The Relation of Orientation and Dimensional Specifications of Window with Building Energy Consumption in Four Different Climates of Köppen Classification

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Abstract: Building energy consumption can be altered by its exterior fenestrations to a great extent. Window, as the most prevalent opening in building skin, needs precise attention in design to avoid excessive undesirable energy loss or gain. Window affects Heating, Ventilation, and Air Conditioning (HVAC) loads of a building. Based on the amount of using natural light, it also plays an important role in determining the lighting energy needed for a building. Different features of window can affect internal energy requirements like Window to Wall Ratio (WWR), orientation, proportion (length to height), and placement of the window in an exterior side of a building. These characteristics of window should be considered with the climatic and geographical features of the building site. In this research, it has been tried to have an investigation on the relation of aforementioned parameters of window and the HVAC and lighting energy loads required for the case study buildings in diverse climatic zones and the aim of this study was to conclude some guidelines about efficient window parameters in different climatic zones, specially, for preliminary phase of design. It has been concluded that a 20-32% WWR for total exterior walls (25-40% window size) is an efficient ratio as an optimum for reducing HVAC and lighting systems loads. The lower effects of solar energy because of the sun angle and huge heating load required in higher altitudes put this ratio lower. On the other hand, in the lower altitudes (specially, second quarter section or 22.5° to 45° N or S), the energy loads of the building can be altered significantly by solar energy.

[Kheiri, F. **The Relation of Orientation and Dimensional Specifications of Window with Building Energy Consumption in Four Different Climates of Köppen Classification,** *Researcher* 2013;5(12):107-115]. (ISSN: 1553-9865). http://www.sciencepub.net/researcher. 15

Key words: energy efficiency, daylight, thermal load, window, building skin, climate

1. Introduction

Buildings are responsible for approximately 30 to 40 percent of primary energy use, greenhouse gas emissions, and waste generation (United Nations Environment Programme, 2007). This fact has put the buildings as an important focus of energy researches. HVAC systems and lighting features demand a considerable amount of energy consumption in a building.

HVAC systems are the biggest energy consumer in most of the buildings. As an example, these systems consume more than a half of the total energy needed in a residential building (2011 Building energy data book, 2012). These systems have been the focus of different researches from building energy regulation (Lombard et al., 2011) to the effects of changing the parameters in a building on changes in HVAC systems (Korolija et al., 2011).

On the other hand, more than 5% of total energy consumed in a residential building is dedicated to lighting (2011 Building energy data book, 2012). Using natural lighting in combination to artificial lighting can reduce the energy needed for this sector. This would have more effects on office buildings which are more likely to be used in specific hours that have considerable overlap with the time when the natural daylight is available. 20-30% of the electricity used in office buildings is dedicated for lighting (Chirarattananon et al., 2002; Krarti et al., 2005). One efficient and economical way to reduce this proportion is using natural light. Integrating daylight with artificial lighting can play an important role in energy conservation (Ruck, 2006; To et al., 2000) and would help to reduce the electricity used for lighting (Doulos et al., 2008).

One of the most important items in building skin which requires considerable attention for energy saving is window. Windows are mostly responsible to provide light, view and ventilation (fresh air) (Lee et al., 2013). Light provided by windows (mostly via sun and trivially via artificial lighting of outside if there is any) can reduce the energy needed for artificial lighting. This does not mean the greater windows would necessarily lead to better designs. The reasons of this are different factors like glaring features which was the focus of some researches (e.g. Osterhaus, 2005), higher initial investments, and the most important factor, the lower values of thermal resistance or higher U-Values (which measure the heat loss) of windows compared with other components of buildings (like walls, ceilings, floors, and etc.). The latter factor is the cause of 20 to 40 percent energy waste in a building (Bülow-Hübe, 2011). Therefore, an efficient design is the one that at least meet thermal and lighting affairs optimally.

There have been different researches on window optimization in office buildings. About 60% of annual saving for lighting and therefore a huge amount (3 tones) reduction in co_2 emission have been the result of one of these researches based on low-carbon "2030" scenario (Jenkins and Newborough, 2007). Also, window openings provide the possibility of visual contact with the outside of the building beside energy efficient and sustainable effects of providing daylighting (Li, 2010).

Consequently, there have been different researches for reducing the environmental effects and energy demands of buildings with the manipulation of window parameters in design phase. A study on 288 buildings in Santiago, Chile, has showed the energy demand of 40kWh/m^{2}year, 40-70kWh/m^{2}year, and 50-155kWh/m^{2}year for 20%, 50%, and 100% WWR respectively (Pino et al., 2012). Also, an investigation has propounded 10kWh/m^2 as the realistic target for electric lighting in future low energy office buildings (Dubois and Blomsterberg, 2011).

