OPTIMIZATION OF ENERGY EFFICIENT WINDOWS IN OFFICE BUILDINGS
FOR DIFFERENT CLIMATE ZONES OF THE UNITED STATES

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Recent research estimates that windows are responsible for 39% of commercial heating energy use and 28% of commercial cooling energy use; this is equivalent to almost 1.5% of the total U.S. energy consumption (Apte and Arasteh, 2006). In addition, the commercial sector in U.S. accounts for 37% of the total electrical energy consumption for lighting (Ander, 2003). Therefore, window design optimization for thermal and daylight performance is important in achieving energy conservation and increasing overall efficiency of office buildings in the U.S.

Because current energy standards [ASHRAE 90.1] focus on thermal performance, they set requirements for fenestration based on minimum thermal characteristics. They suggest window to wall ratio (WWR) values based on thermal performance alone while do not recommend visual transmittance values. Providing fenestration related parameters optimized for thermal and daylight performance may help in achieving efficient design solutions. This study is intended to propose modified fenestration guidelines for the office buildings by investigating the optimization strategies for seven climate zones of the U.S.

To determine the pattern of energy usage with and without daylight utilization, series of computer simulations were conducted using the Radiance link in the IES Virtual Environment simulation software. The optimum ranges of fenestration related parameters were derived to meet the daylight requirement and to conserve energy. The results revealed 10-15% reductions in the total energy use of office buildings with an increase in overall efficiency. Further, the recommended guidelines provide the designers with a simple method for evaluating the fenestration design in the initial design phase to achieve optimized building façade solutions.
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1. INTRODUCTION

1.1 Background

This research is focused on the study of windows as an important building component to overcome the energy demands in the commercial sector. The study considers office buildings in the United States, which represent 50% of all nonresidential building floor area in the country (Carmody, 2004). A window design solution needs to consider the virtues, such as admitting controllable amounts of light and heat, applying fresh air and view, providing a physical and visual connection to the outdoors, insulating interiors from the weather and offering visual privacy. However, being poor thermal insulators, windows admit either too much or not enough sun in building (Johnson, 1981). It is significant to consider the natural benefits of the sun which can be used for supplying a building’s heating and daytime lighting needs by designing a building’s orientation, proportions, and materials to take the advantage of the sun’s path.

With the technological advancement in the glazing industry and the construction technology, the trend of large glass buildings has become popular all over the world in the last few decades. While these highly glazed buildings are beneficial by providing daylighting, view and aesthetic appeal to a building, they also have environmental disadvantages. It is important to note that windows which admit daylight also admit solar heat. Though heat from the sun is welcome in buildings in cold climates; in excess it can make buildings uncomfortably hot during summers. This problem can be found more frequently in the internal load dominated buildings, such as offices, where the internal loads are often large coupled with long summer periods with high outdoor temperatures and intense solar radiation.
A building’s envelope accounts for between 15%–40% of total construction cost and can contribute for additionally 40% costs when impacted by building services (Wigging, 2002). The choice of material, design and construction of an envelope can have a major impact on the overall energy consumption and the related cost of the building. According to a survey conducted by Ellis and Mathew, the replacement cost of the total value of buildings in the US during the 1980s was estimated to exceed the gross national product (GNP) by 20–40%. Existing buildings therefore cannot be replaced too often and thus design of comfortable, energy efficient buildings is receiving a lot of attention. The building skin serves a crucial functional role in maintaining thermally sound internal environments in extreme environmental conditions. This creates the primary technical challenges of environmental control which includes heating, cooling and lighting loads in addition to the depletion of resources (Hammad, 2010).

Various facade technologies and solutions are being developed in progress towards the energy efficient buildings. Daylight utilization, however, is one of the most beneficial sources for the reduction of electric lighting loads. Complimenting the emerging technologies of the envelope construction with daylighting strategies is of significant importance in achieving energy efficiency. In order to achieve energy efficiency, it is important to design a building with the optimum fenestration by focusing on the parameters contributing to energy conservation. These include building’s size, window to wall ratio (WWR) and glazing parameters like visible transmittance (VT), U-factor and solar heat gain coefficient (SHGC). When designed to take the maximum benefits of daylighting, these parameters can be significant in achieving substantial reduction in the energy usage.
1.2 Need

The rapid increase in the world energy use has led to exhaustion of energy sources and has caused heavy environmental impacts in various forms of global warming, ozone layer depletion and climate change. Buildings consume almost 40% of the world’s energy, 16% of the world’s fresh water and 25% of the forest timber, while being responsible for almost 70% of sulfur oxides and 50% of the CO2 emissions (Ghiaus, 2004). It is estimated that energy use in the built environment will grow by 34% in the next 20 years. Also in 2030, consumption attributed to the dwellings and the non-domestic sectors will be 67% and 33% respectively (Pérez-Lombard, 2008).

Buildings are the largest energy consumer in United States, and consume 38.9% of nation’s primary energy, out of which, the commercial portion has risen from 13% to 18% in the last three decades. Also, the total energy consumption in this sector is predicted to increase to 42.4% in 2030 (Glicksman, 2008). The growing trend in building energy consumption is expected to continue during the coming years due to the ever increasing built area and the associated energy needs, as long as the resource and environmental exhaustion allows for it (Pérez-Lombard, 2008). Thus promoting the energy efficient technologies in the construction industry can have a large impact in limiting the energy consumption in the coming years.

With the ever increasing demand for thermal comfort, HVAC systems and their associated energy consumption has become an unavoidable asset which accounts for almost half the energy consumed in the buildings, and around 10–20% of total energy consumption in developed countries. (Pérez-Lombard, 2008). Therefore, designers need to understand the consequences of their design by selecting the glazing types and designing the glazing area for the allowance of daylight whether in terms of thermal discomfort or energy loads due to the heating, cooling and lighting.
The impact of architectural decisions further has a long term influence and a major impact on the future energy use and emission patterns because of the long life of the buildings. The design of a building with respect to its form, fenestration, construction materials and finishes largely determines the building’s lifetime energy consumption and the gas emission patterns (Mazria, 2003). Edward Mazria, in his paper ‘It’s the Architecture, Stupid’, has proposed a new picture by graphically rearranging the traditional way of reporting the energy use and gas emissions in which it becomes clear that architecture consumes approximately 48% of all the U.S. energy produced and is responsible for 46% of all the U.S. CO2 emissions annually, almost double of any other sector (Fig. 3.3) (Mazria, 2003).

Fig. 1.1 U.S. Energy Consumption
Source: Mazria, 2003

Many architects, inspite of being aware of the impact their design can have on the future energy consumption, happen to overlook the fact that building envelope has a significant impact upon the energy consumption and the indoor environment. Designing efficient building envelopes for reducing the energy consumption is a complex task consisting of various interactive factors. However, this complexity is difficult to acknowledge due to the lack of evaluation tools to evaluate the improper envelope design. Further, the limited use of the daylight control systems is another reason which can ultimately lead to the excessive use of energy.
Windows are responsible for 39% of commercial heating energy use and 28% of commercial cooling energy use, or 34% of all commercial space conditioning energy use. This is equivalent to roughly 1.5% of the total US energy consumption (Apte, 2006). Also, commercial sector in U.S. accounts for 37% of the total electrical energy consumption for lighting (Ander, 2003). The balanced fenestration design is thus necessary for achieving energy conservation by optimizing the daylighting levels and thermal comfort and in turn reducing the heating, cooling and electrical lighting loads. However, the use of glazing systems to increase the heat gain through windows and limited use of daylight control systems often results in the increased energy loads of a building.

The optimization strategies are necessary to meet the daylight requirements and to increase the energy conservation. Sullivan and Selkowitz of LBL formulated a model for optimizing solar control and daylighting performance for a prototypical office building. According to their study, the solar and effective daylighting aperture values that minimize the energy consumption may assist in determining optimum performance of the glazing (Sullivan et al., 1992).

Fenestration of a building plays an important role in saving energy and utilizing daylight. However, implementing the optimum daylighting strategies for fenestration design should be considered in order to meet the daylighting requirements and to further increase energy conservation.

1.3 Hypothesis/Problem Statement

With the growing awareness of global warming, an increased demand for improved building regulations related to the energy efficient buildings has become evident. With this ever increasing demand for the high performance and environmentally efficient buildings, it is critical to address these design issues at an early stage in the design. However, in spite of the fact that design
decisions during the schematic design stage can have a significant impact on the building performance, traditionally the analysis for the building performance is often not considered at the initial stages in design. For many buildings energy analysis is conducted only after the design stage (Ko, 2009).

Proper design of the fenestration components at the early stage of design can greatly help in achieving thermal comfort with a minimum usage of HVAC systems, and therefore minimum energy requirements (Al-Homoud, 1997). The collaboration between the initial design decisions of an architect and the building performance analysis is important for the improvement of the building performance. However, the lack of integration effort between these two components often leads to the increased energy utilization. Some of the important factors responsible for this scenario are lack of evaluation tools, improper use of windows and limitation of daylight control systems which can ultimately lead to the excessive use of energy.

Numbers of simulation programs are available for the designers to evaluate the impact of their design on the building performance. However, these programs require expert knowledge and large amounts of input data. Also, these programs are often time consuming because of the accuracy needed for the lengthy input process to obtain the results. Another obstacle to perform simulations is the lack of knowledge regarding the selection of tool and lack of the training facilities. All these factors create significant challenges for designers to conduct the analysis of building performance during the design process, thereby leading to non integrated methods to achieve the overall energy efficiency of the buildings.

Rather than evaluating the building energy use independently for different parameters of the fenestration, it is necessary to consider the optimizing strategies for windows with respect to thermal and daylighting performance. This can result in an integrated approach and is expected to
have a positive impact on the buildings overall energy consumption and thus increasing its overall efficiency.

ASHRAE 90.1, which is the baseline for commercial energy standard, sets absolute minimum requirements for fenestration. It suggests window-to-wall-ratio (WWR) values based on thermal performance alone. It recommends only the U-value and SHGC values for glazing with respect to window to wall ratio in the range of 0-40% for all climate zones. However, it does not recommend the values for visual transmittance, window to wall ratios and aspect ratios of the buildings specific to climate zones. The values for these parameters are important to evaluate heat gain, daylight gain and the associated heating, cooling and lighting loads due to fenestration. It is significant to perform a comparative study of the existing standards and the results acquired in this research to understand the efficiency achieved with the proposed recommendations.

By acknowledging the problems related to fenestration design and energy efficiency, this research aims to propose the fenestration design guidelines for the optimal choice between thermal and daylight performance. The parameters like glazing type, window to wall ratio and building aspect ratio are optimized for different building types and climate zones with an objective to reduce the energy consumption. In summary, the focus of this research is to evaluate optimization strategies to improve energy conservation and indoor daylight levels.

1.4 Research Objectives

The main objective of this study is to recommend fenestration guidelines for office buildings for different climate zones of the U.S. by investigating the optimization strategies for thermal and daylight performance of the buildings. Taking into consideration the key factors related to fenestration such as glazing type, WWR ratio and aspect ratio for varying office building type and climate, this study presents the method to assess the daylight performance and energy usage to
achieve overall efficiency of the buildings. Moreover, the proposed recommendation will be tested against the existing codes and standards; in this case the ASHRAE 90.1 standard, to ensure the adherence to them and to investigate the significance of daylight utilization which is presently not considered in the current standards.

