OPTIMIZING WINDOW TO WALL RATIO FOR CONSERVING ENERGY IN OFFICE BUILDINGS FOR COOLING DOMINANT CLIMATES WITH AND WITHOUT DAYLIGHT UTILIZATION

Madeeha Altaf[1] and Frances Hill[2]

ABSTRACT

The construction of fully glazed commercial building facades responsible for high energy consumption has become a common architectural practice worldwide irrespective of the climate. This paper presents the methodology to optimize the Window to Wall Ratio (WWR) with and without daylight utilization to reduce energy consumption in office buildings for the climate of Lahore, Pakistan, using a simulation tool COMFEN. The impacts of solar heat and daylight entering through the building façade with reference to different WWR and orientation were explored for the selection of optimum WWR. The optimum WWR was selected on the basis of least energy consumption whilst achieving a threshold lighting level. When daylight is not utilized, the energy demand is minimized by the lowest possible WWR. With daylight utilization, energy demand is optimized by use of WWRs of 13% to 30% according to orientation. Optimum WWR with daylight utilization offered a more balanced solution. The methodology used in this study can be applied to any location around the world to find optimum WWR for any glazing type.

KEYWORDS

optimum WWR, building energy demand, daylight utilization, cooling dominant climate, threshold criteria

1. INTRODUCTION

Global energy consumption trends have amplified concerns about the depletion of energy resources, supply difficulties and severe environmental impacts (such as climate change, global warming etc.) (Pérez-Lombard et al., 2008). Unfortunately, the current building stock is oriented towards high energy consumption (Hirst, 2013) and the commercial sector has become the fastest growing energy demand sector globally (EIA, 2016). It is estimated that the building sector consumes up to 40% of global energy and is responsible for around 30% of global GHG emissions (Lee et al., 2013; UNEP SBCI, 2009). Energy savings in the building sector are critical for the achievement of sustainable development (Hee et al., 2015). Current trends of energy use indicate that buildings' energy demands and related emissions will continue to

1. MSc., Assistant Professor, School of Architecture, University of Lahore, Pakistan, madeeha.altaf@arch.uol.edu.pk
2. Ph.D., Senior Lecturer, Graduate School of the Environment, Centre for Alternative Technology, UK, frances.hill@cat.org.uk

increase. However, buildings offer great opportunities to reduce growth in energy demand (Lucon et al., 2014).

The greatest portion of energy is used during the operational phase (use stage) of buildings to meet various energy needs, such as heating, cooling, lighting, appliances etc. (UNEP SBCI, 2009). Glazed building components play an important role in determining the operational energy requirement of buildings (Raheem et al., 2016). Highly glazed commercial building facades have become a modern architectural trend worldwide irrespective of the climatic conditions (Butera, 2005; Bahaj et al., 2008) and the heat and solar gain allowed by excessive use of glass in the building envelope constitutes a major climatic design problem of today's buildings being responsible for high energy demands and emissions (Roaf et al., 2005).

Lahore, the second largest city of Pakistan, has a semi-arid, hot climate. Energy consumption in the commercial sector in Pakistan is increasing at the rate of 11.6% per year (Hameed et al., 2014), and the national energy situation is in crisis. Like other modern cities of the world, it has become common practice to build commercial buildings with extensive glazing in Lahore without any consideration for energy efficiency. These buildings consume more energy (mainly electricity) to maintain a comfortable indoor environment (Saeed et al., 2013; Hameed et al., 2014). Saeed et al., (2013) analyzed energy consumption patterns in a typical highly glazed office building in Lahore. It was found that glazing constituting 46.5% of the wall area without any considerations for orientation coupled with an excessive use of artificial lighting for illumination purposes is responsible for high energy demands. Cooling and lighting, being the dominant loads in the building, consumed 29% and 53% of the total energy respectively.

There is a need to employ energy efficiency and conservation strategies to reduce energy consumption in buildings. Heat loss or gain through the building envelope and solar gain should be considered together with internal energy demands in assessing the energy performance of glazed building components (Grynning, 2013). A careful analysis of glazing configurations at the design stage can help control building energy consumption (Ochoa et al., 2012; Poirazis et al., 2008). Optimizing the glazing system considering area, thermal performance, and localization of glazed building components in a building envelope are ways to reduce energy consumption in buildings (Grynning, 2013), but there is an apparent lack of understanding amongst practitioners of what might be considered appropriate in the warm, semi-arid climatic context of Lahore.

Various studies have been conducted to analyze the impacts of glazing on energy consumption of buildings in diverse climates. However, few studies exist on the optimization of glazing in buildings in Asian regions (Jaber and Ajib, 2011; Arıcı and Karabay, 2010; Lee et al., 2013). This paper fills that gap. The study of daylight integration to reduce artificial lighting energy consumption remains largely unexplored in this context. This paper presents a methodology for considering this along with solar gain to optimize the Window to Wall Ratio (WWR) with and without daylight utilization to reduce energy consumption/demand in office buildings for climates similar to Lahore, Pakistan. The simulation tool COMFEN is used. An office building typology is considered in this study from the commercial sector since office buildings are the largest consumers of energy due to their specific and homogenous energy requirements (e.g. air conditioning, artificial lighting, IT equipment, appliances), particularly in climates with a hot and dry summer period. For example, in Spain, energy use in offices was 33% which was found to be the highest in the commercial sector (Stegou-Sagia et al., 2007; Pérez-Lombard et al., 2008).

