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Climatic, parametric and non-parametric analysis of energy performance of double-glazed windows in different climates

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Abstract

In line with the growing global trend toward energy efficiency in buildings, this paper aims to first; investigate the energy performance of double-glazed windows in different climates and second; analyze the most dominant used parametric and non-parametric tests in dimension reduction for simulating this component. A four-story building representing the conventional type of residential apartments for four climates of cold, temperate, hot-arid and hot-humid was selected for simulation. 10 variables of U-factor, SHGC, emissivity, visible transmittance, monthly average dry bulb temperature, monthly average percent humidity, monthly average wind speed, monthly average direct solar radiation, monthly average diffuse solar radiation and orientation constituted the parameters considered in the calculation of cooling and heating loads of the case. Design of Experiment and Principal Component Analysis methods were applied to find the most significant factors and reduction dimension of initial variables. It was observed that in two climates of temperate and hot-arid, using double glazed windows was beneficial in both cold and hot months whereas in cold and hot-humid climates where heating and cooling loads are dominant respectively, they were advantageous in only those dominant months. Furthermore, an inconsistency was revealed between parametric and non-parametric tests in terms of identifying the most significant variables.

Keywords: Window; Building loads; Energy performance; Principal Component Analysis; Design of Experiment

1. Introduction

The growing trend in the population and lack of accommodation capacity in cities around the world has overshadowed the environmental health of our planet. This affliction, if not managed, will eventually result in irreversible changes and damages to the environment which consequently affects and endangers the biosphere (Haapio and Viitaniemi, 2008). The lack of sufficient non-renewable resources such as oil, coal and natural gas (Aleklett and Campbell, 2003); and some worldwide issues regarding climate change and global warming are two main reasons that make us redouble our efforts to revise current energy consumption patterns (Jonsson and Roos, 2010).

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The majority of countries are taking precautions to enhance the sustainability level specifically in the energy related fields in the construction industry and this is because of the excessive costs of energy and environmental issues relevant to this industry (Orhan, 2000).

Residential buildings amounted to 30% of the country' total energy consumption. Energy use of residential buildings can be reduced through numerous retrofitting actions such as; upgrading of windows, adding internal insulation to walls during renovations and through measures to reduce uncontrolled exchange of inside and outside air (Harvey, 2009). Along with this fact that windows are one of the most important components of buildings, they play a key role in the overall energy conservation plans for buildings. Moreover, the accessibility to outside provided by windows, which has many physical and psychological advantages, positively affects the health, motivation and productivity of occupants (Menzies and Wherrett, 2005a). However, it has been proven that windows act as the weakest thermal component in buildings. Improper insulation and extreme heat transfer attribute of glasses lead to considerable heat and thermal losses.

One way to reduce energy losses through windows is to install double-glazed windows (Orhan, 2000). Window energy performance depends upon window properties as well as the climatic conditions of the location and window's orientation (Burgett et al., 2013). The values of incident solar radiation and, hence, the values of solar heat gain that are useful in offsetting house heating loads, actually depend on local climatic conditions and the direction in which the window is installed. Similarly, outdoor temperatures and wind conditions which determine heat losses by transmission and by air leakage are also dependent on location (Shakouri Hassanabadi and Banihashemi Namini, 2012). During the last decade, many scholarly works were done in order to study and analyze the energy performance of windows with respect to different properties.

2. Review of the previous studies

Karlsson et al. (2001), developed a simple method for assessing the performance of windows in terms of energy consumption and cost based on three main categories; Climate data (direct and diffuse horizontal solar radiation), window data (U-factor, total solar energy transmittance, number of pains and the category of the window) and building data (balance temperature and the time interval). Impacts of the thermal transmittance characteristic of walls, roofs and floors on the total energy savings by different types of windows were studied by Singh and Garg (2009). It was shown that savings by a window depend upon window type, climatic conditions of the place, buildings dimensions, its orientation and thermal transmittance of its wall and roof among which; the last two factors play a critical role in saving energy.

Menzies and Wherrett (2005) studied about four buildings to rate the comfort and sustainability level based on diverse types of multi-glazed windows by concentration on the energy used to emphasize the importance of architectural design on the multi-glazed windows performance. Persson et al. (2006) evaluated the different dimension of windows in terms of energy performance for low energy houses during winter and summer by changing the orientation in Gothenburg. It was illustrated that by reduction in window area, there is a specific enhancement in performance of energy in winter. Gasparella et al. (2011) concluded that window surface does not have a significant role in winter energy requirements but, on the other hand, solar transmittance is the most effective parameter which conducts the major needs for energy in both winter and summer. Furthermore, energy transfer and sunlight absorption rate were analyzed for single and double-glazed windows for wintertime and it was found that around 40% of the solar energy was absorbed (Frederick, 2013). The need for the importance of daylighting and appropriate set of reference data for windows was also highlighted through a comprehensive study regarding the possibilities and limitations of energy performance evaluation (Trząski and Rucińska, 2015).

As a holistic view on the previous studies and in majority of the researches conducted in this field (Singh and Garg, 2009; Tian et al., 2010; Burgess and Skates, 2001; Maccari and Zinzi, 2001; Tahmasebi et al., 2011), the performance of the window was analyzed based on its impact on the annual energy consumption. In this paper, heating and cooling loads are used as the basis of comparison. It should be noted that these are heating and cooling loads, not energy loads. These loads determine how much cooling or heating is required to maintain spaces in a building within the thermal comfort band (Banihashemi et al., 2012). However, energy consumption depends on the efficiency of the devices used in cooling or heating those spaces and apparently, for the same load, different devices with different efficiencies result in different energy consumptions. Therefore, using cooling or heating load as the basis of the comparison shows a more realistic view in terms of the impacts of windows on buildings.

Additionally, many works (Tian et al., 2010; Karlsson and Roos, 2004; Rijal et al., 2007; Citherlet et al., 2000) studied the performance of windows by using a simple box representing a room or a house. However, the complex interconnections of the zones within a building (e.g. adjacency to warmer or cooler zones such as kitchen or staircase) and the impacts of inter-zonal gains and losses on total loads cannot be studied by using a simple box. Consequently, the role that windows play in augmenting or reducing loads due to those inter-zonal losses or gains is ignored and this leads to unrealistic energy performance results.

As the campaign to raise international awareness toward saving the environment is growing and along with the growth in construction activities, it has become imperative that if design tools are to be provided, they can give insights into the sustainability of a building at an early design stage itself, and helps the design team to incorporate the sustainable solutions in a building initial design process (Hassanabadi et al., 2012). The need for analyzing energy performance of available building components for various climatic conditions by considering most effective variables- as much as possible- is perceived more than ever.

Moreover, in recent years, different methods have been used to refine the initial list of variables and simplify the building energy simulation procedures to glean precise but concise results (Jaffal et al., 2009; Lee et al., 2001; Pisello et al., 2011; Sowell and Haves, 2001; van Treeck and Rank, 2007). In 2009, a simplified approach was developed to estimate the heating load of buildings through Design of Experiment (DOE) application in which the number of alternatives was optimized to reduce the efficient simulation (Jaffal et al., 2009). Furthermore, a combination of different methods of Principal Component Analysis (PCA), dynamic simulation, sensitivity analysis and experimental activity was employed to offer an advantageous simulation if buildings in terms of time and spatial resolution (Pisello et al., 2011). In fact, utilizing dimensional reduction techniques for the whole building energy performance simulation seems unavoidable because doing so in the annual basis with high temporal resolution (seconds to hours) restricts the spatial resolution to a rough zonal discretization. However, no attempts have been made to investigate the accuracy of utilizing these methods and reveal the possible impacts they may have on the results.

