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Effect of Window Dimensions on Daylighting and Energy Consumption in Residential Complexes of Hot and Dry Climate of Iran; Case Study: Isfahan City*

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ABSTRACT

The present study aims to achieve daylighting (or natural lighting) and optimal energy consumption in residential buildings. This study selected District 4 of Isfahan as the case study of a city in a hot and dry climate. A mixed method was used to examine the effect of window dimensions: simulation of light and energy, by using Diva, Honeybee, and Ladybug plugins in addition to the Energy Plus simulation engine. In this case, the window percentage to the area of the southern wall was considered as the variable to measure the optimum window percentage in terms of using daylight and energy efficiency, and then the role of window shape and size in daylighting was examined. The purpose of this assessment is to provide guidelines for architects to determine suitable sizes and dimensions of windows in residential complexes located in hot and dry climates. The results of this study show that increased dimensions and size of the window do not expand daylight utilization percentage to the same extent. Although the increased size of the window reduces electrical lighting use, an excessive increase in the size of the window does not have a considerable impact on increasing electrical lighting savings. Moreover, the exposed cooling load by electrical lighting prevents very small windows from reducing cooling energy use in the building. On the other hand, heat loss through windows prevents very large windows to reduce heating energy use. According to the results of the study, around 30% of the most optimum window dimensions occurred in the southern front o the building. Although the obtained dimensions depend on some design conditions of the building, such as the plan, surrounding buildings, and other factors, these sizes and dimensions must be determined for each building separately.

Keywords: Spatial Daylight Autonomy (SDA), Annual Sunlight Exposure (ASE), Electrical Lighting Use, Cooling Use, Heating Use.

* This paper has been derived from the M.A. thesis by the second author under the title of "Design of Residential Complex in Neighborhood Scale with the Optimal Daylighting Approach in Isfahan City" guided by the first author in 2019.

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1. QUESTIONS

1. What is the effect of window dimensions and proportions on daylight use and emergency efficiency in residential complexes located in hot and dry climates?
2. How can determine the optimal window dimensions and proportions by simultaneous consideration of natural lighting and energy consumption in residential complexes located in hot and dry climates?

2. INTRODUCTION

Natural lighting or daylight is one of the underlying functions of windows, so windows are considered the most important source of lighting in the indoor space of buildings. Window features, such as window position, orientation, dimensions, transparency, and shading tools used in light quantity and quality play a role in interior space. The selection of window features is a key step in building design. Accurate design of windows provides better lighting rather than electrical lighting equipment in the building but also results in energy saving. This case is more substantial in the design of residential complexes because a house is a place where occupants spend a long time to achieve peace and comfort. However, studies conducted on features of windows and natural lighting have addressed administrative use, and few studies have been done about the windows of residential complexes. Some of these studies have been carried out by Lartigue et al., Melendo and Roche, Montaser Koohsari, Dabe and Dongre, and Sonawane and Mhaske.

Hence, this study investigated and analyzed the windows of residential space as research variables. Dimensions and proportions of windows are the main subjects in window design. Since window dimensions affect daylight use but also the heating and cooling load of the environment, the optimal dimensions of the windows must be determined by paying attention to daylight use and energy saving but also the impacts of energy spent for heating and cooling the environment must be considered. On the other hand, the selection of optimal dimensions for windows depends on the dominant conditions of the sky in the considered climate. Therefore, the climate conditions of the building location must be examined to find the suitable dimensions of windows. In the hot and dry climate with mostly clear sky, heating through windows become problematic. Although large windows provide more daylight for the space, more thermal radiation leads to overheating of the space. Hence, this study examined the effect of window dimensions on daylight use in the hot and dry climate of Iran (District 4 of Isfahan is one of the cities in this climate).

3. BACKGROUND

Many researchers have studied the effect of windows' dimensions on natural lighting and energy consumption. Lartigue and colleagues carried out a study under the title of "multi-objective optimization of the building envelope for energy consumption and daylight" and proposed a methodology with Daysim and Trnsys software to optimize the envelope of a building concerning three objectives of daylight, heating load, and cooling load. This study was conducted on these optimal indicators that maximize the daylight duration and minimize the energy load. This study addressed some challenges, including complex equations, the multiplicity of indicators, and long simulation duration as problems occurring in daylight design. Moreover, this study indicates that natural light cannot be considered independent of thermal comfort when daylight is addressed (Lartigue et al. 2013, 71-80). Melendo and Roche conducted a study under the title of "effect of window size on daylighting and energy performance in buildings" to examine the effect of window dimensions and proportions on lighting intensity and energy consumption by using simulation through HEED software. According to the results of this study, large windows bring more daylight into the environment while these windows cause extra heating and heat loss, which increases the heating and cooling load of the building. Hence, suitable design of windows by consideration of the simultaneous effect of lighting intensity and temperature can considerably reduce the cooling load and energy consumption of mechanical ventilation systems providing better indoor heat and lighting conditions (Melendo and Roche 2014, 1-8). Montaser Koohsari et al. studied the influence of window dimensions and location on residential building energy consumption. This study used simulation through Radiance, Daysim, and Energy Plus, as well as the simultaneous use of thermal and lighting analyses to examine the effect of window size on lighting and energy consumption of residential buildings in mild and humid climates. According to the findings of this study, the effect of window height on the daylight of indoor space and energy efficiency is higher than the effect of window width. Moreover, the low thermal difference through windows and thermal conduction in this climate makes energy consumption and efficiency of daylight the most important determinant for the window size in computations (Montaser Koohsari et al. 2015, 187-194). Dabe and Dongrea analyzed the performance of daylight in dwelling units and examined the effect of window size and building orientation on daylight duration based on daylight indicators. This study was conducted on a multistory residential building in the hot and dry climate of Nagpur City, India. In this study, visual comfort providing thermal comfort simultaneously was considered through simulation with Ecotect and Daysim software (Dabe and Dongre 2016, 1-14).

