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Impacts of Window Factors and Building Orientation on Energy Consumption in Residential Buildings of Humid Temperate Climatic Zone in Iran

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Abstract: This paper deals with the research into optimal passive design parameters, such as building's envelope components and orientation that result in improving energy efficiency. Despite the ever-increasing demand for residential complexes in developing countries like Iran during recent decades, architects and engineers are deprived of the specific guidelines to design energy-saving residential units. The present paper aims to monitor the influence of window and orientation variables through the case study in the microclimate region in Iran, which is determined to be a temperate and humid climate. The residential unit is simulated by Design Builder to assess the value of energy used to fulfill heating, cooling, lighting, and annual energy consumption regarding controlled variables (shading devices, and mechanical and natural ventilation). The window-to-wall ratio (WWR) is evaluated in the range of 15% to 85% for northern and southern external walls. Subsequently, the most conventional range of width-to-height ratio (WHR) among the regional dwellings reported from the National Road, Housing and Urban Development Research Center is investigated. Additionally, more variables like Building orientation (BO) is considered in the parametric analysis as the effective parameter to design passive solar. The considered building is routed on the ground with the azimuth angles from 0° to 360° with 5° increments in a clockwise direction to create 72 building orientation intervals. The results reveal that WWR is recommended to be 15% and 65% on the northern and southern façade, respectively. Furthermore, the aspect ratio of the north-facing windows has the marginal effect on energy saving compared to south-facing windows. Although there is an optimal building orientation, most of the ideal values can be found in the narrow ranges 175°< BO <190° and 345°< BO < 20°. Findings indicated that the reported variables played an important role in the reduction of energy consumption, particularly in housing units of residential complexes.

Key words: window-to-wall ratio, width-to-height ratio, building orientation, energy consumption

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Nomenclature

Symbols

HDD	Heating degree day
CDD	Cooling degree day
SHGC	Solar Heat Gain Coefficient
HVAC	Heating, Ventilation and Air Conditioning
COP	Coefficient of Performance
ac/h	Air Change per Hour (h^{-1})
WWR	window-to-wall ratio
Af	Tropical rainforest
Am	Tropical monsoon
Aw	Tropical savanna, Semi-arid
Bsh	Tropical savanna, Semi-arid
Bwh/Bwa	Arid
Cfa	Humid subtropical
Cfb	Oceanic
Csa	Mediterranean hot summer
Csb	Mediterranean
Cwa	Tropical wet-and-dry
Dfa	Hot summer-continental
Dfb	Hemiboreal

Subscripts

BO	Building Orientation
WHR	width-to-height ratio
C	Cooling
H	Heating
L	(artificial) Lighting
SEC	Site energy consumption
TOT	total
N	North
S	South
E	East
W	West

1. INTRODUCTION

For the past 50 years, new buildings, construction have momentously increased due to the ever-increasing population all over the world. Building energy consumption is another factor grown remarkably as building energy use has been greater due to the emergence of state-of-the-art systems of heating, air-conditioning, and ventilation (Susorova et al., 2013). The EIA anticipates the future trend of building energy consumption will increase by 34%, at an average rate of 1.1% per year from 2008 to 2035. In 2030, dwelling and non-domestic segments will considerably contribute to usage approximately 67% and 33%, respectively (U.S.EIA, 2011). According to official figures, domestic energy consumption in cities of Iran (A country with a population of around 80 million and an urbanization rate of 3.5%) is noticeable (Statistical Center of Iran, 2018). The sector of households in total energy usage was approximately 25% in Iran in 2010 and increased to 50% in 2019 (Rahmani et al., 2020), making it the top one among other segments. Likewise, in Europe, the average energy consumption within the residential sector is over 3.5 times higher than commercial and office buildings. Heating, cooling, and hot water, constitute 83% of the total energy consumption, while appliances account for only 8%. However, in commercial buildings, lighting is mainly used (IFCO, 2010; Lee et al., 2013). This illustrates that the residential building must be regarded as the major part of energy-saving plans.

The building envelope, which is the heat exchanging interface between exterior and interior parts of a building, encompasses elements including shading and window devices (Raji, Tenpierik and Van Den Dobbelsteen, 2016). In general, windows are thermally weak in terms of energy efficiency. They are responsible for approximately 60% of the overall energy loss that is a result of convection, conduction, and radiation, leading to an increase in energy use for heating, cooling, and lighting (Detsi et al., 2020; Muneer, Abodahad and Kubie, 1999). Lee et al. (2013) reported Bulow-Hube findings (Bülow-Hübe, 2001): windows are the main causes for 20%-40% of the wasted energy in a building. Window systems are the significant parts of the building envelope to provide a thermally internal environment and to decrease the energy consumption of buildings (Pal, Roy and Neogi, 2009). The balance between opaque areas (WWR) and glazing and other parameters related to windows highly influences the energy efficiency of a building. Windows are recognized for not only solar heat gain (energy use for cooling and heating) and heat loss affecting energy use for cooling and heating, but also for the availability of natural daylight affecting energy use for artificial lighting (Rana et al., 2020; Goia, 2016).

Among the aspects corresponding to the design mode of a façade system, the width-to-height ratio and window-to-wall ratio variables affect the architectural appearance. The opacity of a building is often set by paying attention to the aesthetic and architectural applications rather than to the energy performance. Furthermore, this selection is often decided at the beginning step of the design process and is not easily changeable later, while other aspects (such as equipment, operations, and materials) can be modified in the following stages (Goia, 2016).

The orientation is a predominant factor of buildings, influencing the energy consumption level and the thermal property (Jaber and Ajib, 2011). The factors affecting buildings orientation in terms of ambient elements and surrounding conditions include the sun's path, site geometry, rivers and roads. The non-uniform orientation of dwellings in cities is mostly due to these factors (Chi et al., 2020). From a northern hemisphere view, spaces without a southern orientation have negative effects on the energy behavior of a building in three ways: (1) they reduce the daylight availability; (2) they reduce the heating gains from the Sun in the winter; and (3) they have higher cooling loads from solar gain in the summer and in warmer climates. These buildings require more energy for space cooling and heating compared to buildings with suitable passive solar energy design and orientation (Garcia-Hansen, Esteves, Pattini, 2002).

Although various studies on building components (WWR, orientation, glazing systems and so on) are conducted to reduce the energy consumption for heating, cooling and lighting by others, there is still much to be investigated on independent parameters of windows and to create buildings with nearly zero energy consumption in various climatic conditions. Persson, Roos and Wall (2006) studied the distinct orientations, the window types, and size of the terraced houses in Gothenburg (Dfb) to provide thermal comfort using traditional passive solar methods. After reducing the window size in the south and increasing the window size in the north, they evaluated energy consumption. DEROB-LH, which is a dynamic simulation tool, reveals that window size does not considerably affect the heating demand in the winter while it would be effective to meet the cooling demand in the summer. In this article, the recommended optimal size of the window in the south is smaller than the original window size of the case study house.

On the contrary, Gasparella et al. (2011) evaluated the influence of window size, distinct types of glazing system, and orientation on energy consumption in the summer and winter in Paris (Cfb), Milan (Cfb), and Nice and Rome (Csa). Simulation by TRN-SYS showed that utilization of large window size improved the winter performance and slightly deteriorated the peak of the winter load. Moreover, a window with a south orientation enhances the energy performance in winters. Goia (2016) considered window-to-wall ratio and orientation as variables to analyze the energy performance of the office in four European climates (Humid subtropical (Cfa), Mediterranean (Csb), continental (Dfa), and Hemiboreal (Dfb)) via Energy Plus and Matlab. The results revealed that while the optimal WWR and orientation were obtained, most proper values could be found in a narrow range of $0.30<WWR<0.45$. Only south-oriented facades in cold or hot climates needed a WWR value outside this range. The total energy consumption increased in the range of 5-25%, while the poorest WWR was regarded.

Similarly, Kim et al. (2016) analyzed the rare study on the single-family house located in Vancouver, Canada (Cfb-Csb) with 65 different design scenarios in terms of window size, position, and orientation via Autodesk Revit and Autodesk Green Building Studio to calculate the total energy load. They concluded that the energy load rose as the window size increased, - neglecting window position - in all orientations. Marino, Nucara and Pietrafesa (2017) used the Energy plus simulation software to evaluate WWR in the office building situated in 12 cities of Italy with various climatic conditions (Cfa-Csa-Dfa-Cfb-Dfb). Energy consumption was considerably influenced by factors, such as climatic conditions, presence of shading devices, façade configurations, and insulation features of the structures. If the effect of each individual factor is evaluated independently, the optimal WWR does not seem to change remarkably. WWR may be doubled due to the influence of the development of the envelope features and the installed lighting electric power. Alwetaishi (2017) focused on the effects of window-to-wall ratio in various hot dry, hot humid, and moderate climates (Bwh, Bwa and Csa) in Saudi Arabia. This study demonstrated that east and south directions were the worst in terms of the maximum amount of heat gain in the selected locations. According to this research, WWR is recommended to be 10% in hot dry and hot humid climates and 20% in moderate climates using EDSL Tas. Susorova et al. (2013) assessed the role of geometrical factors, such as WWR, window orientation, and building configuration in energy use in commercial and office buildings. Energy simulation is conducted using Design Builder for different combinations of fenestration parameters, and then the optimal approach is determined to save energy for a building located in six climate zones of the United States (Cfa, Csa, Csb, Dfa, Dfb). Geometry factors can decrease the energy consumption in hot climates up to 14%, whereas energy saving in temperate and cold climates is marginal. Moreover, Feng et al. (2017) investigated the influence of WWR and its various orientations on the energy consumption of a nearly zero energy building in the cold climate of ShenGyan in China (Dwa). This study used the Energy Plus software to determine the priority of orientations of WWR in terms of energy consumption and optimal window size. Windows facing east/west, south and north have greater impacts on energy use, respectively. In addition, the energy-efficient WWR for eastern and southern façades is between 10%-15% and 10%-22.5%, respectively.