Therefore, in line with the growing global trend toward energy efficiency in buildings, this paper aims to first; investigate the suitability of double-glazed windows for residential buildings in terms of saving energy in four typical climates of cold, temperate, hot-arid and hot-humid and second; compare the outputs of applying two dominant methods of Design of Experiment (DOE) as a parametric and Principal Component Analysis (PCA) as a non-parametric test in identifying the factors dimension reduction for the simulation of double glazed windows. In this research, Iran was used as a test bed because the authors are from Iran and they are familiar with the condition of this country. Furthermore, having various climatic conditions has made Iran as an ideal one for conducting this research.

Iran is a vast country and due to its geographical situation, climatic conditions differ from each other and from part to part. Central arid and semi-arid regions of Iran are surrounded in the north by the Alborz and in the west by the Zagros. These mountain ranges form a barrier against the infiltration of rainfall to the central parts of Iran. In general, three major factors of sea neighborhood, elevation and large atmospheric system contribute to determination of Iran's climate regions (Modarres and Sarhadi, 2011). These three significant factors divide Iran into four climatic areas; temperate, cold, hot-humid and hot-arid climates that can also be found in other corners of the globe (Soflaee and Shokouhian, 2005). *Temperate Climate* (*Caspian Beaches*): high humidity is a common problem in this region and in terms of human comfort, relatively hot summers and rather cold winters are the climatic features of these regions. *Cold* (*Mountains-High Foothills*): due to cold and dry climate, these regions have temperate summers but very cold winters. *Hot-Arid Climate* (*Semi-high Foothills*, *Plains and Deserts*): summers are rather hot and dry and winters tend to be cold. In these regions protection against cold winters requires more attention compared to that in hot summers. *Hot-humid Climate* (*Beaches*, *Oman and Persian Gulf Islands*): very hot and humid summers and mild winters distinguish these regions from others. Measures to mitigate severe heat and high humidity, are of great importance in these regions (Moradchelleh, 2011). It is worth noting that currently, the proportion of using single-glazed and double-glazed windows in existing residential buildings of Iran are 65% and 35% respectively (Energy Management in Buildings, 2007) and these figures put more highlight on the need for doing relevant extensive research in this context.

3. Research methodology

As stated by Karlsson and Roos (2004), there are four main methods to evaluate a window energy analysis

(1) Comparison based on the physical properties of windows.
(2) Using empirical coefficients based on the energy balance of windows for different climatic conditions and building orientation.
(3) Incorporating simple building properties to distinguish between different building types.
(4) Performing a full scale simulation including climatic data, building type and properties. Category 4 provides accurate results (provided the simulation model is correct) but it also requires a lot of input data, which are not generally available, and experienced users.

This paper uses the fourth method for analyzing the performance of windows in the context of Iran. This model is based on the assumption that windows have direct impacts on the heating and cooling loads of building, which consequently affects the energy loss and consumption and the other building envelops including walls and roofs are excluded. To limit the scope of this study, the following criteria were taken into consideration:

- The simulated case should represent a typical residential building type with common materials used in its envelope in Iran.
- The analysis process should encompass all climatic conditions of country.
- Parametric and non-parametric analysis methods have a wide range of techniques but in this research, DOE and PCA, as the most dominant ones, were selected for being compared.

As a result, a four story building consisting of two symmetric units on each floor was selected for simulation representing the conventional type of residential apartments. The total area of the building is 527 m^2 and the ratio of the total window area to total floor area is 22.8% (Fig. 1). It was modeled in Revit Architecture and exported to Energy plus software for energy analysis purposes. A conventional 22 cm brick wall with two layers of cement mortar and granite stone on the exterior surface and a layer of plaster on the interior side of the wall is used as the exterior wall of the model. The outer surface of the roof is covered by 10 cm layer of asphalt and the inner layer is composed of screed, 15 cm of concrete slab, air gap and 1.2 cm of gypsum which are common materials for covering the roof (Table 1).

Among various factors influencing residential building energy consumption, occupant behavior plays an essential role and is difficult to investigate analytically due to its complicated characteristics (Yu et al., 2011). Management of hours of operation of HVAC is a crucial key in saving energy. The zones must be cooled or heated only when they are occupied. Hence, to simplify the simulation, it was taken for granted that the heating or cooling system in the building becomes active when the inside temperature goes higher or lower than the predefined comfort band. Additionally, it was assumed that residents use mechanical cooling or heating systems for cooling and heating of bed rooms and living room and natural ventilation for the rest of the zones. Also, people use the bedrooms only for resting and spend other times in the living room. For energy simulation, each room in the building was defined as a zone where each zone had its own thermal properties. The thermostat was set between 18 and 26 °C to provide thermal comfort for the occupants. Table 2 indicates the user profile of the zones in the building. Four cities of Rasht, Ardabil, Yazd and Bandar-e-Abbas were chosen as representatives of Temperate, Cold, Hot-arid and Hot-humid Climates respectively (Table 3).

There are many factors to consider in the selection of multi-glazed (double or triple-glazed) windows. These include thermal, aural and visual performance, choice of materials, design, durability and cost. Four physical properties of U-factor, solar heat gain coefficient (SHGC), visible transmittance (VT) and emissivity were the factors taken into consideration for choosing sample windows for the simulation (Menzies and Wherrett, 2005b). Accordingly, one type of casement-single-glazed aluminum frame window which is typically used in residential buildings in Iran was selected as the base window and 25 casement-double-glazed aluminum frame windows, composed of two 6 mm layers of glasses and a 30 mm air gap between them, were chosen from the market for comparison purposes (Table 4).

In order to determine the performance of fenestration systems accurately, considering a plethora of variables such as building types and their orientations, climatic data of the location in which the windows are used, user's profiles such as operation schedules and types of their activities are essential (2009). Therefore in this work, five year weather data (2005–2010) of the selected cities which include monthly average dry bulb temperature, monthly average percent humidity, monthly average wind speed, monthly average direct solar radiation and monthly average diffuse solar radiation were obtained from Iran Metrological

Figure 1. Typical floor plan and perspective of the simulated model.

Table 1
Modeled building properties.

Components	Layer name	Width (mm)	Density (kg/m^3)	Specific heat (J/kg·K)	Conductivity (W/m·K)	*U* Value (W/m^2·K)
Wall	Granite	10	2880	840	3.49	1.88
	Cement mortar	10	1650	920	0.72	
	Brick	220	2000	836.8	0.71	
	Plaster	10	1250	1088	0.43	
Roof	Asphalt	10	2300	1700	1.2	2.56
	Screed	25	950	656.9	0.209	
	Concrete slab	150	2300	656.9	0.753	
	Airgap	600	1.3	1004	5.56	
	Gypsum	12	2320	1088	1.29	

Organization (Wang et al., 2014; Organization, 2011). Table 5 shows monthly mean values of climatic data for the selected cities. As for the physical properties of windows, variables like U-factor, SHGC, emissivity and visual transmittance along with building orientation and climatic data constituted the parameters considered to be used in the calculation of cooling and heating loads in the residential building model.

In order to measure the impacts of various types of windows on the cooling and heating loads, the properties of other components such as walls, roofs etc. were kept fixed and the simulations were run by varying only the properties of windows. In the end, total numbers of 400 simulations were conducted to calculate the monthly loads of the building for four cities and four orientations. In order to calculate the impacts of windows on the cooling and heating loads, the simulation results of 25 window alternatives were subtracted from the base window simulation values, resulting in monthly saved heating or cooling load. Then, these monthly values were aggregated to obtain annual heating and cooling saved loads.

4. Analysis and discussion

The performance of 25 different types of windows in terms of annual heating and cooling saved loads in the different climates was investigated through thermal simulation and the results are given in Figs. 2–9. The negative amounts in the figures represent the saved loads by the windows vis-à-vis the base window and the positive results show the extra heating or cooling loads required to maintain the comfort level of the spaces within the building for occupants.