Glazing features have great influence on thermal and lighting features like details of window (e.g. glazing layers, framing details, and Visible Transmittance (VT) of a window) and total design features (e.g. WWR, proportion, placement, and the orientation of the window). There have been researches on the relation of WWR on HVAC and daylighting in office building located in a temperate oceanic climate (Goia et al., 2013) and the life cycle environmental effects of buildings with different WWR in hot summer and cold winter zone in China (Su and Zhang, 2010).

The important feature that should be considered is the effect of local features of the site. The proper WWR or other features of a window in one macroclimate can differ greatly from one climatic division to another. This is also correct (maybe with lower impacts) on diverse climatic division scales like mesoscale and local scale.

In this research it has been tried to investigate the impacts of WWR, orientation placement, and proportion of windows in four cities in diverse climates. The results of simulations have been compared and some guidelines have been propounded for window specifications in order to have energy efficient buildings in these zones.

2. Background

Although in some cases like atriums sky luminance (equations 1, 2, 3, 4 and table 1) is an important source of natural lighting, more demands are on the investigations on vertical windows (Li, 2010). Also, the differences between orientations can be substantial when illuminance is high (Littlefair, 1990). Therefore, here it has been tried to investigate the effects of fenestrations on four cardinal orientations.

Table 1: Nomenclature

Symbol or Abbr.	Definition	Dimension
HVAC	Heating, Ventilation, and Air Conditioning	Wh
OKB	Osoboe Konstructorskoe Buro (distance from top of the floor to window bottom)	m
VT	Visible Transmittance	dimensionless
WWR	Window to Wall Ratio	dimensionless
L	sky luminance in an arbitrary sky element	cd/m2
Lz	sky luminance at the zenith	cd/m2
Z	zenith angle of a sky element	rad
Zs	zenith angle of the sun	rad
V	scattering angle between the sun and a sky element	rad
ϕ	the azimuth angle of a sky element	rad
ϕ_S	azimuth angle of the sun	rad
$L_{\alpha\phi}$	the luminance of the sky element at α and ϕ	cd/m2
$D_{\alpha\phi}$	the corresponding daylight coefficient	dimensionless
$\Delta S_{\alpha\phi}$	the angular size of the sky element	sr

$$\frac{L}{L_Z} = \frac{f(\chi)}{f(Z_S)} \frac{\varphi(Z)}{\varphi(0°)} \qquad (1)$$

Where L is sky luminance in an arbitrary sky element in cd/m2; *Lz* is sky luminance at the zenith in cd/m2; Z is zenith angle of a sky element in rad; *Zs* is zenith angle of the sun in rad; v is scattering angle between the sun and a sky element in rad.

$$\frac{\varphi(Z)}{\varphi(0°)} = \frac{1 + a\exp(b/\cos Z)}{1 + a\exp b} \qquad (2)$$

Where a and b are appropriate variables.

$$\frac{f(\chi)}{f(Z_S)} = \frac{1+c[\exp(d\chi)-\exp(d\pi/2)]+e\cos^2\chi}{1+c[\exp(dZ_S)-\exp(d\pi/2)]+e\cos^2 Z_S} \quad (3)$$

$$\chi = \arccos(\cos Z_S \cdot \cos Z + \sin Z_S \cdot \sin Z \cdot \cos|\phi-\phi_S| \quad (4)$$

Where ϕ is the azimuth angle of a sky element (rad) and ϕ_S is azimuth angle of the sun (rad).

The exponential term *exp(dχ)* shows the effect of Mie scattering, which decreases rapidly with distance from the sun (Li, 2010). The point is that the daylight illuminance inside a room and external illuminance does not generally have linear relation. This is because of the fact that the illuminance inside a room receives the sky luminance of a specific part of the sky, therefore the changes in different parts of the sky illuminance may have no or trivial effects on inside illuminance (Li, 2010). The total daylight illuminance, *E*, at the point can be calculated as equation 5:

$$E = \int\int L_{\alpha\phi} D_{\alpha\phi} \Delta S_{\alpha\phi} \quad (5)$$

Where $L_{\alpha\phi}$ is the luminance of the sky element at α and ϕ (cd/m2); $D_{\alpha\phi}$ is the corresponding daylight coefficient (dimensionless); and $\Delta S_{\alpha\phi}$ the angular size of the sky element (sr).

Therefore, WWR should be concerned with orientation, proportion of length to height, and OKB of the windows to deduce more accurate investigation.