2. LITERATURE REVIEW

2.1 Window to Wall Ratio (WWR) and energy consumption

Glazing area is one of the important parameters of window system design both due to aesthetics and energy performance. Decisions regarding the glazing area are made in the initial stages of design and are hard to change later (Ochoa et al., 2012; Poirazis et al., 2008). WWR has significant impact on the total energy requirement of the building due to the effects of solar radiations (visible light and heat) and increased heat transfer due to the high thermal conductivity of glazed areas compared to walls (Lee et al., 2013; Su and Zhang, 2010). In general, the annual cooling and total energy requirement of a building increases with an increase in glazing area (Eskin and Türkmen, 2008). Ghisi and Tinker (2005) found that the ideal window areas could be larger on the façade which has smaller solar thermal loads to ensure low energy consumption. They found that for buildings in Leeds (UK), located in the northern hemisphere, the window area tends to be larger on the north orientation due to the very small thermal load on this orientation. While for Florianopolis (Brazil), the window area was found to be larger on the south and east orientations as the solar thermal load was lower for these orientations.

The summer cooling energy demand increases with the increase in window areas due to intense solar gain. However, increased window areas enhance winter performance by reducing heating loads. In their study to find the optimal window system for reducing energy demands in buildings, Lee et al., (2013) identified 50% WWR on the north façade and 25% WWR on the east, west and south facades as being the most efficient for saving energy in buildings for the cooling dominant Asian climates considering window performance properties (U value, SHGC, Tvis) and the variation in Asian climate regions. While investigating the optimum thermal design of office building for minimizing annual energy consumption, Al-Homoud (1997) observed an optimization trend towards a specified minimum glazing area of 15% (neglecting daylight use) for the hot climate zones of the U.S. and Saudi Arabia. A reduction in the glazing area affects many benefits associated with glazing such as aesthetics, views and daylight. However, optimizing WWR solely for visual comfort and aesthetics significantly increases the energy consumption pattern. A compromise has to be reached where unquantifiable project benefits should coincide with the goals of low energy use (Ochoa et al., 2012). Hee et al., (2015) also emphasized that planning a fenestration system for providing natural lighting and external views should be done while keeping a balanced energy performance for the building.

In summer, the window area is a source of increased heat gain which is handled by the cooling air conditioning system (Hassouneh et al., 2010). Rashid et al. (2016) investigated the impact of window size on heat gain in commercial buildings in the semi-arid climate of Lahore. It was seen that heat gain increases with an increasing window size for all orientations so does the cooling load. Minimizing the window size in a small office building in a hot climate was found to save 10.5% of cooling energy (Ahmed et al., 2013).

2.2 Daylight and energy consumption

Daylight utilization offsets the energy consumption of the building by reducing the artificial lighting load and also the cooling load associated with artificial lighting (Mathew and Kini, 2016; Chen and Wei, 2013). This is considered especially important for cooling dominant commercial buildings. (Tian et al., 2010). Bodart and De Herde (2002), while studying global energy savings in office buildings by utilizing daylight, learned that the artificial lighting energy consumption could be reduced by 50–80% by utilizing daylight. In another study, Li et al.,

(2006) discovered that over 30% of electric lighting energy savings were possible by using daylight with dimming controls in cooling office buildings in Hong Kong. Lam and Li (1999) found 11% and 13% reductions in peak cooling load and annual electricity consumption respectively with the proper use of daylight in a generic 40 storey office building in Hong Kong. The impact of solar shading devices on daylight quality was studied by Dubois (2001); the daylight quality was assessed against different performance indicators, including work plane illuminance. The study concluded that all the shading devices considered for study affect the daylight quality.

Window area is critical in determining daylighting entering into the building but a large window area does not necessarily mean significant increase in useful daylight. A 30% WWR was identified as the daylighting saturation point for south-facing facades in Montreal (Tzempelikos and Athienitis, 2007). According to another study, beyond 25% (plus or minus 5%), glazing starts becoming a net energy loser and does not contribute more daylight (Wilson, 2010). Moreover, high levels of daylight illuminance are strongly associated with occupants' discomfort due to glare. Nabil and Mardaljevic (2006) proposed a dynamic daylight performance measure known as UDI (Useful Daylight Illuminances) to determine 'useful' daylight levels for the occupants. UDI are defined as those illuminances that fall within the range 100–2000 lux.

3. METHODOLOGY

3.1 Simulation tool

Design decisions related to technical areas of architecture rely on experimental research, e.g., the issues of building envelope design which are studied through the integration of simulation techniques that comprise a logical and systematic method for building energy research and evaluating architectural design (Groat and Wang 2002; Hui, 1998). The best prospects for improving a building's energy performance arise early in the design process (Hui, 1998) and research by Tzempelikos and Athienitis (2007), Ko, Elnimeiri and Clark (2008) and Al-Homoud (1997) has emphasized that the fenestration/glazed components of a building façade should be studied in the early stages of design to understand their impact on energy consumption for designing energy efficient buildings. COMFEN (COMmercial FENestration), an early design energy modeling tool developed by LBNL (Lawrence Barkley National Laboratory), for comprehensive analysis of building glazing systems with respect to energy efficiency and comfort was used to achieve the objectives of this study. COMFEN uses the powerful calculation engines of EnergyPlus, WINDOW and RADIANCE. This software was developed to promote design and deployment of high performance fenestration systems by making complex simulation comparisons of fenestration alternatives accessible to a wide audience of users. However, there are some limitations that may limit its usefulness for specific design projects. These include internal load and schedule defaults for small office buildings which are currently implemented as they are not customizable. Similarly, a single HVAC system type, packaged single zone, is currently applied.