4.1. Windows energy performance in the cold climate

Fig. 2 illustrates the saved heating loads for the city of Ardabil in four different orientations as compared to the base window. In all four orientations, W-01 proved to have the highest saving and W-25 the least. The amount of saving ranges from the minimum of 7816 kW·h for W-25 in the north to the maximum of 17934 kW·h for W-01 in the east orientation. North orientation compared to the other orientations receives the least amount of solar energy and therefore rooms located in that orientation require more heating load while in the east, the condition is different and due to the direct solar energy received by the eastern fenestrations, rooms that are facing east require less heating load. In general, due to the low value of U-factor of all the windows compared to the base window, all the simulated windows performed better than the base window, which contributed to the minimum of 19 to maximum of 38 percent of savings in the heating load. Ardabil is a heating dominant city in which based on Table 4, in 10 out of 12 months of the year, the average dry bulb temperature is below the assumed comfort band. Therefore, in cold seasons, due to the existing large temperature gradient between indoor and outdoor temperature, using a window with low U-factor highly contributes to saving in heating load and prevention of heat loss through fenestration.

On the contrary, Fig. 3 also indicates that using double glazed windows with low U-factor does not contribute to any savings for the cooling load in Ardabil. Since, on one

Table 2
Occupants' profiles for the zones.

Zone	Area (m^2)	Volume (m^3)	Occupancy	Activity	HVAC system	Comfort band
Living room	18	51.09	4	Sedentary	Mixed-mode system	18–26 °C
Kitchen	6	17.78	4	Cooking	Natural ventilation	NA
Bathroom	5	13.11	1	Sedentary	None	NA
Toilet	3	9.83	1	Sedentary	None	NA
Bedroom	10	28.16	2	Sedentary	Mixed-mode system	18–26 °C

Table 3
Specifications of four selected cities in Iran.

City	Latitude	Longitude	Climate	Dominant thermal system
Rasht	37.28	49.58	Mild humid	Cooling and heating
Ardabil	38.15	48.17	Cold	Heating
Yazd	31.89	54.36	Hot arid	Cooling and heating
Bandar Abbas	27.18	56.26	Hot humid	Cooling

Table 4
Properties of selected windows for simulation.

Window	U-factor ($W/m^2 \cdot K$)	SHGC	VT	Emissivity	Refractive index of glass	Alt. heavy solar gain	Alt. light solar gain
Base	6.00	0.56	0.72	0	1.50	0.47	0.64
W-01	1.647	0.32	0.59	0.035	1.90	0.32	0.29
W-02	1.703	0.38	0.57	0.036	1.90	0.43	0.60
W-03	1.760	0.22	0.32	0.022	1.85	0.40	0.57
W-04	1.817	0.34	0.44	0.024	1.85	0.38	0.35
W-05	1.874	0.15	0.15	0.042	1.82	0.38	0.34
W-06	1.874	0.27	0.47	0.035	1.80	0.37	0.32
W-07	1.931	0.34	0.59	0.042	1.80	0.35	0.44
W-08	1.987	0.34	0.58	0.042	1.80	0.33	0.42
W-09	2.044	0.21	0.46	0.022	1.78	0.43	0.40
W-10	2.101	0.34	0.51	0.107	1.78	0.40	0.38
W-11	2.158	0.3	0.4	0.024	1.76	0.38	0.35
W-12	2.214	0.38	0.4	0.107	1.76	0.43	0.34
W-13	2.214	0.16	0.16	0.035	1.74	0.35	0.32
W-14	2.271	0.4	0.44	0.107	1.74	0.33	0.29
W-15	2.442	0.44	0.54	0.107	1.72	0.31	0.29
W-16	2.498	0.19	0.14	0.107	1.70	0.35	0.43
W-17	2.555	0.3	0.42	0.035	1.68	0.34	0.56
W-18	2.555	0.15	0.15	0.042	1.66	0.42	0.44
W-19	2.612	0.61	0.66	0.107	1.64	0.47	0.42
W-20	2.669	0.64	0.67	0.107	1.64	0.33	0.40
W-21	2.725	0.55	0.59	0.107	1.64	0.43	0.38
W-22	2.782	0.36	0.49	0.107	1.62	0.40	0.35
W-23	2.839	0.27	0.38	0.035	1.60	0.34	0.43
W-24	3.009	0.4	0.42	0.107	1.60	0.42	0.56
W-25	3.180	0.48	0.57	0.107	1.60	0.47	0.64

hand, in hot seasons the outside temperature of buildings in Ardabil rarely exceeds the comfort band and on the other hand, due to the latent loads inside buildings which lead to the interior to be warmer than the exterior, using a window with low U-factor prevents heat transfer from inside to the outside and therefore increases the cooling load in buildings. In case of cooling load, the base window outperforms the other alternatives and this is because of its high U-factor, which leads to a higher heat transfer. Among the 25 types of double glazed windows, W-25 located in the west with 4 percent and W-01 located in the north orientation with 23 percent have the lowest and highest percent increase in the cooling load respectively. There is a downward trend for the excessive cooling load in buildings in Ardabil as the U-factor increases. However, there are some deviations in some points such as W-05 to W-06, W-13 to W-14 and W-18 to W-19. Table 3 shows that although the U-factors of W-06, W-14 and W-19 are higher than W-05, W-13 and W-18 respectively but in the latter group, the amount of SHGC is much higher. The SHGC is the fraction of the heat from the sun that enters through a window. The lower a window's SHGC, the less solar heat it transmits (2009). As the SHGC of a window increases, more incident solar radiation is transmitted into a room and as a result, more energy is required to balance the cooling load. Therefore, in cases of W-06, W-14 and W-19, higher SHGC compared to the U-factor plays a more important role in increasing the cooling load.

4.2. Windows energy performance in the hot-humid climate

Bandar-e-Abbas is a coastal city in the south of Iran with hot-humid climate. In contrast with Ardabil, using double glazed windows appears to have no benefits in saving heating loads in cold months. As depicted in Fig. 4, the positive values suggest that the base window for all orientations for the city of Bandar-e-Abbas is more advantageous in comparison with other alternatives. The amount of extra heating load required to maintain the comfort level in all directions annually ranges from 118 kW·h in the east for W-25 to 236 kW·h in the west for W-01 which equals to 2–4% more heating load

Table 5
Climatic data of four selected cities in Iran for simulation.

City	Month	Dry bulb temperature	% Humidity	Wind speed m/s
Ardabil (38° 15′N, 48° 17′E)	Jan	−2.6	75	1.3
	Feb	−1.1	73	2.6
	Mar	3.2	73	2.8
	Apr	9.7	66	2.7
	May	13	70	2.1
	Jun	16.6	70	2.4
	Jul	19	68	3.4
	Aug	18.5	70	3.4
	Sep	15.6	73	2.4
	Oct	10.7	74	2.1
	Nov	5.3	74	2.5
	Dec	0.3	74	1.7
Bandar-e- Abbas (27° 18′N, 56° 26′E)	Jan	18.1	65	2.2
	Feb	19.4	68	2.3
	Mar	23	67	3.2
	Apr	26.9	64	2.4
	May	31.3	61	3.3
	Jun	33.8	63	2.9
	Jul	34.5	68	3.7
	Aug	34	69	4.1
	Sep	32.5	68	3.2
	Oct	29.6	65	1.6
	Nov	24.4	61	2.1
	Dec	19.8	63	2.8
Rasht (37° 28′N, 49° 58′E)	Jan	6.9	79	4.4
	Feb	6.9	78	4.5
	Mar	9.1	79	4.2
	Apr	14.4	76	4.8
	May	19.6	76	4.1
	Jun	23.6	72	2.3
	Jul	25.9	72	1.9
	Aug	25.6	75	2.1
	Sep	22.3	80	2.9
	Oct	17.7	82	3.2
	Nov	13	80	3.6
	Dec	9.1	79	4.1
Yazd (31° 89′N, 54° 36′E)	Jan	5.5	54	2.2
	Feb	8.5	44	2.3
	Mar	13.6	38	2.7
	Apr	19.7	33	3
	May	25.3	26	3.8
	Jun	30.7	18	2.2
	Jul	32.5	18	3.2
	Aug	30.6	18	2.1
	Sep	26.4	19	1.6
	Oct	19.6	27	1.8
	Nov	12.2	39	1.6
	Dec	7	50	2

compared to the base window. However, as a cooling load dominant city, the merits of utilizing double glazed windows lie in their savings in terms of cooling load. In fact, the amount of extra heating load imposed by the double glazed windows in comparison with the saved cooling load during the hot months is negligible.

