3	3	5	4
Offices	84	86	86	87	83	88	87	83	61	36

Figure 2. Classification of high-rise buildings according to their function from 1930 to 2018 [10]

In Egypt, more than two-thirds of the energy is used in commercial buildings by heating, ventilation and air conditioning system (HVAC) and artificial lights [12]. Several studies have demonstrated that the use of passive design solutions, such as orientation, building envelope design, and building geometric mass, can enhance indoor thermal comfort while reducing energy use [13]. According to the Atheneites and Attia survey [14], about 60% of early-stage design energy models focus on building orientation, geometry, and envelope design. The use of these factors in the early design stages is one of the most effective ways to improve energy performance [15], as the building is still a proposal and has not yet been built. Window to wall ratio (WWR) have an important impact on energy use in buildings, as they are responsible for (20-40%) of energy loss [16]. According to previous research, the building envelope is responsible for 64% of the total cooling loads in hot climatic regions with 45% of these loads are due to solar heat gain and thermal conduction through windows [17], [18]. When it comes to window design determinants, there are usually contradictory requirements in terms of heating, cooling, and lighting performance, which must be balanced. Smaller windows are effective in reducing heat loss in winter and heat gain in summer[19], while the larger window is better at viewing views, daylight, and solar heat gains in winter [20].

Egypt is characterized by the diversity of climatic zones. According to the Köppen climate classification, the Egyptian lands are located in a hot desert climate with the exception of the northern and eastern narrow coastal strips that witness a steppe climate [21]. For the purpose of environmental design, the Local Housing and Building Research Centre (HBRC) classified Egypt into eight thermal design regions (Fig. 3) [22]. All these regions are inhabited areas except for the Sinai High-lands region, which is a rugged and uninhabited mountainous area. Each of the other seven regions has its representative city that accommodates its predominant climatic characteristics. Table 1 shows each Egyptian climatic region and its climatic conditions along with representative city. These data were extracted through climatic analysis of these cities based on the typical meteorological year (TMY) weather files downloaded from the official Energy Plus website [23] to deduce the general features of the climate for each climate region. It is clear from the table that the climatic conditions are significantly vary across cities.

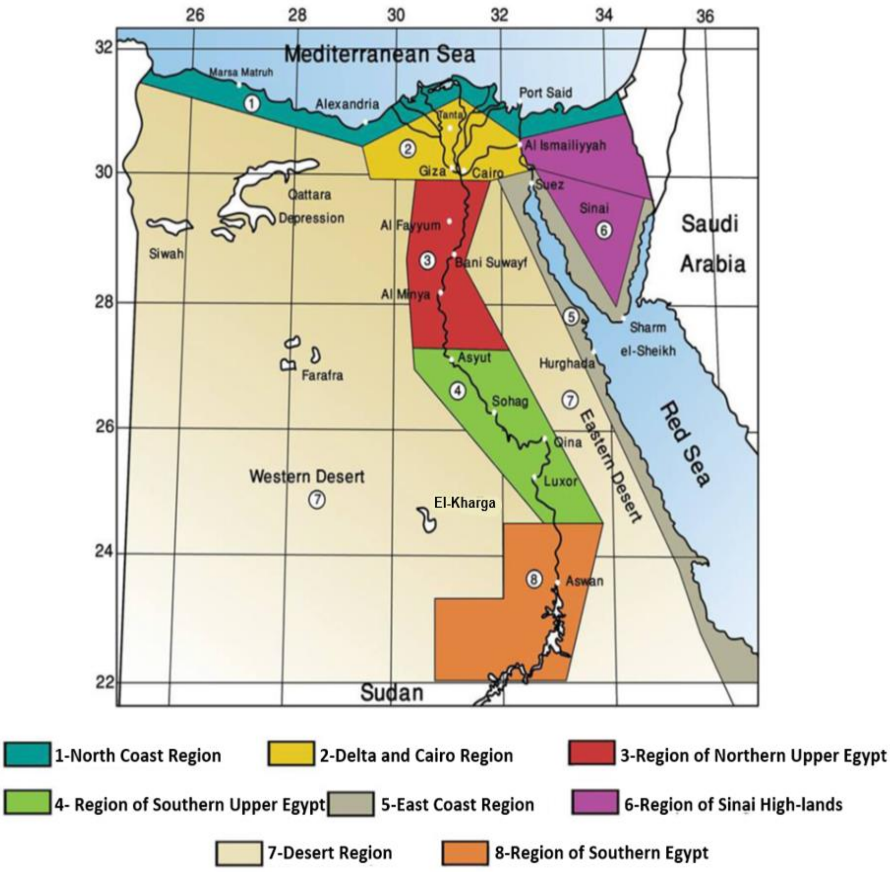


Figure 3. Climatic design regions of Egypt with indicated representative cities[22]

Table 1. Climatic conditions variation between the seven regions and their represintative cities [23]