1.5 Organization of Thesis

Chapter 1 discusses the background of the proposed research, along with its need, problem statement and objectives. Chapter 2 provides the literature review by discussing in detail the glass as a material and its significance in architecture. Further, a historical background for windows as a component for daylighting and energy conservation is described followed by the study of traditional and emerging technologies in windows. Lastly, the issues related to the windows in office buildings along with energy codes and standards related to the commercial buildings are reviewed.

Chapter 3 presents the concept of optimization of fenestration design with respect to daylighting and energy conservation. This study is carried forward by initially presenting the interaction between the fenestration and lighting systems of a building by taking into account fenestration system’s orientation, size, shape and visual transmittance. The second part discusses the interaction between fenestration and energy consumption of the building with respect to window to wall ratio and solar and daylighting apertures. Lastly optimum trades off strategies for energy efficient windows are determined.

Chapter 4 describes the methodology adopted for this research. The first section introduces the building model description and an overview of the fenestration parameters considered for the simulations. In later section, the simulation model carried out for the daylighting and energy performance of the office building is discussed in detail.
Chapter 5 gives the in-depth analyses based on the data acquired by the series of computer simulations. This data includes daylight performance analysis specific to each climate zone followed by the analysis to verify relations between various parameters. The analysis is summarized by evaluating the optimization trends with respect to climate, building form and type, glazing parameters and window to wall ratio. Finally the detailed fenestration recommendations for ASHRAE 90.1 are presented based on the findings of the research.

Chapter 6 gives the conclusion for the performed study and mentions the significance of this research.
2. LITERATURE REVIEW

2.1 Glass

Glass is an amorphous substance produced by the heating of the substances like sand, soda (sodium carbonate) and limestone to a temperature of about 2400° F. A batch of commercial glass is made up of four to six ingredients including dolomite, boric acid, borax, feldspathic materials and lead and barium compounds including the basic raw materials. It is a non-crystalline material that is a super cooled liquid transformed into solid brittle, impermeable and transparent substance.

Historically glass has always been first choice for windows glazing over plastics due to its beauty, weather durability, and clarity. However, traditionally the labor and energy intensive procedure involved in manufacturing of the glass made it a rare material in buildings. Looking back over the dramatic technological changes in the glazing industry in the last century there is a strong relationship between the process of manufacture, the characteristics of the product, and its application.

In past, due to the load-bearing construction, the weight of the structure had to be redirected around door and window openings in exterior walls which limited the size of the apertures at a time when electric lighting was expensive and inefficient. The innovation in steel framing, during the late nineteenth century, contributed largely to the application of the glass as a building material. However this enclosure system required manufacturing advances, function-driven performance standards, and innovative materials for its success (Thomas, 2008).
2.1.1 Production of Glass for Construction Industry

Glass is one of the oldest man made material used without interruption from its invention to this date. The exact period of glass history is unknown; however the oldest found date is 7000 B.C. in the Neolithic period. It was first used in Egypt for decorative objects before 3000 B.C. mainly as colored glaze on stone, poetry and beads but its use in windows appears to have been initiated by Romans (Roger Mears Architects Publication).

The rise of interest in greenhouses and conservatories in 1800 led to the mass marketing for use of glass in architecture. New types of buildings including exhibition halls, railway stations and other public buildings permitted for the design of large well lit spaces with the development of an iron industry in parallel to advancements in glass manufacturing. Glass also played an important role by giving it a unique identity and quality of space (Elkadi, 2006).

Glass making came to America with the first colonists in 1608. It was among to the last of all industries to become modernized since working with molten glass was considered as a highly demanding craft that required a great deal of judgment and manual dexterity, both of which were difficult to replace by early machine processes (Amstock, 1997). In 1875, an independent company built a factory at Crystal City, Missouri, and in 1883, the conglomerate that would soon become known as Pittsburgh Plate Glass, built another at Creighton, Pennsylvania (Thomas, 2008).

First created almost 4,000 years ago, the technology of glass manufacturing has changed dramatically over the period of time. Significantly in last century the technological advances have led to the changes in thermal and luminous characteristics of glass as an architectural material. Industrialization transformed the window glass industry in the years between 1904 and 1920, and by 1928 hand blown window glass production had disappeared in the United States.
2.1.1.1 Traditional Glass Production

The primary innovation of glass making occurred in seventeenth century which involved one of the two methods of production- blowing a glass sphere and shaping it into a disc i.e. Crown method, or blowing a glass cylinder and slitting and flattening it to yield glass sheets i.e. cylinder method. Out of the two methods it was possible to create smaller glass by crown method and cylinder method could reach three to four feet. Both the crown and cylinder techniques limited the glass size to similar dimensions and were labor intensive until more modern cast glass method was discovered in seventeenth century. This process was less labor intensive and involved the passing of molten glass through slots and rollers to form a plate which was later ground and polished (Carmody, 2004).

As hand crafted products, the glass manufactured by crown and cylinder methods came in small sizes and varied in thickness with the glassmaker’s strength and skill and could suffice for domestic and small commercial installations. However, for large applications manual production methods proved disadvantageous. Large windows had to be assembled from small panes and increased labor costs. Also the inherent optical distortions of handmade glass rendered it functionally unsuitable for upscale projects. Thus, to meet the expectations for a clear and undivided window the need for polished plate glass emerged (Thomas, 2008). This glass was optically superior but also quite expensive. Still the market demand was growing for its qualities in American commercial construction. Finally, with gas-based manufacture, American plate glass could begin to compete with French and English imports in quality and cost.
2.1.1.2 Modern Glass Production

The glass production processes developed in 1900’s, namely Fourcault’s innovations of drawing glass (1910) and Pilkington’s float glass technique (1950), were technological advances for better optical quality at lower prices. The technique of float glass (molten glass “floats” over a tank of molten tin) provides extremely flat and uniform surface with least visual disortions making it acceptable in virtually all the commercial buildings of today. The researchers of Pilkington found that the key is that molten tin can react with any oxygen in the float chamber which can cause damage to the physical and chemical interaction at the surface between the glass and tin. They refer to the manufacturing of the float glass requires controlling the atmosphere inside the float bath chambers (Amstock, 1997). This innovation has also been extremely important for recent technological advancements in glass, since the uniformity achieved through float glass technique is necessary for the application of thin coatings that are commonly used in today’s windows (Carmody, 2004).
As a result of oil crisis in 1973, the extensive use of glass in modern movement has been moderated due to energy concerns. The crisis has accelerated the rethinking in use of the extravagant use of natural resources, in construction industry (Elkadi, 2006). The aspects of quality of light and desirable views have since then became a secondary consideration to environmental concerns in many buildings which end up using lots of energy for heating and air conditioning. Thus the emergence of green architecture ideology have led to the much advanced technological discoveries and made glazing much of a less negative factor in energy consumption. Some of the inventions to name are low-e coated glass, selective absorption coated films and/or variations of both. Insulating glass units filled with inert gases such as argon and krypton to improve R-values and the new “smart windows” are the newest contribution to this industry.

Fig. 3.2 Glass manufacturing process (float method)

(Source: http://www.agc.com)
2.1.2 Evolution of Glass as an Architectural Material

During the seventeenth century the development of lead glass made a major step forward in enabling the manufacture of large glazing for windows, “a technology that brought glass into the history of architecture” (Elkadi, 2006). Until 1851, glass was considered to be a luxury good, the conception which was gradually diminished during the industrial revolution due to increased availability of glass (Carmody, 2004). Gradually iron and steel developments running parallel to glass made advancements in metal framing technology with the possibility of large glass expanses, thus making it an inseparable part of modern architecture (Carmody, 2004).

Construction of the Crystal Palace (Fig. 2.3) in 1851, by Joseph Paxton in London marked the transformation of architecture’s traditional opaqueness by creating transparency through glass. He brought glass from the greenhouse to the architectural domain for the first time. Paxton aspired for a totally controlled autonomous climates by combining mechanical environmental systems, to manufacture controlled atmospheric conditions inside large buildings. However, he never accomplished these fully in his own designs (Schoenefeldt, 2008).

‘The light, indeed, will be almost as bright as in the open air, still gentle tempered and diffused by the canvas covering over the outside of the roofs and all the south side of the building.’ (Paxton, 1850)

To achieve uniformly lit interior space and using daylight as the only source of light was one of the major objectives for this project. Thus, in order to pacify the intense sunlight and glare created by this extreme transparency, translucent screens of calico were hung externally in-between the ridge beams of the roof glazing and covered the entire surface of the highly exposed horizontal section of the roof. Later when Crystal Palace was to be relocated in Hyde Park, for the summer, Paxton was primarily concerned with the control of potentially high solar gains. He proposed to
adopt passive shading, cooling and ventilation strategy, which, however, was only partly implemented (Schoenefeldt, 2008).

Architects were increasingly fascinated by the notion of transparent, all-glass buildings. In the first half of twentieth century, Chicago architects were constructing America's first high-rise glazed buildings, while in 1922, Germany's Ludwig Mies van der Rohe envisioned and crafted models of hypothetical 20 and 30 story skyscrapers clad totally in glass which resembles buildings currently being constructed today. It wasn’t until the middle of the last century that technology allowed for the construction of multi-story glass facades such as those on Bunshaft’s Lever House and Mies van der Rohe’s Seagram Building, and the many other glass skyscrapers that comprise the Manhattan skyline.

2.1.3 Challenges of Glass as an Architectural Material

The concept of transparent wall arrived with Paxton’s Crystal palace and was carried forward as a glass curtain wall experiment in 1864 in Oriel Chambers, Liverpool by Peter Ellis (Fig: 2.4). It demonstrated an exceptionally early use of curtain wall glazing and iron frame to maximize light, and minimize solid wall, and strongly influenced commercial architecture in North America. This inspiration could be seen in Willis Polk’s Hallidie office building (Fig: 2.7) in San Francisco (1918) considered as the first curtain wall building in United States. However, this building is not considered very comfortable on sunny days due to south facing glass facade.

Cobusier’s, Cité de Refuge (1933) (Fig 2.5) a hostel for Salvation Army to house elderly people is considered as a regrettable project. The impact it made by the design of entirely glazed southwest facade, quoting Le Corbusier, permitted the “ineffable joy of full sunlight”, and summer season combined together, made of the Cité de Refuge the first documented case of overheating with serious health consequences for the occupants (Butera, 2005). This façade had
to be modified by construction of ‘brise-soleil’ i.e vertical and horizontal shading devices (Fig 2.6).