Based on Fig. 5, the amount of average saved cooling load is 143 times more than the average extra heating load in the building. The maximum saving in cooling load belongs to W-18 in the west with 30,726 kW·h while the minimum amount of saving goes to W-20 in the north with 18,148 kW·h. In general, the variation in the performance of each type of double glazed window in three main orientations of east, south and west is inconsequential but in the north, since fenestrations are not exposed to the direct solar radiation and the rooms located in that part of buildings are generally cooler than other sides, the efficacy of double glazed windows in terms of saved cooling loads is not as remarkable as those in the eastern, southern and western windows.

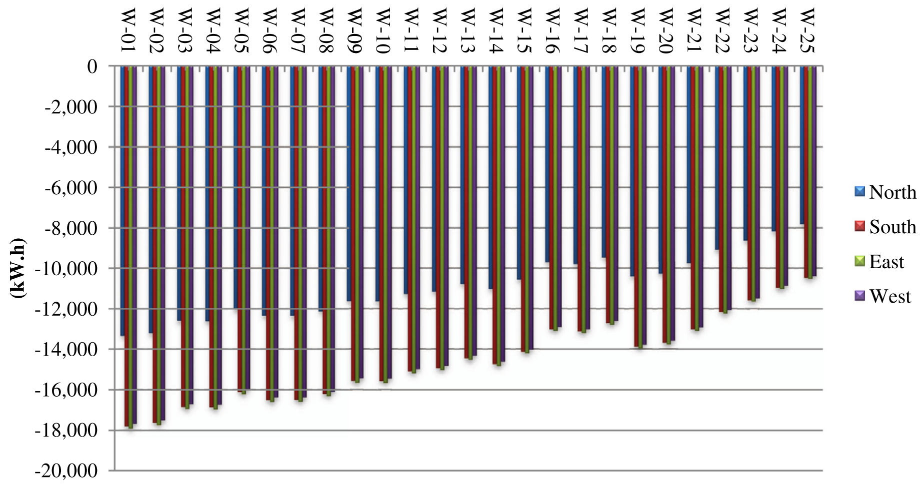

Figure 2. Saved heating load in cold climate by using double glazed windows.

4.3. Windows energy performance in the temperate climate

As located near the Caspian Sea, the temperate climate of Rasht requires buildings to use both heating and cooling devices in cold and hot seasons. Fig. 6 illustrates the fact that utilizing double glazed windows in Rasht as compared to the base window for different orientations with regard to saved heating and cooling loads is profitable. In cold months, the amount of saving for different windows ranges from 14% to 29% in which W-01 in the east orientation with 2,673 kW·h scores the highest and W-25 in the north with 1,196 kW·h scores the lowest for the saved heating load among other window types. Fig. 5 highlights that as the value of U-factor increases; the heat loss through the windows increases as well, resulting in lower saving for heating load. W-01 with the U-factor of 1.647 $W/m^2 \cdot K$ has the lowest and W-25 with the U-factor of 3.180 $W/m^2 \cdot K$ has the highest heat loss. Meanwhile, the contribution of other variables such as SHGC is highlighted from W-18 to W-21. SHGC is a value ranging from 0 to 1 due to the fact that SHGC in W-19, W-20 and W-21 is around 4 times more than that in W-18, it is reasonable that less heating load is required to warm the building by using these windows.

In hot months, the most optimum window in terms of saving the cooling load is W-18 with 5017 kW·h for the west orientation and the least one is W-02 with 1953 kW·h for the north orientation (Fig. 7). As a whole, the performance of windows in the north orientation for the city of Rasht is weaker than the others. One of the reasons to justify this phenomenon can be the impact of sea breeze which is the result of temperature difference between the

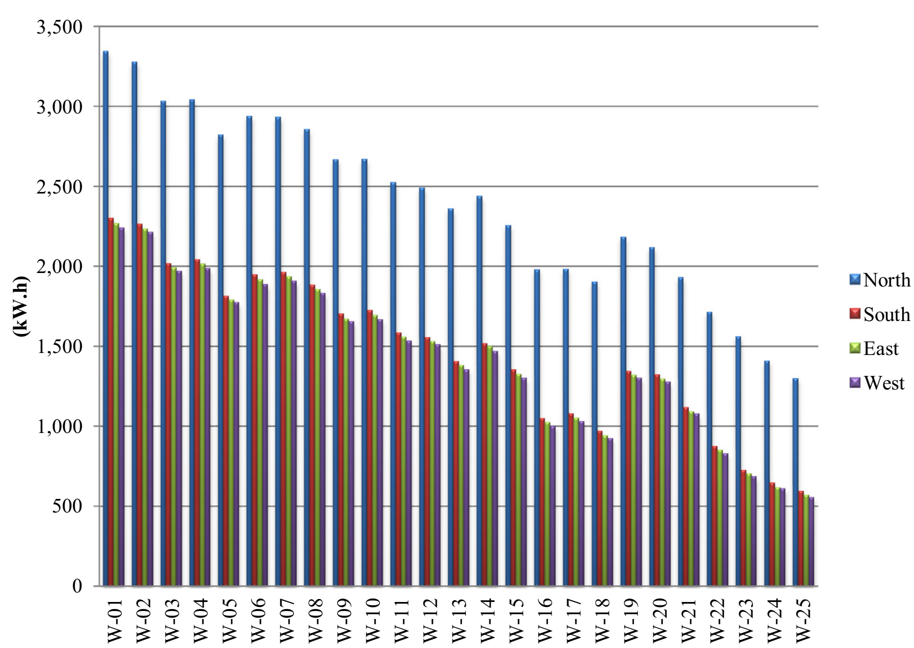

Figure 3. Extra cooling load imposed to the building in cold climate by using double glazed windows.

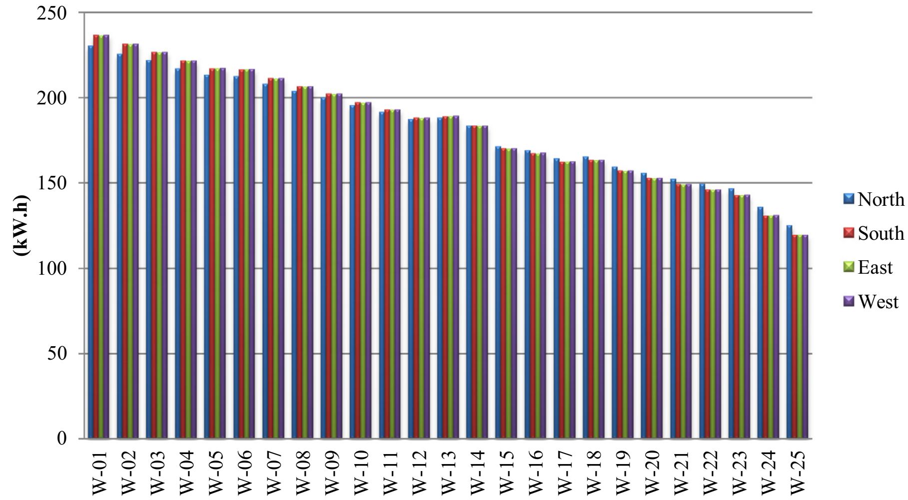

Figure 4. Extra heating load imposed to the building in hot-humid climate by using double glazed windows.

cool sea and hot land. During the day, due to the increase in this difference and development of pressure difference, cool-low-level-sea-breeze blows to the land (Simpson, 1994) and since Caspian sea is located in the north of Rasht, rooms that are in the northern part of buildings are exposed to this breeze during the day which results in having cooler temperature and consequently, less cooling load.

