Comparative Study on the Influence of Window To Wall Ratio on Energy Consumption and Ventilation Performance in Office Building of Temperate Humid Climate: a Case Study in Rasht

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Abstract

The natural ventilation and energy consumption are very important characteristics in buildings. Representation of the patterns for better natural ventilation performance versus lower increase in energy consumption is significant and useful. This study is simulating an office building in the temperate and humid climate of Rasht in Iran, and calculated the annual ventilation and the energy consumption for heating-cooling and total energy using Design Builder v 5.4. This simulation investigated variations in the window-to-wall (WWR) of the building in cardinal directions. Accordingly, the influence index of consumed energies and ventilation from a change in WWR was calculated in cardinal directions. Moreover, the changes in total energy consumption and ventilation indices based on WWR were defined, calculated, and qualitatively analyzed. In the west direction, for the WWR of larger than 20%, a relative jump in total energy consumption is achieved. The ventilation and total energy consumption increased with increasing WWR from 10% to 15% and 20%.Also, for an increase to 25%, the lowest k_{ew}/k_{vw} is attained and demonstrates the appropriate value. The heating energy consumption is positively affected by an increase in the windows area in the north direction. In the south direction, WWR decrease from 25% to 10% showed a better ratio of energy to ventilation indices. With increasing WWR from 25% to 30%, the low index ratio of 0.17 is achieved, demonstrating a larger increase in ventilation than in energy consumption and was considered as the suggested WWR. In the east direction, the increment of WWR from 15% to 20% is a more appropriate option, as the ventilation index significantly increases with slight increase in energy consumption. Thus, using these indices and their analyses, engineering models of the fenestration design of office buildings in the climate of Rasht to be improved in terms of energy consumption and ventilation.

Keywords: Office building, Natural ventilation, Energy consumption, Window-to-Wall ratio, Design builder.

1. Introduction

Creating an ideal environment by providing thermal and mental comfort for residents is essential for every building. Approximately 40% of the energy produced in developed countries is consumed in the building sector. In this regard, ventilation systems account for the majority of this energy consumption (Carroll, 1982). Energy acme and the Necessity of modern architecture led designers to pay more attention to coverage of the building. The building envelope is an important part of building thermal behavior and reduction of energy consumption (Rezazadeh,Medi,2017).Natural ventilation is an effective factor in creating thermal comfort in the buildings. All new buildings should be improved in terms of performance and energy supply systems to become nearly zero-energy buildings by 2020 based on the building energy codes (Siewa,2011). The energy consumption in office buildings is within the range of 100 to 1000 kWh per m2, depending on the location of the buildings, building dimensions, and the number and types of equipment used in them (Siewa,2011). In addition to high energy costs, Chlorofluorocarbon (CFC) is considered one of the most harmful substances in the ventilation and refrigeration industry (Ghiabaklou,2016). According to the international reports that the ventilation and cooling systems consume 25% of the total CFC production, as one of the most important ozone-depleting factors (Kelly,1990).The efficiency evaluation of different cover forms of buildings based on the natural ventilation system illustrates that the form of a building has explicit impact on the internal airflow and a better impact on the internal circulation of air respectively (Soltanzadeh,et al.,2017).Therefore, the energy performance of buildings is expected to lead to consumption reduction since technology alone does not necessarily guarantee a high level of building performance and considering human aspects the design can fulfill this objective (D'Oca,2018)(Altomonte,2013). One of the most important techniques to improve the energy efficiency of the building is the use of technology in their external walls. Therefore, alterations in the window dimensions

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can increase the airflow into the building to provide better natural ventilation. An important element in defining total energy consumption by buildings in modern design is the application of certain openings in the windows and walls, which act like thermal bridges (Misiopecki,2017). In this regard, the use of windows, as a key strategy, has been largely investigated. thermal comfort, air quality, and energy consumption are among the most important concerns. Opening a window can affect the air exchange between the rooms and indoor environment, indoor thermal parameters, and level of pollutants (D'Oca,2017)(Heeboll,2018). The indoor and outdoor environmental conditions, along with the regional climate have specific physical impacts on human, which should be considered in the design process regarding the heating and cooling needs (Taban, *et al.*,2012).Energy needs of a building largely depend on the climate, as it affects the building thermal performance. As a result, climate should be considered as one of the most important determinants in optimal building design (Mahdavinejad,2012). In general, office buildings consume more energy than other building types. A thermally-suitable office building not only makes it a comfortable place to work, but also promotes the productivity and mentality of the staff as well as reduction of energy consumption (Nicol,2002) ventilation is one of the passive systems for cooling, which is based on air movement. Building interior spaces can be cooled with the circulation of air from the building exterior to the indoor environment. In this way, the energy required for ventilation can be reduced. This study intended to discover the major principles regarding WWR in different facades of office buildings with constant forms and proportions in the temperate and humid climate of Rasht. To this end, it attempts to propose a design model to improve ventilation and reduce total energy consumption in these buildings.