Alghoul, Rijabo and Mashena (2017) took the window-to-wall ratio between 0 to 0.9, and window orientation varied in steps of 45 degrees to investigate cooling, heating and total energy consumption in an office building located in the city of Tripoli (Bsh). The energy simulation is validated by the Energy Plus software with an OpenStudio plugin interface for Sketchup. It was found that increasing

WWR could decrease the heating energy use and increase the cooling energy consumption. The addition of windows to the façade results in an increase in the annual total energy use by 6% to 181% depending on WWR and WO. Badeche and Bouchahm (2020) applied the method of taguchi and simulation software programs, including Pleiades and Comfy to examine the interaction between window parameters in order to reduce cooling and heating loads in office buildings regarding three major climates (Csa, Bwh and Bsh) in Algeria. Although window orientation was found as the most effective parameter in the window design performance (54%) in the semi-arid climate in the Mediterranean climate the most prominent factors were window size, solar heat gain coefficient, and thermal conductivity. According to this article, the optimum WWR (40%-50%) was effective in decreasing the energy consumption required for heating and cooling demand.

Jaber and Ajib (2011) searched for the best orientation of the building, window size, and thermal insulation for typical residential buildings in the Mediterranean region in Jordan. They considered these parameters to minimize energy consumption. It is demonstrated that approximately 27.59% of annual energy use can be conserved by opting for the best orientation, size of window and shading device. Morrissey, Moore and Horne (2011) investigated orientation of building to maximize passive solar benefits through 81 different detached dwelling designs in Melbourne (Cfb), and Victoria (Csb) classified as mild temperate climate. This study indicates that smaller houses as well as higher performing designs maintain their performance better in various orientations than in larger houses over 250 m^2. Similarly, Xu et al. (2012) investigated the energy performance by optimizing buildings, orientation in cities such as Shanghai (Cfa), Beijing (Dwa), Kunming (Cwb), Guangzhou (Cfa), and Harbin (Dwa), in China. They revealed that buildings facing both south and north located in Beijing, Shanghai and Harbin were more energy efficient. Moreover, the annual energy use of the building decreased dramatically by appropriate use of daylighting and shading devices. Tokbolat, Tokpatayeva and Al-Zubaidy (2013) investigated the effect of buildings' orientation parameter on energy consumption in buildings located in extremely cold weather conditions (Dfb) like Astana. They used Design Builder for their simulations. The results indicated that orientation of the building was able to considerably affect the rate of energy consumption. The facing orientations of south and north are discovered to be the most energy efficient (orientation is 35 degrees toward the northeast). Abanda and Byers (2016) studied the impact of orientation on energy consumption, and evaluated how BIM could be utilized to facilitate this process. A real-life building in Hertfordshire, UK (Cfb) was modeled by Revit and then exported to Autodesk Green Building Studio. Building was routed from 0° to 360° with 22.5° steps. Based on these analyses, a well-orientated building can save a significant value of energy throughout its lifecycle. The most cost-effective orientation for this case is 180° from the base level. Their orientation contained an external façade, which faced a southerly direction.

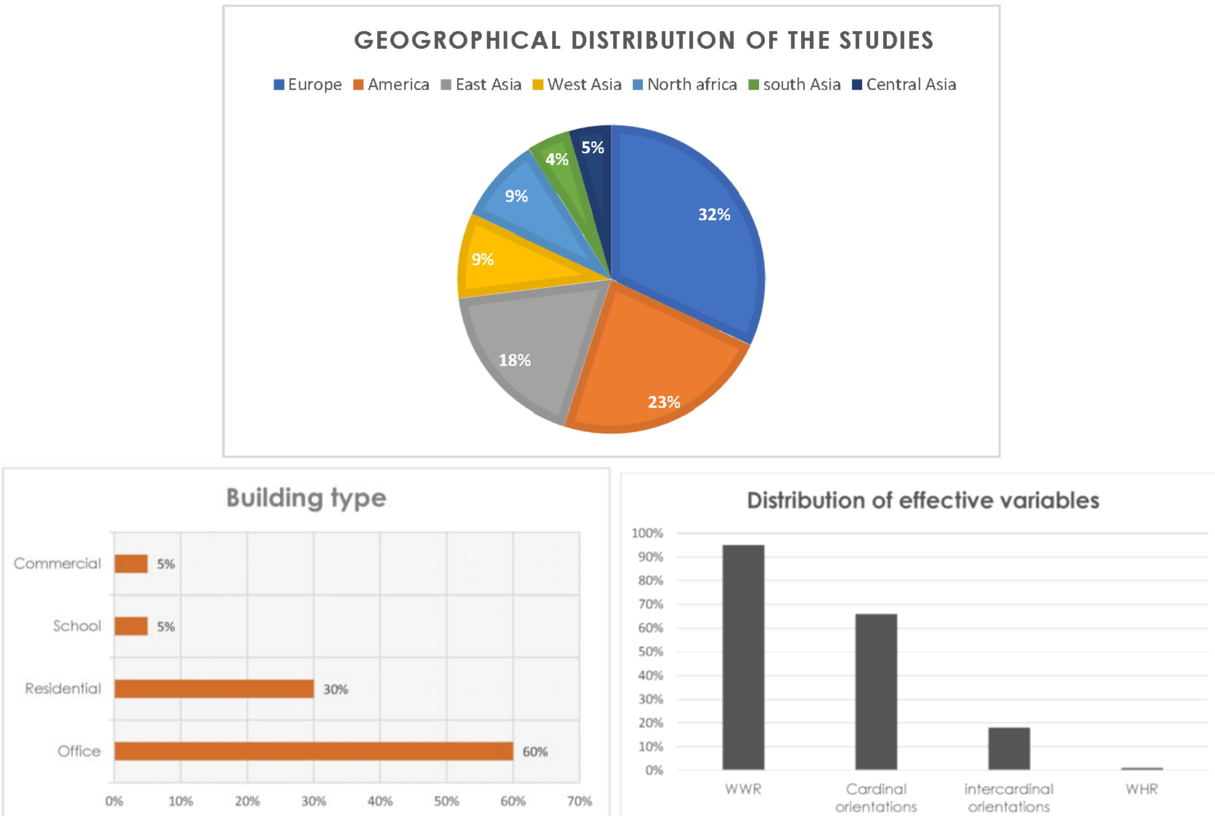


Figure1. Analysis of previous studies that presented energy consumption through building.

According to Figure 1, most case studies in recent decades are conducted in developed countries in Europe and America continents with arid and cold climatic conditions, and most regions with temperate climate are disregarded by researchers and architects, particularly in west Asia and developing countries like Iran. Accordingly, there is a lack of guidelines for sustainable design in these countries. Therefore, most researchers analyze office buildings, while residential condominiums with a high number of housing units contribute much more to annual energy use in urban areas. Furthermore, most previous studies generally considered the effects of cardinal orientations (N-S-W-E) of the studied model on energy consumption, while we aim to analyze the effects of BO between cardinal directions (N-S-E-W) and intercardinal directions (N-E, N-W, S-E, S-W) (0° to 360°) with 5° steps. In fact, the energy efficiency of architectural decisions is a parametric method investigating the effect of various architectural factors on the energy consumption of buildings. This method uses dynamic energy simulation tools to find the optimum value for each architectural parameter from an energy efficiency viewpoint. Factors, such as BO, WWR and WHR apply to the main façade (north and south facade), since most buildings in this area benefit from the east-west direction and achieve solar radiation from north and south-facing windows. Thus, this study focuses on investigating the energy performance of building orientation concerning the thermal performance of north and south-facing windows with different WWR and WHR factors.

This paper has three perspectives with respect to the conducted studies. Firstly, to determine the most optimal WWR, the effective combination of the controlled variables on WWR, including shading device, natural ventilation (opening window), mechanical ventilation, and climatic conditions are considered. As a result, the window system not only is considered a heat-exchanging interface between indoor and outdoor, but also is responsible for ventilation and cooling in the building.