4.4. Windows energy performance in the hot-arid climate

Fig. 8 shows that replacing a single glazed window by a double glazed window is more energy efficient in terms of saving in heating and cooling loads in hot-arid climate. In five months of the year which the average temperature is below the comfort band, for every window, the best performance is observed where the window is placed in the east side of the building. This trend is followed by south, west and north. Once again, W-01 with 3,651 kW·h saving in heating load is considered to be the best choice for buildings in this city whereas W-24 with 1139 kW·h is seen to be the worst alternative. Yazd is one of the driest cities of Iran with summer temperatures exceeding the thermal comfort band and even uncomfortable nocturnal temperature. Winter days are mild and sunny with cold dawns falling below 8° C. The prevailing cold wind blows in December, January and February from south-east to north-west (Ali, 2010) which causes the northern part of the building to have lower temperature gradients in comparison with the eastern and southern parts.

According to Fig. 9, most savings in cooling load for each type of window are achieved when the windows are placed in the west orientation. The simulation results reveal that not only using double glazed windows saves heating load but they are also advantageous to save cooling load. The saved cooling load ranges from 10 percent for W-20 in the north orientation to 17 percent for W-18 in the west orientation. On average, the saved heating load for five cold months of November–March is significantly lesser

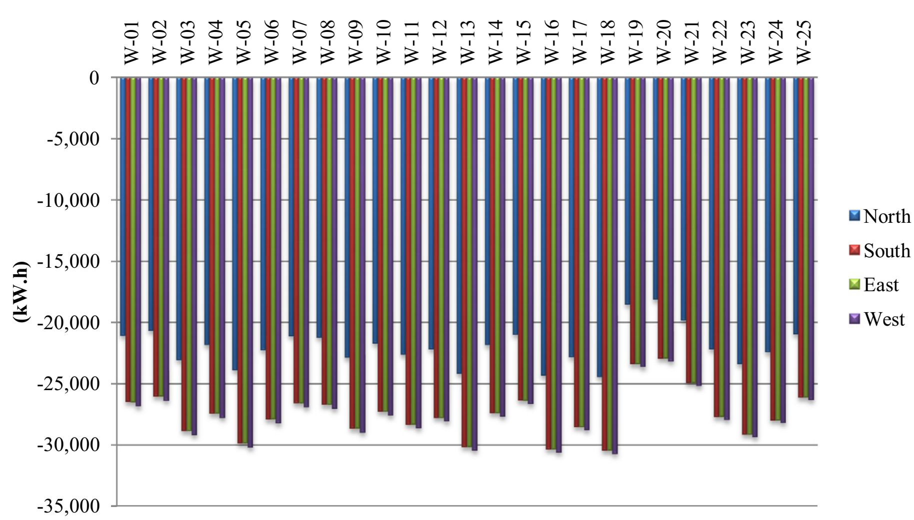

Figure 5. Saved cooling load in hot-humid climate by using double glazed windows.

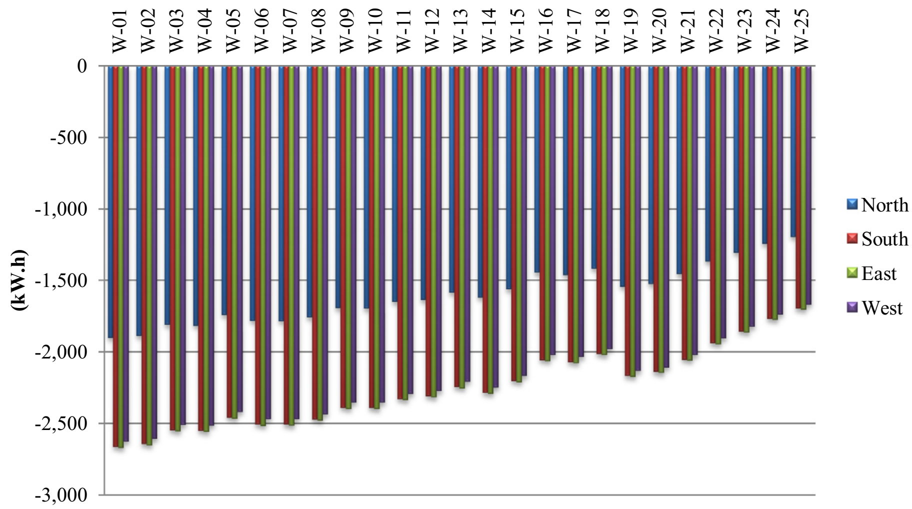

Figure 6. Saved heating load in temperate climate by using double glazed windows.

than the average saved cooling load for five hot months June–October. In fact, the mean of saved cooling loads for all windows in all orientations compared to those for saved heating load is six times greater which highlights the suitability of these windows for the hot months.

As a summary, Table 6 indicates which types of double-glazed windows have in total the best and worst performances in terms of saving energy loads in different climates and cities. It also highlights that the North and West orientations are the most suitable and unsuitable directions for buildings in all four cities, respectively, where the lower energy consumption is a priority. Despite the fact that double-glazed windows enhance energy performance of the buildings, it should be noted that in the hot-humid region (e.g. Bandar-e-Abbas) using double-glazed windows saves relatively higher amount of energy loads in comparison with the other studied climatic conditions.

4.5. Design of Experiment (DOE)

Following the investigation of the energy performance of double glazed windows and their behavior in different climates, the DOE method was used to analyze the level of significance of factors and their relationships with calculated heating and cooling loads (response). This method and PCA that would be introduced in the next section were conducted over the whole climatic conditions but due to the high similarity among the results, the outcomes of the cold climate areas were reported as a representative for evaluations and comparison. This finding also reckons that these parametric and non-parametric analyses are independent from the climatic conditions.

DOE is a broad concept that can be used to design any information-oriented experiment especially where the variation and its observation is of high importance. It is

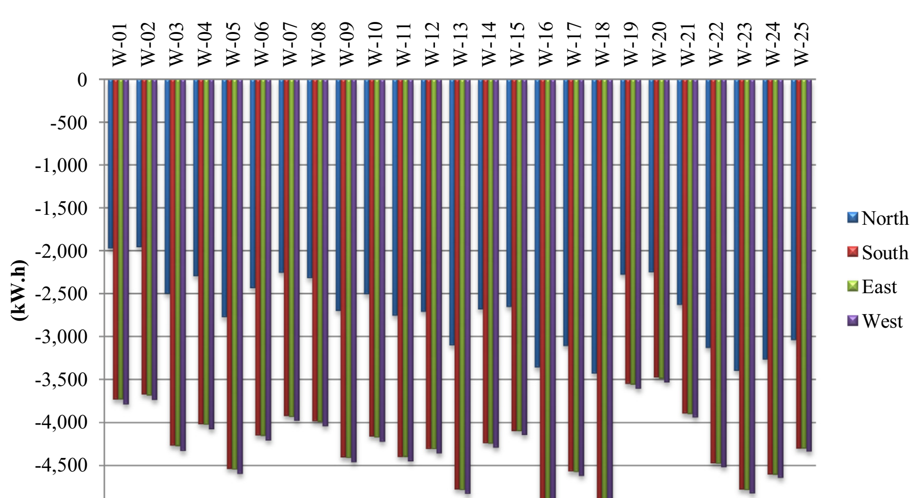

Figure 7. Saved cooling load in temperate climate by using double glazed windows.