2. Natural Ventilation in Building

The principles of the wind and airflow are regarded as the driving forces of ventilation and as in the natural ventilation system. For thousands of years, ventilation through natural forces has been used by humans and animals to create a better life condition. The mechanical driving forces, like fans, have been utilized in the 21st century for natural ventilation (Demrati,*et al.*,2001). Inside the building, the dimension, shape, and position of windows significantly affect the performance of natural ventilation (Sacht and Lukiantchuki,2017). Cooling and air conditioning is a major and costly challenge facing modern buildings in hot and even temperate climates across the world. Apartment blocks, high-rise buildings, commercial centers, and office buildings have been constructed without considering natural ventilation potentials. In many office buildings, costly mechanical ventilation and cooling systems are used even in cold seasons because of the delivered heat from equipment and artificial lights (Ghiabaklou,2016). Ventilation refers to air displacement to supply fresh air for cooling. In the air conditioning industry for buildings, air conditioning refers to the use of natural methods and mechanical equipment to ventilate the indoor environment by the outdoor air; however, natural ventilation is the main source of heat loss in buildings (Fouiha, et al.,2012). The opening performance has the greatest effect on ventilation of the indoor environment. The effective factors can be divided into environmental and non-environmental ones (Pan, et al.,2015). Window direction has a considerable role in the thermal comfort of the residents. The habit of using air conditioning in a normal house has also been investigated (Cheng, et al.,2015). Natural ventilation through openings is an effective method that reduces energy consumption for conditioning indoor environment and improving satisfaction. It is very important to use simple strategies to reduce energy consumption (Bayoumi,2017).

3. Literature Review

A study, carried out by (Mahmoudi and Pourmosa,2010) airflow inside and outside of some residential complexes in Rasht is investigated to achieve optimal use of airflow. The outdoor and indoor properties and effect of landscape design were among the important proper factors in this study. In this regard, the maximum use of natural ventilation in this region was achieved by considering the proper distance between buildings, optimum direction, positioning of windows, and airflow between the buildings.

There are general studies into the field of natural ventilation and air conditioning. In this regard, there are scant case studies into office buildings in cities with temperate and humid climate. Therefore, this study aimed at addressing this issue through simulation method to achieve optimal window openings to improve natural ventilation and total energy consumption. However, plenty of papers and dissertations have focused on natural ventilation optimization in, this study evaluates the integrated effect of WWR on the ventilation rate and energy consumption in office buildings located in the temperate and humid climates using the Energy Plus dynamic simulation engine of Design Builder v5.4.

A study by Prajongsan and Sharples (2011), investigated air velocities in predefined stops of occupied rooms, with and without ventilation shaft. Then, another assessment was done using CFD package in Design Builder, and the comfort hours during summer-time in both rooms were calculated based on the operative temperature of the room after they had been moderated by the elevated air velocities (Prajongsan,2011) A doctoral dissertation in 2013 in Iran University of Science and Technology (Vakilinejad,2013), investigated factors such as WWR, shading depth, and type of terraces and its effect on different types of day-time and night-time ventilation, using Energy Plus and Fluent. In a study, in Malaysia (Chung,2014) use of solar chimney in terraced houses in a hot and dry climate was investigated, as a strategy to enhance ventilation and thermal performance. This study was done using the Design Builder simulation. Torrea and Yousif investigated buoyancy effects through chimneys using Design Builder-Energ Plus. Many simulations have been conducted to achieve the most optimal performance of windows to obtain the best ventilation conditions.(Torrea and Yousif, 2014)

4. Methodology

This study used bibliographical research method, derived from field studies, to investigate the index of behavioral changes in natural ventilation and annual energy consumption. Computer also simulation was utilized as the second phase of research The first step was the collection of data from simulating the office building. The climate data of Rasht in the format of an EPW4 file was entered into the Energy Plus engine of Design Builder for simulation. To investigate the annual energy consumption and natural ventilation(From January 1stto December 31st), data of the office tested building was used by considering the WWR in four cardinal directions. The case building was the headquarter Building of Islamic Azad University, Rasht Branch. The properties of building materials and surfaces (e.g. external walls, internal walls, partitions, floors, ceilings, roof, doors, and windows) were collected based on their existing conditions. Regarding the physical properties of materials, information was set based on the standards and properties of software. The Energy plus engine v8.6 and Design Builder v5.4 was used for simulation, and its output data was analyzed with MATLAB software. Design Builder is an Energy Plus based software tool used for simulating the environmental performance of new and existing buildings. Design Builder's advanced building performance simulation tools minimize modeling time and maximize efficiency. Models either imported within Design Builder include energy and comfort, VAC, day lighting, cost, design optimization, and reports complying with several national building regulations(designbuilder.co.uk),(Zhang et al.,2017),(Pelaz et al.,2017).In each step, three other directions were assumed constant and WWR was simulated for six variants in the considered direction. In total, 24 tests were conducted. Using the quantitative and qualitative analysis, the optimum WWR for an integrated index of the energy consumption and ventilation in the office building was proposed. According to these findings, the engineering models of windows for office buildings in climates were addressed in terms of energy consumption and ventilation.