3.2 Simulation methodology

This section describes the methodology used to find the optimum WWR for reducing energy demand in office buildings for cooling dominant climates. The impact of altering WWR on the energy consumption of a building with and without daylight utilization was studied for each orientation (north, south, east, west). The energy use intensity (EUI), in MJ/m^2-yr for each variant was determined to find the optimum WWR. Without daylight utilization, the optimum size was identified on the basis of lowest EUI for each orientation. Investigation of the optimum WWR with daylight utilization required the use of a dynamic daylight performance metric. For this, DA (Daylight Autonomy) was used to implement daylighting in a building. DA is defined as a percentage of occupied times of the year when the required minimum illuminance threshold is met by daylight alone. It uses illuminance at the work plane as an indicator of sufficient daylight and use of occupancy hours as a time basis (Reinhart et al., 2006). DA is regarded as a comprehensive parameter since it considers the effects of orientation, climate and fenestration optical properties to describe the daylighting performance of the space (Tzempelikos and Athienitis, 2007). With daylight utilization, identification of optimum WWR for each orientation was based on the lowest energy consumption for the parameters at which the work plane illuminance threshold criteria of 500 lux was met by daylight alone for 50% of the occupancy time during the year. Annual energy consumption and daylight availability at the work plane were calculated.

3.3 Input data

ASHRAE standards recommend separating perimeter and interior zones of a building for energy modeling (ASHRAE, 2010). A reference room 4.0m wide and 3.6m high was established with a perimeter zone depth of 4.57m (considered as thermal and daylight lighting zone depth as per ASHRAE standard 90.1 and International Energy Conservation Code (IECC). It was assumed that the reference office room forms part of a perimeter zone of an office building. The reference office room had single exterior façade wall and adiabatic interior walls, ceiling/roof, and floor. The base case glazing was double glazed, clear glass (DGI). It was assumed that there was no shading from additional shading devices or any surrounding buildings.

Input data required in this study for an office building/reference room including thermostat set points, schedules (occupancy, lighting, equipment), and outdoor air flow rate were set according to the default values of COMFEN. The loads for each schedule were set according to ASHRAE standards. Work place density, miscellaneous equipment power and artificial Lighting Power Density (LPD) for an office building were specified as 9 m^2/ person, 8.07 W/m^2 and 10.76 W/m^2 respectively (assuming fluorescent lighting). The illumination level of 500 lux was specified at the work plane height during office hours as recommended by ASHRAE standards and IESNA (Illuminating Engineering Society of North America). Daylight control logic is embedded in the software COMFEN. A daylight photo sensor is positioned at 2/3 of zone depth from the façade wall and positioned at a desk height of 0.76 m above the floor (Mitchell et al., 2012). Continuous lighting controls were modeled in this study as providing continuous dimming control based on daylight levels to maintain constant, undisturbed, fluorescent light levels during office hours.

A WWR of 80% has been included in the pattern considering the current trends of maximizing glazing in building facades, and reduced values of 40%, 30%, 20% and 10% were initially considered for simulation (Figure 1). Window position has significant effect on lighting energy demand when there is a daylight control system. Windows positioned in the center of the façade were considered in this study as being most advantageous when daylight controls are to be used (Bokel, 2007).

The outdoor climatic data used in this study included monthly average temperatures, horizontal solar radiations, horizontal illuminance was obtained using TMY2 hourly weather data file (Figure 2).

FIGURE 1. Different WWRs (10%, 20%, 30%, 40%, 80%) used for the simulation.

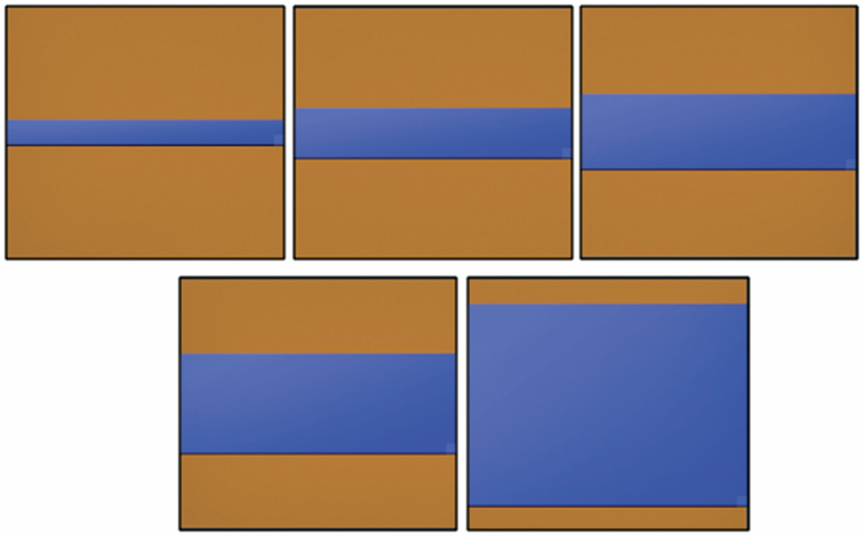
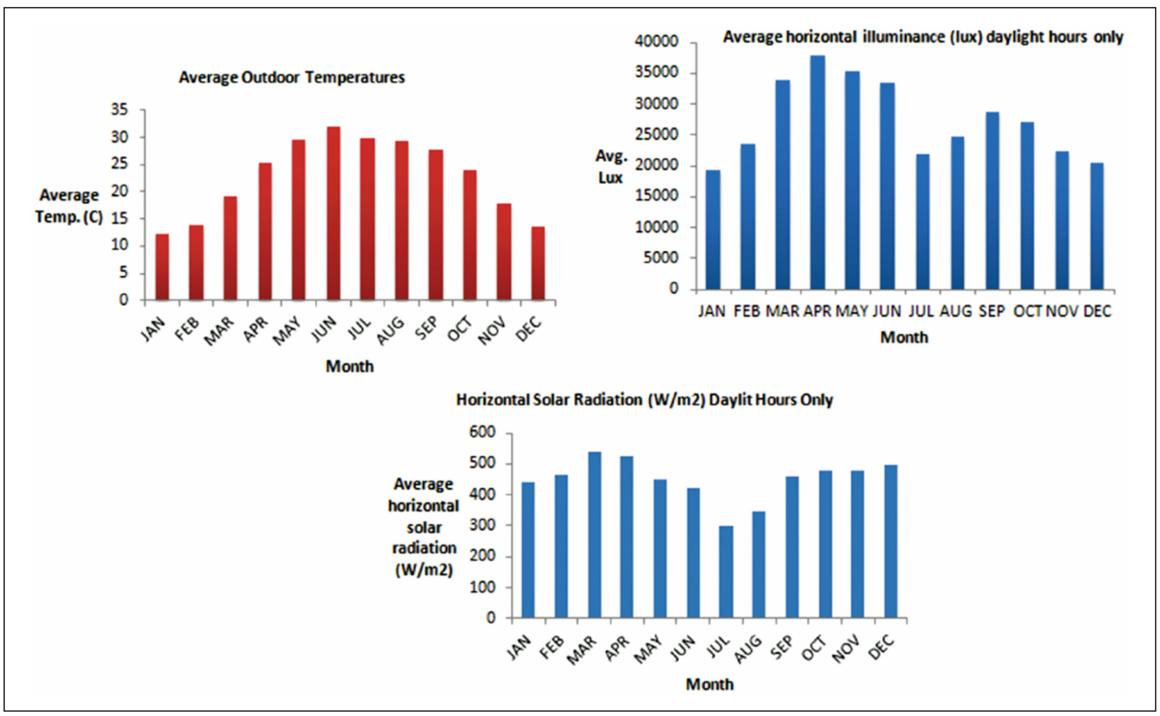