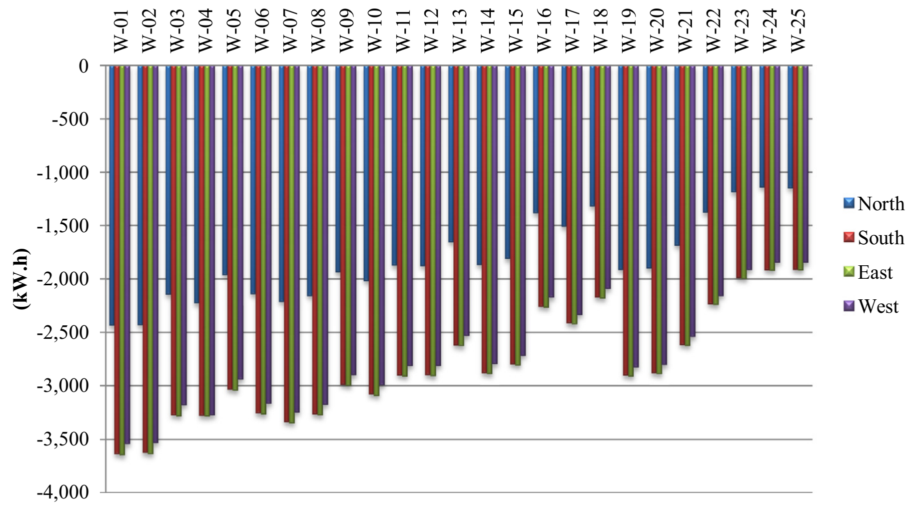

Figure 8. Saved heating load in hot-arid climate by using double glazed windows.

a very efficient branch of parametric tests at evaluating the effects and possible interactions of several factors through its factorial design tool (Bailey, 2008). “The two-level-full factorial design” relies on the approximation of the model by a polynomial expansion of the following equation:

$$F(X) = \beta_o + \sum_{i=1}^{k} \beta_i x_i + \sum_{j>i}^{k} \beta_{ij} x_i x_j + \cdots + \beta_{12\ldots k} \quad (1)$$

“where the x_i’s and x_j’s are the standardized inputs and 2^k coefficients β_i’s mean 2^k possible combinations of the factors multiplied by the specified range of levels of values” (Mara and Tarantola, 2008).

Therefore, a two level of factorial design of highest (+1) and lowest (−1) ranges for the variables of U-factor, SHGC, VT, Emissivity and orientation along with the annually aggregated heating and cooling loads as the response were set and 32 runs (2^5) of equation were calculated (Table 7). It is evident that yearly aggregating of climatic variables does not make sense and so, they need to be excluded from consideration in this stage. In order to depict the results visually, half-normal probability plot was employed that is a graphical tool using the ordered estimated effects to assess which factors are important and which are unimportant (NIST/SEMATECH, 2012).

Fig. 10 indicates the half-normal probability plot for the independent variables used in this study. All effects that lie along the line are negligible, whereas larger ones are far from the line. Hence, the main effects including U-factor and orientation are significant for annual heating and

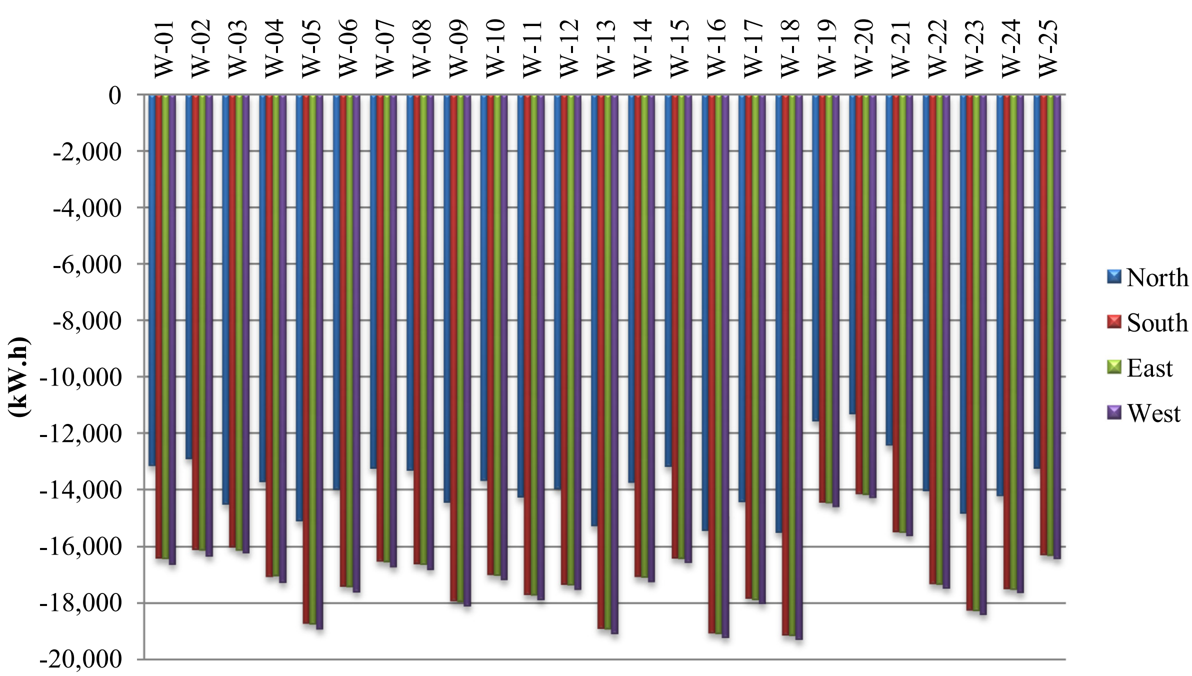

Figure 9. Saved cooling load in hot-arid climate by using double glazed windows.

cooling loads (response) within the levels and conditions tested. The importance of U-factor has been always addressed in the literature but in the present study, in addition to U-factor, it is observed that the parameter of orientation also plays a key role in having an effect on the response. This phenomenon may be a result of this fact that all selected cities for our research have an extreme weather and are the most radical cases among their climatic categories. Hence, variations between direct and indirect exposures of buildings to sun-lights cause more variations in the amount of required heating or cooling loads.

As a tool to check the accuracy of calculations and analyses, the normal probability plot of the studentized residuals is illustrated in Fig. 11. The normal probability plot is a graphical technique for assessing whether or not a data set is approximately normally distributed. The data are plotted against a theoretical normal distribution in such a way that the points should form an approximate straight line (NIST/SEMATECH, 2012). The points on this plot lie approximately close to the straight line, confirming that the errors were normally distributed with mean zero and constant.

4.6. Principal Component Analysis (PCA)

PCA is a non-parametric method to identify underlying variables, or factors that explain the pattern of correlations within a set of observed variables. It is often used in data reduction to come up with a small number of factors that explain most of the variance observed in a much larger number of manifest variables. The following steps were taken into consideration for analyzing the function of this dimension reduction application in this research:

Step 1: As applying PCA for discrete variables is error-prone, the variable of orientation, that is the only discrete one among others, was transformed into a continuous variable through the Kruskal's Secondary Least Squares Monotonic Transformation (Kruskal, 1964):

$$d_{ij} = \sqrt{\sum_{i=1}^{t} (x_{ij} - x_{ji})^2} \quad (2)$$

where d_{ij} are those numbers that minimize the distance of x_i (continues objects) from x_j (discrete objects) in t-dimensional space.

Step 2: PCA matrix containing 31 subsets of combination of variables, based on the direct method (Jolliffe, 2005) rule ($2^v - 1$ where v is the number of variables) was composed.

Step 3: For minimizing the risk of selecting variables with similar magnitude, the Varimax rotation method was applied. In Varimax, each factor has a small number of large loadings and a large number of zero (or small) loadings. This simplifies the interpretation because, after a Varimax rotation, each

Table 6
Best and worst windows in different climates.