Fig. 2.3 Crystal Palace, Sydenham, 1854
(Source: RIBA British Architectural Library)

Fig. 2.4 Oriel Chambers, Liverpool, 1864
(Source: http://www.liverpoolworldheritage.com)

Fig. 2.5 Cite de Refuge, Paris, 1933
(Source: http://www.technome.info)

Fig. 2.6 Cite de Refuge, Paris (brise soleil)
(Source: http://www.galinsky.com)
Another important building of the era is Mies van der Rohe’s Farnsworth House which was a weekend home. The construction of the building began in 1946 and took six years to plan and build. This rectangular shaped home was of glass and steel frame. The Farnsworth House acted as a single module for Mies’s Lakeshore Drive Apartments (1951) (Fig: 2.8) which is steel clad with walls entirely of glass and considered as first international style residential building in U.S. However, the use of clear glass caused glare and occupant discomfort and thus this project is often stated as “struggle for survival of the unfortunate occupants” (Butera, 2005). The building is recently being restored for problems including corrosion of the building’s exposed steel frame leading to distorting the glazing framing and cracking the glass (Krueck & Sexton, 2009).

The Seagram Building (Fig 2.9) and the Lever House (Fig 2.10) in New York completed in 1952 and 1957 respectively are considered as first largely glazed commercial buildings. These buildings were successful in achieving reduction in solar heat gains moreover conflicting with the
desire of transparency and in turn compromising on light transmission within the building (Samyn, 1997). Virtually designed as a sealed air conditioned boxes for occupants comfort, they had significantly inferior thermal/insulation performance compared to partly glazed buildings (Oldfield, 2009).

The John Hancock Tower, Boston (Fig: 2.11) is known for the most extraordinary glass facade failure the building industry has known. When the building was still under construction in 1972, the failure became noticeable during a wind storm of January 1973 causing the glass being pulled off the pane at the glass-bond layer interface. This failure was originally attributed to nickel sulfide (NiS), however this was later disproved and the exact cause was considered as the glass being ill equipped to cope with the stress increased with the edge damage (Johnson, 2008). The cracking at the lead sill and micro cracking transmitting through silver film due to excess movement of the building is considered as one of the issues for the failure. Following the discovery of this issue, all glass panels on the building were replaced with tempered glass at a very high cost. Much less known is that some of these replacement panels suffered from nickel sulfide failure (Schwartz, 2001).

The problems suffered by buildings with large quantities of single glazing are well documented after the second half of the 20th century and before the 1973 oil crisis. Most of these buildings not only faced vast heat losses in the winter, but also overheat from excess solar gain in the summer. Compensating with air-conditioning alone lead to excessively high primary energy consumption and responding to this many developed nations brought in building energy performance codes, leading to use of high performance glazing of today.
Figure 2.9 Seagram Building, 1957
Figure 2.10 Lever House, 1952

Fig. 2.11 John Hancock Tower, Boston
(Source: Feld & Carper, 1997)
2.1.4 Significance of Glass in Architecture

The main function of the glass in a window or a fully glazed facade is primarily to provide sunlight, daylighting, view and solar gain/loss in summer/winter. In past, the introduction of glass in the windows was mainly as a need out of concern for weather protection and its primary objectives were ventilation and daylighting. However, because of the technological advancements in electric lighting, mechanical ventilation and constructional techniques leading to increased floor depths, windows have begun to lose their importance of its basic functions.

In 1929-34, Le Corbusier described History of Architecture as a century old “struggle for the light, the struggle for the window” (McGrath, 1937). The Modern Era of 20th century brought a new need to architecture, and changed the concept for “look out” by need to look at and in the structure. As architecture was going longer, taller and larger, so was the struggle for the window.

Accompanied by the development of the metal frame, the glass as a material for “skin” of the building was considered as a significant element in the technical development of the skyscrapers that was essential to the functioning of the building. In the last few decades, the architectural language has given significance to the “lightness” and the “transparency” of buildings, emphasizing on fully glazed envelopes. Though the question persists whether these fully glazed buildings claiming themselves as environmentally concerned, are actually sustainable? (Butera, 2005).

2.2 Issues Related to Fenestration

The design for the successful window is one of the most important decisions in the building design and often considered as an optimization problem, and therefore, minimum as well as optimum performance specifications for each function of the window has to be set for a problem
to become soluble. Markus in his study regarding the functions of window mentioned five different criteria for window function which relate to- daylight, sunlight, ventilation, view and Privacy (Opposite aspects of the same problem) and contribution to the general visual character (Markus, 1967).

The criteria of daylighting and ventilation in buildings with full air conditioning and artificial lighting are not critical. However the significance of these issues has grown rapidly in the past few decades due to the need for energy conservation. Figures from energy audits performed by Tenaga conducted on offices in Malaysia indicated that the electricity use in commercial buildings was primarily attributed to the air conditioning, artificial lighting and office equipment, with 52-60%, 18-42% and about 22% of the total consumption respectively (Tenaga, 2005). Also, the energy audits and surveys of fully air-conditioned commercial buildings in typical commercial buildings in subtropical Hong Kong have revealed that the lighting and air-conditioning account for 20–30% and 40–60%, respectively, of the total electricity use (Chan, 1994).

The oil crisis of the early 1970’s brought about an awareness of need to reduce the energy consumption levels. The technological advancements in the window design further helped in achieving the reduction of the thermal transmittance coefficient or U-value. But the thermal insulation thus obtained, increases the greenhouse effect in fully glazed buildings and further renders the task of dealing with solar heat gains more difficult (Samyn, 1997). As a solution for this problem, the passive solar design and daylighting have long been recognized as potential energy-efficient design strategies for buildings.

2.2.1 Window as a Daylighting Aperture

Throughout the history daylight has been the primary source of lighting in the buildings. In 1900 daylight was in competition with the various forms of artificial light, but as we entered in mid 20th
century, the permanent artificial lighting and air-conditioning began to replace the historic dominance of daylight and natural ventilation in many buildings. With the advent of inexpensive electricity and widespread use of the fluorescent lighting in 1950’s and 1960’s, the building codes began to abandon the requirements of minimum daylighting within the building (Heschong, 2002). Fortunately, during the last quarter of the 20th-century and early years of this century, architects and designers have started recognizing the importance and value of introducing the natural light into the buildings (Kroelinger, 2005).

Electric lighting accounts for approximately 20-25% of the total electrical energy use in the United states and the commercial sector account for 37% (34% internal and 3% external) of the electrical energy consumption for the lighting (Fig: 2.11) (Ander, 2003). Using natural light from the sun costs nothing to the environment but pays big dividends to building occupants. This helps in gaining efficient lighting solution that also protects the environment. By consuming less energy, daylit buildings reduce the fossil fuel use and carbon dioxide emissions associated with the global warming and climate change (Daylighting Collaborative, 2011).

![Fig. 2.12 Commercial Electricity Use in United States](Source: Ander, 2003)
Highly variable and dynamic daylighting conditions are achieved depending on the season of the year, weather, and time of day combined with the predictable movement patterns of the sun. In cold climates, with overcast skies, a better lighting source can be achieved by even and diffuse light. In contrast, daylighting is most challenging in hot and sunny climates due to the immense amount of illumination received from the sky and the lengthy sunshine hours. Thus, the right placement, area, and size of the windows as well as the characteristics of glass contribute to effective daylighting. Excessive daylight not only result in the heat gain within building interiors but also provide glare, visual discomfort and the ‘cave effect’ (ill distributed level of light within the interior space) (Aboulnaga, 2006).

Successful daylighting is beyond simply providing large windows, and involves thoughtful integration of the design strategies. The design of the daylight must address heat gain, glare, and variations in light availability and direct beam penetration into the building (Ander, 2003). Daylighting can not only increase the comfort of the occupants but can also potentially reduce the energy consumption of the buildings.

2.2.1.1 Daylighting and Occupants

Windows as a source of daylight are extremely useful to health. It is essential for the healthy well being and productivity of the building inhabitants hence, the choice and the design of windows or glazing is vital. Glazing can either contribute positively or negatively to the level of daylighting and distribution in the building interiors. Inefficient design of windows could lead not only to poorly daylit building interiors but can also contribute significantly to fatigue, insomnia, depression and seasonal affective disorder (SAD) (Aboulnaga, 2006).

Various studies have shown that the productivity of comfortable workers with respect to thermal and visual conditions is greater. In the survey conducted in an office building in Seattle,
Heerwagen and Heerwagen, reported that more than half of the occupants believed that daylight was better for psychological comfort, office appearance and appeal, general health, visual health, and the color appearance of the people and the furnishings (Heerwagen, 1986).

Further, Veitch et al. demonstrated that 65% to 78% of the total occupants studied in Canada, endorsed the superiority of the natural light over artificial light (Veitch et al., 1993). Thereafter, Veitch and Gifford refined their questionnaire and administered it again to office workers and university students and came up with the similar conclusions as the previous study and also reported that 52% of the surveyed people worked best in places that were illuminated by the natural light (Veitch et al., 1996).

In yet another study by Wells, the office occupants in UK were surveyed to identify the relationship between the actual physical conditions of a building and beliefs and attitudes of people towards window, daylighting and natural lighting. 89% of the respondents believed that a view of the outside was very important; further 69% felt that it was better for their eyes to work in daylight than in electric light (Wells, 1965).

Lisa Heschong, in her study for daylight and human performance, studied three school districts in California. The study concluded that students in the classrooms with most daylighting were found to have 7% to 18% higher scores in the tests than those with the least window area. The reasons for the positive association between daylight and improved performance of the students were considered as improved visibility due to higher illumination levels and better light quality, mental simulation and improved mood, behavior and well-being (Heschong, 2002).

Based on this literature review it can be observed that there is a strong relationship between the daylight and health and productivity of the people. Also it can be concluded that daylit
workplaces are preferred over the artificially lit spaces because of improved visibility and superior light quality.

### 2.2.1.2 Daylighting and Building Energy Consumption

With the proper fenestration design, daylighting can be an important energy saving tool while in contrast the improper fenestration design can adversely become an energy wasting tool. Thus, to be an effective energy saving tool, daylighting should be integrated with the other building parameters, thereby becoming an important part of an energy conservation program.

Good daylighting design can result in the energy savings and can shift peak electrical demand during afternoon hours when daylight availability levels and utility rates are high (Aboulnaga, 2006). As per Zain Ahmed et al., the use of artificial lighting not only consumes energy but dissipates waste heat into the building space which contributes to the heating or cooling. In their research they demonstrated that 10% of energy saving could be achieved in Malaysian buildings by using daylighting strategies (Zain Ahmed et al., 2002).

According to recent study by Doulas et al. on the energy savings due to daylighting, Szerman found 77% for lighting energy savings and 14% of total energy savings (Szerman, 1993). Embrechts and Van Bellegem measured that an individual lighting dimming system can offer 20–40% of lighting consumption savings (Embrechts and Van Bellegem, 1997). In 1995, Opdal and Brekke in their study compared measurements and calculation results and obtained results of 40% of lighting savings from calculation and 30% of lighting energy savings from measurements.

In the other study performed by use of electric lighting under the dimming control in the tested office, Li et al estimated annual savings of 33%. By using the artificial lighting management as a function of daylighting, Rutten demonstrated 46% of lighting savings (Rutten, 1991).
Lighting control schemes that perform on-off operations due to time scheduling, occupant presence, manual dimming, automatic dimming, demand control and lumen depreciation, have been found to have a great potential in reducing the lighting energy consumption (Doulas et al., 2007). In the literature review study most researchers indicated that energy savings of 14% to 46% can be achieved by daylighting scheme. These savings finally depend on the climate zone, shape of the buildings and location and size of the window.