3. Methodology

In this research it has been tried to scrutinize the effects of length, width, and orientation of the window in diverse global climatic zones. A brief sequence of different steps of this research can be described as:

a) Setting the building model
b) Selecting a representative region for any diverse global climate zone
c) Creating different predefined variations of window size and orientation for each selected region
d) Calculate the thermal and lighting outputs for each case
e) Comparing the outputs and creating the analysis diagrams
f) Concluding prescriptions with the help of analysis diagrams

For having a comprehensive point of view on the effects of changes of the size, placement, proportion, and the orientation of the windows, 6 different situations have been tested for each of the four sides of the building. 16.8, 8.96, 4.48, 3.2m^2 windows have been examined for each of the north, south, east, and west sides. Windows with 16.8m^2 area have 6m length and 2.8m height which covers the total area of one side of the building. Those with 8.96m^2 area have 5.6m length and 1.6m height (OKB=0.8m). Two different models have been examined for 4.48m^2 area windows; one a strip horizontal window with 5.6m length and 0.8m height in upper parts of the wall (OKB=1.2m) and the other one the same window in lower parts (OKB=0.8m). Windows with 3.2m^2 area are also divided into two sets; one a single window in the middle of the wall with 2m length and 1.6m (OKB=0.8m) height, and the other one is composed of two windows with 1m length and 1.6m height at two sides of a single wall (OKB=0.8m). All of the models have been simulated with Ecotect Analysis software.

3.1. Building characteristics

An office zone with 6×6×2.8m^3 (length, width, height respectively) is the case study in this research. Windows are double glazed with aluminium frame (no thermal break), with the U-Value of 2.41W/m^{2}K and VT of 0.6111. Layers used in walls in this zone are 0.11m brick masonry in inner side and 0.05m polystyrene in outer side with 0.01m plaster building (molded dry) in either side. The total U-Value of the wall is 2.63W/m^{2}K. Ceiling and floor are composed of 0.1m plaster board, 0.05m air gap, 0.1m concrete, 0.05m concrete screed, and 0.01 ceramic tiles from bottom to up. The U-Value of the ceiling and floor is 2.9.

As the consequent of WWR calculated via equation 6, the lowest window size in this research is 3.2m^2. For getting the net glazing area of this window, the mullions and framing should be subtracted from the window area. Approximately 80% of the windows are composed of glazing area (Connor, 1997). Hence the minimum net glazing area here is 2.56m^2. Consequently, the lowest WWR would be 3.8 percent of total gross exterior wall area. Of course this is not the desirable WWR for a building because the window is just considered in one side of the building. The implementation of windows in one side of the building has been performed to eliminate all extra factors from diverse windows and is for scrutinizing the effects of manipulations of each window on specific sides of the building separately.

$$WWR = \frac{Net \quad Glazing \quad Area}{Gross \quad Exterior \quad Wall \quad Area} \quad (6)$$

The type of HVAC system in the simulated buildings is mixed mode system with efficiency of 95%. The operation hours for these systems has been set from 6 up to 18 except two days of weekend when HVAC systems has been supposed to be off. Also, the calculation precision has been set on high. Other parameters have been remained as their default setting.

3.2. Climatic features

Köppen climate classification as one of the most widely used climate classifications has been used for choosing regions with different climatic features. Based on this classification, climates have been divided into five different types as:

a) Tropical/megathermal climates
b) Dry (arid and semiarid) climates
c) Mild Temperate/mesothermal climates
d) Continental/microthermal climate
e) Polar climates

Considering the population concentration in aforementioned divisions and the available data, four cities have been chosen from the first four divisions to cover a wide range of climates. These regions are Miami (Florida), Las Vegas (Nevada), Sheffield (United Kingdom), Saint Petersburg (Russia) for climate zones "a", "b", "c", "d" respectively. Location of these cities is showed in figure 1 and the comparisons of the temperature and precipitation of these regions are showed in figures 2, 3.

Figure 1. Location of selected cities in world map

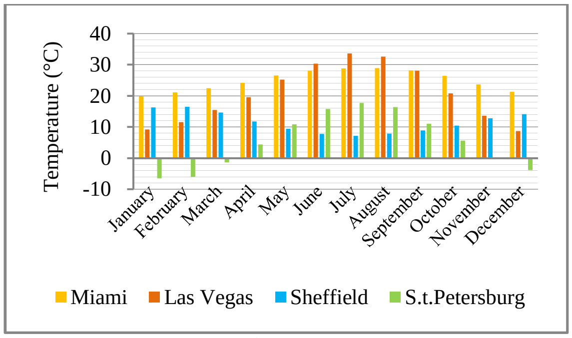

Figure 2. Comparison of temperature in selected cities

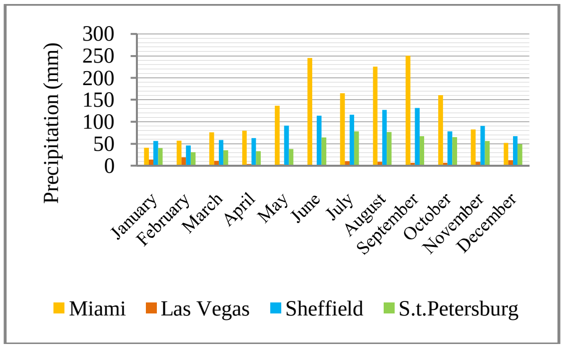

Figure 3. Comparison of precipitation in selected cities

3. Results and Discussions

As it has been depicted in figures 4-7, in all four different climates, the southern windows have the largest share in transmittance. It is because all of these cities are placed in northern hemisphere and southern windows are more probable in gaining solar rays.