Climatic category	Performance level	Window	Orientation	Variation in heating load consumption with the base window (kW·h)	Variation in cooling load consumption with the base window (kW·h)	Overall saved load (kW·h)
Cold	Highest	W01	West	−17,819	2300	15,519
	Lowest	W25	North	−7817	1299	6518
Hot-humid	Highest	W18	West	163	−30,727	30,564
	Lowest	W20	North	156	−18,149	17,993
Temperate	Highest	W13	West	−2211	−4837	7048
	Lowest	W20	North	−1543	−2249	3792
Hot-arid	Highest	W05	West	−2942	−18,946	21,888
	Lowest	W20	North	−1902	−11,323	13,225

original variable tends to be associated with one (or a small number) of factors, and each factor represents only a small number of variables (Kaiser, 1958):

$$v = \sum (q_{i,j}^2 - q_{i,j}^{-2})^2 \quad (3)$$

where v is the Varimax, $q^2_{i,\ j}$ is the squared loading of the ith variable on the j factor and $q^{-2}_{i,\ j}$ is the mean of the squared loadings.

Fig. 12 represents the PCA analysis results for five variables of U-factor, SHGC, emissivity, VT and orientation pre and post-Varimax-rotation. Cumulative percentages of initial eigenvalues as well as other initial ones prove their imprecision in interpretation and deduction of most influential factors. On the other hand, once rotating and obtaining an orthonormal distribution of data, it can be inferred that based on rotation sums of squared loadings, U-factor and SHGC can be easily identified as the most influential factors on the total energy performance of double glazed windows.

Table 7
Factors and response levels.

Elements	Lowest level (−)	Highest level (+)
U-factor (W/m^2·K)	0.29	0.56
SHGC	0.15	0.64
VT	0.14	0.67
Emissivity	0.02	0.11
Orientation	−1	+1
Total load	204,759,264	225,812,336

Moreover, in order to test the accuracy of PCA calculations, scree plot which is one of the non-parametric graphical tools were depicted. This plot presents the corresponding eigenvalue of the variance explained by each component in which as one moves to the right, toward later components, the eigenvalues drop. When the drop ceases and the curve makes an elbow toward less steep decline, scree test says to drop all further components after the one starting the elbow (Jolliffe, 2005). Therefore, it is obvious that all PCA calculations were carried out properly and U-factor and SHGC were affirmed to be the significant components (Fig. 13).

4.7. DOE and PCA analogy

As a similarity, the application of DOE and PCA resulted in 32 and 31 batch of datasets for five variables of U-factor, SHGC, emissivity and orientation in order for parametric and non-parametric analysis of annual energy performance of double glazed windows. This similarity is a consequence of attempts in applying coherent rules for dimensional reduction of the initial used datasets including 100 subsets. However, implementing these almost the same dimensions in DOE and PCA generated different outputs in which through the former method, U-factor and orientation were found to be significant but using the latter one brought U-factor and SHGC into being the most influential parameters. It should be noted that the required validation tests such as half-normal probability and scree plots were taken for corroboration of the results. Furthermore, DOE and PCA are among approaches that have no parameters to be tweaked or coefficients to be adjusted by

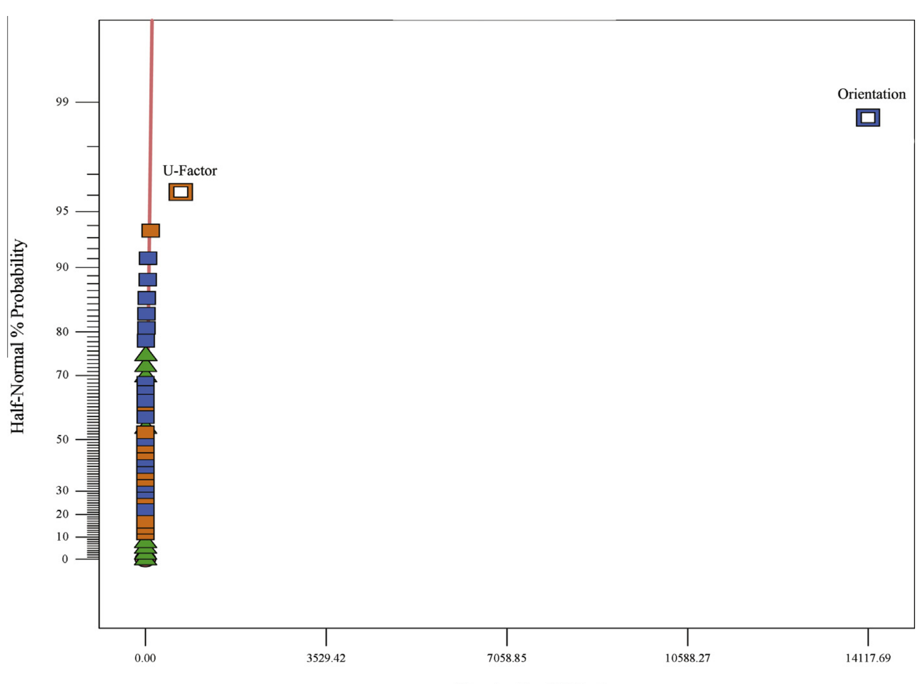

Figure 10. Half-normal probability plot for the independent variables.

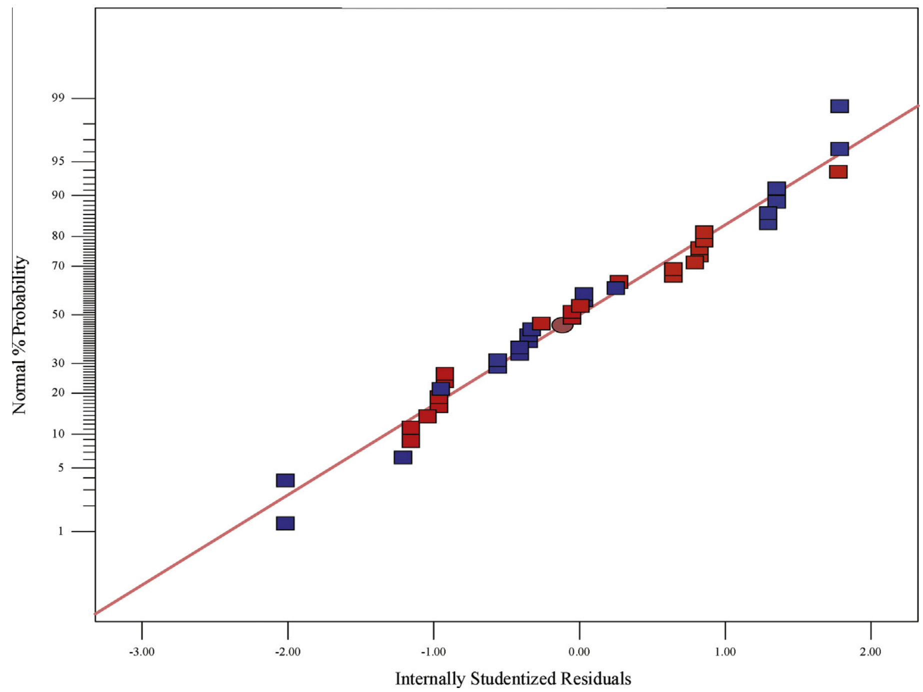

Figure 11. Normal probability plot of residuals.

user experience and so their answers are unique and independent from users. In the holistic view, this inconsistency may be considered minor and its possible impacts may be neglected but through a close scrutiny, when it is to simulate windows energy performance as the most thermally weak component of buildings and reduce its factorial dimension, it can be concluded that omitting factors of orientation or SHGC which have no multicollinearity interrelationships significantly affect the results.