5. Model Assumptions

This section tried to reduce the energy consumption of the modeled office building, investigate the potentials, and propose an improved state. This building was located in the temperate and humid climate of Rasht and simulated with Design Builder.

In this study, the WWR as considered constant in three directions and variable in one direction by simulating at 10%, 15%, 20%, 25%, 30%, and 40%. The required energy index for heating and cooling (kW per hour) and ventilation (ac/h) was calculated by simulating with each value above.

The weather file of Rasht city was produced by Meteonorm software. Information of all-weather stations in cities of the world by latitude and longitude are available in the software. The exported file is in EPW format which is imported in Design Builder.

6. Simulation Results and Analysis

This section explained the simulation results, and their qualitative and quantitative analysis.

6.1. Annual Energy consumption of office building

In the first experiment, the energy consumption indices of heating (E_h), cooling (E_c), and total (E_t) for the base case building were calculated for various WWR in north direction from 10%, 15%, 20%, 25%, 30%, and 40%. According to Figure 1, the annual energy consumption for cooling, heating increase as WWR increases.

In the second experiment, the WWR was considered constant in three direction and variable in the west direction at values from 10%, 15%, 20%, 25%, 30%, and 40%. Simulation results are illustrated in Figure 2.

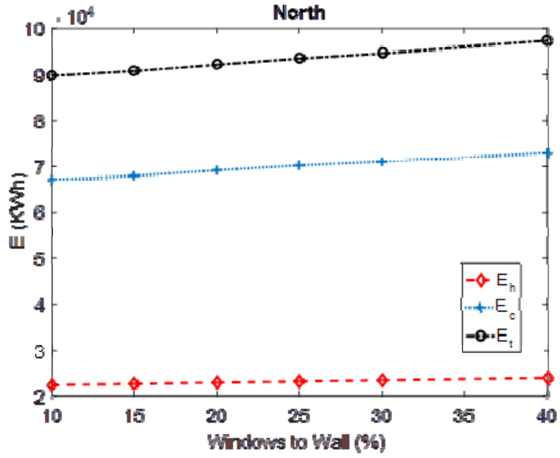


Fig. 1. Heating (E_h), cooling (E_c), and total energy consumption (E_t) for different WWRs at north direction.

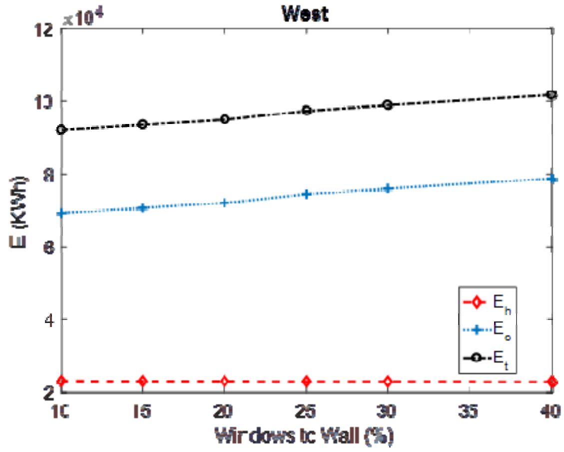
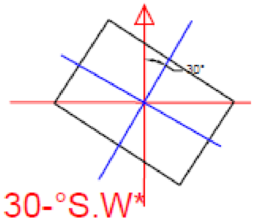
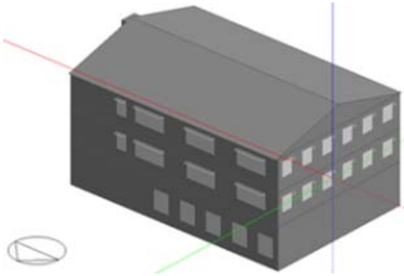
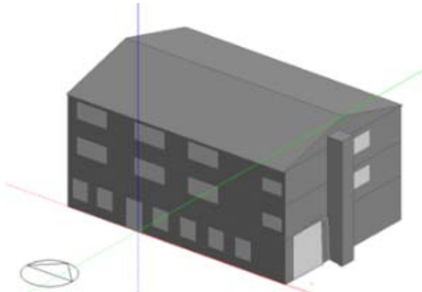


Figure2. Heating (E_h), cooling (E_c), and total energy consumption (E_t) for different WWRs in varying north direction.