Sonawane and Mhaske estimated and analyzed daylight use in residential apartment buildings by using GIS. They used Relux and Gramm ++ software and proposed a simplified analytical method based on GIS to evaluate the daylight potential of internal space when the sky is clear. This study was conducted to evaluate internal lighting intensity obtained from external lighting intensity in residential apartments. In this research, a residential apartment in Pan City, India was examined to find the effect of site climate, window size, and orientation on the lighting intensity of residential space. According to the results of this study, the increased size of window size does not lead to the same increase in lighting rate. Moreover, larger cities can create more glare, so will require more shading (Sonawane and Mhaske 2016, 1-10).

Lee et al. analyzed the daylight and optimization of building windows. This study was conducted in Asian regions to optimize window parameters to increase daylight gain and energy efficiency by examining daylight elements and solar heat gain. In this study, the main variable of the study was window wall ratio (WWR). This study examined five Asian countries of China, Japan, the Philippines, Taiwan, and Korea based on computer simulation through Comfen software. According to the results of this study, WWR must equal 25% for western, eastern, and southern facades and at least 50% for the northern façade to increase daylight gain and energy efficiency (Lee et al. 2013, 522-531).

4. THEORETICAL FOUNDATIONS

Suitable daylight indicators must be selected to evaluate sufficient and appropriate daylighting through windows. In this case, Carlucci et al. presented the indices for visual comfort evaluation and their uses in processes optimizing building design. This study introduces some indices, including the amount of life, illumination, daylight autonomy, and useful daylighting (Carlucci et al. 2015, 1016-1033). Long-time indices that examine the daylight performance of buildings throughout a year are preferred to short-time indices such as the amount of light to evaluate climate-associated daylight. Therefore, this study selected spatial daylight autonomy (SDA) and Annual Sunlight Exposure (ASE) to evaluate daylight sufficiency and appropriateness, respectively. These indices have been introduced herein.

4.1. Daylight Autonomy (DA)

Reinhart and Walkenhorst (2001) introduced this index. This index indicates the percentage of times a space is occupied throughout a year when the minimum required illumination rate is provided only through daylight (Reinhart and Walkenhorst 2001,7). According to the international LEED standard (2014), 300 lux is the minimum light required for residential space (Andersen 2014, 18).

(1)

$$DA = \frac{\sum_i (wf_i \cdot t_i)}{\sum_i t_i} \in [0,1]$$

$$\text{with} \quad wf_i = \begin{cases} 1 & \text{if} \quad E_{Daylight} \geq E_{limit} \\ 0 & \text{if} \quad E_{Daylight} < E_{limit} \end{cases},$$

4.2. Spatial Daylight Autonomy (SDA)

This index is related to the DA index, which is considered as a percentage of space (floor surface) in which, a certain amount of daylight (300 lux) is provided during a certain time in which space is occupied annually (Illuminating Engineering Society (IES), 2012). For instance, SDA (300 and 50%) indicates a percentage of space in which the illumination level is greater than 300 lux in more than 50% of annual hours of space occupancy. Hence, this index is expressed as sDA300/50%. According to this standard, at least 50% of space in at least 50% of occupancy hours over a year gain minimum illumination of 300 lux.

(2)

$$sDA_{x/y\%} = \frac{\sum_i (wf_i \cdot DA)}{\sum_i p_i} \in [0,1]$$

$$\text{with} \quad wf_i = \begin{cases} 1 & \text{if} \quad DA \geq DA_{limit} \\ 0 & \text{if} \quad DA < DA_{limit} \end{cases},$$

4.3. Annual Sunlight Exposure (ASE)

ASE index determines the annual sunlight exposure as a percent of level and direct illumination rate greater than 1000 lux during more than 250 hours of occupancy time (direct radiation). The maximum acceptable ASE for suitable daylight equals 10% (ASE1000/250h<10%). It means that a maximum of 10% of the space floor must receive the maximum light rate of 1000 lux in a maximum of 205 hours over a year.

5. METHOD

This study used a simulation method to examine daylight gain and energy efficiency in residential complexes. For this purpose, honeybee and ladybug plugins were used in the grasshopper's environment through Rhino software and energy plus simulation engine to simulate energy and used Diva plugin to simulate daylight. To do this, Isfahan City was selected as a city located in the hot and dry climate of Iran to examine the effect of window size on natural lighting and energy performance in this climate. EPW format of meteorological data in Isfahan City was used to conduct the simulation. To determine a case study, District 4 of Isfahan was selected and a case study similar to the common form of buildings in this area was modeled.

5.1. Introduction to Isfahan Climate

Isfahan city is located in the central plateau of Iran with geographical latitudes of 32° and 38s and altitudes of 51° and 39min. According to the Köppen climatic classification, Isfahan is located in the hot and dry area of Iran (BWK). Direct radiation is severe in this area producing 700-800 k.cal/m2 energy per hour and square meter at horizontal levels. This rate is intensified when reflected radiation from barren lands increases. The sky in this area is mainly clear without clouds most of the time (Kasmai 2003, 84).