FIGURE 2. Monthly average values of outdoor temperature, horizontal illuminance and horizontal solar radiation used for simulation for Lahore (Summarized by authors from TMY2 hourly weather data file).



4. RESULTS AND DISCUSSION

4.1 Optimum WWR without daylight utilization

EUI and window annual heat gain (per unit floor area) were found for each WWR without daylight utilization (Figures 3-6), with DGI.

It is evident from the results that building energy consumption increases linearly with an increase in WWR, on all orientations, cooling loads being the most prominent while lighting loads remain constant when daylight is not being utilized. A range of WWRs was modeled, from 80% down to 10%, in order to explore the impact on EUI. When daylight is not utilized, the energy demand is minimized by the smallest WWR. A 10% WWR showed a 22% to 36% reduction in EUI compared to 80% WWR depending upon orientation. Therefore, reducing

FIGURE 3. Comparison of energy consumption and heat gain of different WWRs for East orientation.

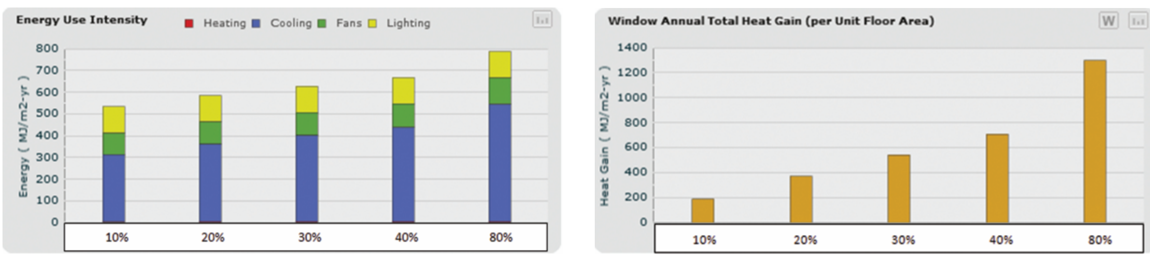


FIGURE 4. Comparison of energy consumption and heat gain of different WWRs for West orientation.

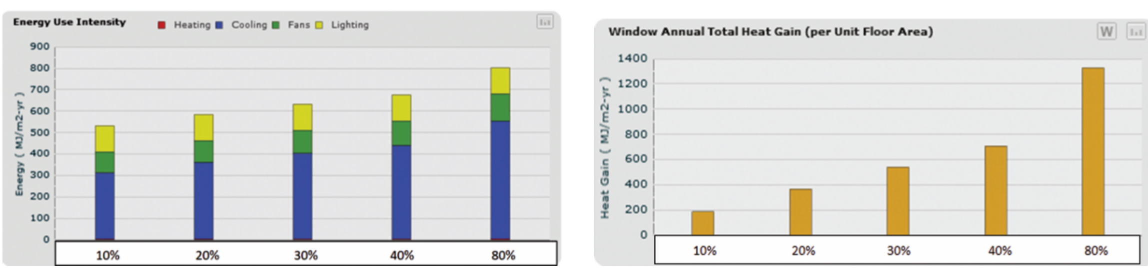


FIGURE 5. Comparison of energy consumption and heat gain of different WWRs for South orientation.