Secondly, the analysis is conducted to validate the energy performance of conventional width-to-height ratios used through the window system of Iranian housing based on the published report by the Road, Housing and Urban Development Research Center in Iran. Thirdly, the case study is simulated on a parametric basis to study the effect of the numerical simulation of the building orientation on energy use. The most effective combinations of WWR, width to height ratio and building orientation are recommended for residential complexes becoming popular in urban areas due to an ever-increasing population.

Consequently, it is revealed that WWR, window dimensions, and building orientation affect a decreasing trend of cooling, heating, and artificial lighting load of the residential complex. These numerical simulations can be valuable references in developing countries like Iran, where proper guidelines do not exist in terms of passive solar approaches for architects and engineers to construct energy-efficient houses.

2. METHODOLOGY

2.1. SIMULATION SOFTWARE

To investigate the impact of the glazing system, the model geometry of a single housing unit was created in the Design Builder software. Then, the variables of effective building envelope (WWR, WHR, and orientation) and controlled variables with numerical simulation are analyzed by the Energy Plus simulation software. Since a building is a complicated environment where elements of building, building envelope, systems, installation equipment and lighting play significant roles in energy consumption, Design Builder as an integral and interface system is able to present acceptable accuracy in calculation of energy consumption (Yu, Yang and Tian, 2008). In fact, Design Builder enables designers to analyze energy performance of buildings by considering climatic data and other building characteristics (You and Ding, 2015). To simulate annual energy consumption, the Design Builder software is used to provide a typically hourly simulation of energy consumption. Subsequently, technical effects of several passive design variables will be investigated. These variables are WHR, selection of the best façade orientation, and the window-to-wall ratio with a shading device in north and south façades (Aksoy and Inalli, 2006).

2.2. PERFORMANCE EVALUATION PROCEDURE

2.2.1. THE CLAMATIC DATA OF THE STUDIED CITY

Climate mostly plays a crucial role in building energy use, particularly in residential buildings. Thus, to design a nearly zero-energy housing unit, the climatic characteristics of the area have to be determined as one of the major factors to calculate the building energy performance. Electric lighting, cooling, and heating energy consumption can be assessed by designing the window system in conjunction with the climatic condition of the locality (ASHRAE, 1993). Iran is a large country with various climatic conditions. This country is situated between 25° and 40° N latitudes, demonstrating its location in the hot region of the world (Table 1).

Table1. Meteorological database of the studied city.

City	Latitude (° N)	Longitude (° N)	Altitude (m)	HDD(°C) Baseline: 21°C	CDD(°C) Baseline: 24°C	Koppen climate classification	ASHARAE standard climate zone
Rasht	37° 16'	49° 34'	37m	2135	268	Csa	4A

Based on Koppen's classification of Iranian climate, six climatic zones exist: Dsa: Hot summer- Continental climates, Csa: Mediterranean- Hot summer, BWk: Arid-Cold desert climate, Bwh: Arid- Hot desert climate, BSk: Cold semi-Arid climate, BSh: Hot semi-Arid climate (Koppen, 1936). Concerning these categories, Rasht is classified with a Mediterranean climate (Csa) with warm temperature and dry summer. The summer average temperature ranges from 19 to 29°C, and the average temperature in the wintertime is around 6 to 13°C (Figure 2). This climatic classification as dry summer is not a precise division due to the high humidity during the year, which is 65% to 75% (Figure 3) (Pourvahedi and Ozdeniz, 2013). Rasht as the target city in this paper is located at 49° east longitude and 37° north latitude, and it belongs to the high latitude area. Moreover, the temperature difference between daytime and nighttime is marginal, and its total annual global solar radiation at horizontal surface is approximately 1259 kWh/m²/year (Sabziparvar, 2007). As Figure 4 shows, the amount of solar radiation reaching the ground over a wide area is extremely low. Accordingly, the sky is semi-dark and dark during the year.

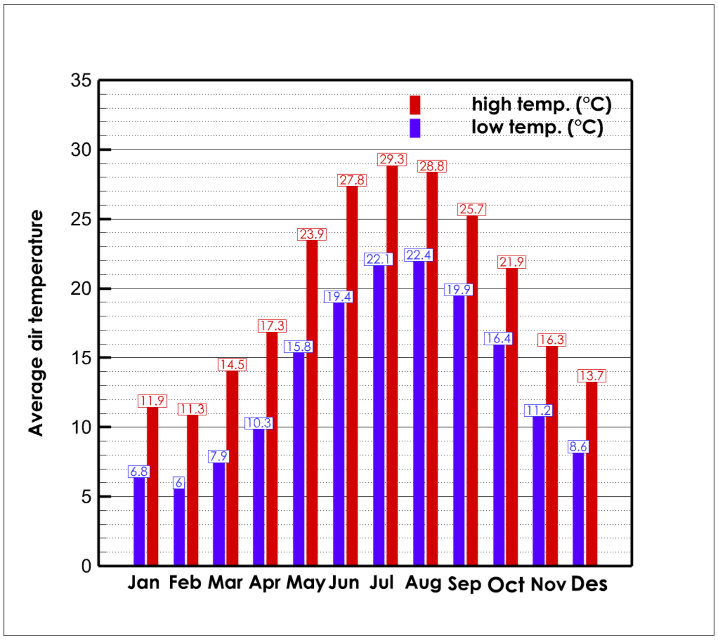


Figure2. Average air temperature in Rasht (°C) (IRIMO).

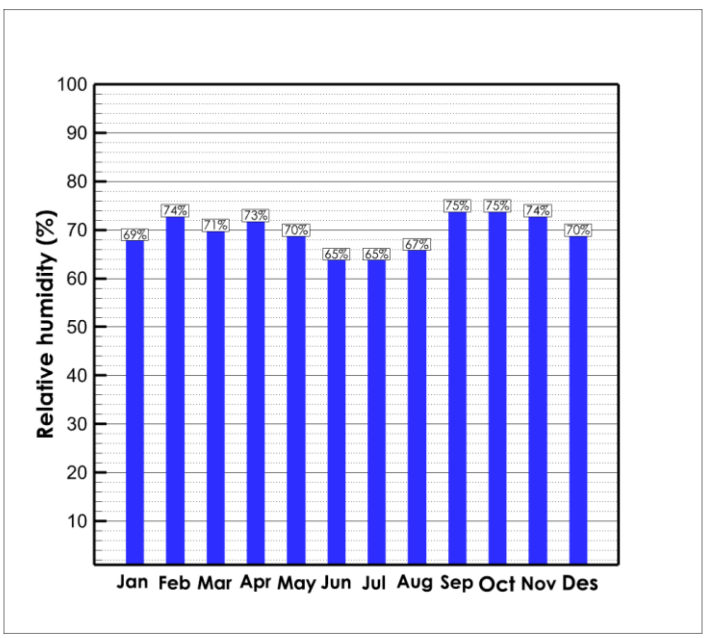


Figure 3. Average relative humidity in Rasht (%) (IRIMO).

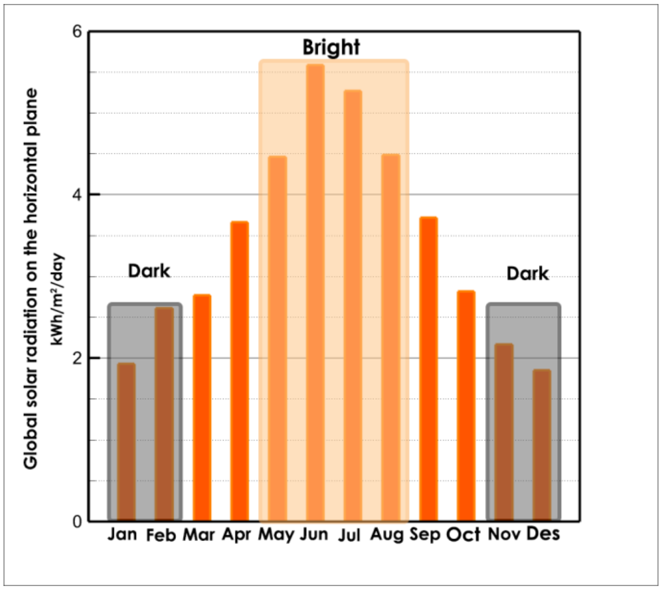


Figure4. Monthly mean daily global solar radiation on the horizontal plane in Rasht(kWh/m^2/day)(Sabziparvar, 2007).

As Figure 5 depicts, according to the World Meteorological Organization and the Iranian meteorological organization standards, Iran has five continental climates (hot-humid, temperate-humid, hot-dry climates, and hot-dry with cold winters) (Ganji, 2003). Based on the climate classification of ASHRAE Standard 90.1, the distribution of Asian climate ranges from Zones 1 to 5 in which the intended area is situated through 4A with a mixed-humid climate (ASHRAE standard 90.1, 2019). Table 1 illustrates more information concerning other meteorological and geographical features of Rasht city.