6. RESEARCH PROCESS

This study aims to evaluate the effect of window size on daylight gain and energy performance of buildings. For this purpose, the effect of the window percent on the area of the wall of the southern wall of the building (WWR) was evaluated in the first phase. In this step, WWR was considered a variable factor, while other factors remained fixed. The optimum WWR was measured based on the simulation results of daylight and energy performance. In the next step, this study analyzed the effect of window size and shape on daylight gain. To do so, window size and shape were investigated separately. Figure 1 illustrates the size and plan of the studied spaces. This space has been considered with 2.8m in height and residential or dwelling use on the first floor of a building with 25° rotation relative towards east from the south direction. This direction was selected based on the radiation and optimum direction of the hot and dry climate of Iran in a way that the southern front receives the highest and lowest sunlight during winter and summer, respectively (Kasmai 2003, 84). Moreover, the first floor was selected because the lower floors receive less illumination with weaker quality and need more electrical lighting rather than the upper floors.

Fig. 1. Model Plan

Figure 2 shows the neighborhood units and the distance between them and the studied building.

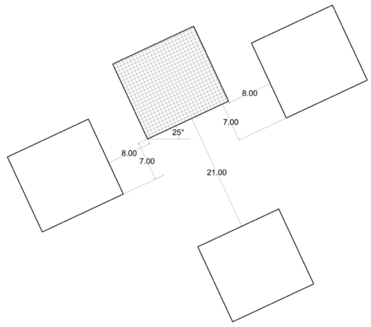


Fig. 2. Building's Neighborhoods

Because adjacent rooms, upper and lower floors affect the energy load of the building, these spaces were modeled and evaluated in energy simulation (Fig.s 3 & 4).

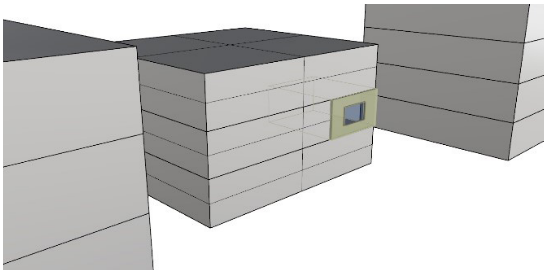


Fig. 3. Daylight Simulation Model

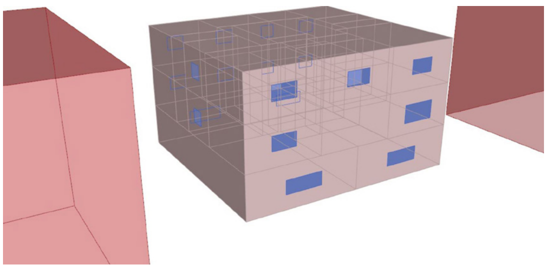


Fig. 4. Energy Simulation Model

6.1. Effect of Window Size on Daylight Use and Energy Performance of Building

To examine the effect of window size on daylight use and energy performance, a 25×25 network was defined at work surface height (70cm from the ground floor) on the model plotted in the software, and WWR rates of 10, 15, 20, 25, 30, 35, 40, 45, 50, and 55 were applied to software as research variables. In the next phase, variations in ASE and SDA in the Diva plugin were calculated in the defined network surface based on the defined values. The Ladybug plugin was then used to define sunrise to sunset hours to measure daylight and space occupancy hours and assigned to Diva plugin as the scheduling program. Moreover, the honeybee plugin was used per WWR rates to measure heating and cooling energy and electrical illumination to evaluate the energy performance of the building. For this purpose, the standard proposed in the instruction of Topic 19 of the National Building Regulations of Iran was used to select materials. Surface reflection and heat transfer rates of materials were used for computations based on Table 1. Moreover, visible light transmission through glass equaled 0.78 in the software.

Table 1. Reflection (%) Defined for Simulation of Daylight through Diva Software and Heat Transfer Rates for Energy Simulation through Honeybee Software

Surface	External Walls	Internal Walls	Floor	Ceiling	Frame	Window
Reflection (%)	0.3	0.5	0.2	0.7	0.5	
Heat Transfer Rate	1.01	1.01	1.83	0.63	-	3.4

6.2. Effect of Window Shape and Size on Daylight Use of the Building

Two variables of window size and shape were defined to evaluate the role of window size in daylight use of the building and daylight was analyzed for each variable based on the simulation results of daylight.

6.2.1. Effect of Window Shape on Daylight Use

Three types of vertical, horizontal, and square shapes of the window were considered to evaluate the effect of window shape on daylight use, and following the result of the optimum percent of window size to the external wall (WWR) obtained from the previous step, the size of all three windows equaled 30% of the southern wall. According to the results of available studies, glare must be avoided to improve visual comfort. Glare through windows appears when the illumination of entered light is higher than the total lighting of indoor space. In this case, adjacent spaces of windows cause exhaustion of sight perception mechanism and glare due to higher contrast and lighting rate. Therefore, architects must achieve uniform distribution of light in the space to bring low contrast between minimum and maximum lighting in the space to reduce glare and improve visual comfort in the spaces (Qiyabaklo 2013, 66). Hence, the best shape of the window creates less glare and more light rate uniformity in the work surface. Therefore, a 25×25 network with 70cm height from the floor surface was defined at 12:00 in January using simulation in the Diva plugin to find the optimum window shape, and then lighting rate distribution uniformity formed on it was examined.

6.2.2. Effect of Window Size on Daylight Use

The width-to-height ratio of windows equaled 3, 2.5, 2, 1.6, and 1.5 considered as five variables in this step of research to evaluate the effect of window size on daylight use, and the effect of these dimensions was examined to achieve optimum WWR percentage obtained from previous steps. According to the results of previous steps that introduced the horizontal shape of windows as the most suitable form for uniform light distribution, the shape of windows in this step was horizontal, and their area of them was considered equal to 30% of the southern façade's area. Moreover, the threshold height of all windows equaled 85cm. daylight use indices were then measured for all varying values using the Diva plugin through Rhino software. Figure 5 depicts the variables considered for window shape and size.