City	Dry bulb temperature (C°)		Relative humidity (%)		Direct solar radiation (KWh/m^2)		Wind speed (m/s)	
	Min	Max	Min	Max	Min	Max	Min	Max
Alexandria	13.5	27	61.5	72.82	85	147	3.2	4.9
Cairo	14	29	45.07	66.37	110	210	2.8	4.5
Minya	12.5	29	34.31	65.88	90	155	2	4.1
Asyut	12.5	30	23.3	55.03	150	260	3.4	5.1
Aswan	16	35	16.78	43.37	160	300	4.15	5.9
El-Kharga	14.5	33.5	25.78	53.39	160	250	2.2	5
Hurghada	17	32	33.8	49.24	155	225	4.9	7.25

As known, different climatic conditions dictate diverse design considerations and buildings' treatments. Many studies discussed the impact of building's WWR on energy efficiency and were conducted in a variety of climatic regions such as desert, tropical, temperate, continental, and cold. The findings of these studies help in extracting this study's variables. In the context of hot arid desert climatic conditions, two studies were conducted. The first[8] was in Tripoli City where a small office space (4.0 m x 4.0 m x 4.0 m) was simulated to provide a simple relationship between facade design and office building energy consumption. The study relied on Energy plus as an Open-Studio interface simulation tool to examine the effect of routing and WWR on annual heating and cooling loads. The results indicated that the higher the WWR, the higher the cooling power consumption and the lower the heating power consumption. Due to the climate of the region, heating loads can be neglected if compared to cooling loads. Therefore, the increase in WWR increased the total annual energy consumption by 6 -181%.

The second study [24] used a simulation analysis in Tunisia and Kuwait to study the correlation between building geometric variables and total energy consumption in office buildings. The study was based on simulating rectangular and (L) shape with 0% and 25% WWR using DOE-2 simulation software. The results showed that the total energy consumption increases with the increase in window size. In addition, the energy consumption in Tunis was found to be lower than it in Kuwait. Continental climate was targeted by two studies relating to the effect of WWR on the total annual energy consumption of tall buildings. One of them was conducted in Tianjin, China [25] used a north-oriented office building model. The model was supposed to be square shaped with an area of 1444 square meters, 18 stories (4.2 meters floor to floor height), and 50% WWR. The building was designed and simulated by the Design Builder simulation tool with WWR ranges from 30% to 70%. The results indicated that the decrease in total power consumption was observed with decreasing WWR.

The other study [20] was conducted in Boston and applied to a high-rise building with 100 m height, 30 m width, and 40 m length by using the Energy Plus simulation tool. The results showed that the optimal values for WWR were 48% for the central zone of the facade and 30% for the rest of the facade. Within the hot and humid tropical climate of Katwaniki in Sri Lanka, a study was performed [26] to examine the impact of WWR and some other design parameters on lighting energy consumption and thermal comfort in residential buildings. Three different building shapes (square, rectangular, and L-shape) with two floors were simulated by Design Builder. Four WWR (20%, 40%, 60%, 80%) where assigned to each shape. The total area of the building is assumed to be 68 m^2 with a height of 3.0 m per floor. The results showed that the lowest WWR provides the best thermal comfort but the highest use of lighting energy. The optimal WWR for lighting energy efficiency was 80%.

For the cold climate of North East England, the effect of the window-to-wall ratio on the heating energy performance of the building was tested [27]. A four-story office building of 8000 m^2 was created using the Design Builder simulation software. The results of this study revealed that when the WWR was reduced from 53% to 20%, a significant reduction in heating energy consumption by about 33.9% was achieved.

In Iran, Tabriz and Yazd were chosen as representative cities for cold and desert climates, respectively to be investigated [28]. This investigation aimed to reveal the relationship between window-to-wall ratio and energy consumption in high-rise buildings using eQUEST simulation tool with DOE-2.2 as a calculation engine. The study model was set to be an open rectangular shape (35m x 26m) with an area of 745m^2 and a height of 18 floors. A range of 20% to 100% WWR was examined. It was found that the total energy consumption increases as the WWR increases within the two cities. The reduction in total energy in hot climate use was found to be more than the reduction in cold one. Also, WWR 20% reduced energy consumption by 7% and 5% in Yazd and Tabriz respectively.

J. Lee et al [16] evaluated the effect of different window-to-wall ratios on building's power loads in five different Asian climatic zones, Manila, Taipei, Shanghai, Seoul, and Sapporo (from hottest to coldest). Four WWRs (25%, 50%, 75%, 100%) were tested for power loads in each climate. An office building with a length, width and floor height of 30.5 m, 23.75 m, and 3.05 m respectively has been simulated by Energy plus. In all cities, it was found that a 25% window-to-wall ratio resulted in the lowest power loads. Susorova *et. al.* [29] conducted a study to determine the role of geometric parameters, including window-to-wall ratio, in enhancing building energy performance for office buildings. Simulation analysis was performed in six hot, temperate, and cold climate zones in the United States by the Design Builder simulation software. The model that was proposed was rectangular in shape with rooms' depth of 6 m. Seven WWRs (from 20% to 80%) were assigned to the model. The results showed that a WWR of 20%-30% achieved the best energy efficiency in hot and cold regions, but 40% WWR was best in temperate climates.