Except Miami in which west side windows transmit solar energy trivially more than east ones, in all cases the sequence of transmitted energy from highest to lowest level is south, east, west, and north (figures 4-7).

The greatest difference between maximum (south) and minimum (north) transmitted energy can be seen in Las Vegas (figure 5) and the lowest one is in Sheffield (figure 6). Las Vegas has the lowest precipitation and is categorized as a dry zone (figure 3). Also it has the highest temperature among other cities (figure 2) while Sheffield has more moderate climate with lower temperature and an approximately high precipitation during the year (figure 2, 3).

It has been showed that the highest transmitted energy is for lower middle latitudes (figure 8). Of course this is for vertical windows and the results for horizontal fenestrations can be different.

Figure 9 shows the importance of choosing the facet in which window has been implemented for different latitudes. It depicts that the second quarter of northern latitudes from equator (about 22.5°N to 45°N) has greatest amounts. This does not lessen the importance for choosing the best facet in other regions, but just emphasizes the required extra attention in the aforementioned zone.

In the case of total annual heating and cooling loads of Miami, the increase in amount is trivial mainly up to 5.3% WWR (21.2% WWR for each side). The increase for the total window in one side of the façade is also lower than other cities (figure 10).

Results related to total heating and cooling of Las Vegas has showed a constant amount except the great increase in western and northern fenestrations above 10.6% WWR (42.4% of the related side WWR) (figure 11)

Related results of Sheffield is somewhat different from others in the case that the total amount for heating and cooling decreases (although trivially) in a rather steady way (except some fluctuations in the diagram related to the north side) (figure 12).

The optimum results of total heating and cooling for Saint Petersburg is in 5.3% WWR (21.2% of the related site). The important feature in this case is the significant increase in energy needed when the northern WWR deviates from the optimum amount (figure 13).