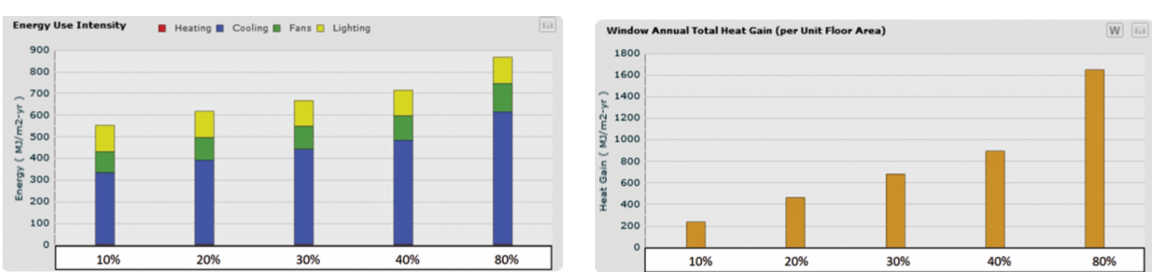
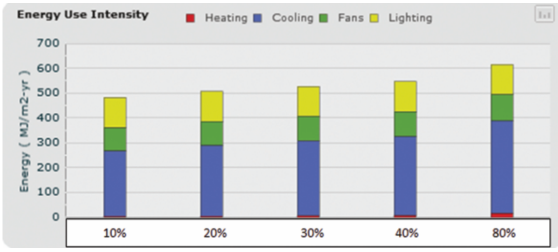
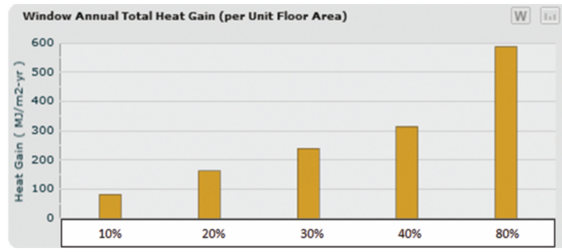


FIGURE 6. Comparison of energy consumption and heat gain of different WWRs for North orientation.





the penetration of solar radiation/heat through windows is essential for saving energy in cooling dominant climates. Energy consumption for different purposes, and heat gain at 10% WWR for all the orientations are presented in Table 1. The impact of window size on energy consumption of a building was found to be maximum on a south orientation and minimum on a north orientation due to the variation in amount and penetration of solar radiation. Since windows on the north façade had the least impact on energy consumption compared to other orientations, a higher WWR could most readily be planned on the north side for cooling dominant regions.

4.2 Optimum WWR with daylight utilization

It was found from the simulation results that daylight utilization reduced building energy demand significantly by reducing the artificial lighting requirement and also the cooling load associated with artificial lighting. Optimum WWR selection with daylight utilization was based on the lowest energy consumption for the parameters which satisfied the preset threshold criteria of 500 lux provided at the work plane by daylight alone. For this purpose, intermediate WWRs between 20% to 30% were simulated to investigate the optimum condition for energy demand reduction and find the minimum WWR that provided the required daylighting (Figures 7, 8 and Tables 2, 3). A WWR of 23% was found to be optimum for east and west orientations, providing the required illumination at the work plane with daylight alone for 55% of the working time. High illumination levels (causing glare or visual discomfort) were observed during morning and evening hours for east and west orientation due to low solar altitudes.

TABLE 1. Total energy consumption and heat gain at 10% WWR for East, West, South and North orientation without daylight utilization.

Orientation	WWR	Heating MJ/ m^2-yr	Cooling MJ/ m^2-yr	Fans MJ/ m^2-yr	Lighting MJ/m^2-yr	Total energy consumption MJ/m^2-yr	Window total heat gain MJ/m^2-yr
East	10%	1.85	311.98	97.27	121.41	532.53	188
West	10%	1.93	310.72	97.61	121.41	531.68	187
South	10%	1.20	332.50	98.09	121.41	553.20	235
North	10%	3.12	264.12	94.21	121.41	482.86	82

FIGURE 7. Comparison of energy consumption of different WWRs for East orientation with daylight utilization.

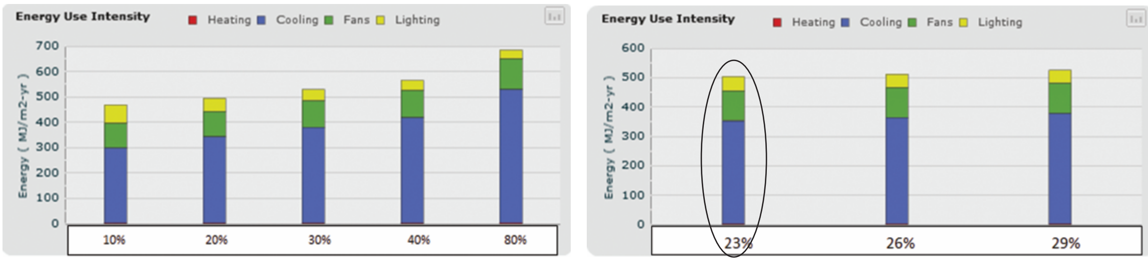


FIGURE 8. Comparison of energy consumption of different WWRs for West orientation with daylight utilization.

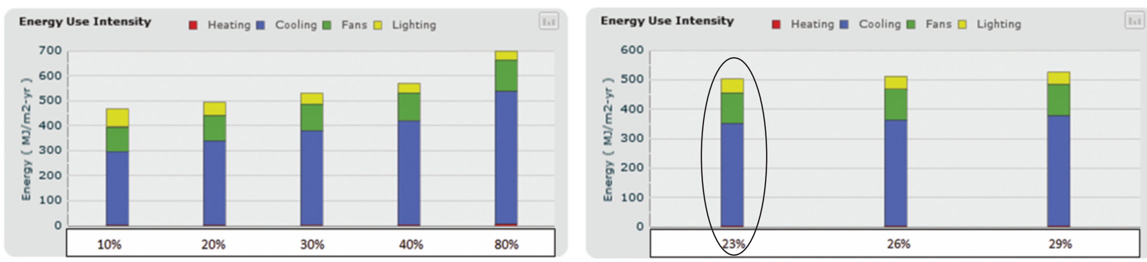


TABLE 2. Annual average hourly daylight (lux) at different WWRs for East orientation.

WWR	Annual average hourly daylight (lux) for five counted hours				
	9.00 AM	10.00 AM	11.00 AM	12.00 PM	1.00 PM
20%	3037	1594	944	629	454
23%	3806	1761	1068	712	514
30%	4666	2198	1391	927	668

TABLE 3. Annual average hourly daylight (lux) at different WWRs for West orientation.