Table1
Properties of office building under investigation in temperate and humid climate of Rasht

Location of the case study in google map **Orientation angle: 30 degrees south-west**		
Geometry: **Plan form: Rectangular** **Plan proportions (2:3)** **Number of floors: Three floors**		
WWR: North: 20%, West:10%,South: 25%, East:15%		
Number of Equipment in compliance with software standards **Number of People in compliance with software standards** **Lighting system and Functional time table: In compliance with software standards**	**Heat transfer factor of outer wall:** $1.765 \frac{W}{m^2.K}$ 	**Heat transfer factor of ceiling:** $0.356 \frac{W}{m^2.K}$ 

In the third experiment, the WWR ratio was considered constant in three directions and variable in the south direction at 10%, 15%, 20%, 25%, 30%, and 40%. As seen in Figure3, cooling and total energy consumption increases while heating energy drops for higher WWRs.
In the fourth experiment, the WWR was considered constant in three directions and variable in east direction.According to Figures 2, 3, and 4, the heating energy consumption reduced with increasing the WWR in cardinal directions; whereas, the cooling and total energy consumption increased in these directions. There was a severe heating energy reduction in the south direction. Figure 5 compares the total energy consumption for varying WWRs in all four directions. Variations in WWRs have the greatest influence in the west side. As illustrated in Figure 2 for WWRs more than 20%, a noticeable growth is observed in (E_t) in west direction. Increased WWRs has the least impact on total energy consumption in the south side.

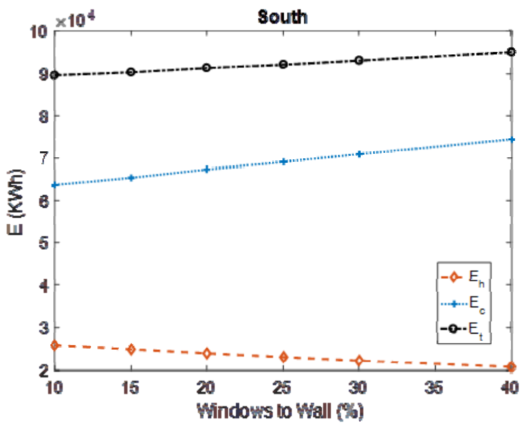


Fig. 3. Heating (E_h), cooling (E_c), and total energy consumption (E_t) for different WWRs in varying south direction

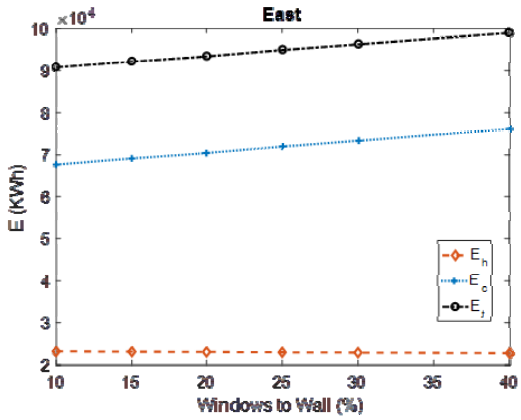


Fig. 4. Heating (E_h), cooling (E_c), and total energy consumption (E_t) for different WWRs in varying east direction.

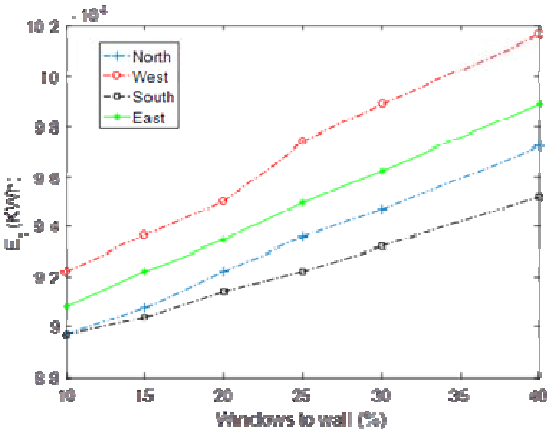


Fig. 5. Total energy consumption (E_t) of building for various WWRs in four cardinal directions

6.2. Influence index of energy consumption in WWR

Asearlier presented, the values of total energy consumption changes with WW ratio variations in different directions. This section investigated the extent at which the heating, cooling, and total energy consumption are affected by the WW ratio. To define this index, the derivative of the energy consumption to WWR was used; in addition, the mean value of the given numerical derivative was calculated to obtain a unique index. The index of thermal energy influenced by the WWR is defined as follows.

$$i_h = \text{mean}\left(\frac{d(Eh)}{d(WWR)}\right) = \frac{1}{n}\sum_{j=1}^{n}\frac{Eh(j+1)-Eh(j)}{WWR(j+1)-WWR(j)} \quad (1)$$