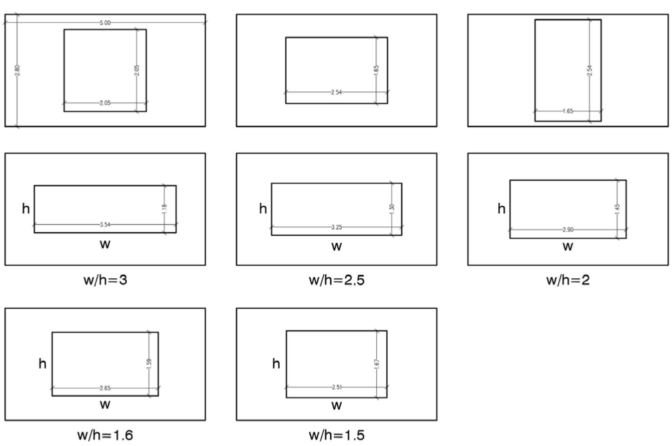


Fig. 5. Variables Considered for Window Shape and Size

7. DATA ANALYSIS

Table 2 reports the results of daylight and energy performance simulations for different WWR percents. It should be explained that the mechanical ventilation system used for energy performance evaluation was the Ideal Air Loads system so this unreal system was just used to compare the energy+ simulation engine.

Table 2. Daylight and Annual Energy Performance Indices for Different WWR Percentages in Building

Window-to-Wall Ratio	Spatial Daylight Autonomy	Annual Sunlight Exposure	Annual Electrical Light Energy Consumption	Cost of Annual Electrical Light Energy Consumption	Annual Cooling Energy Consumption	Cost of Annual Cooling Energy Consumption	Annual Heating Energy Consumption	Cost of Annual Heating Energy Consumption	The Sum of Annual heating and Cooling Energy Consumption	The Sum of Annual Heating and Cooling Energy Consumption Cost	The Sum of Annual Energy Consumption	The Sum of Annual Energy Consumption Cost
(WWR)	(SDA)	(ASE)	(kwh/m^2)	(\$/m^2)	(kwh/m^2)	(\$/m^2)	(kwh/m^2)	(\$/m^2)	(kwh/m^2)	(\$/m^2)	(kwh/m^2)	(\$/m^2)
10	22.9	16.5	59.272	1.894	73.81	2.363	18.134	0.580	91.944	2.946	151.216	4.837
15	35.2	22.1	47.873	1.52	71.007	2.270	18.032	0.577	89.039	2.852	136.912	4.367
20	44.2	27.7	40.184	1.31	69.202	2.216	17.836	0.571	87.038	2.878	127.222	4.097
25	50.6	31.9	35.802	1.14	67.312	2.156	17.749	0.568	85.061	2.724	120.862	3.864
30	57.1	36.7	32.435	1.03	67.476	2.161	17.707	0.567	85.183	2.728	117.618	3.758
35	59.8	40	30.756	0.98	69.711	2.232	18.069	0.578	87.78	2.810	118.535	3.790
40	64.8	42.7	29.736	0.92	72.453	2.319	18.379	0.588	90.832	2.907	120.568	3.827
45	69.2	45.2	29.062	0.92	74.982	2.401	18.747	0.601	93.729	3.002	122.791	3.922
50	73.3	47.9	28.424	0.909	78.459	2.510	19.225	0.616	97.683	3.126	126.107	4.035
55	77.5	49.2	28.086	0.898	80.711	2.580	19.61	0.628	100.32	3.208	128.407	4.106

7.1. Effect of Window Size on SDA Index

Figure 6 indicates the results of spatial daylight autonomy (sDA) relative to the WWR of the building. According to this graph, the research results indicate that increased WWR would increase the sDA index. This result indicates that a higher WWR would lead to a larger amount of light entering the indoor space. This graph shows that the lower sDA value for WWR 10% equaled 22.9, while the highest value for WWR 55% equaled 77.5. Moreover, because the minimum acceptable sDA equals 50% based on the LEED standard, the minimum WWR that obtains this amount equals 25%.

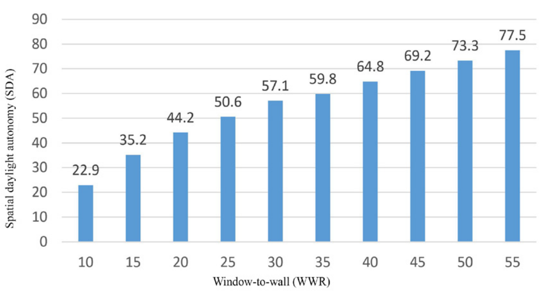


Fig. 6. SDA-to-WWR Ratio

7.2. Effect of Window Size on SDA Index

Figure 7 depicts the variations in the sDA index based on per 5% increase in WWR. According to this graph, the results of the study show that as WWR increases, sDA-to-WWR changes become descending. In this case, when WWR is enhanced from 10 to 15%, the sDA value experiences a 12.3 rise, while when WWR increases from 50 to 55% then the sDA value experiences a 4.2 increase. On the other hand, no considerable variation occurs in the sDA index when WWR exceeds 30%. This result indicates that WWR of 30% provides sufficient light for the environment and the increased size of the window does not considerably affect daylight sufficiency.