Inspite of the significance of daylighting utilization in substitution for the electric lighting energy loads, this strategy is not commonly incorporated. The surveys have shown that only 10% of the U.S. commercial buildings have some daylighting schemes while almost 50% of the buildings are equipped with an energy efficient lamps and ballasts (Krarti et al., 2005). The lack of simplified evaluation tools which are capable of providing the information on the suitability of daylighting and its potential to save energy is considered as one major reason for the reluctance of the building professionals in incorporating daylighting features in their design (Krarti et al., 2005).

### 2.2.2 Window as a Solar Aperture

The natural benefits of sun can be used for supplying the maximum buildings heating and daytime lighting needs by designing a building’s orientation, proportions, and fenestration to take the advantage of the sun’s path. However, it is important to note that windows which admit daylight also admit solar heat, and though heat from the sun is welcome in buildings in cold climates, in excess it can make buildings uncomfortably hot in summers. It is therefore, important to be able to assess the trade-off between the natural daylight and unwanted heat gain.

According to ASHRAE Handbook-Fundamentals, 2010, fenestration solar heat gain has two components. First is the directly transmitted solar radiation which is the quantity of radiation entering the fenestration directly and is governed by the solar transmittance of the glazing system.
The second component is the inward flowing portion of the absorbed solar radiation, radiation that is absorbed in the glazing and framing materials of the window and is subsequently conducted, convected and radiated to the interior of the building (Nikpour et al., 2011).

The two parameters which are dominant in controlling the solar heat gain in the buildings through the windows are- Solar Heat gain Coefficient and window to wall ratio (Nikpour et al., 2011). Integrated design approach for these parameters can assist in achieving an optimum solution for achieving maximum daylighting with minimum heat gain.

2.2.1.1 Passive Solar Design in Cold Climates

For passive solar design in cold climates, the sun is admitted directly into the inhabited spaces through windows, skylights etc. The main factors affecting the solar gain through the window within the building are orientation, size and type of solar glazing. Control options for heat gain and loss through the glazing needs to be addressed to avoid the under performance of the windows (Givoni, 1991).

In winter as the sun’s rays strike horizontal object obliquely, the solar radiation is spread over a larger area and less energy is available for absorption. The situation for the vertical, south facing surface is exactly the opposite. The rays from the low winter sun strike a vertical surface more directly, allowing more solar energy within the building (Fig. 2.12). “Although the winter solar exposure time is less, the winter sun spends more time in front of a south facing vertical surface than it does in summer.” (Johnson, 1981). This large wintertime collection potential for vertical, south facing windows is the reason direct gain solar heat works.

Apart from some radiation that is lost by absorption in the upper atmosphere and scattered by atmosphere, the remaining energy contributes to the diffuse radiation. This diffuse radiation
contributes to 10-20% of the total incoming radiation that strikes a vertical south facing surface. It can be an important source of heat along with direct sunlight gathered for heating purposes.

The amount of diffuse and reflected radiation striking any vertical surface is nearly the same at any instant, because light is diffusely reflected by the ground, and diffuse radiation from the sky is evenly distributed around the compass points of the sky vault, so the north wall get approximately as much diffuse radiation as south walls. Thus orienting the building with the east-west as major axis for longer side will ensure maximum sun exposure on north and south side which can compensate the heat loads.

Fig. 2.13 Sunpath diagram for winter and summer

Increasing the area of glazing in the buildings proportionately increases the solar gain in the daytime, however, it also increases the heat loss through the glazed area during the winter nights. The large glazing areas can also result in undesirable heat gain during the summer. The impact of these two thermal effects depends on the severity of the seasons in the given region as well as on
the properties of the glazing. Designing the glazing with insulation and shading devices can help in overcoming these penalties of heat loss in winter and excessive heat gain in summer.

2.2.1.2 Passive Solar Design in Hot Climates

The solar heat gain through a window is the sum of the transmitted radiation and that part of absorbed radiation which is transmitted inwards through fenestration. If large windows are desired to admit sunlight or to provide a view, the excess heat gained along with the size of the window may be removed by air conditioning equipment, but at the expense of ductwork, cooling plant and running costs.

Lam & Hui, determined that in cooling dominated office buildings in Hong Kong, the solar heat gain accounts for just over 50% of cooling loads due to building envelope heat gains (Lam & Hui, 1993). They suggested that most parameters like WWR and SHGC which related to building load vary linearly with the total building energy consumption. It is essential to assess the tradeoff between beneficial natural daylight through large WWR and unwanted solar heat gain. Daylight utilization and introduction of solar controls and shading devices are the passive methods that can be used in hot climates to compensate on the excessive solar gain and cooling loads.

It is important to determine the maximum permissible areas of glass and the glazing type to be used in buildings when heat gain by solar factor is part of the design criteria. The window openings and overhangs should be designed specific to direction of exposure of the wall. The north side can be provided with large windows and shallow overhangs since this orientation will provide natural daylight without direct solar heat gain. South, east and west orientations should be designed for windows with deeper overhangs for protection against direct heat gain. The larger size of windows for these orientations could be designed with sun control devices to gain protection in summer.
2.3 Characteristics of Glass

In this section thermal, optical and structural properties are described in detail to understand the basic functioning of the glazing in these three scenarios.

2.3.1 Thermal Properties

Heat flow through a window assembly occurs in three ways: conduction, convection and radiation. When there is a temperature difference between interior of the window and its exterior, heat transfer will occur via conduction through glass and solid frame materials, convection/conduction through air space, long wave radiation between glass surfaces on either side of an air gap. There are two types of radiation or radiant heat transfer: Long wave radiation which refers to radiant heat transfer between objects at room or outdoor environmental temperatures and short wave radiation which refers to radiation from sun (Carmody, 2004). When radiant energy meets the boundary between one medium and another, some of it is reflected, and rest passes into second substance, where some of it is absorbed and some transmitted (Washington, 1938). Solar radiation in the building converts into the heat gain and then
contributes to buildings cooling load. The four basic properties of glazing that affect radiant energy transfer are- transmittance, reflectance, absorptance and emittance.

2.3.1.1 Transmittance
Transmittance is the percentage of radiation that can pass through the glazing. Transmittance can be defined for different types of light or energy eg; visible transmittance, UV transmittance or total solar energy transmittance. Transmission of visible light determines the effectiveness of the type of glass in providing the daylight and a clear view through the window. The total solar energy transmittance determines how the glazing responds to a much broader part of the spectrum and is more useful in characterizing the quantity of total solar energy transmitted by the glazing (Carmody, 2004).

2.3.1.2 Reflectance
The proportion of light incident on a glass surface which is reflected depends on the frequency of the radiation, on the angle of incidence, on the refractive index of the surface and on the condition of the surface. The reflection results in the loss of light (Washington, 1938). The sharper the angle at which the light strikes, the more is the light reflected rather than transmitted or absorbed. Also the reflectivity of the various glass types becomes more apparent in low light conditions (Carmody, 2004).

2.3.1.3 Absorptance
Energy that is not transmitted through the glass or reflected off its surface is absorbed. Once the glass has absorbed any radiant energy, the energy is transformed into heat, raising the glass temperature. The absorptance of glass is increased by glass additives that absorb solar energy. If they absorb visible light, glass appears darker. If they absorb ultraviolet radiation or near infrared,
there will be little or no change in visual appearance (Carmody, 2004). The proportion of absorbed light depends on the thickness of the pane (Wurm, 2007).

2.3.1.4 Emittance

When solar energy is absorbed by glass, it is either convected away by moving air or reradiated by the glass surface. This ability of a material to radiate energy is called its emissivity. Window glass, along with all other objects, typically emits, or radiates heat in the form of the long wave infrared energy. Reducing the window’s emission of heat can greatly improve its insulating properties (Carmody, 2004).

2.3.2 Optical Properties

Being transparent to light is one of the basic properties associated with glass, and is the prime importance of the uses to which glass is put. The varying relations between refractive index and dispersion result can result into effects of changes in the nature and properties of glass (Washington, 1938). The glazing types vary in their transparency to different parts of the visible spectrum. For example different tints of glass can vary in the amount of sunlight they transfer, and can absorb or reflect different colors. Glass is opaque to long wave infrared radiation but generally transparent to solar infrared radiation. Strategic utilization of these variations has made possible some high performance glazing products (Carmody, 2004).

2.3.3 Structural Properties

The glass used in construction is composed of 75% silicon dioxide (silica), sodium oxide (soda) is added to lower the transformation temperature and calcium oxide (lime) is added to increase chemical resistance. The tensile and bending strength of the glass reflects surface quality and is not a constant value and is related directly to size and age of the pane. The glass deforms linear elastically under increasing load at right angles to the plane of the pane until it exceeds its load
bearing capacity. The brittleness, high compressive strength and elastic deformative behavior of the material are of prime importance in the design of glass structures (Wurm, 2007).

The primary structural requirement of fenestration products and systems in commercial buildings is a capacity to withstand wind and other structural loads. Another concern in structural design of glass is thermal stress. Thermal breakage of glass is generally caused by uneven heating of glass by solar radiation. If the glass is not properly strengthened to meet the anticipated thermal loading conditions, a thermally induced crack will be introduced. Thus, it is important to perform a thermal analysis of a glass before using it in a construction (Carmody, 2004).

2.4 Effect of Windows on Energy Use Patterns

The glazing is a component in a window which separates the exterior from the interior, so it must have properties which are appropriate to prevailing conditions, both climatic and concerning the building properties and usage (Wilson, 2004). For comparison of different glazing options for a window it is necessary to have a understanding of the basic properties related to them. In this section some typical parameters describing windows from energy aspects are introduced.

2.4.1 Thermal Transmittance (U Value)

The thermal transmittance or the U-value quantifies the rate of heat flow or thermal transmission through the material or assembly in units of heat flow per unit area per unit of temperature difference between indoor and outdoor and is expressed in units of BTU/hr sq.ft. or W/sq.m.K. It is responsible for the amount of energy a glazing system transfers by conduction and convection. This value is also given as R-value or resistance to heat transfer which is reciprocal of the u-value.
U-Value represents the performance of the entire window unit including the glazing, frame and spacer material. Often two U-values are used to classify windows- glazing u-value and total U-value of the window. A window with the lower U-value is considered more energy efficient than one with the higher U-value since they allow minimum thermal leakage through them. Therefore, U-value is an important factor to reduce heating loads in cold climates.

2.4.2 Solar Heat Gain Coefficient (SHGC)

While U-value is an important characteristic for all the building components including the opaque ones, solar heat gain coefficient is mainly concerned with the transparent components such as glazing. It is defined as the ratio of solar heat gain through a window to the solar radiation striking the outer surface, for a given incidence angle (Usually perpendicular to the glazing surface) and environmental condition (indoor and outdoor temperature, wind speed etc.). The total solar energy transmittance is the sum of two components: the solar radiation which is transmitted by the glazing unit, and that portion of solar energy that is initially absorbed in the glazing and is then transferred as heat to the indoor environment. (Wilson, 2004).