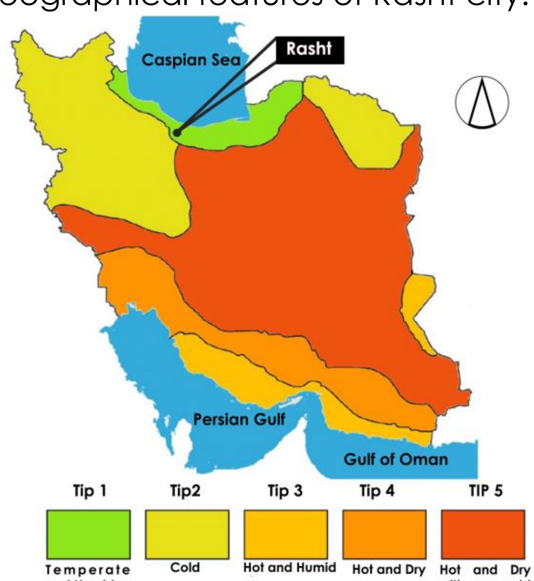


Figure 5. The location of the selected city in Iran (Ganji, 2003).

2.2.2. THE SIMULATED MODEL

According to Figures 6 and 7, the selected case study is a housing unit of the complex including two bedrooms with an area of 90 m^2 (6*15) and a height of 3 m. It is situated in the middle floor of a residential complex with 300 units. This unit was a typical one in terms of area and floor plan design opted among the units of the complex. Moreover, the simulated unit was located between two neighboring units on east and west sides. Since most housing units in complexes gain direct solar radiation from windows facing north and south due to the regulation limitations as well as advantages of southern and northern natural light, this study focuses on the typical housing unit, and the investigations and simulations are all conducted on two major faces of north and south.

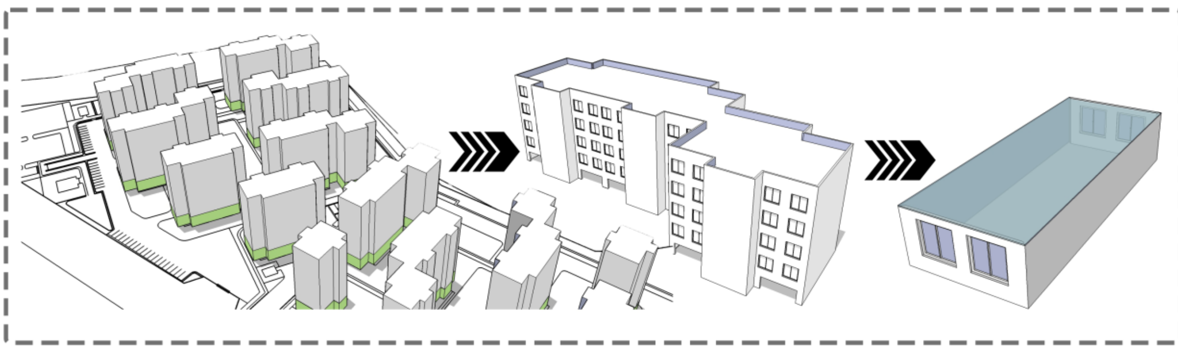


Figure 6. The selected housing unit from residential complex as a case study for analysis in design builder.

Figure 7. Case study plan.

As Tables 2, 3 and 4 show, input settings, such as appropriate U-value and R-value for external wall, floor and ceiling, intermediate wall, window, and characteristics of the HVAC system, are determined based on ASHRAE/Energy Plus; however, the climatic conditions of the selected area and actual systems of the Iranian dwellings are also regarded. ASHRAE standard 90.1 is the energy standard for buildings except low-rise residential buildings that sets the minimum requirements for the energy performance of building elements (ASHRAE standard 90.1, 2019). This system uses the electricity for cooling, lighting and gas for heating, and the total (H+C+L) energy consumption is assessed in terms of the site energy consumption (SEC) in the selected building. Most energy analyses of buildings are conducted with the energy measured on the site. The building site energy is typically measured by the utility meters and is the total of the electrical, gas and other energies delivered to the facility. Site energy consumption can be useful to understand the performance of the building and building system (Deru and Torcellini, 2007). The energy information administration (EIA) defines the site energy consumption (SEC) as “the Btu value of energy at the point it enters the home, building or establishment, sometimes referred to as “delivered energy” (EIA, 2007).

Table2. Defining construction features of the tested residential (ASHRAE Standard 90.1, 2019).

Construction	**Layers**	**Thickness(m)**	**U-Value(**W/m^{2}K**)**
External wall	Brick work	0.025	0.459
	Cement mortar	0.03	
	AAC block	0.2	
	Gypsum plasterboard	0.03	
Floor/ ceiling	Terrazzo	0.025	0.451
	Cement mortar	0.03	
	AAC block	0.2	
	Gypsum plastering	0.03	
Intermediate wall	Gypsum plasterboard	0.03	0.71
	AAC block	0.1	
	Gypsum plasterboard	0.03	

Table3. Specification of glass and window frame (ASHRAE Standard 90.1, 2019).

Glazing, frame type	SHGC	Solar transmittance	Light transmittance	U-Value(W/m^{2}K)
Double- glazing 6mm/13mmARGON/4mm UPVC window frame	0.72	0.65	0.79	2.53

Table4. The input information applied for residential use (ASHRAE Standard 90.1, 2019).

Input Data	
Artificial lighting	
Power density	7.5 W/m^2
control type	Linear
Lighting set point	300 lux
working plane height	0.75m
HVAC	
Radiator COP	0.8
Set-point temperature	20°C
Split Cop	3
Set-point temperature	25 °C
Window Opening	50%(March-April-May)
Infiltration rate	0.7 ac/h
Minimum Fresh Air l/s-person	7.5

Accordingly, by considering the climatic classification related to this city, heating demand is more dominant than cooling demand. Mechanical and natural ventilation were set as the controlled variables throughout the simulation. The window openings, as natural ventilation, not only are the most energy-efficient strategy to improve the indoor environment, but also fulfill occupants 'demand for both indoor air quality and thermal comfort (Li et al., 2015). The performance of window opening is related to energy consumption, thermal comfort, and indoor air quality in buildings. Thus, 50% of the window is regarded open during the spring months while the outdoor temperature is cooler than indoor spaces based on the hourly climatic data (solar radiation, relative humidity, and ambient temperature) extracted from Design Builder (Lai et al., 2018). The typical practice of indoor design conditions for cooling is a maximum of 50–65% relative humidity, and 25°C dry Bulb temperature; for heating, the relative humidity and dry Bulb temperature are regarded as 30% and 20°C, respectively (ASHRAE, 2005).

2.2.3. EXTERNAL SHADING DEVICES

There are four main causes for space cooling and heating loads; solar heat gain through apertures, ventilation/infiltration, internal loads, and heat conduction. Additionally, if glazing facades are designed by considering the climatic condition, shading system, and other window parameters, it prevents the penetration of undesired solar radiation and direct sunlight into the building in cooling periods and permits the desired solar gains in heating periods (Ahmad and Fikry, 2019; Kirimtat et al., 2016). Thus, horizontal shading devices for southern façades and vertical ones for north-facing windows are considered based on various aspects, including building type, latitude, natural light, building form, and orientation (Figure 8) (Kirimtat et al., 2016). Shading devices should be selected according to the window orientation (Saifelnasr, 2015). South-facing windows require the use of fixed horizontal shading devices, particularly in moderate climates (Mehrotra, 2005). External horizontal shading devices on south orientation can achieve both shading in the summer and penetration of solar radiation in the winter, as the sun is higher in the sky during the summer than the winter (Kirimtat et al., 2016). In moderate climates, vertical fixed shading devices are useful for north-facing windows to improve the protection in winter months by acting as a windbreak. Moreover, fixed shading devices reduce the thermal load during the cooling period and alleviate extreme summer daylight and sunlight causing the cooling load (Mehrotra, 2005).

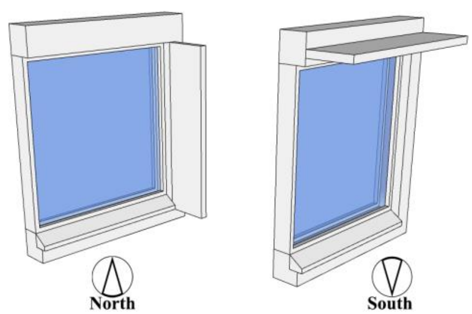


Figure 8. External vertical and horizontal shading devices on the north-facing and south-facing windows.

To calculate the depth of the horizontal shading devices, the vertical shadow angle (VSA) is required; it is the angle between the ground line and the altitude of the sun. Furthermore, horizontal shadow angle (HSA) is required for vertical shading devices; it is the horizontal angle between the normal window width and the azimuth of the sun. Thus, as Table 5 displays, the depth of horizontal and vertical external shading devices is calculated according to their height and width in diverse WWRs, respectively.

Table 5. Numerical prosperities of the tested external shading devices.