Another study [30] was conducted in three different climatic zones Amsterdam (temperate), Sydney (subtropical) and Singapore (tropical) to study the impact of WWR. A prototype of a high-rise office building with a total area of 60,000 m^2 that divided into 40 typical floor plans has been simulated by the Design Builder simulation tool. The results indicated that the optimal WWR in temperate climate ranged between 20% and 30%, while for the tropical climate it ranged between 30-45%. In the Egyptian context, Shahin [31] conducted a study aimed to improve the energy efficiency of the Egyptian office building using envelope's design parameters. A six-story office building with footprint of 1,112 m^2 is designed employing four WWR variants (20%, 40%, 60%, 80%). The set models were tested in three cities (Alexandria, Cairo, and Aswan) representing three different climatic regions using Energy Plus software. Simulation results indicated that 40% WWR achieved the lowest total energy consumption in all selected regions.

Another study [32] was conducted in Egypt to find the relationship between envelope design alternatives and total annual energy use. The proposed prototype was a house with area of 240 m^2, two floors height, and a window-to-wall ratio of 15%. A parametric analysis based on two design parameters *(Orientation and WWR)* was performed in five cities (Alexandria, Cairo, Siwa, Assiut, Aswan) representing five different Egyptian climatic zones using ENER-WIN Software. The results indicated that the optimum WWR was 20% and 15% for the northern and southern, respectively. However, WWR of 0% was the optimum for both eastern and western facades. Algendy, *et. al.* in 2017 [33] attempted to achieve energy efficiency in low-rise residential buildings in three Egyptian climatic zones (the delta region, the northern coast and southern Egypt). This study focused on exploring the effect of orientation and WWR on energy consumption the building. A standard dwelling with length of 6.7 m and 5 m width was employed as a base model for this study. The base model was simulated using the Design Builder software with changing the WWR from 10% to 100% in 10% steps. In all climatic zones, it was confirmed that the lower the WWR, the lower the energy consumption.

The above discussion emphasized the significant impact of WWR on building energy consumption in different climatic conditions. It can be clearly concluded that energy consumption decreases as WWR decreases in all climates, while the optimal ratio varies from climatic region to another. The effect of WWR is greater in hot regions than in other climates. The variation in the Egyptian climatic conditions across Egypt and its different climatic regions raises the necessity of studying and evaluating the effect of WWR on energy consumption within the Egyptian context. None of the outlined above studies' results could fulfill this need. This gap in the knowledge is defined and approached in this research.

2. Main Aim and Objectives

The main aim of this study is to investigate the effect of window-to-wall ratio (WWR) on the energy consumption of high-rise office buildings for each Egyptian climatic design region. Moreover, it attempts to determine the optimal WWR in terms of energy performance and efficiency that should be adopted by architects for each climate region. This aim can be achieved through the following objectives:

1. Determine the optimal building forms which achieve the best energy performance in Egyptian climate regions.
2. Determine the models' orientation and the operation details which is suitable for the office buildings' occupants.

3. Research Methodology

To achieve energy efficiency in high-rise office buildings in Egypt, the study relied in determining the optimal WWR for each climatic region on using computer simulation analysis in the early-stage design. For this purpose, the research methodology follows two steps:

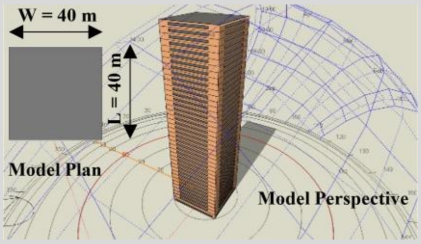
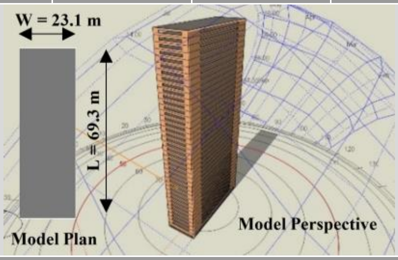
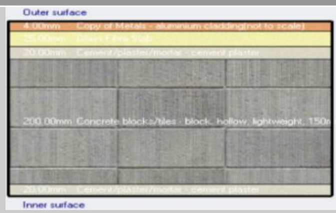
1) Setting up the study proposed models through identifying their geometrical characteristics and variables,
2) Employing simulation computerized tool in parametric analysis by using variables set in first step.

3.1 Setting up proposed models' variables

Square and rectangular floor plan shapes with width-to-length *(W/L)* of 1:1 and 1:3 respectively was adopted. This selection of *(W/L)* ratio was based on studies from Olgay [34] and Yeang [35], which suggested that building forms with a *(W/L)* ratio of 1:1 and 1:3 are optimum in both, moderate and hot climates. The height of the models is set to 145m, as the height of tall buildings in Egypt does not exceed this height [36]. The floor plan area is assumed to be 1600 m^2 with the total building area of 64000m^2 divided into 40 typical floors. The area and the height of the models were set to achieve surface-to-volume ratio (S/V_{ratio}) ranging between *(0.085 and 0.16)*. This range was found to be the frequent range, which was obtained from the five generations classification of high-rise buildings based on energy consumption. Building envelope's parameters such as, envelope material and glazing type were set to be compatible with their locally used variables.