Accordingly, the equations of the influence index of cooling and total energy consumption are as follows:

$$i_c = \text{mean}\left(\frac{d(Ec)}{d(WWR)}\right) = \frac{1}{n}\sum_{j=1}^{n}\frac{Ec(j+1)-Ec(j)}{WWR(j+1)-WWR(j)} \quad (2)$$

$$i_t = \text{mean}\left(\frac{d(Et)}{d(WWR)}\right) = \frac{1}{n}\sum_{j=1}^{n}\frac{Et(j+1)-Et(j)}{WWR(j+1)-WWR(j)} \quad (3)$$

The indices of heating, cooling, and total energy consumption influenced by WWR in the north, west, south, and east directions are presented in Figure 6. According to this Figure, the heating energy consumption (i_h) is directly affected due to the increase in the opening area in the north direction. In other words, energy consumption increases in line with the increase in opening area the north direction. Comparatively, the WWR variation has the highest influence on the heating energy consumption in the south direction. According to this Figure, a noticeable downward behavior is as well as the lowest influence index observed in south direction. Therefore, increasing the area of windows in this direction is a proper design solution for reducing heating energy consumption. In the west direction an increase in WWR resulted in the maximum influence index of cooling and total energy consumption. According, in such a climate, designers should specifically consider the high importance of energy loss through windows in the west –side walls.

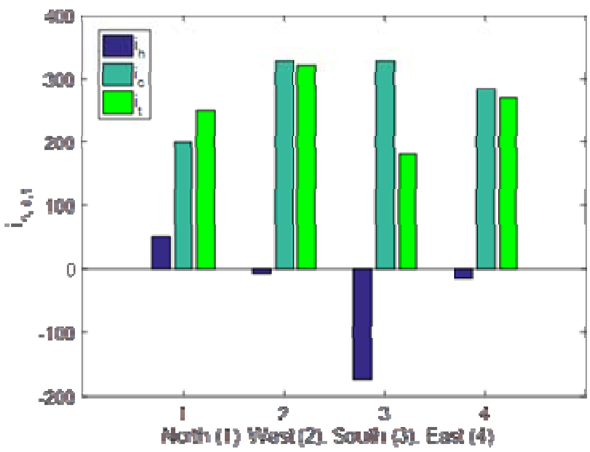


Fig. 6. Influence index of heating (i_h), cooling (i_c) and total (i_t) energy consumption from WWR in cardinal directions

6.3. Annual natural ventilation in office buildings

This section addressed ventilation simulation in four experiments in cardinal directions and WWR of 10%, 15%, 20%, 25%, 30%, and 40%. According to Figure7,

the ventilation rate in the west direction significantly increased as WWR grows from 20% to 25%. In general, the ventilation was maximized byincreasing the number of windows in the west direction. The west direction reaches the highest ventilation rate at the largest opening area, compared to other
directions.

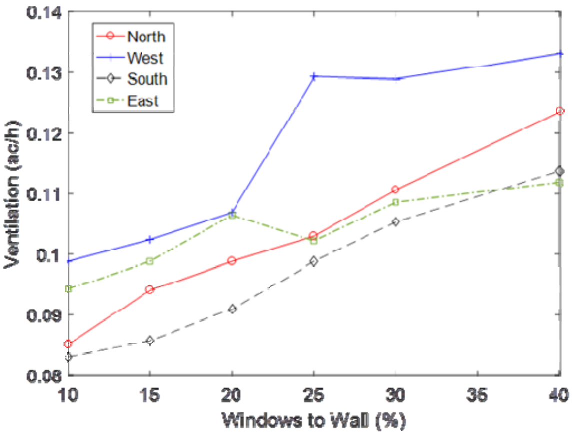


Fig. 7. Annual natural ventilation with increasing WWR in cardinal directions

The influence index of ventilation is calculated based on equation1. As illustrated in Figure8, the west-side and east-side windows show the highest and lowest effects due to WWR increase, respectively.
Variations ofventilation in the north-side is observed to be relatively similar to the west-side.

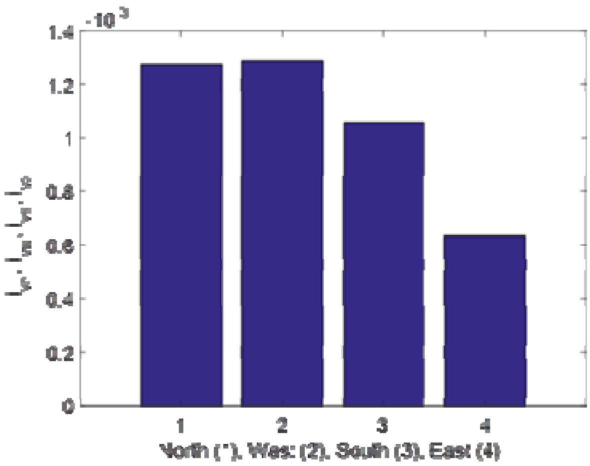


Fig. 8. Influence index of ventilation in cardinal directions

6.4. Index of changes in ventilation and total energy due to changes in WWR and comparative analysis

To compare the simultaneous changes in ventilation and total energy consumption in this building due to the variation changing of WWR, $k_{vn}$and k_{en} indices were defined for ventilation and total energy consumption, respectively in four directions:

kvn= 100 ×{(ventilation for new WWR) - (WWR=%20 Ventilation for the current condition)} / (WWR=
(4) %20ventilation for the current condition)

ken= 100 ×{(energy consumption for new WWR)-(WWR=%20 energy consumption for the current condition)/ {(energy consumption for the current
(5) condition WWR=%20)

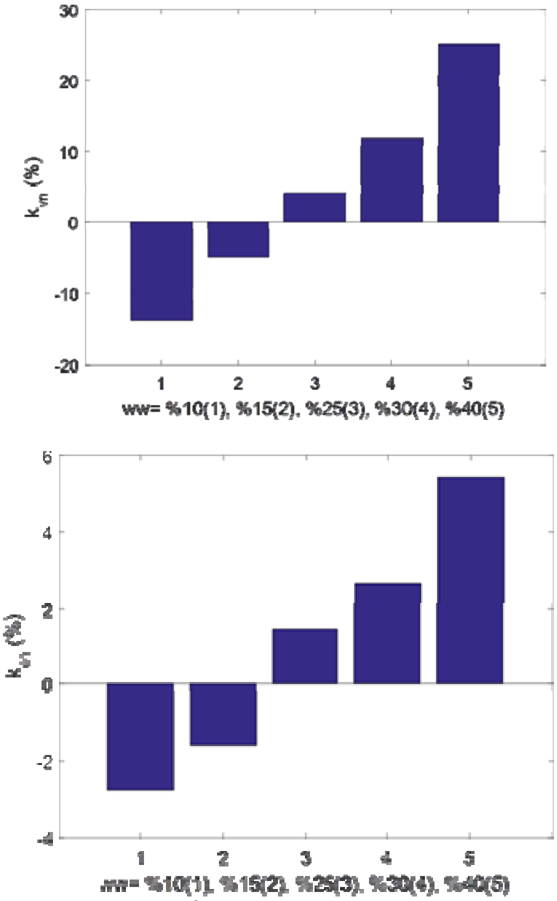


Fig. 9. Indices of changes in ventilation and total energy consumption due to the variation of WWR in North direction

As shown in table2, as WWR reduces form 20% to 15%, the energy consumption decreases while the ventilation rate slightly falls as well (2.75%).However, a higher reduction of WWR to 10% leads to the undesirable significant decline of ventilation (13.77%) in line with higher energy preservation. Greater WWR ends in higher energy costs and better ventilation performance. In ventilation-dominants climates, where the main priority is put on the natural ventilation, the WWR of 40% with the lowest ken/kvn provides the best solution.

Table 2
Indices of changes in ventilation and total energy consumption due to the variation of WWR in north direction

North-side: variable, Other sides: (current condition, WWR= %20)	%10	%15	%25	%30	%40
k_{en} (%)	-2/75	-1/58	1/46	2/66	5/43
k_{vn}(%)	-13/77	-4/75	4/2	11/95	25/13
$\frac{k_{en}}{k_{vn}}$	0/2	0/33	0/34	0/22	0/21

Table 3
Indices of changes in ventilation and total energy consumption with changing WWR in west direction

West -side: Variable, Other sides: (current condition, WWR= %10)	15%	20%	25%	30%	40%
k_{ew} (%)	1/54	3/02	5/61	7/25	10/21
k_{vw} (%)	3/65	8/17	30/86	30/43	34/78
$\frac{k_{ew}}{k_{vw}}$	0/42	0/36	0/18	0/23	0/29