WWR (%)	Horizontal shading device		Vertical shading device	
	Height	Depth	Width	Depth
%15	1.50	0.87	0.90	0.21
%25	1.50	0.87	1.50	0.35

%35	1.50	0.87	2.10	0.48
%45	1.50	0.87	2.70	0.62
%55	1.68	0.97	2.98	0.67
%65	1.98	1.14	2.98	0.67
%75	2.20	1.27	2.98	0.67
%85	2.59	1.50	2.98	0.67

2.3. BRIEF DESCRIPTION OF ENERGY SIMULATION

During the simulation process, it is vital to reach the most effective parameters on energy consumption. Thus, an approach, which is used in this process, is changeable regarding the aims of the present paper as well as the circumstances of the residential unit through the complex (with two facades) and site. To properly analyze the effect of building orientation in this region and to help architects to set the array of buildings at the first stage considering projects, layout (Figure 9), the parametric analysis is applied to evaluate effects of the building envelope orientation. Despite the parametric approach regarding building orientation to assess the annual energy consumption for heating, lighting, and cooling, the window-to-wall ratio and the window area depending on the window width and height are simulated by the intended orientations and dimensions.

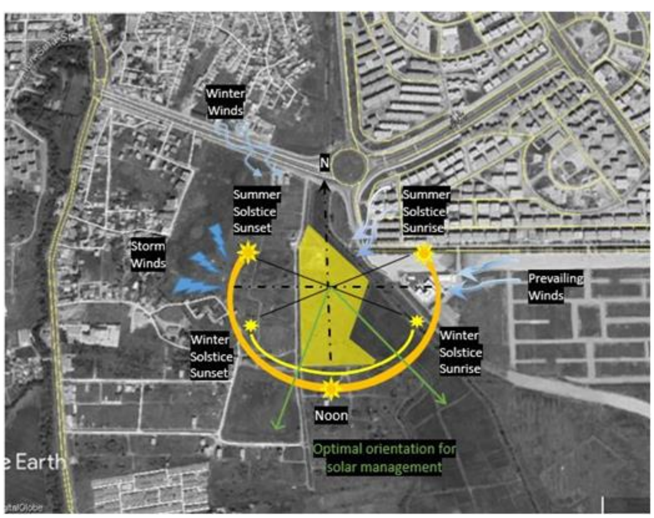


Figure9. Overall layout of the selected residential complex.

The research methodology is carried out through three main sections. The first one concentrates on window-to-wall ratio, width-to-height ratio, and building orientation. This section evaluates the performance of passive solar design for enhancing energy saving. The window ratio in the present article is the ratio of the transparent area (glazing) to the opaque area (external wall) that is multiplied by the length of the wall to the useful height (from floor to ceiling).

Window-to-wall ratio is evaluated separately in the northern and southern facades of the unit. The maximum recommended value of WWR in residential buildings with more than three stories is 40% for all climate zones based on the ASHRAE 90.1 Energy Standard (ASHRAE standard 90.1, 2019). This value is considered the baseline; however, higher and lower WWRs are conducted in this study to trade off the energy performance of the building. As a result, the window to wall ratio is defined through 8 scenarios from 15% to 85% for both sides (Figure 10). To evaluate the most optimum WWR for the southern façade, the value of the WWR facing north remains constant with 30% (width 3.60 and height 1.50). After analyzing the simulation results, the most optimal case for the southern façade is extracted by Design Builder. Subsequently, these processes are conducted for the northern facade again to determine an appropriate WWR through 8 steps.

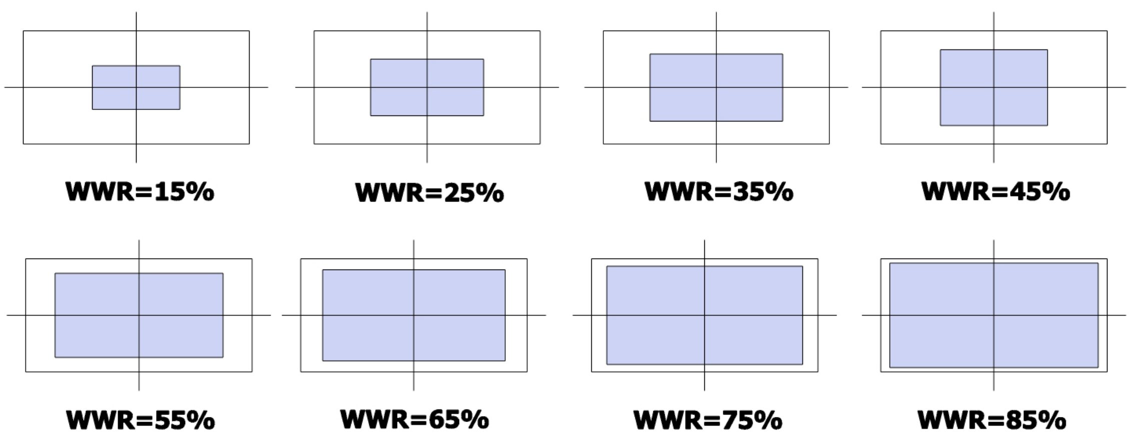


Figure 10. Window-to-wall ratio scenarios.

In the second section, various WHR are assessed, which are recommended by the Iranian Road, Housing and Urban Development Research Center as the conventional WHR through windows in Iranian dwellings, to investigate the influence of window dimensions, including width and height on energy consumption (Qasemzadeh, 2012). As Figure 11 shows, the aspect ratio is changed through 29 cases, while the position of window is remained constant in the middle of the wall with O.K.B of 80 centimeter (O.K.B: the height of the wall that is built from the floor of the room up to the window sill) except for windows with a height of 2.40 and 2.70 (w08-w16-w22-w23-w27-w29). It is worth mentioning that windows shown with continuous lines have been presented as the most conventional in the Iranian housing sector. Thus, north-facing and south-facing windows are evaluated by Design Builder, and then the most optimum width-to-height ratio is determined based on the total and H+C energy consumption.

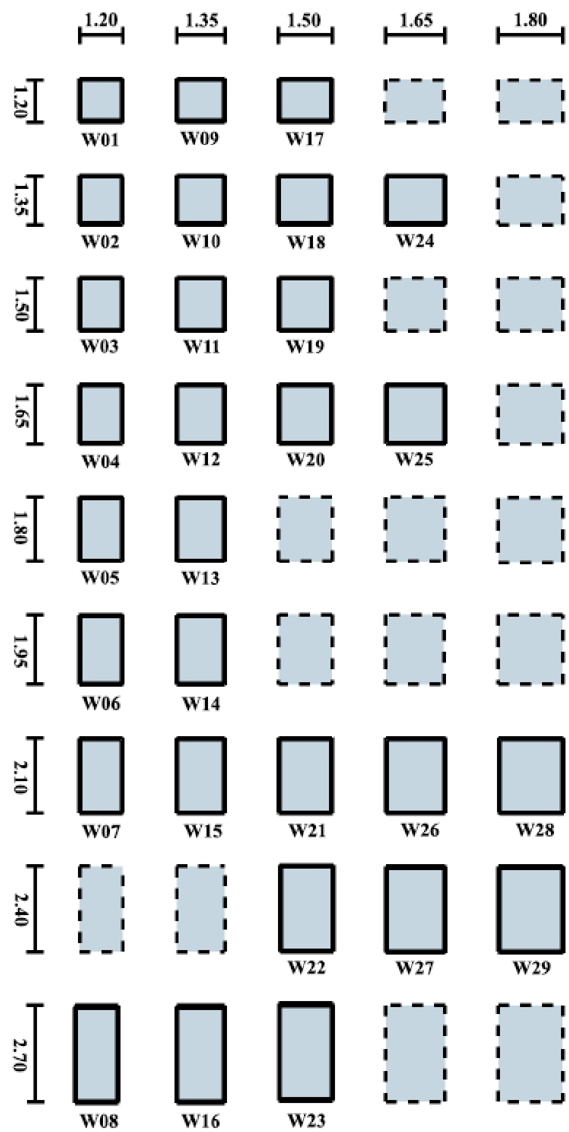


Figure 11. Window in different WHR on the façade (Qasemzadeh, 2012).

In the third step, the parametric method and its output based on total energy consumption (kWh/m^2) are used to determine the efficient amplitude of the building orientation parameter in order to evaluate the energy performance. This method leads to 72 simulation cases. Building orientation is important, since it improves protection from the summer sunlight and access to the winter sun. If one aims to design a solar efficient structure, the first step is gaining an insight through the geometrical relationship between the sun and earth, thereby helping to make a suitable orientation of the building regarding the location of the sun. Based on previous research, the optimum orientation for a region with a moderate climate is 17.5° from the south to south-east direction (Mahmoodi, 2012). Moreover, Mahmoodi concluded that the most appropriate orientation during the year is 30° from the south to south-east direction. It shows that the north side of the building is suitable in warm seasons, and spaces not requiring the direct sunray are situated in this part (Kasmaei, 2003). To simultaneously investigate the energy performance of both façades (north-south), the building is rotated in the Design Builder software on the parametric basis. The considered building is routed with the azimuth angle from 0° to 360° with 5 increments creating 72 BO intervals (Figure 12). In fact, different BOs are investigated aiming at conducting an in-depth investigation of the influence of WWR and WHR on the energy performance.