Several studies indicated that the orientation of buildings towards the north is considered the best direction in hot areas, where the building obtains the greatest amount of shading that protects it from direct solar radiation [37]. El-Agami et. al. [38] used weather data to identify the optimum orientation in each Egyptian climatic region by applying the Szokolay technique [39]. This method is integrated into the Autodesk Weather Tool. It was found that the northern direction is the best for all studied regions because it reduces exposure to solar radiation. Therefore, in this study, all models were oriented towards the north direction. Table 2 summaries the characteristics of the proposed base models.

Table 2. The characteristics of the proposed base model

<table>
<tr><th></th><th colspan="4">Square model</th><th colspan="4">Rectangle model</th></tr>
<tr><td rowspan="2">Model shape and aspect ratios</td><td>W/L</td><td>1:1</td><td>S/Vratio</td><td>0.107</td><td>W/L</td><td>1:3</td><td>S/Vratio</td><td>0.122</td></tr>
<tr><td colspan="4">
</td><td colspan="4">
</td></tr>
<tr><td>Area</td><td colspan="8">1600 m²</td></tr>
<tr><td>Total floor area</td><td colspan="8">64000 m²</td></tr>
<tr><td>Height</td><td colspan="8">145m</td></tr>
<tr><td>No. of floors</td><td colspan="8">40</td></tr>
<tr><td rowspan="2">Floor to floor height</td><td colspan="8">3.6m for repeated floors</td></tr>
<tr><td colspan="8">4.6m for ground floor</td></tr>
<tr><td>Orientation</td><td colspan="8">North</td></tr>
<tr><td>External walls</td><td colspan="4">- Aluminium cladding: 4mm
- Glass fibre insulation: 25mm
- Cement mortar: 20mm
Concrete blocks: 200mm-
- Cement mortar: 20mm</td><td colspan="4">

U value = 0.748 W/m². K</td></tr>
<tr><td rowspan="2">Openings glazing type</td><td colspan="5">Double Low-E (10 mm/ 13 mm Argon)</td><td colspan="3">U value = 1.15 W/m². K</td></tr>
<tr><td colspan="5">Aluminium window frame</td><td colspan="3">U value = 573 W/m². K</td></tr>
<tr><td>Facades' design</td><td colspan="8">Four identical facades</td></tr>
</table>

3.2 Simulation phase setting

The models' energy simulation has been performed using Design Builder V6 software. It uses Energy Plus as a simulation engine, which has been thoroughly tested for accuracy and stability in the calculation of heating, cooling, lighting, total energy loads, etc. [40, 41]. Also, it takes into account wind speed variation with the change in height according to *(ASHRAE)* equation [42]:

$$U_{H=}\ U_{met}\left(\frac{\delta_{met}}{H_{met}}\right)^{a_{met}}\left(\frac{H}{\delta}\right)^{\alpha}$$

An open-plan office building model of two shapes (square and rectangular) was built using the characteristics and orientations mentioned in the previous methodology step. The parametric analysis for WWR design parameter was adopted with variable of this parameter ranged between 10% and 90%. An incremental of 10% steps for all interfaces was adopted. An annual energy simulation was conducted to find out the total annual energy consumption.

All WWRs were tested in the seven representative cities by assign weather files (TMY) to the models. The details of the model's operation data and inputs have been carefully studied. According to the density of occupants, they were calculated as follows:

- **Assumptions:**
  - 30% of floor area is services core and not used for office activities.
  - Each person needs *($6m^2$)* office space.
- **Calculations:**
  - Net office activity area = 1600 (gross floor area) – (0.3 × 1600) = 1120 m^2
  - Total number of occupants = 1120 / 6 = 186.67 ≈ 187 Person
  - Density = 187 / 1600 = ***0.117* Person/m^2**