The shading coefficient (SC) was the primary term used to characterize the solar control properties of the glass in windows; however, it is being replaced by the solar heat gain coefficient (SHGC). Similar to U-value the lower SHGC value indicates better performance. Glazing systems with high SHGC values provide substantial solar gain, whereas lower values provide lesser solar gains, therefore SHGC is more important factor for hot climates.

2.4.3 Visible Transmittance (VT)

Visual Transmittance is an ability of glazing product to transmit daylight. It is defined as the ratio of light transmitted by the glazing to light incident on the glazing, for perpendicular incidence if not specified otherwise (Wilson, 2004). It measures the amount of light entering through the
product and is expressed as a number between 0 and 1. Since the daylight penetration in the building is directly related to the fenestration area and VT, a higher value indicates increased potential for daylighting.

VT is an important factor related to energy conservation by implementing daylight strategies. Though high VT values provide lot of natural daylight, in excess it can be a source of excess glare if proper control measures are not provided. On the contrary lower VT value can potentially protect occupants from glare; however it can make the interiors dark and gloomy. Therefore, determining the optimum VT values has tremendous potential in energy conservation and occupant comfort.

### 2.5 Types of Glazing

The most basic glass today is manufactured by the float glass process and only 10% of the glass used in construction is drawn or rolled. The manufacturing of the float glass is followed by two or more processing stages to optimize the material for specific technical functions such as solar control, structural or safety needs or aesthetic aspects such as color effects.

The group of basic glass types is extended by float glass that is coated in an on-line process directly after forming. Physical and chemical processes are used to place thin film or functional coatings on the surface of the glass, primarily to change the optical properties such as amount of transmitted light and energy. At the end of this processing generally two or more panes of glass are layered or bonded to form laminated safety glass or often fabricated into insulating glass units by means of spacer bars along the edges of the panes. Intermediate stages can involve bending of the glass panes, enameling the glass surface with ceramic frits, tempering or heat strengthening of glass depending on the requirements (Wurm, 2007).
Although float glass is the most commonly used, there are various technological advances that have made different types of glass available as per the needs of a particular project. With the increasing number of innovations the properties of the glass can be enhanced along with giving the choice of various colors and appearances. In practice many of the technological advances are combined to create high performance energy efficient windows in commercial buildings (Wurm, 2007).

2.5.1 Traditional Glazing Technologies

Traditionally, many technological advances were achieved in glass by introducing different processes at various stages of glass manufacturing. Tinted glazing is processed at the primary stages of manufacturing. Low e coated and reflective coated glasses are essentially the physical process at intermediate stage of manufacturing while insulating and laminated glass are produced at the end stage.

2.5.1.1 Tinted Glazing

Tints are introduced by altering the chemical formulation with special inorganic additives. Sometimes coatings can also be applied after manufacture. The color is durable and does not change over time. Glass with various color tints absorb a portion of solar heat and block daylight. Tint can also be helpful for retaining visual privacy. However, the primary uses of the tinted glazing are reducing the glare from bright outdoors and reducing the amount of solar energy transmitted through the glass.

Traditional tinted glazing often leads to reduced visual transmittance and usually not compromised upon solar heat gain coefficient which can decrease glare by reducing the apparent brightness of glass surface, but it also reduces the amount of daylighting in the room. To overcome this problem of daylighting, manufacturers have introduced high performance tinted
glazing or spectrally selective glazing. This glass transmits the daylight portion of the solar spectrum but absorbs the near infrared part of sunlight. Sometimes they are also combined with low e coatings to enhance their performance further (Carmody, 2004).

2.5.1.2 Low E Coating

The ability of a material to radiate energy in the form of long wave or far infrared is called its emissivity. Reducing the window’s emittance can greatly improve its insulating properties. There are two basic processes in making low emittance glass, sputtered and pyrolytic. A sputtered coating is multilayered and is deposited on glass or plastic film in a vacuum chamber. A typical pyrolytic coating is a metallic oxide with some additives, which is deposited directly onto a glass surface while it is still hot.

The first low e coatings were specifically intended for residential use and were designed to have high solar heat gain coefficient and high visible spectrum to allow maximum amount of sunlight into the interior while reducing the u factor significantly. The second generation of low e coatings still maintains the low u factor but are designed to reflect the solar near infrared radiation, thus reducing the total SHGC while providing high levels of daylight transmission (Carmody, 2004).

2.5.1.3 Reflective Coating

A reflective coating can be used to lower the solar heat gain coefficient by increasing the surface reflectivity of the material. These coatings are comprised of thin metallic or metal oxide layers and can be applied to clear or tinted glazing. The degrees by which the SHGC can be reduced depend on the thickness and reflectivity of coatings and its location in the glazing system. Durable reflective coatings can be applied on the exposed surfaces while others can be protected by sealing in insulating glass units. Reflective coatings which face light, acting like mirror on
exterior side, can intensify the sun’s effect. This coating can act like mirror on inside during the night and disallow privacy.

2.5.1.4 Insulated Glazing
One of the drawbacks of the glass is its poor insulating properties which can be potentially tackled by the assembly of multiple panes of glass with air spaces of any other gas in between. The edge spacers placed between the panes of the glass are helpful in holding the insulating unit apart at appropriate distance. However, apart from this basic function it also helps in accommodating the induced stress, providing a moisture barrier, providing a gas tight seal and creating an insulation barrier.

The space between the insulating units was originally filled with air or dry nitrogen. Now days with the technological advancements to improve the thermal performance of the insulating glass, the conductance of the air space is reduced by using less conductive, more viscous or slow moving gas like argon or krypton. However krypton has a better thermal performance than argon and is more expensive to produce.

2.5.1.5 Laminated Glass
Laminated glass consists of a tough plastic interlayer made of polyvinyl butyral (PVB) bonded between two panes of glass under heat and pressure. Laminated glass provides durability, high performance and multifunctional benefits while preserving the aesthetic appearance. Laminated glass offers increased protection as upon impact glass particles tend to adhere to the plastic interlayer rather than become free falling.

The glass layers used in laminated glass can be equal or unequal, heat strengthened or tempered, with reflective or low e coatings or with frit patterns depending upon the function that it has to serve. Single pane laminated glass with a spectrally selective low e sputtered coating on plastic
film sandwiched between two panes of glass offers the energy performance of single pane and a safety protection of laminated glass.

2.5.2 Emerging Glazing Technologies

Though the efficiency of today’s windows is much more than the windows from prior decade, they are still significant energy liabilities. The advancements in the emerging technologies in the form of insulation filled, evacuated and smart windows can potentially result in the design and construction of highly efficient and advanced buildings that can have minimum impact on depleting energy sources (Arasteh, et al., 2006). Based on the recent report by Carmody et al. this section provides an overview of the advanced window technologies (Carmody et al., 2004).

2.5.2.1 Insulation Filled Glazing

These types of glazing system are assembly of panes with highly insulated materials like aerogel, honeycombs and capillary tubes sandwiched between them. These materials allow diffused light within the building with the unclear views of the exterior. Aerogel, however, has received attention for its ability of being highly transparent and insulating. There exists a technical possibility of producing the aerogel windows with the u values as low as 0.05. The limitation for this product is however its production in small quantities and sizes which has to be used in bead forms as a infill material within glass panes, thus providing the limited visibility.

2.5.2.2 Evacuated Windows

The evacuated windows are the assembly of glazing panes without any gas fill (vacuum) and thus considered to be most thermally efficient. By keeping the vacuum pressure low enough, the heat exchange between panes of the glass in the form of conduction or convection can be eliminated thus resulting into low U-values. The vacuum effect alone is however not enough, a good low-e coating is necessary for this type of assembly to reduce the radiative heat transfer.
In spite of the being thermally efficient, evacuated windows present a number of engineering problems. One of the major issues is the structural requirement to resist normal air pressure and variable pressures caused by wind and vibration. Another issue is the maintenance of an airtight seal around the unit edge. The seal must be maintained to eliminate gaseous conduction by keeping the air density within the unit to less than one millionth of normal atmospheric pressure; an air density of only ten times this amount is sufficient to re-establish conduction to its normal value. This vacuum seal must remain intact for the life of the window, through manufacture, transportation, installation, and normal operation, wear, and weathering. This unit also has the advantage of being thin and thus suitable for many glazing retrofits. However, edge condition losses are larger than for conventional IGU designs, although these can be compensated for in the frame design. A major glass company now offers this technology as a commercially available product in Japan.

2.5.2.3 Smart Windows

These facade systems include switchable windows and shading systems such as motorized shades, switchable electrochromic or gasochromic window coatings, and double envelope window-wall systems that have variable optical and thermal properties that can be changed in response to climate, occupant preferences and building system requirements. By actively managing lighting and cooling, smart windows could reduce peak electric loads by 20–30 percent in many commercial buildings, increase daylighting benefits throughout the United States, improve comfort, and potentially enhance productivity.

There are two basic types of switchable windows—passive devices and active devices. Passive devices respond directly to a single environmental variable such as light level or temperature, and active devices that can be directly controlled in response to any variable such as occupant preferences or heating and cooling system requirements. The main passive devices are
photochromics and thermochromics. Active devices include liquid crystal, suspended particle, and electrochromics.

**Photochromics**- Photochromic materials can change their transparency in response to light intensity. They may be useful in conjunction with daylighting, allowing just enough light through for lighting purposes, while cutting out excess sunlight that creates glare and overloads the cooling system. Although small units have been produced in volume as a consumer product, cost-effective, large, durable glazings for windows are not yet commercially available.

**Thermochromics**- Thermochromics can change transparency in response to temperature. Some materials like gels sandwiched between glass and plastic which can switch from a clear state when cold to a more diffuse, white, reflective state when hot are currently under development. In the switched-on state, the view through the glazing is lost. Such windows can also turn off the sunlight when the cooling loads become too high. Thermochromics could be very useful to control overheating for passive solar heating applications. The temperature of the glass, which is a function of solar intensity and outdoor and indoor temperature, would regulate the amount of sunlight reaching the thermal storage element. A thermochromic window can also be activated by a heating element in the window, making it operate like other switchable glazings, but this tends to be less energy efficient. Prototype glazings of this type have been tested but are not yet commercially available.

**Liquid Crystal Device Windows**- In this type of windows, a very thin layer of liquid crystals is sandwiched between two transparent electrical conductors on thin plastic films. The entire emulsion or package (called a PDLC or polymer dispersed liquid crystal device) is laminated between two layers of glass. When the power is off, the liquid crystals are in a random and unaligned state and scatter light due to which the glass appears as a translucent layer, which
obscures direct view and provides privacy. The material transmits most of the incident sunlight in a diffuse mode, thus its solar heat gain coefficient remains high. When power is applied, the electric field in the device aligns the liquid crystals and the glazing becomes transparent in a fraction of a second, permitting view in both directions.