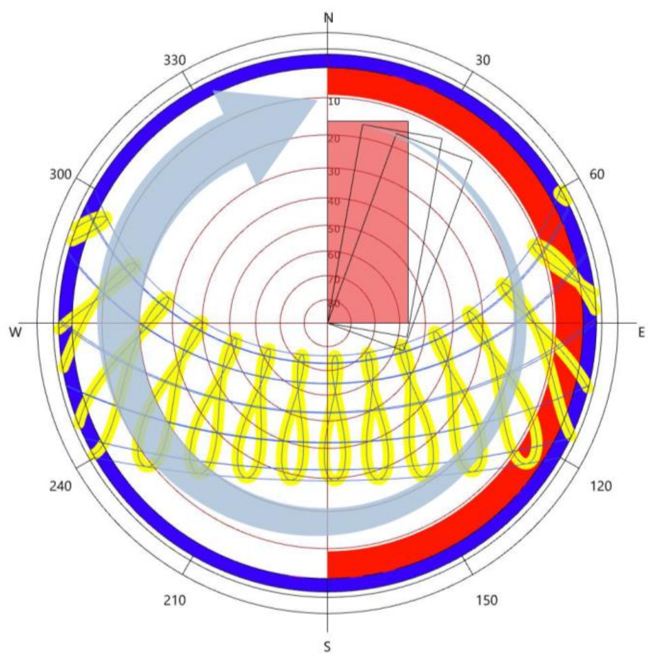


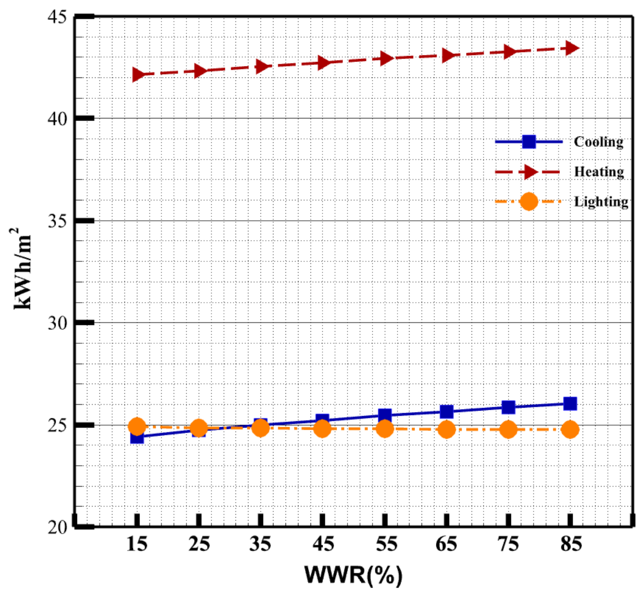
Figure 12. The tested residential unit in different orientations.

3. RESULTS AND DISCUSSIONS

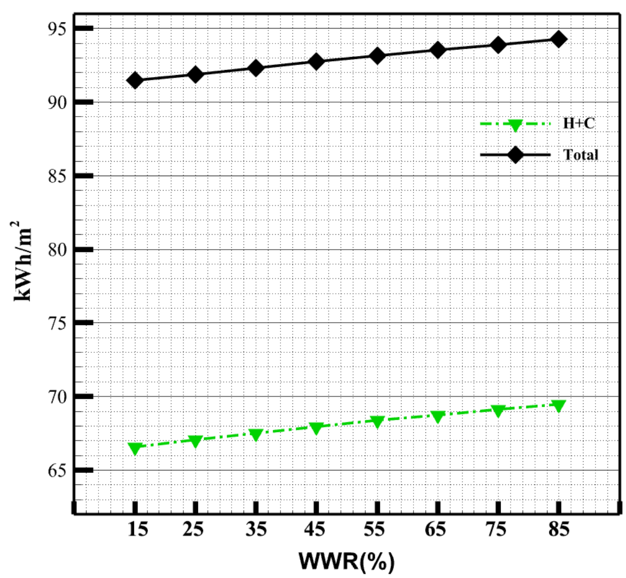
After simulating the building, parameters, such as cooling, heating, lighting, H+C, and annual total energy consumption, are calculated by considering WWR, WHR and BO in Rasht with mild and humid climates.

3.1. THE IMPACT OF WINDOW-TO-WALL RATIO ON ENERGY CONSUMPTION

Figure 13 (a) and (b) depicts the correlation between WWR and energy consumption in the northern façade. According to these simulation results, as WWR increases from 15% to 85%, the cooling load increases moderately compared to the heating load experiencing a slight upward trend, and lighting remains constant. As the window-to-wall ratio increases, solar heat gain rises and leads to an increase in the cooling load in the summer and spring. In addition, the northern façade with the high window size wastes energy mostly in the winter by convection mode of heat transfer. The case with WWR of 15% has the lowest cooling load equals 24.42 kWh/m^2. This value of the cooling load increases by 2 kWh/m^2, when WWR increases to 85%. Similarly, the same scenario occurs for the heating load value; this value rises from 42.13 kWh/m^2 to 43.45 kWh/m^2, while WWR increases from 15% to 85%. The effects of WWR on the lighting consumption are marginal in the northern façade. It is necessary to mention that since the heat generated and the energy consumed by electric lighting are no longer negligible, it is therefore imperative to combine the energy demand for lighting into the total energy consumption of the building. Considering the fact that the daylighting metrics are disregarded in the present paper due to our objective, which is investigation of the determinate variables through passive solar design, we use the total heating and cooling as an index to determine the optimal WWR for the southern or northern façade. To determine the most optimum WWR for a north-facing window, we consider the total energy consumption and the H+C index. Although the influence of the window to wall ratio facing north is marginal, the window ratio of 15% has an effect on energy cooling and annual total energy consumption. These findings are similar to the previous study conducted by Person et al. (2006) in terms of an increase in cooling demand by north-facing windows. Since this evaluation is conducted for a unit, it can be effective on the whole residential complex with 300 housing units. Similarly, Hassouneh, Alshboul and Al-Salaymeh (2021) investigated the optimum amount of WWR in various conditions of internal gains. They concluded that higher solar heat gain and window size led to more efficient heating and less efficient cooling components. Conversely, lower solar heat gain meant less efficient heating and more efficient cooling components (Goia, 2016); however, there was an exception. In the northern direction, the energy losses exceeded the energy savings; therefore, it contains negative percentages of energy savings (Hassouneh, Alshboul and Al-Salaymeh, 2021).



(a) Cooling, heating, lighting consumption in the different WWRs.

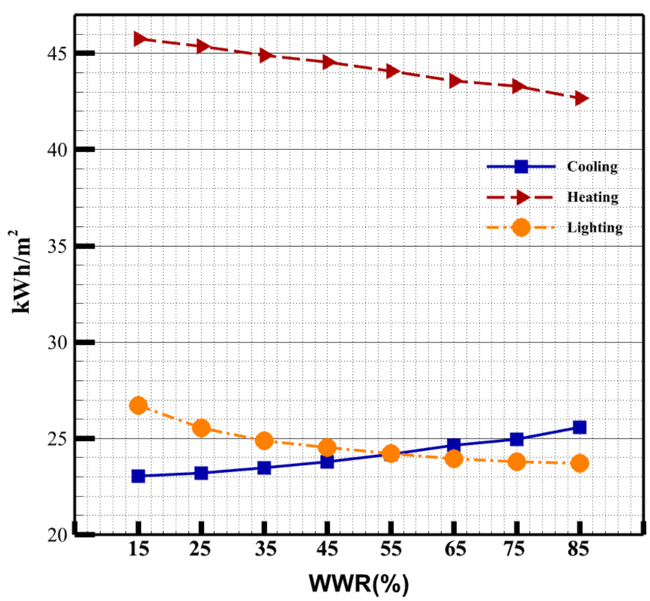


(b) H+C and total energy consumption in the different WWRs.

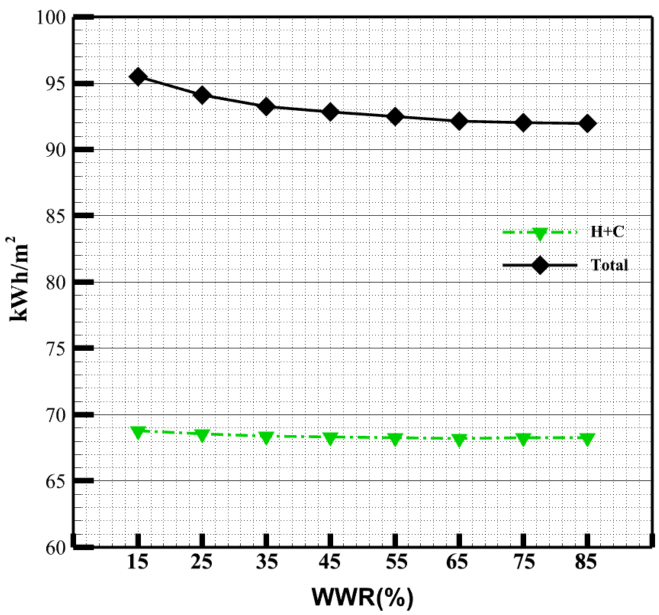
Figure 13 (a) and (b). Energy consumption of the residential unit with different window-to-wall ratios on the northern façade.