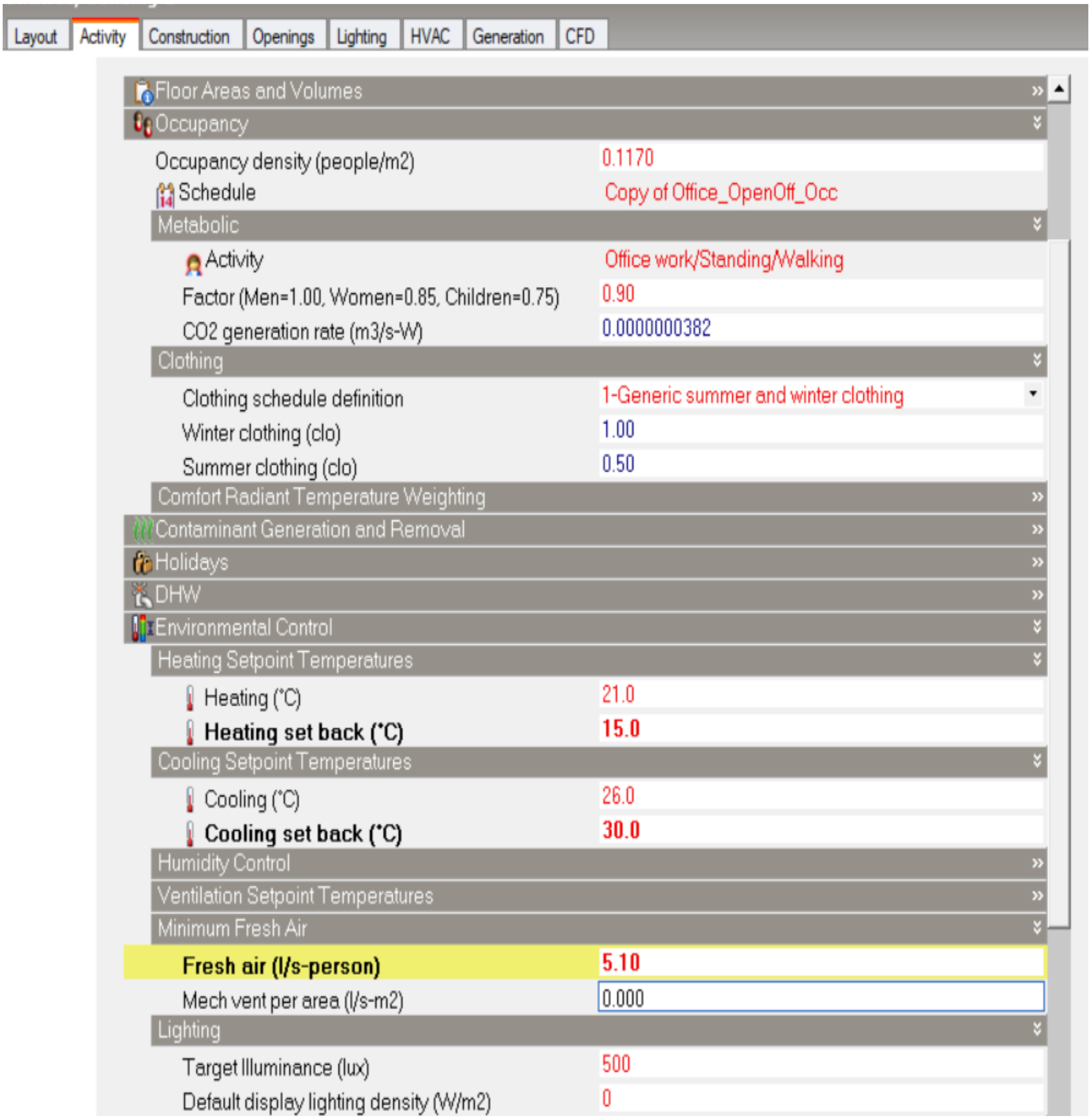


Figure 4. Activity data inputs as an example for software setup

For heating, cooling, ventilation rates, and relative humidity, the study relied on the specified values in *" The Egyptian Code to Design and Execute HVAC Works"* [43]. The Egyptian code indicated that the acceptable range for heating and cooling temperatures are *(21:23°C)* and *(24:26°C)*, respectively. The study utilized the highest *(26°C)* and lowest *(21°C)* values as setpoint inputs. The model is assumed to be a fully air-conditioned building as common in high-rise buildings, and it is hard to use natural ventilation in such kinds of buildings because of the wind high speed. Variable air volume *(VAV)* system was selected as heating, ventilating, and air-conditioning *(HVAC)* system for its suitability for large open areas. Based on the ASHRAE [42] calculation method, the minimum fresh air requirement per person was calculated and set to be *(5.1 L/S per Person)*.

The required lighting level was adjusted to fulfill European standards [44], which stated that the acceptable glare factor and illuminance for office activity are *(19)* and *(500 lux)*, respectively. It is assumed that the lighting, equipment, and HVAC system in the office models will be turned off on weekends.

Table (3) shows the model's operation inputs that were adjusted by the researcher. Other than these inputs, the default values Within the software domain have been kept.

Table 3. Simulation inputs for model's operation details

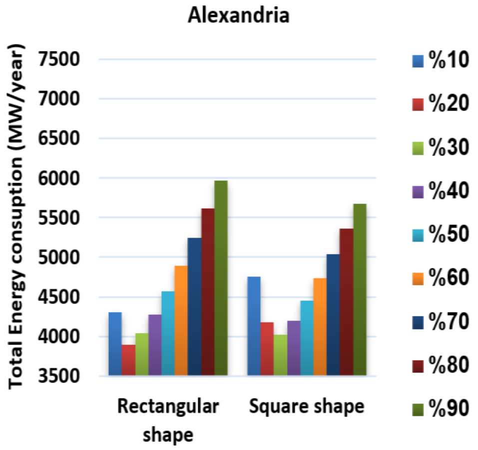
Category	Sub-Category	Item	Input
Activity	Occupancy	Density	0.117 people/m2
		Metabolic rate	Office activity
		Metabolic factor	0.9
		Occupancy schedule	8.00 am to 16.00 / 5 days per week
		Clothing	1Clo/winter - 0.5Clo/summer
	Other gains	Office equipment	w/m^2 13
	Environmental control	Cooling setpoint	26ºC
		Heating setpoint	21ºC
		Fresh air	5.1 L/S/Person
		Humidity control	20-50%
		Lighting, target illuminance	500 Lux
Lighting	LED lighting (with daylighting control)		
	Power density		2.5 w/m2-100 lux
	Luminaire type		Recessed
	Working plan height		0.8 m
	Glare		19
HVAC	VAV, Air-cooled chiller, Fan-assisted Reheat		
	Heating system coefficient of performance (COP)		0.85
	Cooling system coefficient of performance (COP)		1.8
	Auxiliary energy		35 KWh/m^2
	Ventilation rate		6 ac/h