WWR	Annual average hourly daylight (lux) for five counted hours				
	1.00 PM	2.00 PM	3.00 PM	4.00 PM	5.00 PM
20%	479	699	1040	1683	3190
23%	542	790	1176	1858	3930
30%	705	1029	1532	2699	4790

After comparing all the WWRs for daylight availability for north and south orientation, a WWR of 30% was identified as optimum for north orientation, providing the required daylight illumination levels throughout the working time. It was observed that a WWR of 20% could not provide the required threshold of 500 lux for any hour during the working time for north orientation. For south orientation, WWRs between 10% and 20% were simulated to find the optimum condition for energy demand reduction in order to find the minimum WWR that provided the required daylighting. A WWR of 13% was identified as optimum glazing size for south orientation satisfying the pre-set criteria for 66% of the working time. Energy consumption and daylight availability at different WWR for these two orientations are presented in Figures (9, 10) and Tables (4, 5).

As direct sunlight does not strike the north façade at this latitude in the northern hemisphere, higher WWRs (30% to 80%) on the north orientation were found to provide sufficient daylight levels throughout the occupancy hours with reasonable energy demand (Figure 11). If required, a higher WWR could most readily be planned on the north façade due to low solar

FIGURE 9. Comparison of energy consumption of different WWRs for North orientation with daylight utilization.

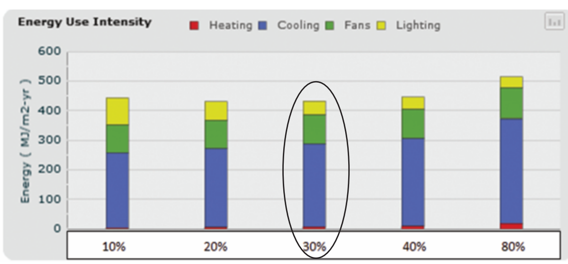


FIGURE 10. Comparison of energy consumption of different WWRs for South orientation with daylight utilization.

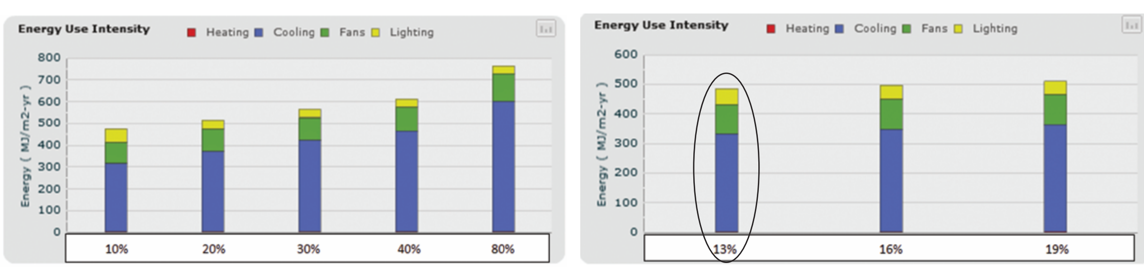


TABLE 4. Annual average hourly daylight (lux) at different WWRs for North orientation.

WWR	Annual average hourly daylight (lux) for five counted hours				
	10.00 AM	11.00 AM	12.00 PM	1.00 PM	2.00 PM
20%	372	371	364	361	368
30%	545	544	535	532	540

TABLE 5. Annual average hourly daylight (lux) at different WWRs for South orientation

WWR	Annual average hourly daylight (lux) for five counted hours				
	10.00 AM	11.00 AM	12.00 PM	1.00 PM	2.00 PM
10%	388	486	541	558	535
13%	505	632	704	727	697
20%	773	969	1080	1114	1068

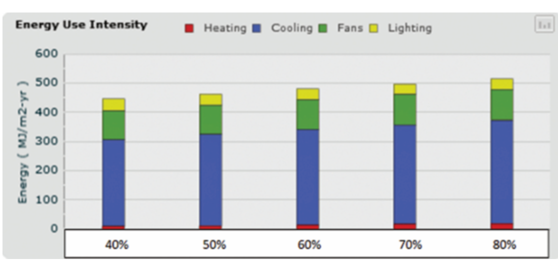
gains from this direction. The south orientation was found to be better than east and west orientations for useful daylighting with useful acceptable illumination levels throughout the working time up to 40% WWR. However, minimum energy demand was found with a WWR of 13%, allowing natural light to bathe the space for most of the working time without causing glare or overheating.

Total annual energy consumption and artificial lighting reduction with daylight utilization at optimum WWRs are presented in Table 6. It was also found that a WWR of 80% consumed 19% to 57% more energy depending upon orientation compared to optimum WWRs with daylight utilization.

4.3 Most appropriate choice

Annual energy consumption with optimum glazing size without and with daylight utilization was compared to find the most suitable choice for conserving energy. It was found that optimum WWR with daylight utilization saved around 5.2%, 5.4%, 10.4% and 12% more energy for east, west, north and south orientations respectively in comparison to optimum WWR without daylight utilization. Moreover, the optimum WWR for all orientations with daylight utilization

FIGURE 11. Energy consumption and daylight availability at different WWRs for North orientation.



WWR	Annual average hourly daylight (lux)								
	9.00 AM	10.00 AM	11.00 AM	12.00 PM	1.00 PM	2.00 PM	3.00 PM	4.00 PM	5.00 PM
40%	641	712	712	700	695	707	718	701	602
50%	769	856	856	842	837	850	863	842	723
60%	885	986	987	971	965	980	994	970	832
70%	973	1083	1084	1067	1060	1075	1091	1065	915
80%	1064	1185	1186	1168	1159	1176	1193	1165	1001

TABLE 6. Total annual energy consumption and artificial lighting reductions at optimum WWR for East, West, North and South orientation with daylight utilization.