In the southern façade shown in Figure 14 (a), the large size of the window improves the heating load in the winter, while it worsens the cooling load in the summer. Since Rasht is in a heating-dominated climate, the need for heating load decreases from WWR=15% (heating load equal to 45.73 kWh/m^2) to WWR=85% (heating load equal to 42.67 kWh/m^2) due to high solar heat gain.

Similarly, the lighting load decreases from 26.71 kWh/m^2 to 23.70 kWh/m^2 by increasing the window size. On the contrary, the consumption of cooling energy rose from 23.03 kWh/m^2 to 25.58 kWh/m^2 gradually by rising the window-to-wall ratio in the southern façade. It is similar to the northern façade due to the amount of solar radiation entering through transparent areas. This radiation affects indoor air temperature, and the need for air-conditioning and ventilation grows. The total annual energy consumption in Figure 14 (b) shows that the most optimum WWR is 85% in the southern facade. However, the total heating and cooling are considered the reasonable index to determine the optimal WWR and make a trade-off between heating and cooling load without regarding artificial lighting consumption. Consequently, the most efficient WWR in the southern façade is 65% with an energy index of 68.21 kWh/m^2. Gasparella et al. (2011) and Alghoul, Rijabo and Mashena (2017) studied the range of WWR in the south façade and found that reducing window size led to the reduction of heat gain, solar radiation, and cooling load. Furthermore, increasing the window size reduces the heating load. Based on this study, WWR on each facade decreases the total energy consumption up to 3.5 kWh/m^2 on the average, demonstrating that the effect of WWR on the temperate climate is not considerable. Similarly, Susorova et al. (2013) concluded that geometry factors like WWR would decrease the energy consumption in hot climates up to 14%, whereas energy saving in temperate and cold climates is marginal.



(a) Cooling, heating, lighting consumption in the different WWRs.

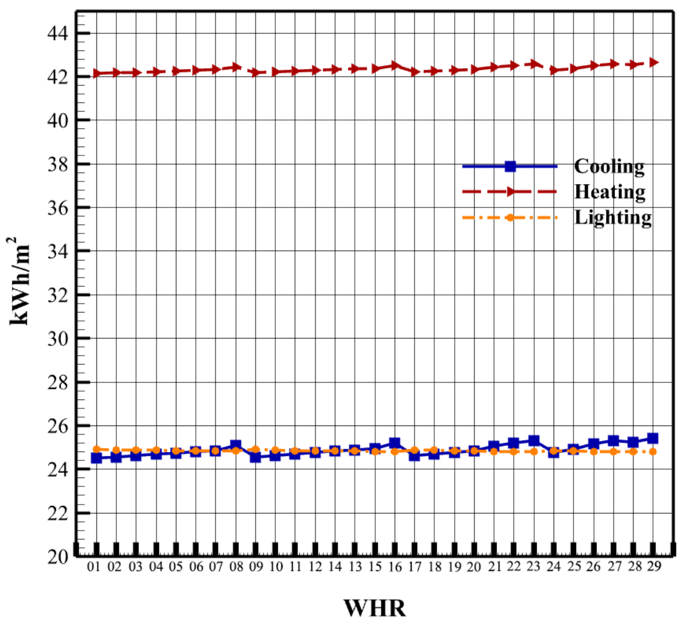


(b) H+C and total energy consumption in the different WWRs.

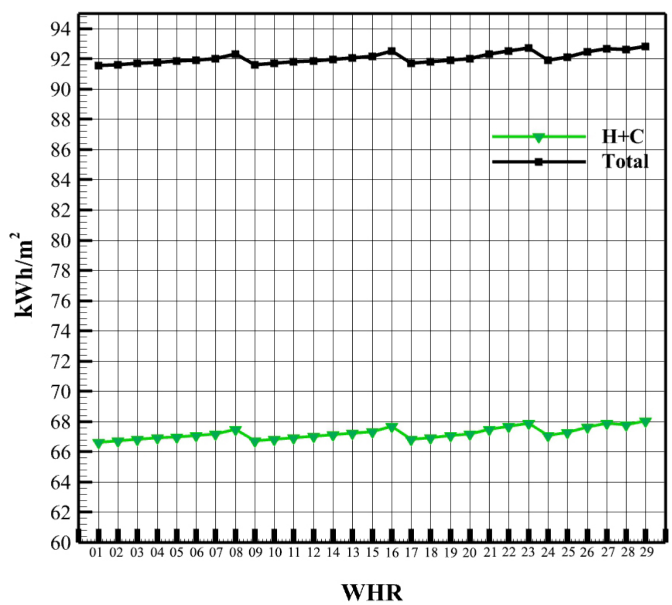
Figure 14 (a) and (b). Energy consumption of the residential unit with diverse window- to- wall ratios on the southern façade.

3.2. THE IMPACT OF WHR ON ENERGY CONSUMPTION

Regardless of WWR, the conventional width-to-height ratios of windows are used through Iranian dwellings. These ratios are investigated to provide the optimum amounts of parameters for architects and engineers. As Figures 15 (a) and (b) show, the results of simulation reveal that windows with a rise in the height and the constant width or vice versa have more impact on heating and cooling loads than on lighting. In fact, as the height or width increases in the north facade, the consumption of heating and cooling rises slowly. It is vital to mention that although the effect of window aspect ratio is marginal on the energy consumption in the northern facade, the recommended WHR is 1.2×1.2 (W01) and an area of 1.44 with 91.54 kWh/m^2. On the contrary, windows with a width of 1.8 and a height of 2.4 and an area of 4.32 (W29) with an energy index of 92.84 kWh/m^2 consume the highest total energy for heating, lighting, and cooling.



(a) Cooling, heating, lighting consumption in the 29 scenarios of WHRs.

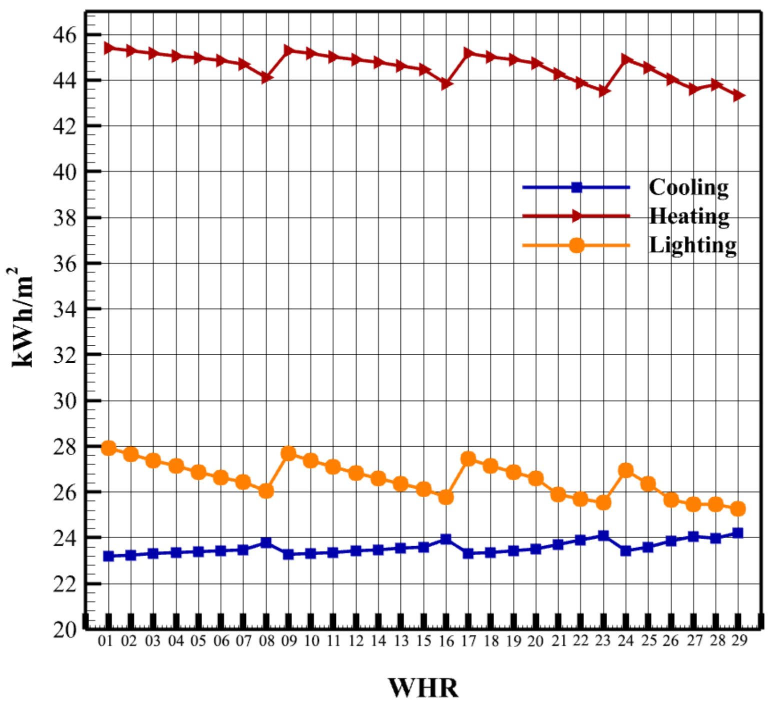


(b) H+C and total energy consumption in the 29 scenarios of WHRs.