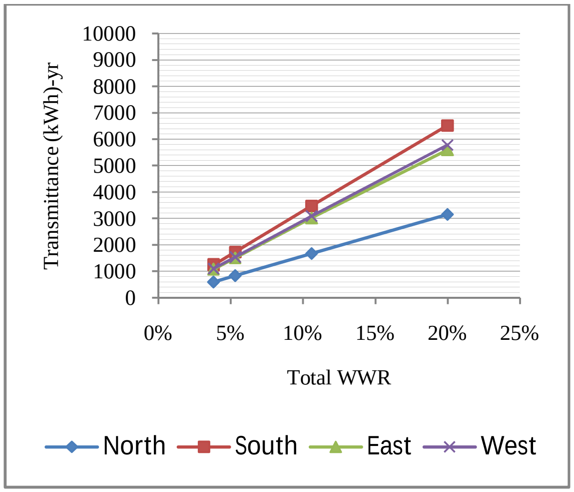

Figure 4: WWR and Transmittance of Miami (kWh) per year

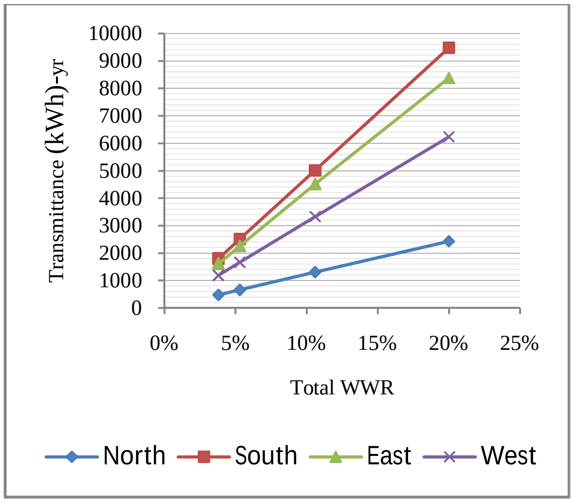

Figure 5: WWR and Transmittance of Las Vegas (kWh) per year

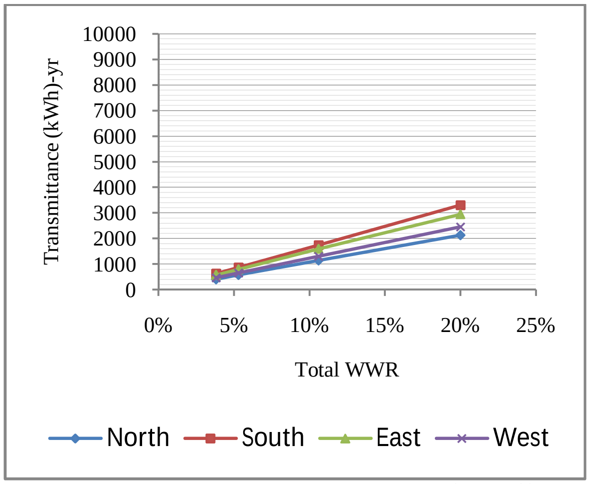

Figure 6: WWR and Transmittance of Sheffield (kWh) per year

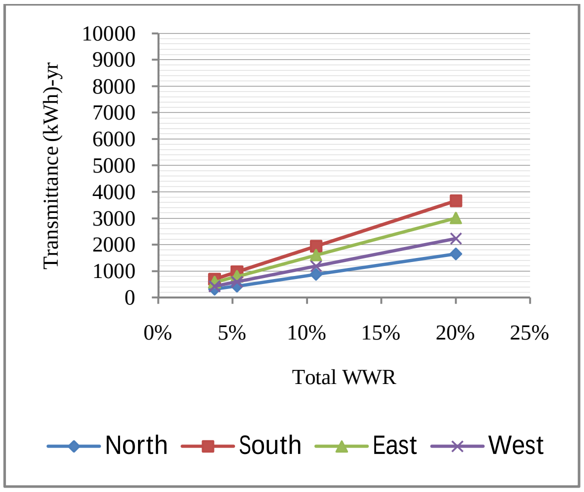

Figure 7: WWR and Transmittance of Saint Petersburg (kWh) per year

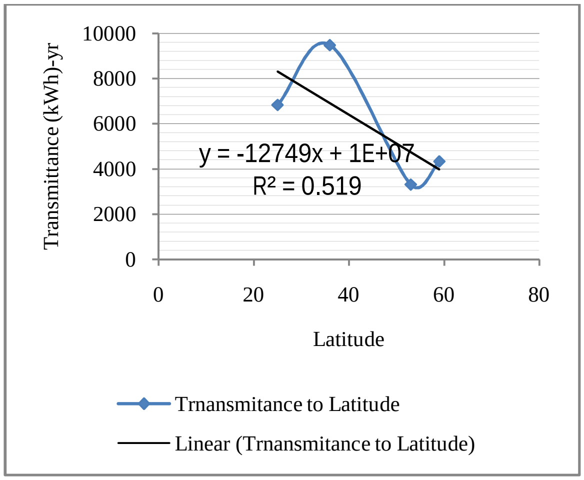

Figure 8: Latitude and Transmittance

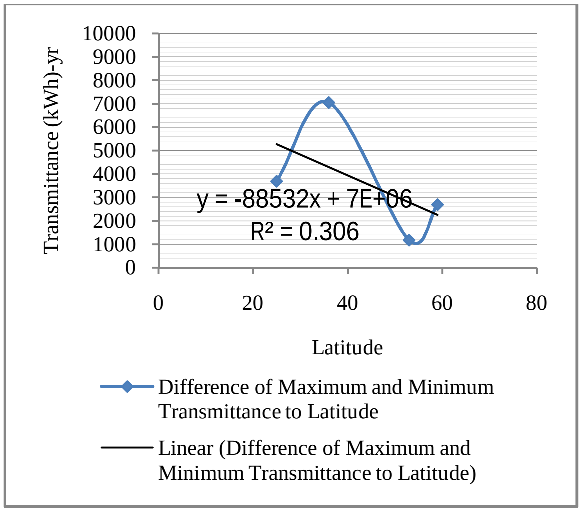

Figure 9: Difference of maximum and Minimum Transmittance to Latitude

Comparing the amount of energy losses for these cities shows the considerably greater amount for colder regions with higher latitude like Saint Petersburg and Sheffield compared with warmer cities in lower latitudes like Miami and Las Vegas (figure 14).

The energy gained is a little more complicated than energy losses of these cities and does not exactly obey the opposite rules of energy losses. For example although Las Vegas has higher latitude than Miami, it gains more energy. This is because the research has been performed on vertical windows and in middle latitudes these fenestrations can gain more energy in deeper parts of the rom. But this effect will be lowered in very high latitudes where we see trivial energy gains compared with Miami and Las Vegas and compared with the energy losses of themselves (figure 15).