Orientation	WWR	Heating MJ/ m^2-yr	Cooling MJ/ m^2-yr	Fans MJ/ m^2-yr	Lighting MJ/ m^2-yr	Total energy consumption MJ/m^2-yr	Reductions in artificial lighting requirement %
East	23%	2.11	351.31	100.86	50.03	504.32	59%
West	23%	2.46	349.57	102.82	48.20	503.04	60%
North	30%	6.22	281.47	97.54	47.30	432.54	61%
South	13%	1.35	331.37	99.24	54.07	486.06	55%

was higher than the optimum glazing size without daylight utilization, allowing for greater visual connection.

5. CONCLUSION

This study highlighted that significant energy savings in glazed commercial buildings in cooling dominant climates are possible by utilizing optimum WWRs. Without daylight utilization, the study identified a WWR of 10% as the optimum size for saving energy for north, south, east, west orientations. A range from 28% to 57% of the energy could be saved by reduction of WWR to 10% for all orientations from the currently conventional 80% WWR. The optimum glazing size is different for different orientations with daylight utilization due to different solar conditions. In terms of WWR, 30% WWR on north orientation, 23% WWR on east, west orientation and 13% WWR on south orientation were found to be optimum for energy conservation in cooling dominant regions. With daylight utilization, energy demand is reduced by 38% by use of optimum WWR for east and west, while 57% and 19% reductions are available from optimum WWRs for south and north orientations, respectively, compared to 80% WWR. These optimum WWRs provide daylighting levels above 500 lux at desk level for more than 50% of the working time. The results showed that the heat gained through windows is responsible for the excessive energy demand in Lahore (a cooling dominant region). Therefore, the control of penetration of solar radiations through windows is essential for saving energy. Daylight utilization reduced the building energy demand by reducing the artificial lighting energy requirement and the cooling load associated with artificial lighting.

In order to reduce energy demands, a choice, therefore, needs to be made between taking advantage of natural daylighting through appropriate WWR; thus, minimizing the use of artificial lighting and minimization of WWR to 10% to reduce heat gains through windows. Optimum WWR with daylight utilization offers a more balanced solution than the optimum WWR without daylight utilization for all the orientations due to being more energy efficient as well as providing better visual connection to the outside.

Analysis of daylight utilization was one of the main objectives of this research; therefore, shading devices were not considered. Additional feature optimization for each orientation, with shading included, would need further research.

REFERENCES

Ahmed, K., Badshah, S., Rafique, A.F. and Khan, M.A. (2013). Windows optimization for office buildings in Islamabad Pakistan. *International Journal of Scientific & Engineering Research*, 4(4), pp. 1658–1664.

Al-Homoud, M. (1997). Optimum thermal design of office buildings. *International Journal of Energy Research*, 21(10), pp. 941–957.

Arıcı, M. and Karabay, H. (2010). Determination of optimum thickness of double-glazed windows for the climatic regions of turkey. *Energy and Buildings*, 42(10), pp. 1773–1778.

ASHRAE (2010) *ASHRAE standard 90.1-2010. Energy Standard for Buildings except Low-Rise Residential Buildings*. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Bahaj, A.S., James, P.A.B. and Jentsch, M.F. (2008). Potential of emerging glazing technologies for highly glazed buildings in hot arid climates. *Energy and Buildings*, 40(5), pp. 720–731.

Bodart, M. and De Herde, A. (2002). Global energy savings in offices buildings by the use of daylighting. *Energy and Buildings*, 34(5), pp. 421–429.

Bokel, R. (2007). The effect of window position and window size on the energy demand for heating, cooling and electric lighting. In: *10th International IBPSA Conference; International Building Performance Simulation Association*. Beijing, China.

Butera, F. (2005). Glass architecture: is it sustainable? In: *International Conference of Passive and Low Energy Cooling for the Built Environment*. Santorini, Greece, May 2005.

Chen, H. and Wei, P. (2013). Utilization of natural daylight in office buildings. *International Journal of Smart Grid and Clean Energy*, 2(2), pp. 301–306.

Dubois, M. (2001). *Impact of Solar Shading Devices on Daylight Quality (Measurements in Experimental Office Rooms)*. Department of Construction and Architecture, Lund University, Lund. Available at: http://www.lth.se/fileadmin/byggnadskonstruktion/publications/Report3061.pdf [Accessed 29 Aug. 2018].

EIA. (2016). *International energy outlook 2016-Buildings sector energy consumption*. [Online]Available at: https://www.eia.gov/outlooks/ieo/buildings.cfm (Accessed: 4 February 2017).

Eskin, N. and Türkmen, H. (2008). Analysis of annual heating and cooling energy requirements for office buildings in different climates in Turkey. *Energy and Buildings*, 40(5), pp. 763–773.

Ghisi, E. and Tinker, J.A. (2005). An ideal window area concept for energy efficient integration of daylight and artificial light in buildings. *Building and Environment*, 40(1), pp. 51–61.

Groat, L.N. and Wang, D. (2002). *Architectural research methods*. New York, NY: Wiley, John & Sons.

Hameed, R., Nadeem, o., Altaf, S. and Ameen, F. (2014). Improving the energy efficiency of existing commercial buildings in Lahore through retrofitting technique. *Journal of Faculty of Engineering & Technology*, 21(2), pp. 95–104.

Hassouneh, K., Alshboul, A. and Al-Salaymeh, A. (2010). Influence of windows on the energy balance of apartment buildings in Amman. *Energy Conversion and Management*, 51(8), pp. 1583–1591.