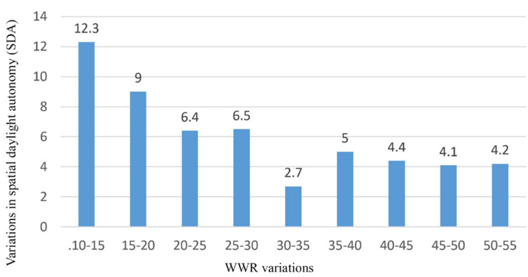


Fig. 7. SDA Variation Based on per 5% Increase in WWR

7.3. Effect of WWR on ASE

Figure 8 depicts the ASE per WWR. According to this graph, the results of this study indicate that an increase in ASE leads to a rise in WWR implying that the need for excessive illumination control through shading rises when WWR is increased. According to Figure 8, the lowest ASE index for WWR 10%, and the highest ASE for WWR 55% equaled 16.5 and 49.2, respectively. Because the 10% rate is defined as the highest rate for the ASE index based on the LEED standard, excessive radiation control through shading is needed for the case study even in small window dimensions.

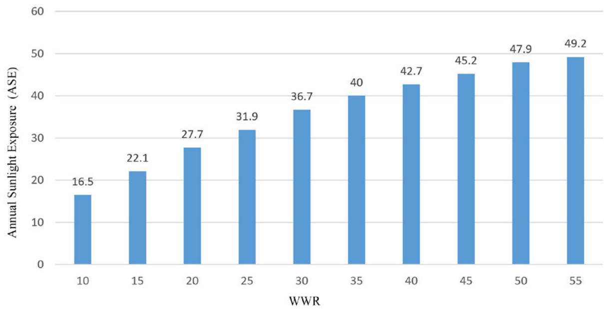
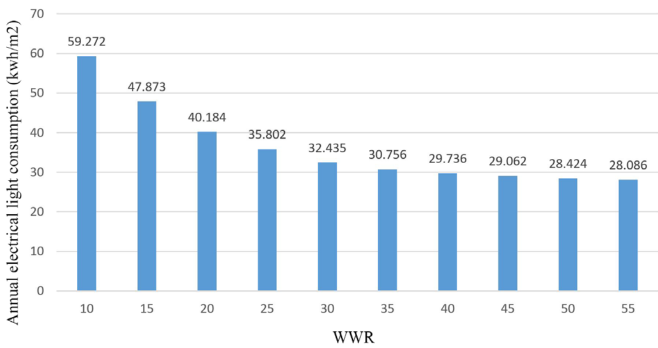


Fig. 8. ASE Based on WWR

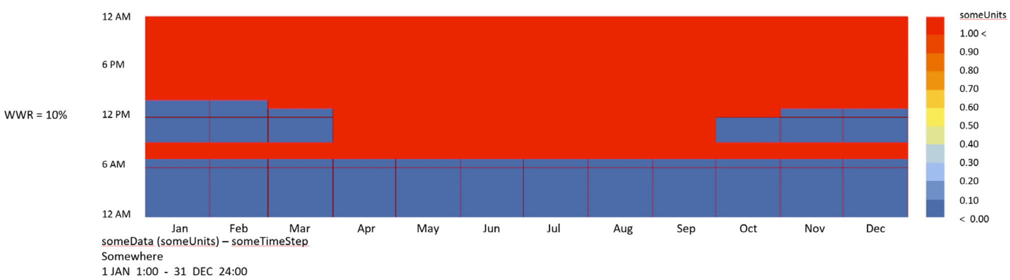
7.4. Effect of Window Size on Annual Electrical Light Energy Consumption

Annual electrical light energy (kwh/m2) and annual electrical light consumption cost ($) based on each m2 of WWR are indicated in Figure 9. According to this graph, the results of this study indicate that the annual energy of electrical light drops when WWR rises. In this case, when WWR equals 10% then electrical light consumption equals 59.272 kWh/m2, while this rate reaches 28.086 kWh/m2 when WWR is 55%. Hence, the electrical light need will be reduced when the illumination rate of the interior space is increased due to enhanced WWR. Figure 10 depicts the schedule of electrical light of the research model for different WWR values from 10% to 30%. In this research, the occupancy hours of the model are between 7:00 and 00:00.



Window-to-wall (WWR)	Annual electrical light energy (kwh/m2)	Annual electrical light consumption cost ($/m2)
10	59.272	1.894
15	47.873	1.52
20	40.184	1.31
25	35.802	1.14
30	32.435	1.03
35	30.756	0.98
40	29.736	0.92
45	29.062	0.92
50	28.424	0.909
55	28.086	0.898