4. Results

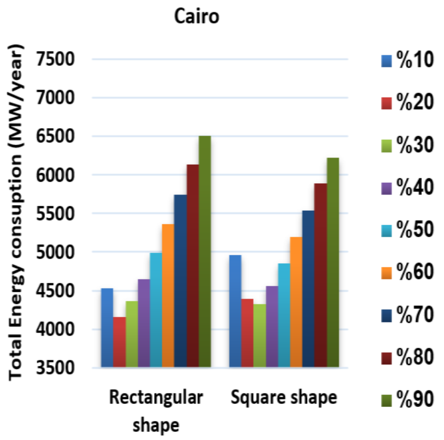
This section presenting the results, analysis of the total energy consumption generated by simulating the square and rectangular models with the different input variables of WWR for the seven representative Egyptian cities. The results of the rectangular building shape (fig. 5) illustrate that the WWR of 20% provides the best energy efficiency in all climatic regions with no exception. The results of the square shape indicate that the WWR of 30% is the optimal solution in four cities *(Alexandria, Cairo, Asyut, and Hurghada)*, (figure (5-a), (5-b), (5-d), (5-f)), while it was 20% for the other three cities *(Minya, El-Kharga, and Aswan)*, (figure (5-c), (5-e), (5-g)).

The amount of saved energy, in the rectangular model, by comparing the best and worst cases of WWR is *(53.3%, 56.4%, 60.8%, 55.7%, 57.6%, 55.4%, and 53.4%)* for *(Alexandria, Cairo, Minya, Asyut, Hurghada, El-Kharga, and Aswan)*, respectively. For the square model, the increase in energy consumption because of using the 90% WWR, which achieved the greatest energy consumption, is between 41% and 49%. The city of Minya obtained the highest rate of energy consumption savings, while the city of Alexandria achieved the lowest rate of savings in the two models. This demonstrate that Minya is the most sensitive city to a change in the WWR, unlike Alexandria which has the lowest difference range between the best and worst case.

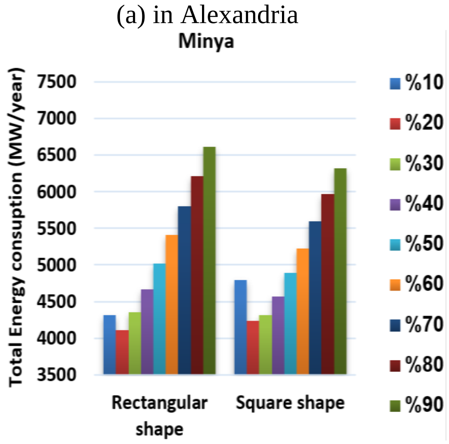
From all previous results, it can be clearly concluded that the optimal WWR ranges between 20-30% for the square shape and 20% for the rectangular shape in all Egyptian climatic regions. These ratios proved their efficiency in providing the lowest energy consumption across the year. The energy consumption general trend reveals that the more WWR the less building energy efficiency except for WWR of 10%.