Hee, W.J., Alghoul, M.A., Bakhtyar, B., Elayeb, O., Shameri, M.A., Alrubaih, M.S. and Sopian, K. (2015). The role of window glazing on daylighting and energy saving in buildings. *Renewable and Sustainable Energy Reviews*, 42, pp. 323–343.

Hirst, N. (2013). Buildings and Climate Change. In: R. Yao, ed., *Design and Management of Sustainable Built Environments*, Springer London.

Hui, S. (1998). Simulation based design tools for energy efficient buildings in Hong Kong. *Hong Kong papers in design and development*, 1, pp. 40–46.

Jaber, S. and Ajib, S. (2011). Thermal and economic windows design for different climate zones. *Energy and Buildings*, 43(11), pp. 3208–3215.

Ko, D., Elnimeiri, M. and Clark, R. (2008). Fenestration guidelines for improving energy conservation in an the office building with a daylight control system. In: *Proceedings of the World Sustainable Building Conference*, Melbourne, Australia, 21–25 Sep 2008. CSIRO—Commonwealth Scientific and Industrial Research Organization.

Lam, J.C. and Li, D.H.W. (1999). An analysis of daylighting and solar heat for cooling-dominated office buildings. *Solar Energy*, 65(4), pp. 251–262.

Lee, J., Jung, H., Park, J., Lee, J. and Yoon, Y. (2013). Optimization of building window system in Asian regions by analyzing solar heat gain and daylighting elements. *Renewable Energy*, 50, pp. 522–531.

Li, D., Lam, T. and Wong, S. (2006). Lighting and energy performance for an office using high frequency dimming controls. *Energy Conversion and Management*, 47(9–10), pp. 1133–1145.

Lucon, O., Ürge-Vorsatz, D., Ahmed, A., Akbari, H., Bertoldi, P., F. Cabeza, L., Eyre, N., Gadgil, A., Harvey, L., Jiang, Y., Liphoto, E., Mirasgedis, S., Murakami, S., Parikh, J., Pyke, C. and Vilariño, M. (2014). *Buildings in Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Available at: https://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_chapter9.pdf [Accessed 23 May 2017].

Mathew, M. and Kini, S. (2016). Daylight Analysis of a Typical Low Rise Office Building for Different Climate Zones of India. In: *International IEEE Conference on Energy Efficient Technologies for Sustainability*, Nagercoil, India, 7–8 April 2016. IEEE

Mitchell, R., Yazdanian, M., Zelany, K. and Curcija, C. (2012) *COMFEN 4.1: Program Description*. A PC Program for Calculating the Heating and Cooling Energy Use of Windows in Commercial Buildings. Available at: https://windows.lbl.gov/software/comfen/4.1/COMFEN4.1-UserManual.pdf [Accessed 26 Mar. 2017].

Nabil, A. and Mardaljevic, J. (2006). Useful daylight illuminances: A replacement for daylight factors. *Energy and Buildings*, 38(7), pp. 905–913.

Ochoa, C.E., Aries, M.B.C., van Loenen, E.J. and Hensen, J.L.M. (2012). Considerations on design optimization criteria for windows providing low energy consumption and high visual comfort. *Applied Energy*, 95, pp. 238–245.

Pérez-Lombard, L., Ortiz, J. and Pout, C. (2008). A review on buildings energy consumption information. *Energy and Buildings*, 40(3), pp. 394–398.

Poirazis, H., Blomsterberg, Å. and Wall, M. (2008). Energy simulations for glazed office buildings in Sweden. *Energy and Buildings*, 40(7), pp. 1161–1170.

Raheem, A., Issa, R. and Olbina, S., (2016). Environmental performance and economic analysis of different Glazing–Sunshade systems using simulation tools. *Journal of Computing in Civil Engineering*, 30(5), p. C5016001.

Rashid, M., Malik, A.M. and Ahmed, T. (2016). Effect of window wall ratio (WWR) on heat gain in commercial buildings in the climate of Lahore. *International Journal of Research in Chemical, Metallurgical and Civil Engineering*, 3(1), pp. 122–125.

Reinhart, C., Mardaljevic, J. and Rogers, Z. (2006). Dynamic Daylight Performance Metrics for Sustainable Building Design. *L E U K O S*, 3(1), pp. 7–13.

Roaf, S., Crichton, D. and Nicol, F. (2005). *Adapting buildings and cities for climate change*. Amsterdam: Architectural Press.

Saeed, I., Khan, A., Arif, S. and Mushtaq, M. (2013). Electricity consumption for energy conservation in office buildings in lahore-pakistan. *Pakistan Journal of Science*, 65(2), pp. 243–246.

Stegou-Sagia, A., Antonopoulos, K., Angelopoulou, C. and Kotsiovelos, G. (2007). The impact of glazing on energy consumption and comfort. *Energy Conversion and Management*, 48(11), pp. 2844–2852.

Su, X. and Zhang, X. (2010). Environmental performance optimization of window–wall ratio for different window type in hot summer and cold winter zone in china based on life cycle assessment. *Energy and Buildings*, 42(2), pp. 198–202.

Tian, C., Chen, T., Yang, H. and Chung, T. (2010). A generalized window energy rating system for typical office buildings. *Solar Energy*, 84(7), pp. 1232–1243.

Tzempelikos, A. and Athienitis, A.K. (2007). The impact of shading design and control on building cooling and lighting demand. *Solar Energy*, 81(3), pp. 369–382.

UNEP SBCI, (2009). *Buildings and Climate Change*. (Summary for Decision makers). Available at: http://www.unep.org/SBCI/pdfs/SBCI-BCCSummary.pdf (Accessed: 25 November 2016).

Wilson, A. (2010). *Rethinking the All-Glass Building*. [ONLINE] Available at: https://www.buildinggreen.com/feature/rethinking-all-glass-building [Accessed 13 Jun. 2017].