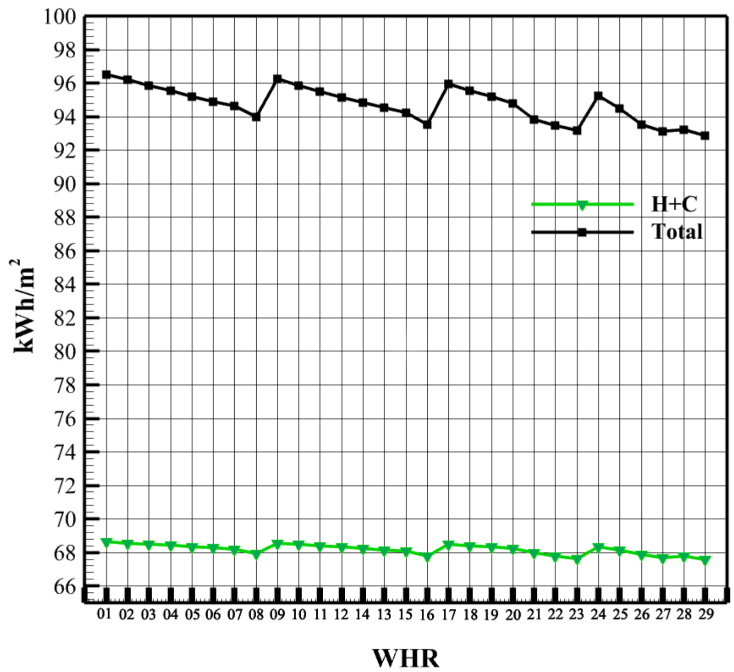
Figure 15 (a) and (b). The impact of north-facing windows with diverse width -to- height ratios on the energy consumption.

According to Figures 16 (a) and (b), the width-to-height ratio is more effective on southern façades than on north ones. By increasing the height and width, the heating load decreases moderately from (W01) 45.40 kWh/m^2 to (W29) 43.34

kWh/m². Similarly, the lighting load decreases by an increase in the area from 27.91 kWh/m² to 25.27 kWh/m². On the contrary, the need for cooling increases gradually by increasing the width-to-height ratio. The previous study conducted by Manigandan et al. (2016) indicated that the natural ventilation depended not only on the size of windows, but also on the orientation of the inlet and outlet. The air inflow rate changes owing to window size changes. Buildings with adequate ventilation keep the heat away from the building; thus, less energy is required to cool the building by the forced system (Manigandan et al., 2016). Regarding the total energy consumption and H+C, W01, W02, W09 and W17 cause the energy consumption to increase; while, the best choices of the conventional WHR used by architects in Iran are as W29 (1.8×2.4), W27 (1.65×2.4), W23 (1.5×2.7), W28 (1.8×2.1), W22 (1.5×2.4), W26 (1.65×2.1), and W16 (1.35×2.7), respectively.



(a) Cooling, heating, lighting consumption in the 29 scenarios of WHRs.



(b) H+C and total energy consumption in the 29 scenarios of WHRs.

Figure 16 (a) and (b). The impact of south-facing windows with diverse width -to- height ratios on the energy consumption.

2.5.THE IMPACT OF BUILDING ORIENTATION ON ENERGY CONSUMPTION

Buildings with optimum design and the most efficient orientation have a remarkable impact on the natural daylighting, solar heat gain during cold season, and ventilation. They cause a reduction in the heat gain through the window during hot times of the year. Finding the best orientation of building, which provides the maximum usage of these natural factors, causes a decrease in energy consumption [34]. As Figure 17 depicts, a building with an azimuth angle of 0° with north and south-facing windows consumed the lowest total energy (97.98 kWh/m^2). It is worth mentioning that the rotation of buildings from northwest to northeast is more efficient than other directions. In other words, energy consumption decreases from 345° (99.39 kWh/m^2) to 20° (99.43 kWh/m^2). Subsequently, as the building is rotated from 20° to 100° while windows are on west and east façades, there is overheating due to the sun's low angle, and energy consumption rises sharply to 109.03 kWh/m^2. Energy consumption slumps rapidly as long as the building orientation meets the south direction. Thus, the second efficient amplitude for building orientation is from southeast (175°) to southwest (190°). The value of energy usage in this amplitude is between 99.72 kWh/m^2 and 99.96 kWh/m^2. These amplitudes certify the findings of simulations conducted by Xu et al. (2012); Tokbolat, Tokpatayeva and Al-Zubaidy (2013) and Abanda and Byers (2016). According to these findings, the north and south facing orientations are discovered to be the most energy efficient orientations. The BO trend experiences the rapid surge and hits the peak load at an azimuth angle of 270° with 109.49 kWh/m^2 when the bedrooms and living room are situated in western and eastern sides, respectively. Afterward, as the azimuth angle becomes close to 0°, energy consumption is decreased by 11.33 kWh/m^2. It is necessary to note that the output of the BO is most energy-saving between northwest and northeast due to the rooms located in the north and living room in the south. Moreover, when the living room receives the northern light through the second amplitude (southeast-southwest) and the rooms situated in the south, the energy consumption decreases considerably. This finding is in agreement with previous results reported by Morrissey, Moore and Horne (2011) and Xu et al. (2012). They revealed that the exposure of the living room window to the southerly direction reduced the demand for mechanical heating; however, energy consumption is increased, while this window faces north, east, and west.

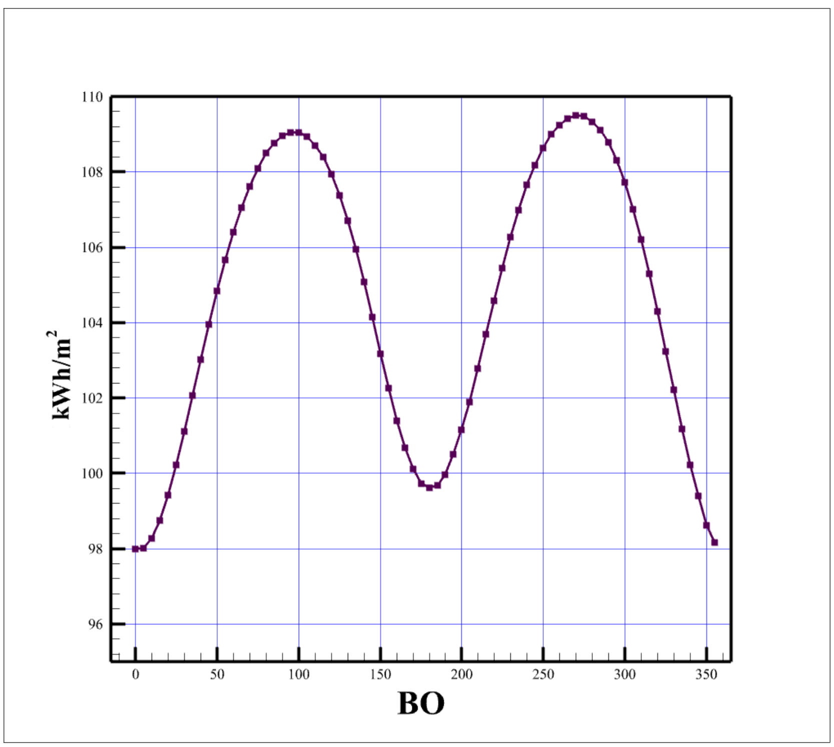


Figure 17. The impact of building orientation on the total energy consumption.

4. CONCLUSION

Designers should consider various parameters of the building, including the glazing system, orientation and other elements of the building to provide the proper daylighting and make a balance between the visual demands of occupants and energy consumption. Consequently, design recommendations based on the passive solar approach are offered in this paper by investigating the complex function of window-to-wall ratio, width-to-height ratio, and building orientation. The determination of the most energy-efficient WWR, orientation and other variables can affect the total annual energy consumption and help to save energy in the long term. Moreover, they are easily implemented at the early stage of design, while a retrofit at later stages may be extremely complex, expensive, and sophisticated. These parameters are analyzed through a segregated process in this paper. The aim of this analysis is to compare the effectiveness of the parameters in the energy performance of the building and to consider all complexities. By simplifying this trend, designers and engineers receive the comprehensive vision of the energy performance of the building. The findings of this paper illustrate that building orientation is found to be the most effective parameter in energy consumption with a percentage of (12%) in a moderate climate. Whereas, there is an optimal building orientation (0°), most of the optimum value can be found in these ranges of 175°< BO <190° and 345°< BO < 20°.

According to WWR, the north-facing windows with 15% opening benefit from the lowest energy use when the amounts of heating, cooling, lighting and total energy are compared to each other. Various WWRs on the northern façade considerably affect cooling load rather than heating or lighting. The most optimum WWR for the southern façade is 65%. To determine the best WWR for the south façade and make a balance between natural light and sunlight, H+C is used as the important index regardless of artificial lighting consumption. Window-to-wall ratio is found to be the second effective parameter to reduce energy consumption by 8% in this region.

The width-to-height ratio of windows in the northern façade has the marginal effect on energy consumption compared to the southern façade, since solar radiation is strong all year round on this surface, particularly in locations with high latitudes. For the north façade, the best choice of the WHRs used conventionally in Iranian housing is W01 (1.2×1.2), and the most optimum WHRs for southern façade encompass W29 (1.8×2.4), W27 (1.65×2.4), W23 (1.5×2.7), W28 (1.8×2.1), W22 (1.5×2.4), W26 (1.65×2.1), and W16 (1.35×2.7), respectively. The suggested

WHRs are mostly regarded as guidelines for designers and help them through the design stage of the façade system in developing countries like Iran, where proper energy efficiency standards for the façade design of residential buildings are not defined.

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