Fig. 9. Annual Electrical Light Energy Based on WWR



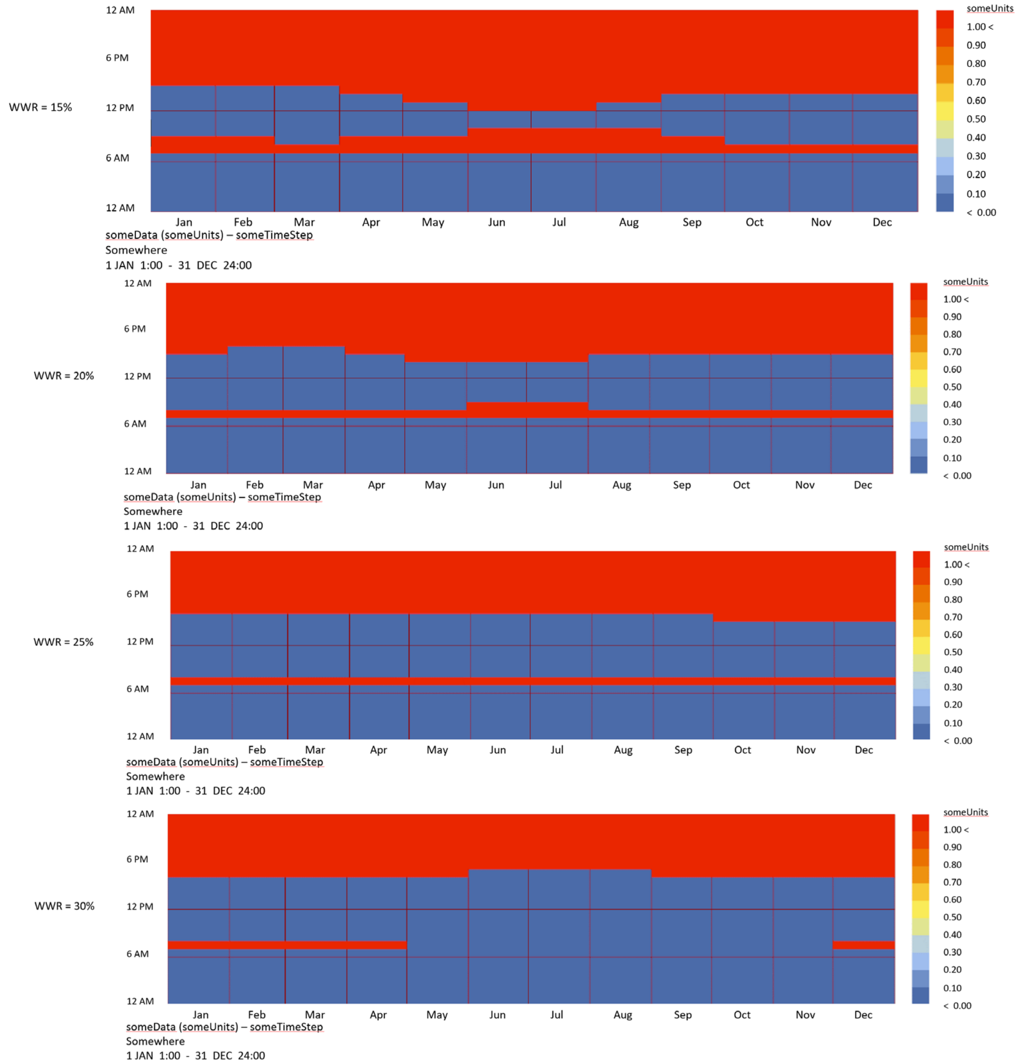


Fig. 10. Scheduling Plan or Electrical Light of Model for Different WWR Rates from 10% to 30%

Blue-colored areas in Figure 10 indicate the turned-off light during considered hours. As seen in this table, daylight is not sufficient for small-sized windows, so more electrical light is needed.

7.5. Effect of Window Size on Saving Variations in Annual Electrical Light

Figure 11 indicates saving variations in electrical light consumption based on per 5% WWR rise. The results of this study show that with an increase in WWR, saving variation in electrical light decreases. Moreover, Figure 11 indicates that when WWR exceeds 30% then no considerable rise occurs in electrical light saving. Hence, the results reveal that an increase in WWR up to 30% brings sufficient light into the indoor space, and a higher increase in window size has no significant effect on the electrical light consumption saving.

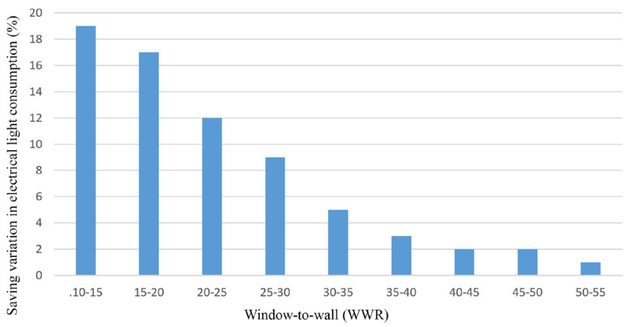


Fig. 11. Saving Variation in Annual Electrical Light Consumption Based on a 5% Increase in WWR

7.6. Effect of Window Size on Annual Cooling Energy Consumption

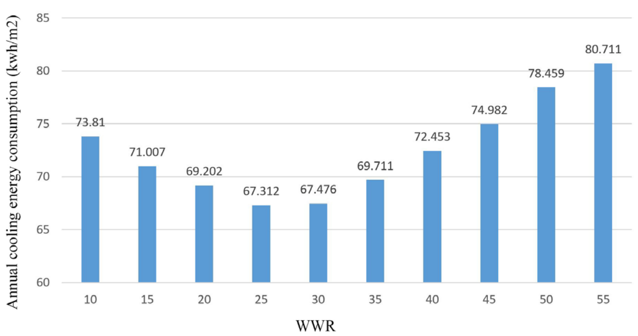
Figure 12 indicates the variations in annual cooling energy consumption (kwh/m2), as well as the cost of annual cooling energy consumption ($) based on each m2 of WWR. According to this graph, the results of this study indicate that when WWR increases from 10% to 25% then cooling energy consumption decreases from 6.34 to 8.8 kWh/m2. Hence, the results of the study explain that increased cooling load resulting from increased window size is compensated by reducing cooling load imposed by lights (due to electrical light consumption saving). Furthermore, when WWR varies between 10% and 25%, sufficient thermal energy enters the environment, so it does not get to hots. On the other hand, when WWR increases from 25% to 55% then cooling energy consumption (%) reaches 13.4 kWh/m2, which is a 20% rise implying that more heat produced by sunlight covers the cooling load decline due to saving in artificial lighting. As seen in the graph, increased cooling energy consumption per WWR=30% is minor and ignorable compared to the WWR=25%.