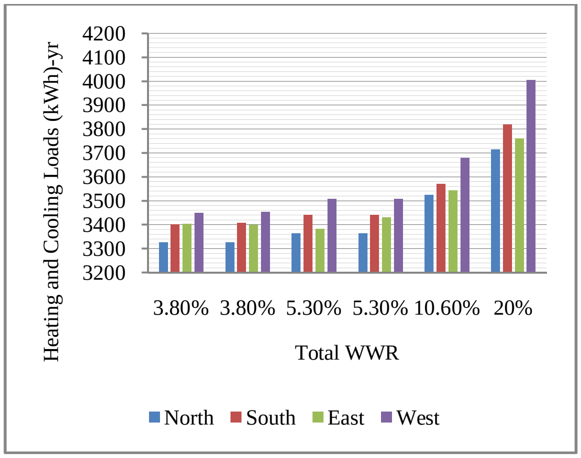

Figure 10: WWR and Total Annual Heating & Cooling Loads of Miami (kWh)

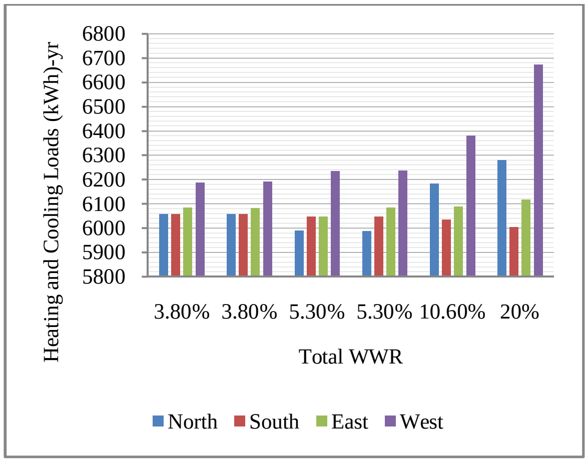

Figure 11: WWR and Total Annual Heating & Cooling Loads of Las Vegas (kWh)

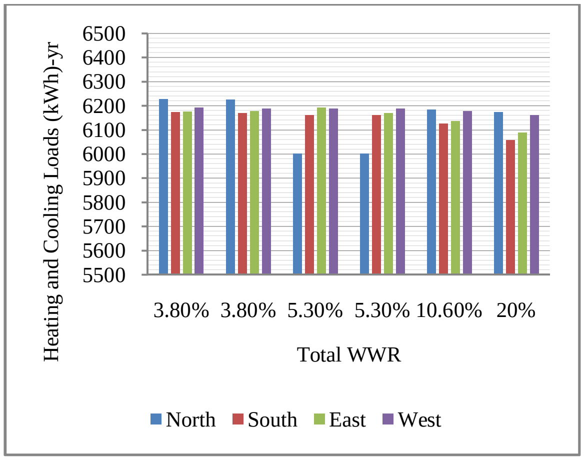

Figure 12: WWR and Total Annual Heating & Cooling Loads of Sheffield (kWh)

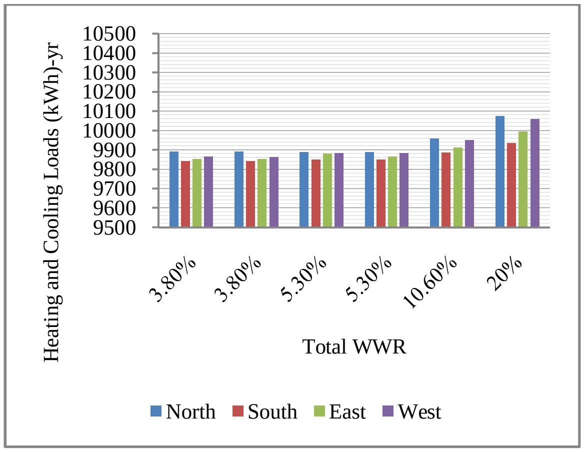

Figure 13: WWR and Total Annual Heating & Cooling Loads of Saint Petersburg (kWh)

The gained load by Miami and Los Vegas are greater than their losses. On the other hand, the losses load of Sheffield and Saint Petersburg is considerably higher than their gains. The mentioned amounts have much more greater deviation from one climate to another compared with different WWR of one climate.

Altogether, it can be deduced that the use of solar energy can be efficient in lower latitudes. The upper latitudes have severe cold climate which may require something more efficient than just increasing the WWR to gain more passive solar energy (figures 16, 17). These requirements can be high-efficient insulating systems, investments on renewable resources of energy, or any other technical related concern. It is worthwhile to mention that this fact does not mean the passive solar energy is needless in upper latitudes, but it means the priority and importance of many factors can have deeper effects.