Most of these devices have only two states, clear and diffusing. The power of about 0.5 W/sf, operating between 24 and 100 volts AC must be continuously applied for the glazing to remain in the clear state. The visible transmittance range is typically 50–80 percent and the SHGC is 0.55–0.69. The dyes can be added to darken the device in the off state.

**Suspended Particle Device (SPD) Windows**

This electrically controlled film utilizes a thin, liquid-like layer in which numerous microscopic particles are suspended. In its unpowered state the particles are randomly oriented and partially block sunlight transmission and view. Transparent electrical conductors allow an electric field to be applied to the dispersed particle film, aligning the particles and raising the transmittance.

Typical visible transmittance (VT) and solar heat gain coefficient (SHGC) ranges for the film alone are VT=0.22–0.005 or 0.57–0.12 and SHGC=0.56–0.41 or 0.70–0.50, respectively, with near instant switching times (less than one second). The device requires about 100 volts AC to operate from the off state (colored) to the on state (near transparent) and can be modulated to any intermediate state. Power requirements are 0.5 W/sf for switching and 0.05 W/sf to maintain a constant transmission state if not off (the most colored, cobalt blue state). These products are now entering the market, but cost remains an issue.

**Electrochromic Windows**- This is the most promising switchable window technology today. An electrochromic coating is typically five layers, about one micron thick, and is deposited on a glass substrate. The electrochromic stack consists of thin metallic coatings of nickel or tungsten oxide
sandwiched between two transparent electrical conductors. When a voltage is applied between the transparent electrical conductors, a distributed electrical field is set up which moves various coloration ions (most commonly lithium or hydrogen) reversibly between the ion storage film through the ion conductor (electrolyte) and into the electrochromic film. The effect is that the glazing switches between a clear and transparent prussian blue-tinted state without degradation in view.

The main advantages of EC windows is that they typically only require low-voltage power (0–10 volts DC), remain transparent across its switching range, and can be modulated to any intermediate state between clear and fully colored. Typical EC windows have an upper visible transmittance range of 0.50–0.70 and a lower range of 0.02–0.25. The SHGC ranges from 0.10–0.50. A low transmission is desirable for privacy and for control of direct sun and glare, potentially eliminating the need for interior shading. A high transmission is desirable for admitting daylight during overcast periods. Therefore, the greater the range in transmission, the more able the window is to satisfy a wide range of environmental requirements.

The higher initial price of the electrochromic glazing can be partially offset by factors such as reduction in HVAC equipment size and window treatment. Electrochromic technology has been actively researched throughout the world for over thirty years, and promising laboratory results have led to prototype window development and demonstration. Examples of electrochromic window prototypes have been demonstrated in a number of buildings in Japan and more recently in Europe and the United States.
2.6 Energy Codes and Standards Related to Commercial Buildings

As part of the nation’s drive to reduce energy consumption, building energy codes have been enacted and enforced by most states and jurisdictions, which include specifications for the efficient fenestration. Most of the states in U.S. consider ASHRAE standard 90.1 as the baseline for commercial energy standards. However, there are some states with unique energy codes (i.e., those that do not adopt/amend the International Energy Conservation Code [IECC] or Standard 90.1) and have highly capable energy offices that routinely assess their codes against the national codes.

Building energy codes and standards have been developed to monitor the construction and reflect the societal interest in the energy efficiency. ASHRAE 90.1 provides the standards for energy efficient designs for the commercial building which includes building envelope, HVAC, hot water, and lighting with respect to eight climate zones defined by ASHRAE. It takes in to account the values such as dry-bulb temperature, wet-bulb, temperature, dew-point temperature, enthalpy, and wind speed at various frequencies of occurrence over a long-term period, corresponding mean coincident values of some other parameters, and averages of some extremes (Thevenard, 2009). However it does not acknowledge the solar radiation factor which is a necessary input for the fenestration heat gain calculation and in turn the heating and cooling load analyses along with the lighting gains.

The ASHRAE 90.1-2007 which is considered as the baseline for the commercial energy standards sets absolute minimum requirements for the fenestration. It recommends only the U-value and SHGC values for glazing with respect to the window to wall ratio in a range of 0-40% for all the climate zones. Moreover it recommends WWR values based on thermal performance alone and does not recommend the visual transmittance value, window to wall ratios and aspect ratios of the
buildings specific to climate zones. These are extremely important parameters to evaluate the heat gain, daylight gain and the associated heating, cooling and lighting loads due to fenestration.

This study is done based on ASHRAE Standard 90.1-2007 as it is the baseline commercial energy standards established in the American Recovery and Reinvestment Act of 2009 and also sets requirements for the cost-effective use of energy in the commercial buildings.
3. WINDOW OPTIMIZATION

By definition “optimization is the process of seeking the most favorable condition or solution to a goal by balancing the trading-off results on more than one criterion”. In mathematics optimization is derived from finding the minima or maximums of objective functions, normally the first derivative of a certain function specify the point at which the function has maximum or minimum values (Alzoubi, 2005). The focus of this thesis is lighting and energy based performance and thus requires dealing with optimization as different concept. The solution for this study is not to find the minimum or maximum values as optimal solutions, but to find the range of values for parameters in which the energy penalty of increasing the window area is minimized. This study will focus on achieving optimum situation in terms of thermal and lighting performance of the building.

The application of optimization techniques to different building design problems has been used over the past 30 years for various fields of spatial allocation problems, site developments, and land use to the design of structural and mechanical systems in buildings (Al-Homoud, 1997). However, for the thermal design of buildings, most of the efforts were directed to the development of simulation models. With the speed of the computers in the present day and with the availability of the suitable energy simulation programs, it is possible to integrate the simulation models and optimization techniques for the efficient decision making purpose of thermal design of the building. (Lawrence Berkeley Laboratory, 1979).

3.1 Need for Optimization

Heating, cooling and lighting are the primary sources of energy consumption by commercial buildings in the United States and are responsible for 14%, 13% and 27% respectively, of the total energy consumption by commercial sector in U.S (Fig. 3.1). The selection and arrangement
of fenestration components of the building can significantly impact its thermal performance which is a determining factor in its consumption of energy (Al-Homoud, 1994). Also, addressing the fact that a building is essentially an environment modifier, and there is an intimate relation between building design and indoor environment, it is necessary to consider environmental design as an integral part of the overall design and planning process (Gupta, 1970). The occupants being the user of the building, providing them with comfortable environment is an ultimate goal of the building. The literature review for daylighting benefits determines that occupant comfort, their health, productivity and visual satisfaction are the factors which are directly related to the daylight utilization in the building and hence need a serious consideration in the fenestration design. To determine the optimum thermal performance based on occupant comfort, the relationship between the thermal comfort and daylight performance of the building needs to be established. This relationship can be further used to select optimum fenestration parameters to achieve the desired objectives.

Fig. 3.1 U.S. Commercial Buildings Primary Energy End-Use, 2005.

Determining the optimum fenestration parameters for office buildings will be beneficial for the designers to design efficient buildings, for building owners and operators to achieve energy use reductions and running costs and finally for building occupants to achieve comfort, productivity and well-being.

3.2 Literature Review for Optimization

Over the past few decades many studies have been conducted to estimate energy saving potentials of windows using optimization techniques. With the advancements in computational techniques, the optimum window design for minimizing building energy consumption and maximizing the daylighting performance has been explored (Sullivan, 1992; Al-Homoud, 1997; Inanici, 2000; Haglund, 2010).

Sullivan, Selkowitz and Lee of LBL formulated a model for optimizing solar control and daylighting performance for a prototypical office building of Los Angeles by using series of DOE-2 building energy simulations. According to their study, the solar and effective daylighting aperture values that minimize energy consumption may assist in determining optimum performance of the glazing. Using regression analysis procedures, electric energy and peak performance patterns were characterized as function of solar aperture (product of shading coefficient and window to wall ratio) and effective daylighting aperture (product of visible transmittance and window to wall ratio). The results indicated that daylighting contributed to around 40% of the primary energy savings (Sullivan, 1992).

Al-Homoud, studied the impact of mainly envelope related parameters on the thermal performance to minimize annual energy consumption for office buildings in six different cities of US and Saudi Arabia. The optimum thermal design summary was based on the parameters of
The optimization results revealed both lower energy use as well as lower peak heating and cooling loads which can further reduce operating as well as initial HVAC equipment costs. The result essentially indicated the relative importance of building envelope design in climate related thermal performance, effect being more critical for cold climate and of less importance in hot-humid climate. The energy saving of 6.6% to 22.4% could be achieved in different climate zones by means of envelope optimization (Al-Homoud, 1997).

The study by Inanici et al., analyzed the process of minimizing heating and cooling loads by means of optimum window size and building aspect ratio. The study was carried out for five different climatic regions of Turkey by the aid of the computer based thermal analysis program SUNCODE-PC. The south window size and insulation value were found to be the most remarkable features for thermal gains, thus sizing of these features was carried out by the parametric study. It was concluded that window to wall ratio of 25% on the south orientation was optimum in hot climates due to the need for decreasing heat gain in summer while, in cold climates, larger window to wall ratio up to a certain point are preferred due to the need for increasing heat gains in winters (Inanici et al., 2000).

In a recent study by Haglund, the senior research fellow at University of Minnesota, the study of two cities in extreme climate, Phoenix (Cooling dominated) and Minneapolis (Heating dominated) is performed to understand optimization in high-performance commercial buildings. Baselines from the existing data set, code budget building and existing building stock database were determined from which to specify the top performing window design options and establish the targets. The top 50 performing windows in terms of annual energy and peak demand were studied with respect to orientation, WWR, shading type and glazing type. The results for energy
savings achieved in the study were compared to the Commercial Buildings Energy Consumption Survey (CBECS) and ASHRAE standards and are summarized in the table below-

<table>
<thead>
<tr>
<th>Cities</th>
<th>Phoenix</th>
<th>Minneapolis</th>
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<tbody>
<tr>
<td></td>
<td>Compared to base case</td>
<td>Compared to base case</td>
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<tr>
<td></td>
<td>Compared to CBECS</td>
<td>Compared to CBECS</td>
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<tr>
<td></td>
<td>database</td>
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<tr>
<td></td>
<td>Compared to the ASHRAE</td>
<td>Compared to the ASHRAE</td>
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<tr>
<td></td>
<td>90.1-99</td>
<td>90.1-99</td>
</tr>
<tr>
<td>North</td>
<td>18.53–24.94%</td>
<td>11.76–22.81%</td>
</tr>
<tr>
<td></td>
<td>13.20–42.03%</td>
<td>34.47–47.57%</td>
</tr>
<tr>
<td></td>
<td>18.53–24.94%</td>
<td>11.76–22.81%</td>
</tr>
<tr>
<td>East</td>
<td>23.46–37.91%</td>
<td>10.15–32.30%</td>
</tr>
<tr>
<td></td>
<td>20.79–42.03%</td>
<td>35.23–47.57%</td>
</tr>
<tr>
<td></td>
<td>23.46–37.91%</td>
<td>10.15–32.30%</td>
</tr>
<tr>
<td>South</td>
<td>28.10–41.43%</td>
<td>23.92–33.90%</td>
</tr>
<tr>
<td></td>
<td>38.73–42.03%</td>
<td>35.23–47.57%</td>
</tr>
<tr>
<td></td>
<td>28.10–41.43%</td>
<td>23.92–33.90%</td>
</tr>
<tr>
<td>West</td>
<td>30.51–38.95%</td>
<td>22.86–33.32%</td>
</tr>
<tr>
<td></td>
<td>38.7–42.03%</td>
<td>39.84–47.57%</td>
</tr>
<tr>
<td></td>
<td>30.51–38.95%</td>
<td>22.86–33.32%</td>
</tr>
</tbody>
</table>

Table 3.1: Energy savings compared to CBECS and ASHRAE standards (Haglund, 2010).