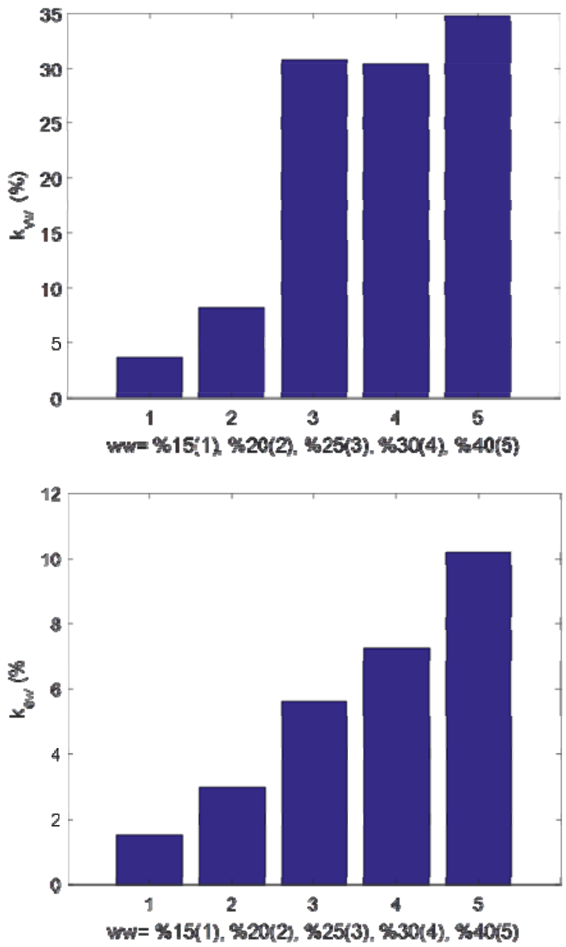


Fig. 10. Changes in ventilation and total energy consumption indices due to the variation of WWRin west direction

The indices of k_{ew}, k_{vw}, and k_{ew}/k_{vw}in the west directionare presented in Table 3. Since the higher k_{vw} and lower k_{ew} are desired. For the purpose of this study, a smaller ratio indicates a better result. In general, the ventilation and total energy consumption demonstrates a growing trend for higher WWR. However, at the interval of 25%, the ratio of energy index to ventilation is the lowest. Therefore, this WWR is considered the most appropriate one.

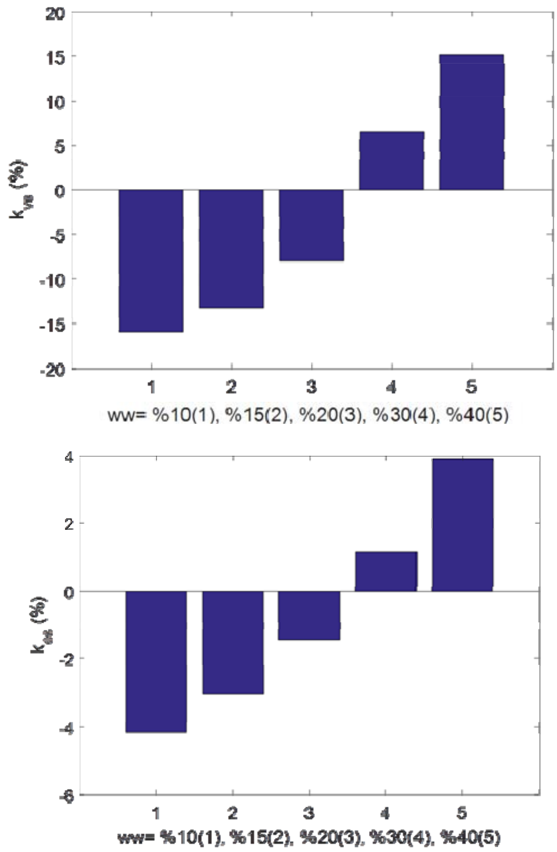


Fig.11. Changes in ventilation and total energy consumption indices due to the variation of WWRin South direction

The values of k_{es}, k_{vs}, and k_{es}/k_{vs} are presented in Table 4. Same to the previous test, lower K_{vs}, and higher k_{es}, are desired for the purpose of ventilation improvement. As a result, a higher ratio provides better conditions. According to Table 4, the reduction of WWR from 25 %(current condition) to 10% showed higher ratio of energy to ventilation indices. Regarding the increase in ventilation and energy consumption, higher K_{vw}, and lower k_{ew}, an increase in the WWR to 25% was suitable. As a result, a lower ratio produces better conditions. With increasing the WWR to 30%, the index ratio of 0.17 was obtained, which indicated a greater increase in ventilation than energy consumption. therefore, 30% is a suitable value for WWR in the south-side walls. On the other hand, regarding the higher ratio of indices, the value of 40% is not suggested.

Table 4
Changes in ventilation and total energy consumption indices due to the variation of WWRin south direction

South -side: variable, Other sides: (current condition, WR= %25)	%10	%15	%20	%30	%40
k_{es} (%)	-4/16	-3	-1/44	1/18	3/9
k_{vs} (%)	-15/89	-13/16	-7/89	6/59	15/13
$\frac{k_{es}}{k_{vs}}$	0/26	0/22	0/18	0/17	0/25

Regarding the WWR reduction from 15% to 10% due to the variation of WWR ventilation rate noticeably reduced. However, it is recommended to increase the WWR from 20% as a slight increase in energy consumption significantly increases the ventilation index. The ratio of 0.2 approves this explanation. Regarding the severe drop in ventilation, the higher WWR of 25% is not recommended.