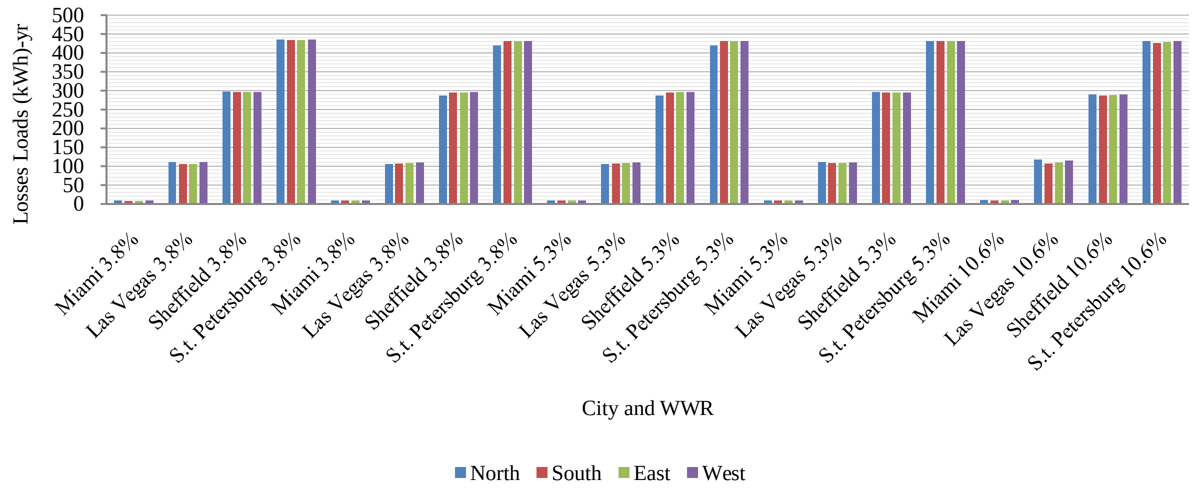

Figure 14: Annual Losses in different cities and different sides

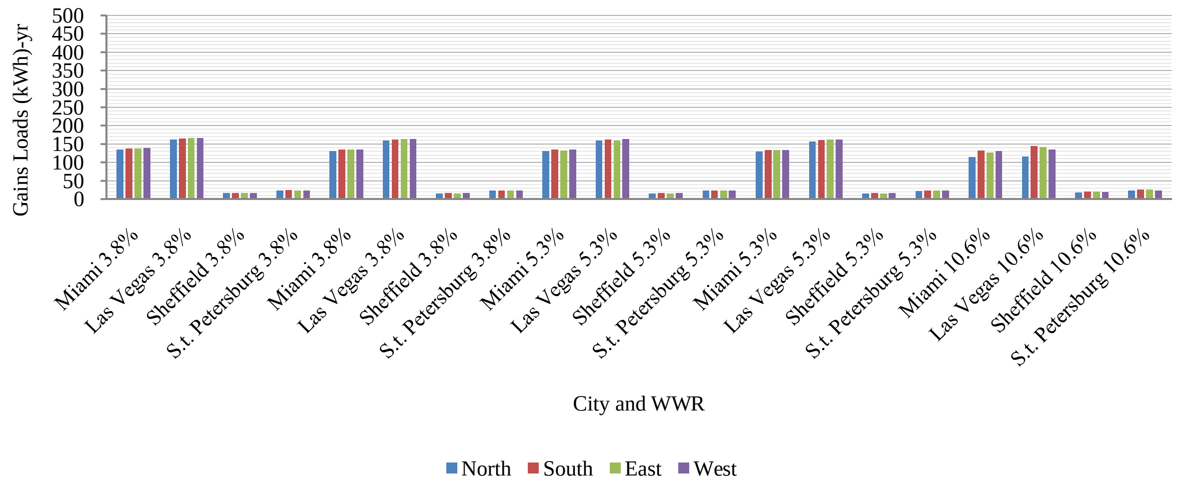

Figure 15: Annual gains in different cities and different sides

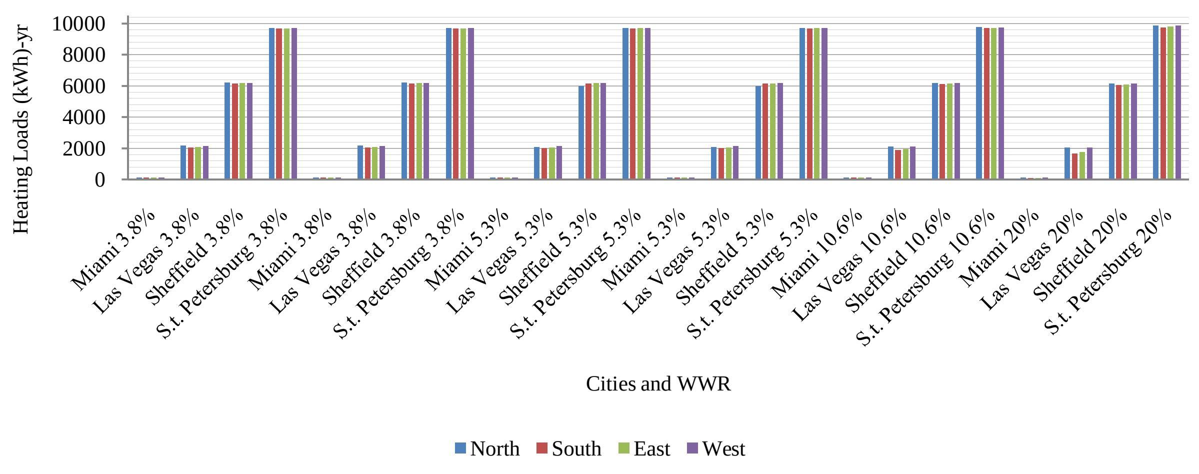

Figure 16: Annual Heating of different cities and different sides

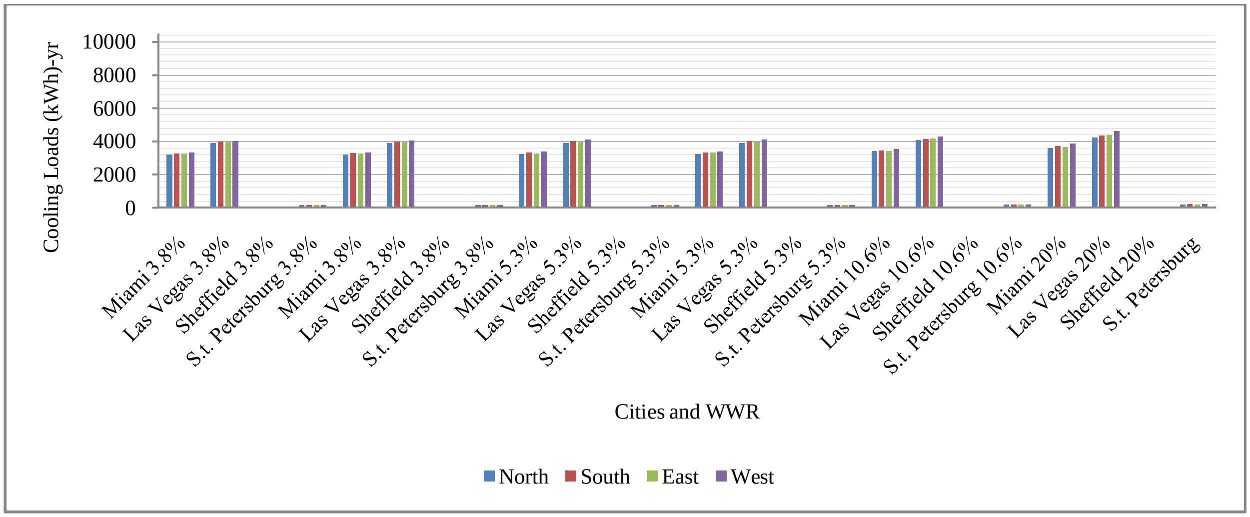

Figure 17: Annual Cooling of different cities and different side

4. Conclusion

Window characteristics can affect thermal and lighting loads of a building. These effects are mostly based on the placement, orientation, proportions, details, WWR, VT, and different other factors related to this element.

It has been concluded that WWR has an optimum of about 5-8% of one side (20-32% total WWR). This amount multiplied by 1.25 shows the approximate total window size (glass and framing) which would give the 25-40% total window to wall ratio.

The WWR above the upper threshold cause nonlinear extreme enlargement in energy loads when lowers the lighting loads which is trivial compared with HVAC loads. Also, it can cause glaring problems. North and west side in colder climates, and west side in warmer and drier climates can cause more drastic increases in energy loads and therefore should be considered as priorities in design.

Totally the solar energy in vertical fenestrations play an important role in second quarter part of the latitudes from the equator. But for higher latitudes where the energy demand is too much higher for heating and the solar energy is trivial because of the angle of the sun and the hours that sun is in the sky, this energy is not as effective as the lower latitudes.

Losses and annual heating and cooling loads of severe cold climates are too much high. Consequently, high-efficient insulations, investigation on renewable energy sources, and design composition play significant role. Although WWR and other features of fenestrations are important, but there are other factors that can have more significant effect on reducing the energy loads needed in buildings.

For middle and lower latitudes the source of solar energy can significantly affect the energy loads required for HVAC systems and lighting systems. If glaring factor is controlled, the south faced windows can enhance the performance of the building to a great extant.

These investigations have been done on buildings with double glazed windows. The effects of the WWR, orientation and proportions of buildings can affect by choosing other types of windows. Also, the local climate and policies play important roles in design features like window characteristics. Therefore, further investigations are necessary based on local characteristics.

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11/01/2013