7.7. Effect of Window Size on Annual Heating Energy Consumption

Figure 13 indicates the variations in annual heating energy consumption (kwh/m2), as well as the cost of annual heating energy consumption ($) based on each m2 of WWR. According to this graph, the results of this study indicate that when WWR increases from 10% to 30% then heating energy consumption experiences a decrease of 0.43 kWh/m2. This reduction may result from more heat gain due to the larger size of the window. Moreover, when WWR reaches 30% to 55%, heating energy consumption experiences an increase of 1.91 kWh/m2. It is concluded that this ascending trend occurs because WWR exceeds 30% and heat loss through the window is more than a reduction in heating energy consumption due to more heat gained from sunlight. On the other hand, fewer turned-on electrical lights based on the larger window size leads to a higher heating load.

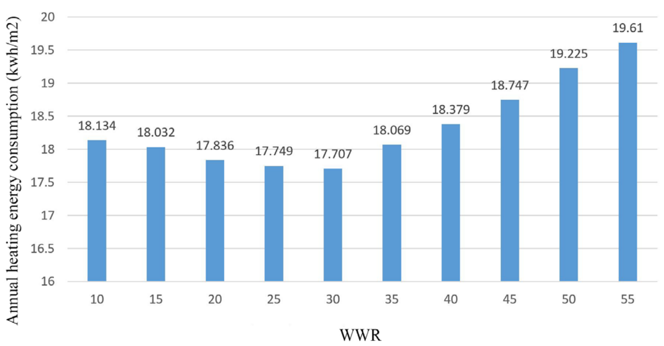
7.8. Effect of Window Size on the Sum of Heating-Cooling Energy Consumption

Figure 14 depicts the variations in the sum of annual heating and cooling energy consumption (kwh/m2), as well as the total cost of annual heating and cooling energy consumption ($) based on each m2 compared to WWR. According to this graph, the results of the study indicate that when WWR increases from 10% to 25%, the sum of heating and cooling energy consumption will be reduced and then its trend become ascending. However, this increase is not considerable for WWR=30% rather than WWR=25%.



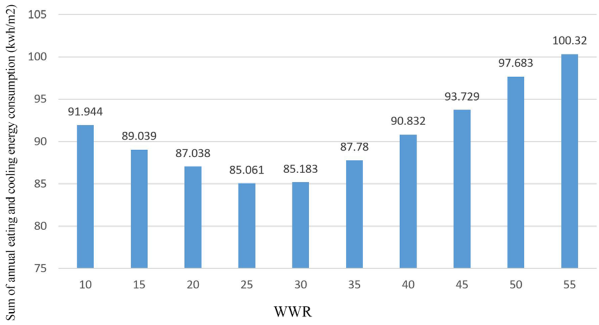
Window-to-wall (WWR)	Annual cooling energy consumption (kwh/m2)	Cost of annual cooling energy consumption ($/m2)
10	73.81	2.363
15	71.007	2.27
20	69.202	2.216
25	67.312	2.156
30	67.476	2.161
35	69.711	2.232
40	72.453	2.319
45	74.982	2.401
50	78.459	2.51
55	80.711	2.58

Fig. 12. Annual Cooling Energy Consumption Based on WWR



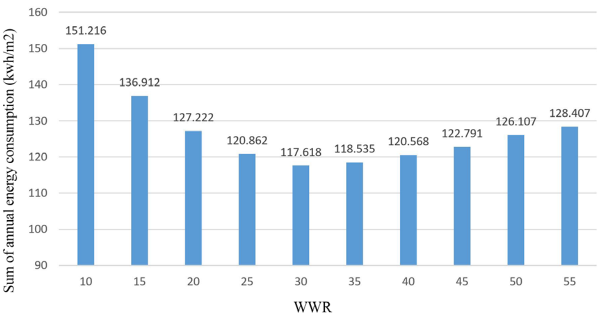
Window-to-wall (WWR)	Annual heating energy consumption (kwh/m2)	Cost of annual heating energy consumption ($/m2)
10	18.134	0.58
15	18.032	0.577
20	17.836	0.571
25	17.749	0.568
30	17.707	0.567
35	18.069	0.578
40	18.379	0.588
45	18.747	0.601
50	19.225	0.616
55	19.61	0.628

Fig. 13. Annual Heating Energy Consumption Based on WWR



Window-to-wall	Sum of annual heating and cooling energy consumption	Sum of annual heating and cooling energy consumption cost
(WWR)	(kwh/m2)	($/m2)
10	91.944	2.946
15	89.039	2.852
20	87.038	2.878
25	85.061	2.724
30	85.183	2.728
35	87.78	2.81
40	90.832	2.907
45	93.729	3.002
50	97.683	3.126
55	100.32	3.208

Fig. 14. The Sum of Annual Heating and Cooling Energy Consumption Based on WWR



Window-to-wall ratio	Sum of annual energy consumption	Sum of annual energy consumption cost
(WWR)	(kwh/m2)	($/m2)
10	151.216	4.837
15	136.912	4.367
20	127.222	4.097
25	120.862	3.864
30	117.618	3.758
35	118.535	3.79
40	120.568	3.827
45	122.791	3.922
50	126.107	4.035
55	128.407	4.106

Fig. 15. The Sum of Annual Electrical, Heating, and Cooling Energy Consumption Based on WWR

7.9. Effect of Window Size on the Sum of Electrical Light and Heating-Cooling Energy Consumption

As seen in Figure 15, research results indicate that the sum of annual electrical light, heating, and cooling energy consumption experiences a decline of 33.6 kWh/m2 when WWR reaches 10% to 30%, and then this rate rises when the window size is increased. Hence, the lowest sum of energy consumption is gained when WWR=30%. Hence, the research model indicates that the optimum WWR for daylight gain and energy efficiency for the southern front of the building equals 30%.