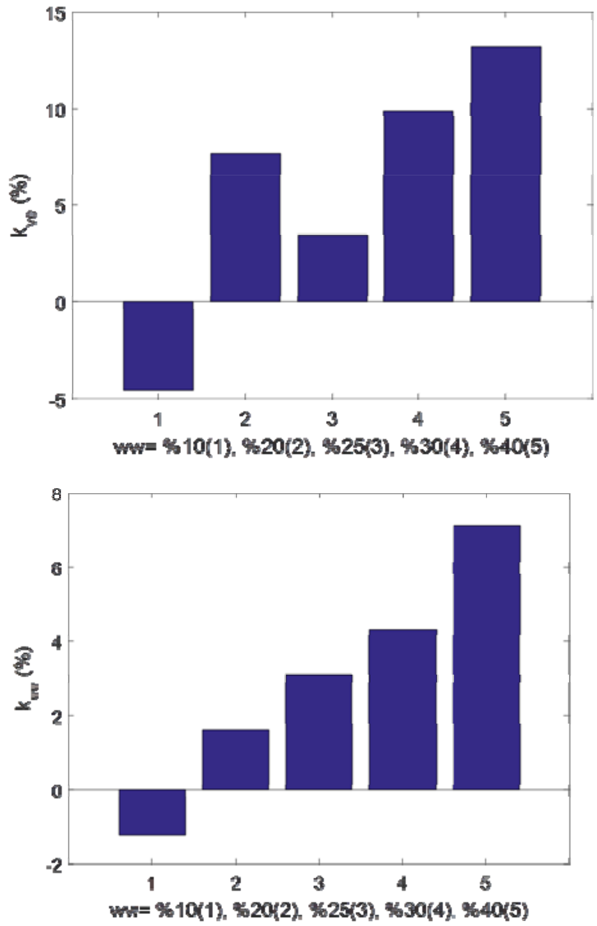


Fig.12. Changes in ventilation and total energy consumption indices due to the variation of WWRin east direction

Table 5
Changes in ventilation and total energy consumption indices due to the variation of WWR in east direction

East-side: variable, Other sides: (current condition,WWR= %15)	%10	%20	%25	%30	%40
k_{ee} (%)	-1/18	1/6	3/1	4/3	7/12
k_{ve} (%)	-4/55	7/73	3/44	9/89	13/26
$\frac{k_{ee}}{k_{ve}}$	0/25	0/2	0/9	0/43	0/53

7. Conclusion

In this study, the case office building was simulated with its current WWR to calculate the heating, cooling, ventilation and total energy consumption. In order to optimize WWR regarding the best ventilation performance, the WWR was set constant at three directions and the fourth direction was varied for six WWR internals. This process was replicated in four cardinal directions. The output data of the annual energy consumption showed that an increase in the ratio of windows in the south and west directions caused the least and highest energy consumption in the building. Respectively, For the WWR of greater than 20%, a relative jump in total energy consumption was observed in the west direction. Moreover, the annual natural ventilation resulted in a significant increase in ventilation in this direction, specifically from 20% to 25%. In general, the highest values of ventilation rate were obtained in the west direction, despite a high amount of energy. In the next section, the influence index of energy consumption with an increase in the WWR was calculated. It was observed that heating energy consumption was positively affected by an increase in the area of the window in the north direction. Regarding the results obtained from the south direction, the high downward influence behavior, and the minimum influence index of total energy compared to the other three directions, an increase in windows area in this direction is a proper climatic design solution. The extent to which the ventilation is affected by changes of WWR is maximum in the west direction and minimum in the east. Ventilation rate performance due to the WWR changes in the north direction was relatively similar to the west direction.
In the last phase, the index of simultaneous changes in ventilation and total energy because due to the changes in the ratio of windows was defined and calculated. This index contributes to the comparative analysis of ventilation and energy consumption. With reducing the WWR from 20% to 15%, the energy consumption reduced as well as the relatively slight ventilation reduction. However, more reduction to 10% led to the unintentional reduction of ventilation rate by 13.77% the ventilation was improved with increasing WWR, which resulted in a higher ventilation rate and greater energy

cost, which is inconsistent with energy consumption priority. Is the higher priority of design strategies If the higher priority placed on ventilation purposes, this value is suitable regarding the lower k_{en}/k_{vn} at 40%.in the west direction the ventilation and total energy consumption increased with increasing WWR from 10% to 15% and 20%. However, for an increase to 25%, the lowest k_{ew}/k_{vw} was achieved and indicates the optimized value. In the south direction, WWR reduction from 25% to 10% showed a better ratio of energy to ventilation indices, and thus was a suitable option. With increasing WWR from 25% to 30%, the low index ratio of 0.17 was obtained, indicating a greater increase in ventilation than in energy consumption and was considered as the suggested WWR. In the east direction, increased WWR from 15% to 20% is a more suitable choice, as the ventilation index significantly increases with a slight increase in energy consumption. The low ratio of 0.2 confirms this preference rather than other WWR.

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