The key findings for top performing windows in Phoenix and Minneapolis was as follows-

- For the north and east orientations, many of the top performers for annual energy are also the top performers in terms of peak demand, mostly used in combination with shading devices.
- For the east and west orientations, window options were removed due to poor performance in terms of glare.
- For the east, south, and west orientations, all orientations, the best performers for annual energy are often the worst performers for peak demand. Peak demand is not as critical of an energy-performance attribute in a heating climate as it is in a cooling climate.
- There is little or no performance penalty for using high-performing glazing with a large window area.
- For the north orientation, no external shading
top performers use some sort of external shading device.
  • The design options in the north orientation have the lowest annual energy use compared to the other orientations resulting from the lack of direct solar gain.
  • For the north orientation, no external shading or shallow devices are preferred, allowing for ample indirect light.
  • For the east orientation, to reduce peak demand, WWR must also be reduced.
  • For the south and west orientations, large WWR is used in combination with deep shading devices.

or shallow devices are preferred.
  • The design options in the south orientation have the lowest annual energy use compared to the other orientations resulting from the benefits of passive solar gain.
  • For the south orientation, shallow shading devices are used with moderate WWR and deep shading devices are used with large WWR, both of which limit exposure to the southern sun.
  • For the west orientation, moderate to large WWR used in combination with various shading devices is prevalent.

Table 3.2: Key findings for top performing windows in Phoenix and Minneapolis (Haglund, 2010).

The study shows that the energy savings in the range of 13%-43% was achieved for Phoenix while savings in the range of 10-48% could be achieved for Minneapolis. Also for all of the simulations, the results using daylighting controls outperformed the results of not using daylight controls (Haglund, 2010).

All the authors in the above mentioned study agree that considerable energy can be conserved when windows are designed with the optimization strategies. Following are the lessons learned from these studies –

1. Energy performance of the fenestration system and lighting system can be optimized by considering the relationship between window size, shading coefficient, visible transmittance, orientation, building aspect ratio and daylighting control strategies.
2. The fenestration design with respect to window to wall ratio and shading devices can have considerable impact on the HVAC loads of the building. Thus it is necessary to consider these factors for the optimization of the fenestration design.

3. The parameters such as daylighting and orientation are significant with respect to energy savings and thermal performance and do not cost any appreciable money, making them a valid contributor in window optimization.

4. The occupant comfort which is very important factor for commercial office buildings is not considered in above mentioned studies and needs to be addressed along with energy conservation.

3.3 Fenestration and Lighting Systems

There is complex relationship between the fenestration of the building, its lighting system and energy consumption (Fig.3.1). The orientation, size and shading characteristics of the fenestration system modify the solar gain and thus impact the heating and cooling demand of a building. The visible transmittance however controls the daylight availability which can affect electric lighting loads.

The daylighting utilization can potentially reduce the electricity use and peak demand depending by minimizing electric lighting use through implementation of daylight control strategies. After daylight saturation (the level where the illumination provided by daylight equals or exceeds the illumination provided or needed by electric lighting) is reached, the dependence on the electric lighting can be reduced to use the natural daylight.

For defining the optimum levels of the variables like window size, shading coefficient and visible transmittance, it is important to determine the solar gain impact on the selected glazing against its
daylighting potential separately for the incremental difference between the HVAC system loads and lighting energy (Sullivan, 1992). By achieving maximum daylight with large WWR and VT, one can not only save electric lighting loads but also influence the cooling requirement of the building which is often increased due to sensible heat gain of lighting system into conditioned space. However, it can further result into the disadvantage of the solar heat gains within the building thus resulting in the cooling loads.

The visible transmittance accounts for the eyes’ relative sensitivity to different wavelengths of the light. The glazing with high visual transmittance is relatively clear and provides sufficient daylight, however they can create glare problems; while glazing with lower values being darker can minimize glare but can create gloomy interiors (O’Connor, 1997). Thus, visual transmittance of the fenestration controls the daylight availability which in turn affects electric lighting requirements. Though the amount of daylight entering the space determines the savings on electric lighting cost, window glare needs to be addressed for the occupant comfort level.

The lighting system when designed to integrate with daylight can affect electricity use and peak demand by providing the variation of the lighting power density through lighting controls by lighting control strategy and desired illumination level. Incorporating a daylighting strategy can also increase the lighting quality of the spaces (O’Connor, 1997) which in turn can increase the occupant comfort level. Increased occupant comfort can also be realized by properly designing fenestration and shading system to minimize radiant gains and glare but still providing good illuminance (Arasteh, 1985).
Daylighting is essential for the energy savings of the buildings, but energy is not merely saved by daylighting. Dimming of the lights by switching on/off the electric system is a major factor involved for saving electric light energy consumption. Following section provides an overview of daylight control systems and its effects on electric consumption.

**3.4 Daylight Control Systems and Energy Consumption**

Lighting controls that perform on–off operations due to occupant presence, time scheduling, manual dimming, automatic dimming in connection to daylighting, demand control and lumen depreciation have great potential in reducing lighting energy consumption (Doulas, 2008). The lighting system designed to integrate with daylighting by providing controls for high performance, comfortable and energy efficient lighting can maximize lighting energy savings (O’Connor, 1997).
3.4.1 Daylight Control Strategies

There are two basic daylighting control strategies-

1. Simple on/off switching: This system allows the electric lights to be turned on or off depending on the level of daylight illuminance within the building. The fig 3.2 shows the schematic representation of the lighting in the room with stepped lighting controls. The curves indicate the change in the lighting levels as a result of daylight and electric light, based on which the set light level is maintained. As the daylight level is increased near the window the electric lights are switched off. Similarly when outdoor illuminance decreases, the artificial lights are turned on.

However, the problem with this system is the user reaction to its operation. The bad programming caused by the rapid switching of lights to turn on and off with the fluctuating daylight levels annoy occupants as well as reduce lamp life. Various techniques such as the differential switching control have been developed to reduce the number of switch offs (with introduction of dead bands) and switching with time delay (Doulos et al., 2005).

![Schematic representation of lighting in a room with lighting controls](image)

Fig 3.3: Schematic representation of lighting in a room with lighting controls

(Source: Tips for daylighting with windows, 1997)
2. Photoelectric dimming: In this case the artificial lights are dimmed or brightened as required and in response to daylighting in order to maintain the set indoor illuminance levels (Fig 3.3). A sensor at the station point dims or brightens the artificial lights with respect to exterior illuminance and target illuminance.

This system may be expensive due to the requirement of the special lamps and ballasts and the overall control system. It is also more acceptable to occupants because changes in the electric light levels are least disturbing. Also this system generally increase energy savings and extend lamp life (Doulos et al., 2008)

Fig 3.4: Schematic diagram of a room with a photoelectric dimming system
(Source: Tips for daylighting with windows, 1997)
3.4.2 Impact of Daylight Control Systems on Energy Consumption

ASHRAE 90.1, 1989 is observed to be one of the first to discuss about the technology of offering a simple method to account for energy savings by means of lighting controls (Reinhart et al., 2004). A paper published in year 2000 by Roisin et al. overviewed several studies of buildings that saved 20-75% energy by using lighting control strategies. The study conducted by Opal and Brekke documented the saving potential due to daylight dimming systems to be about 30–40% for south-facing rooms and 20–30% for north-facing (Brekke, 1995). Knight measured gains from 44 to 76% using daylight control systems (Knights, 1999). Jennings et al. conducted a comparative study for advanced lighting control options and found that light sensor control could save up to 27% as compared to manual switching (Jennings, 2000). Li et al. evaluated the performances of daylight dimming and on/off control system. They concluded that the daylight dimming system reduces the energy consumption by 33% (Li, 2006).

Lee and Selkowitz conducted a study for the performance of daylighting control system for New York Times Headquarters by using a daylighting mock up. The study was performed by evaluating the performance of two types of daylighting control systems- the open loop proportional control system (A) and the closed loop integral reset control system (B). They concluded that 30% average savings was achieved at 3.35 m from the window with a sidelite west-facing condition in Area A while 50-60% were achieved with a bilateral daylit south-facing condition in Area B. At 4.57-9.14 m from the window, 5-10% and 25-40% savings were achieved in Areas A and B, respectively. Average savings for the 7-m deep dimming zone were 20-23% and 52-59% for Areas A and B, respectively, depending on the lighting schedule (Lee et al., 2006).

While the benefits from the daylighting strategies cannot be denied, previous surveys have indicated comparatively low number of commercial buildings to incorporate these strategies. For
instance, only 10% of the commercial buildings in U.S. have incorporated daylighting schemes while almost 50% of the buildings are equipped with energy efficient lamps and ballasts (Krarti et al., 2005). One of the major reasons for the reluctance of building professionals in incorporating daylighting features in their design is the lack of simplified evaluation tools, capable of providing information on the suitability of daylighting and its potential to save energy.

Based on the literature reviews in this section, all the authors have agreed that daylighting strategies can save considerable energy. However, disadvantages such as extra heat gain or heat loss needs attention in the design process with regard to daylighting. An integrated approach with an optimum design for cooling, heating and lighting energy savings can assist in achieving better daylighting and thermal performance of a building.

**3.5 Fenestration and HVAC System**

A heating or cooling load is the amount of heat that needs to be added to or removed from a conditioned space in order to ensure occupant comfort. However, windows in the U.S. consume 30% of building heating and cooling energy, representing an annual impact of 4.1 quadrillion BTU (quads) of primary energy. This includes the impacts of unwanted conductive losses and gains (i.e. heat transfer due to temperature differences across the window), unwanted solar heat transmission, and infiltration (Arasteh et al., 2006). According to Ellis & Mathews, buildings and their Heating, Ventilation and Air-Conditioning (HVAC) systems are required to be more energy efficient while adhering to an ever-increasing demand for better indoor air quality and performance. However, this is accomplished with certain constraints like economical considerations which include installation and operating costs, ease of maintenance, flexibility and spatial requirements and environmental issues such as energy use, the reduction and banning of certain refrigerants and noise pollution (Ellis & Mathew, 2002).
Most of the energy used for commercial buildings in U.S., is utilized to maintain acceptable comfort levels within the building and HVAC systems contributes to 27% of the total energy use and forms the largest consumption items. In UAE, the highest electrical load comes from HVAC equipment which accounts for an average of 40% of the total year around electrical load and up to 60% of the peak electrical load during the summer time (Hammad, 2010). In Greece, the commercial sector space heating represents 52% consumption and air conditioning 17% of the total energy which is observed as a rising tendency (Papakostas et al., 2005). In the energy audits and surveys of fully air conditioned commercial buildings in Hong-Kong revealed that air conditioning account for 40-60% of the total electricity use (Chan, 1994). These numbers indicate the emergency to address the HVAC systems while designing the fenestration system for energy conservation.