All in all, it is rather difficult to simulate a comprehensive energy modeling for buildings and associated components due to the complicacy of interrelationships among a wide range of parameters such as climatic, physical and occupant-oriented variables. That is why researchers and practitioners use statistical dimension reduction techniques to narrow down the factors into the most significant ones. The found inconsistency between the two most dominant methods of DOE and PCA address the risk of an

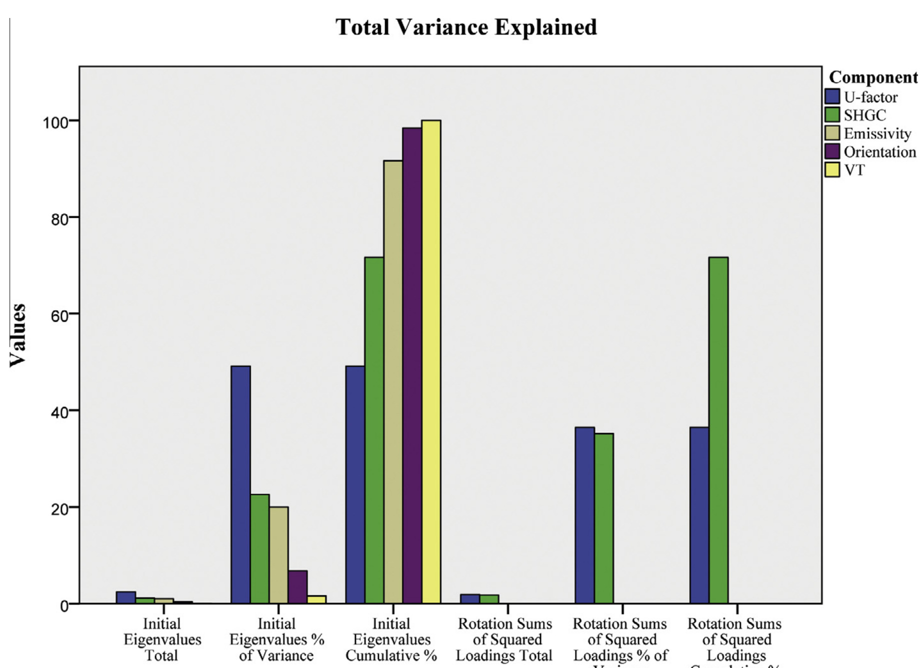

Figure 12. Total variance explained by PCA.

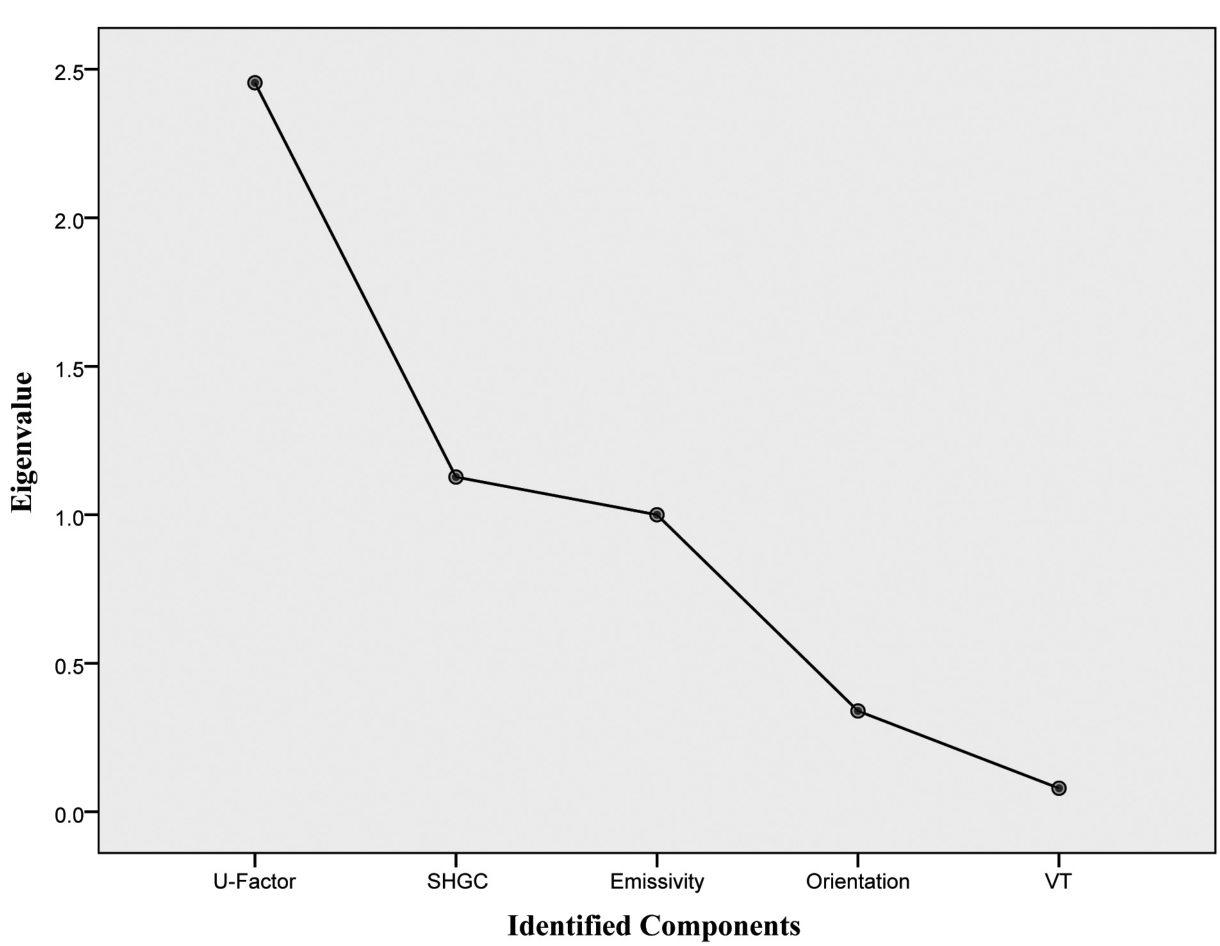

Figure 13. Scree plot for PCA components.

inaccurate simulation and an imprecise energy performance analysis of building envelopes as a serious repercussion.

5. Conclusion

It was observed that windows act differently in terms of energy performance depending on the location, climatic condition and physical properties. In two climates of temperate and hot-arid, using double glazed windows was beneficial in both cold and hot months whereas in cold and hot-humid climes where heating and cooling loads are dominant respectively, they were advantageous in only those dominant months. Using double-glazed was advantageous for saving energy loads in overall of the four climates nonetheless; using this type of windows in the hot-humid climatic conditions proved to have considerably higher values of saved energy than the others. Since the cities chosen for simulations are the representatives of extremely cold, hot and moderate climates, conducted analyses can be reliable for other cities worldwide that have similar climatic condition extending the applicability range of this study.

An inconsistency was detected between parametric and non-parametric investigation of DOE and PCA when the dimension reduction strategy performed for involved variables of energy performance simulation for double glazed windows. This lack of conformity between the results, in spite of applying coherent rules and validation tests, widens the gap of actual and simulative-based analysis and may lead to a distorted view toward energy performance of different components.

Each research faces some challenges and limitations in its development process and this study is not an exception of this rule. Generally, in doing an energy simulation based study, researchers who are to investigate the effects of a specific component on the energy consumption of a building, keep other parameters fixed and just focus on the relationship between the variable and its target. Therefore, this paper did not consider the effects of other variables such as ventilation and infiltration as well as other building envelopes like wall, roof and shading while the interaction of these components may affect the results of this study.

The present study took a step toward more energy efficient buildings by providing succinct information regarding the performance of windows and aimed at examining current methods of dimension reduction of building energy simulation. Further research is recommended for analyzing more components and variables and assessing the possible impacts of such an inconsistency in the final energy outputs.

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