7.10. Evaluating Data Related to Window Shape

Table 3 reports findings of daylight illumination simulations related to window shape. As seen in the simulation presented in this table, illumination distribution is reduced when moving from right-had or left-hand. It means that the best and worst illumination rates are gained by horizontal and vertical windows. Hence, it is argued that horizontal window creates more suitable uniform illumination rather than other shapes.

7.11. Evaluating Data Related to Window Size

Table 4 reports the simulation results of daylight illumination related to window size. As seen in the results, when the width-to-height ratio of the horizontal window is reduced the spatial daylight autonomy (sDA) index and annual sunlight exposure (ASE) are increased. Hence, it is concluded that when the width-to-height ratio of the window is reduced then the daylight illumination enters a deeper depth of space; however, more shading is required for controlling excessive illumination intensity. Figures 16 and 17 depict the sDA and ASE values based on the window size.

Table 3. Simulation of ASE and SDA Indicators for Different Sizes of Horizontal Window

ASE	SDA	The Width-to-Height Ratio of the Window
38.3	56.7	3
39.6	60.6	2.5
41.5	62.7	2
41.9	65.2	1.6
41.9	66.3	1.5

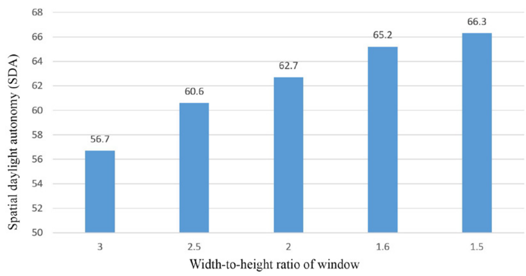


Fig. 16. The SDA Index Based on the Width-to-Height Ratio

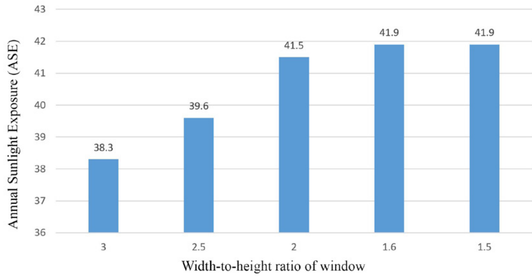
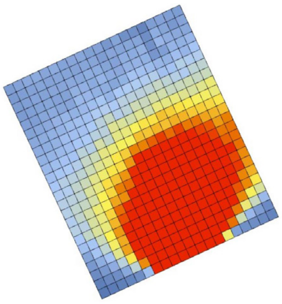
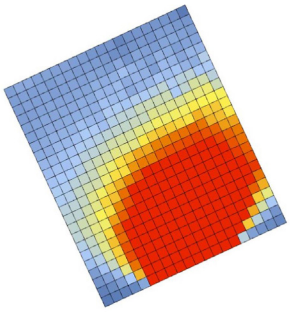
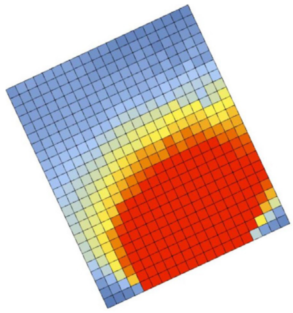


Fig. 17. ASE Index Based on the Width-to-Height Ratio

Table 4. Results of Simulated Illumination Distribution of Horizontal, Vertical, and Square Windows

		
Simulation of Illumination Intensity Distribution for Vertical Window	Simulation of Illumination Intensity Distribution for Square Window	Simulation of Illumination Intensity Distribution for Horizontal Window

8. CONCLUSION

This study examines the effect of window size on daylight use and energy performance in residential complexes located in hot and dry climates (Isfahan City), and the research process was done by using computer simulations. First, the sitting room of an apartment was modeled to do a simulation analysis. In the next step, daylight use was evaluated by using sDA and ASE indices for light sufficiency and daylight appropriateness. According to the results of the sDA index, increased window size does not increase daylight to the same extent. Hence, it is true that increased window size reduces electrical illumination consumption but an excessive increase in window size does not have a considerable effect on saving electrical illumination. On the other hand, the optimum window size must be determined by analyzing the heating and cooling energy consumption required for sufficient daylight and saving electrical illumination consumption. The results of the research indicate that although it is assumed that very small windows can reduce cooling energy consumption, this decline in cooling energy consumption is covered by the cooling load imposed by increased electrical illumination consumption. Moreover, although increased window size reduces the heating energy consumption due to higher input solar radiation or sunlight, excessive increase in window size increases the heating energy consumption due to greater heat loss through the window.

In this research, the results obtained from analyzed data of daylight and energy efficiency simulations indicate that WWR=30% is the optimum rate for daylight use and energy efficiency. In addition, it was argued based on the daylight simulation results that horizontal windows provide better illumination uniformity rather than other window shapes in indoor space. Furthermore, when WWR rises then sDA and ASE indices are increased in indoor space implying that daylight enters into the depth of space, while shading is required to control excessive illumination intensity.

Finally, it should be reminded that this study aims to examine the effect of window size and dimensions on daylight use and energy efficiency in residential complexes not to find optimum window size, so optimum dimensions must be measured for each project separately. Hence, the method proposed in this research can be applied to similar cases of measuring optimum dimensions.

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