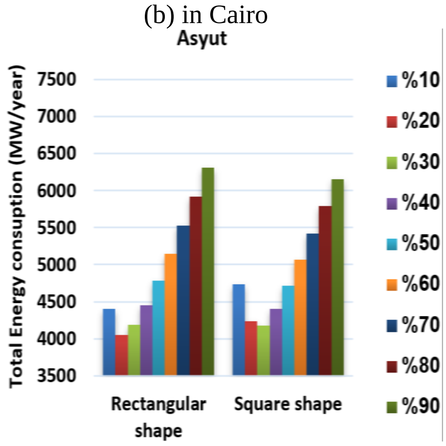
(a) in Alexandria



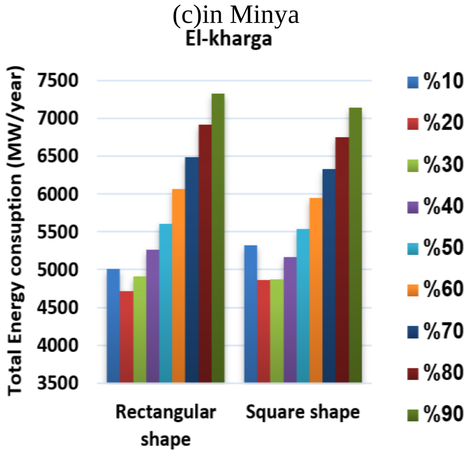
(b) in Cairo



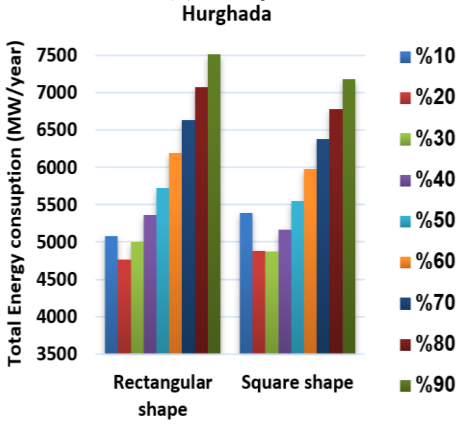
(c)in Minya



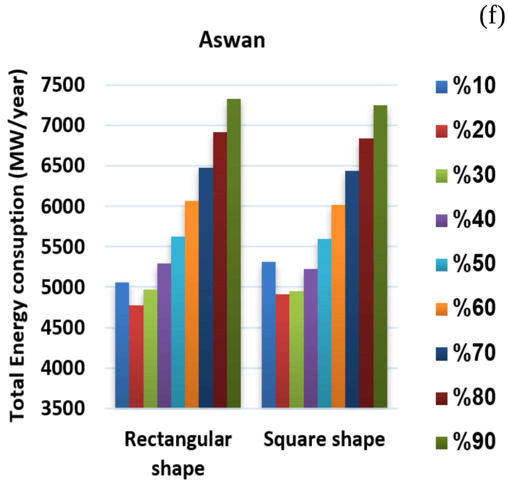
(d) in Asyut



(e) in El-Kharga



(f) in Hurghada



(g) in Aswan

Fig 5. The relation between total annual energy consumption and different WWR in the Egyptian climate regions

5. Comparative Analysis and Discussion

A comparison was made between the optimal solutions of the square and rectangular models to determine the case with the best performance (Fig.6). The rectangular building with the *(W/L)* of *(1:3)* and WWR of 20% has the best performance with the lowest annual energy consumption across all cities. This agrees with several previous studies [34, 35, 45] that reported the rectangular building with a *(W/L)* ratio of 1:3 is ideal in terms of energy consumption within hot climates, like Egypt. Nevertheless, the square shape did not have the same quality of performance due to the small Surface to Volume ratio S/V_{ratio} which makes it difficult to lose the heat in summer and gain solar radiation through the building envelope in winter. This, in turn, increases cooling, heating, and lighting loads. Additionally, the rectangular building benefits more from the north direction due to the large north facade, that receives almost no solar radiation, this in turn reduces the cooling loads.

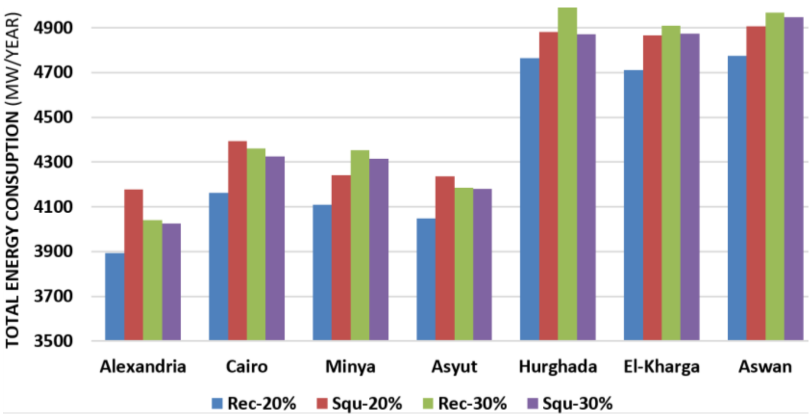


Figure 6. comparing the best results for WWR in square and rectangular shapes

In a rectangular building, the energy consumption rises dramatically with the WWR, so care must be taken when determining the rectangular building mass's WWR. the S/V_{ratio} of rectangular shape is relatively large, so the use of small WWR, such as 20%, achieves energy efficiency. This is because of north orientation that protects the building from absorbing a large amount of solar radiation, which in turn, minimizing the dominant cooling loads in such hot climates. Surprisingly, the WWR of 10% did not achieve higher efficiency. This performance may be caused by indoor overheating in summer due to decreasing heat loss and dissipation through small openings. In addition, very small WWR increases the energy required for artificial lighting and increases heating loads in the winter because of not benefiting from the solar radiation.

In the square building, the WWR of 30% resulted the lowest energy consumption in four regions. This may be due to its relatively small S/V_{ratio} in comparison to the rectangular building. This requires a larger shaded WWR that can help in dissipating heat gains and allows sufficient natural lighting. In Aswan, El-Kharga, and Minya, the WWR of 20% was found to be the optimal. From table 1, the climatic data for each city, it can be noted that the cities of Aswan and El-Kharga have the highest temperatures and direct solar radiation and the lowest relative humidity during the year. This could explain the small WWR in the square model compared to the rest of the cities, to protect the building from external climatic conditions.

For the city of Minya, it has high diurnal difference in temperature between day and night-time, as well as highest temperature variations between winter and summer [46].

This could explain the reason for the small WWR required to achieve energy efficiency, despite it is not among the hottest cities. Also, this clarifies the wide range of consuming energy between the best and the worst solution. Small openings can protect the building from weather fluctuations and harsh climate, thus WWR value is critical in Minya. For high-rise buildings' energy performance in each Egyptian climatic region, it is clear that very hot cities like *(Hurghada, El-Kharga, Aswan)* experiencing a significant increase in building's energy use compared to cities with a temperate climate like Alexandria.

6. Conclusion

This study investigated the impact of one of the most significant design parameters, WWR, on the annual total energy consumption in high-rise office buildings across Egypt. All other parameters have been fixed based on an in-depth study. The output findings proved that optimizing the building window-to-wall ratio can enhance energy performance and reduce its consumption with a considered proportion in all climatic zones. The main conclusions of the parametric analysis can be summarized as follows:

- In the rectangular model, the optimal WWR is 20% in all climatic zones. This WWR can conserve energy by 53.3% and 60.8%, in comparison to the worst case within the same context.
- In the square model, the optimal WWR is 30% for *(Alexandria, Cairo, Asyut, and Hurghada)* and 20% for *(Minya, El-Kharga, and Aswan)*. These WWR can conserve energy by 41% and 49%, in comparison to the worst case within the same context.
- The rectangular building with *(W/L)* of *(1:3)* has generally better energy performance than the square one with the same WWR.
- Minya is the most sensitive city to the change in WWR, as the energy consumption has achieved the widest range between the best and the worst cases.
- In the rectangular high-rise building, the rate of energy growth by increasing the WWR is relatively large, so it must be ensured that the optimal percentage of openings is used when using this shape.

7. Research Limitations, Recommendations and Further Work

This work was focusing on the role of WWR on energy conservation in each climate region across Egypt. Other factors such as building form and orientation, which influences energy consumption, have been reviewed and selected to obtain the best possible performance. Because of the considerable annual energy consumption in hot climatic regions, the authors propose that high-rise buildings not to be built in the regions with such hard climates.

However, the integration of new technologies and change in other factors might have a considerable impact on the results. The combined influence of WWR, orientation and building form should be studied further. In addition, future study should investigate the impact of incorporating passive strategies into the building envelope, as well as incorporating smart and renewable energy solutions, which can save a lot of energy. Moreover, there are a few points that need to be addressed for the proper implementation of the findings and the research's future improvement. All studied models are an open office plan with a single zone and single activity template. The positive side is that it decreases the complexity of the models and reduces simulation time. On the downside, changes in the activities of specific regions have an influence on energy consumption that is not considered in this work’s model. Additionally, the increasing in occupants' density will raise the internal gains. This in turn increases heating, cooling, and lighting loads.

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تأثير نسبة الفتحات بالواجهات على استهلاك الطاقة بالمباني الإدارية المرتفعة في الأقاليم المناخية المصرية

الملخص بالعربي:

تزايدت أعداد المباني المرتفعة تزايدا ملحوظا نتيجة التطور التكنولوجي وارتفاع سعر الأرض خاصة في المدن الكبرى، ويتسم هذا النوع من المباني باستهلاكه المرتفع للطاقة، ويرجع هذا إلى العديد من العوامل التي تتضمن عوامل معمارية وأخرى تشغيلية، ويتعبر الاعتماد بشكل أساسي على أنظمة التكييف والتدفئة والتهوية الصناعية من أهم العوامل التي تتسبب في استهلاك مكثف الطاقة، ونتيجة أزمات الطاقة العالمية بجانب التطور في أدوات وبرامج المحاكاة، توجه المعماريون نحو تحسين أداء الطاقة في المباني من خلال التحكم في المتغيرات الهندسية للمبنى، ويناقش هذا البحث تأثير تغير نسبة الفتحات بالنسبة لمسطح الواجهات على إجمالي الاستهلاك السنوي للطاقة بالمباني الإدارية المرتفعة، حيث يهدف هذا إلى تعيين نسبة الفتحات المثلى بالواجهات والتي تحقق أقل استهلاك طاقة في مختلف الأقاليم المناخية المصرية، وقد تم عرض العديد من الدراسات التي تناولت تأثير نسبة الفتحات بالواجهات على استهلاك الطاقة بالمبنى في أقاليم مناخية مختلفة، وذلك بغرض الاستفادة من نتائجها، وقد تم اختبار تأثير تغير نسبة الفتحات بالواجهات من ١٠٪ إلى ٩٠٪ في نموذجين لمبنيين أحدهما مربع والآخر مستطيل ذو نسبة طول إلى عرض (١:٣)، وذلك باستخدام برنامج المحاكاة Design Builder، واختبرت هذه النماذج في سبع مدن مصرية (الإسكندرية، القاهرة، المنيا، أسيوط، الغردقة، الخارجة، أسوان) ممثلة لسبعة أقاليم مناخية مختلفة، وتوصلت النتائج إلى أن النسبة المثالية للفتحات بالواجهات هي ٢٠٪ في المباني المستطيل و(٢٠-٣٠٪) في المبنى المربع في جميع المدن محل الدراسة، ويقدر الفرق في استهلاك الطاقة بين هذه الحلول المثلى والحلول الأعلى استهلاكا للطاقة بنسبة (٥٣,٣-٦٠,٨٪)، و(٤١-٤٩٪) في كلا من الشكلين المستطيل والمربع على الترتيب.