Windows are responsible for 39% of commercial heating energy use and 28% of commercial cooling energy use, or 34% of all commercial space conditioning energy use. This is equivalent to roughly 1.5% of total US energy consumption (Apte, 2006). Due to prevalence of International style, the extensive use of highly glazed building facades and development of curtain wall system had a significant influence on building envelope design and associated architectural trends. However, this creates a challenging dilemma to the aspect of energy consumption since large glazed area can provide sufficient daylighting but also the increased energy consumption due to thermal disadvantages like heat gain in summer and heat loss in winter. This in turn can lead to increased HVAC loads which can be responsible for the excessive energy consumption. Following literature shows that efficient windows can be integral part of energy conservation strategies related to HVAC system.

The study by Erwin and Heschong suggested that energy saving up to 15–20% of total building energy bills can be achieved by proper use of window ‘Superwindows’ which contains low-
emissivity, or low E-coating that allows visible light to enter, while blocking long wave radiation (infrared or heat) from entering (Erwin & Heschong, 2002). The study conducted by Miyazaki et al. concluded that by using the optimum PV window with 50% WWR, the electricity consumption can be reduced by 55% compared to the single glazed window (Miyazaki et al., 2005). In the study by Lee et al. of Lawrence Berkeley National Laboratory, compared to low-e window, the electrochromic window showed annual peak cooling load reductions from control of solar heat gain of 19-26% (Lee et al., 2006).

While today’s windows are much more efficient than the windows from prior decade, they are still significant energy liabilities (Arasteh et al., 2006). Proper design and selection of building components at the early stages of the design process can greatly help in achieving thermal comfort with minimum reliance upon HVAC systems and, therefore, minimum energy requirements (Al Homoud, 1997). The above mentioned studies indicate that potential energy conservation on heating and cooling loads can be achieved through the improved window techniques, though there needs to be the trade-offs in energy use, peak demand, visual comfort, interior brightness, direct sun control, and view for these advanced window systems to provide optimized solutions for particular building applications.

### 3.6 Fenestration, Window to Wall Ratio (WWR) and Orientation

Many researchers in the past have aimed to verify the relationship between the occupants of the building and the preferred window type with respect to the size and orientation. Both these parameters have psychological and physical aspects related to them. The following literature review presents the various studies that have investigated the WWR and orientation with respect to human-environmental relationship and energy conservation.
Past studies have shown that the window size, shape and location have psychological impacts on the occupants of the buildings. Keighley, of Building Research Station, has found out visual satisfaction is achieved when window area is 30% (Keighley, 1973). However, Ludlow has suggested the preferred window size as 50–80% for visual satisfaction (Ludlow, 1976). Imamoglu has stated psychological satisfaction is at its ideal level when the proportion is between 15% and 30% of the wall area (Imamoglu, 1973). The field study conducted by Dogrusoy and Tureyen for occupant preferences in Izmir–Turkiye have suggested that large-sized uninterrupted windows as window-wall and horizontally continuous windows have been the most preferred window types (Dogrusoy et al., 2007). However, Butler and Biner’s investigation of window preference and size in survey conducted at Indiana, US concluded that large window was not the preferred choice for the majority of spaces. The results indicated that only 43% occupants preferred large windows as a choice of window for office environment while 46% chose medium sized windows (Butler et al., 1983).

The literature review have also indicated that increased window size results in increased cooling loads, while results into decreased heating loads because of enhanced solar gain. Inanici et al. investigated the south window size and the building aspect ratio in five different climate zones of Turkey. It was concluded that WWR of 25% on the south side was optimum in hot climates while the large south windows were preferable in cold climates from thermal performance point of view (Inanici et al, 2000). Al-Homoud carried out an optimization study on building design variables to minimize annual energy consumption and concluded that minimum glass area of 15% was the optimum in his research except the cold climate where larger glass area was required to utilize solar gain for heating (Al-Homoud, 1997). Also Johnson et al. investigated the economically optimum window size and orientation and concluded that the WWR of less than 20% resulted in
minimum lifecycle cost. In addition, the north orientation was preferred for large glass to wall ratios. (Johnson et al., 1990).

The above literature review reveals that the preferred WWR for strong human-environmental relationship can have a very wide range from 15-80% depending on the visual and psychological satisfaction. However, the WWR in between the range of 15-25% was found to be optimum for the purpose of energy conservation with preferably large windows on northern and southern orientation.

3.7 Fenestration and Shading Devices

Shading devices are critical for occupant visual and thermal comfort and for minimizing mechanical cooling loads. The shades can be on the exterior, interior or in the plane of the windows. The efficient shading devices can result in cooling load reductions and also modify the intensity and distribution of daylight entering the space. It can efficiently block the uncomfortable direct sun and thus reduce glare and view of the bright sky, ultimately leading to occupant satisfaction. The size and positioning of shading devices depend on the orientation of building facade, the size of the windows and the relative importance of heating and cooling loads (Manzan, 2009).

According to the study by Santamouri et al, it is possible to reduce approximately 7% of the total cooling load of air conditioning by using efficient shading devices (Santamouri et al., 1993). Research has also proved that the use of shading devices could represent a way to prevent glare (Chauvel, 1982; Dubois, 2003). Carbonari et al. presented a study on the optimal shading device in relation to the orientation of buildings (Carbonari et al., 2001). There are many studies which have discussed the impact of shading devices considering the single parameter. However, very
few studies have considered the integrated approach in the analysis and following is the overview of them.

Gugliermetti and Bisegna studied fixed external shading devices versus different daylighting and artificial lighting control strategies and window systems in terms of energy performances with the aim to individuate the optimal energetic solution still assuring indoor visual and thermal comfort. They concluded that a simple change of the window system and the interchange of external overhang with the substitution of the internal shading device doesn’t improve energy performances of the environment (Gugliermetti, 2002). Yener presented a mathematical model to determine the optimal solution for fixed shading devices, comparing them with different solar glass systems in terms of visual comfort and daylight availability in rooms (Yener, 2001). Ho et al. analyzed the sun shadings for daylight illumination of a subtropical classroom in Taiwan. According to this study, the optimal sun shading device not only improved the illuminance conditions within the classroom, but also reduced the lighting power cost by 71.5% as compared to the case where all of the lights are turned on (Ho et al., 2008).

All the above mentioned studies have been developed to optimize the functionality of external shading devices from different viewpoints without considering the factor of changes of the external natural light. It is important to select the shading devices, considering the requirements to achieve both energy efficiency control of solar radiation and interior visual comfort due to daylighting. Their optimal design requires a correct trade-off among visual and thermal comfort and energy-saving requirements (Gugliermetti, 2006).
3.8 Optimum Trade Off Strategies for Energy Efficient Windows

The complexity involved due to different interactive factors and involvement of experts from different disciplines is the reason why building industry has not made much progress in improving energy efficiency (Kennington, 1993). Numbers of parameters are involved in determining the energy performance of the building since its response to the complete system to the outdoor environment and the indoor condition needs to be considered. “Windows can admit solar heat when it is needed to offset heating energy needs, reject solar gain to reduce cooling loads, significantly mitigate a building’s peak electricity demand, and offset much of a building’s lighting needs during daylight hours.” (Arasteh, 2006). However, to take advantage of these benefits, windows must have better fixed properties, like lower U-factors and higher visual transmittance than are standard today, moreover, they must also incorporate dynamic capabilities that allow for tradeoffs between winter and summer conditions, glare and view, and daylight and solar gains.

It can be relatively simple to find the best characteristics of a building under winter or summer conditions. However, while tackling the two problems simultaneously, there needs to be tradeoff between the two seasons. This is also true for the large office buildings where the indoor space needs to be conditioned with the help of air conditioning even if there is no actual need for cooling for given temperature. Also, increasing the energy performance usually requires the use of special devices resulting in a high construction cost; thus the factor of economical optimization also plays an important role.
3.9 Codes Response and Standards to Window Optimization

Building codes, standards and rating systems that regulate the different building components like walls, fenestration, lighting system and HVAC systems have a major impact on the building energy consumption. In US the general codes and standards are developed by private organizations in collaboration with US DOE; The International Energy Conservation Code (IECC) has been developed by International Code council (ICC) while the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) standards are developed by ASHRAE. Moreover, the need for the updated requirements for the codes and standards related to energy efficient buildings cannot be denied.

Most states employ IECC for low rise residential buildings while ASHRAE standard are used for large and complex buildings. The first energy conservation standard ASHRAE standard 90-75 was published in 1975 which was later revised to ANSI/ASHRAE/IES standard 90-1980 introduced for the first time the idea of specifying overall thermal transfer value (OTTV) for the building envelope control. Thereafter, OTTV’s was modified by many US states and over the years it has been evident that the standards have been effective in reducing energy utilization in buildings.

The extensive research and practical applications over the years recognized that significant cost effective improvements can be made to ASHRAE standard 90-80 leading to the upgraded edition ASHRAE standard 90.1-1989. An important point to be noted in this upgradation is that approach and the structure of its building envelope section have been revised substantially and that OTTV method is no longer used (Hui et al., 1991). Thereafter a new approach, AHRAE/IESNA 90.1-2004 was introduced to specify building envelope requirements, which is based on the combination of system performance, prescriptive requirements and energy cost budget.
Currently, ASHRAE Standard 90.1-2007 is the baseline commercial energy standard in most of the US states. The quantitative analysis of the energy consumption of buildings built to Standard 90.1-2007, as compared with buildings built to Standard 90.1-2004 was performed by US DOE. It indicated that the national source energy saving of approximately 3.7% of commercial building energy consumption could be achieved by the former. The most recent publication of ASHRAE standards is ANSI/ASHRAE/IESNA Standard 90.1-2010 on which DOE issued a preliminary determination that Standard 90.1-2010 would achieve national source energy savings of approximately 18.2% of commercial building energy consumption as compared to standard 90.1 2007.
4. METHOD

A building which yields a lifetime of energy efficiency and lower operating costs can be considered as high performance building (LBNL, 1997). Adopting a holistic design approach is necessary for an efficient design and energy conservation. However, if the critical interaction between the building façade (which exchanges heat and admit light), electric lighting and HVAC system is not addressed sensitively, it can result in an uncomfortable and inefficient building that is expensive and difficult to retrofit. For investigating this complex relationship, this study is focused on the optimization techniques of fenestration design for office buildings by evaluating trading off strategies between lighting and thermal performance.

The literature review has shown that optimizing the thermal and daylighting performance of buildings can reduce the energy consumption and increase the overall efficiency. For this reason, it is significant to understand the factors affecting thermal comfort and daylighting performance. Thermal comfort is affected by air temperature, humidity, air velocity, and mean radiant temperature (MRT), as well as non environmental factors such as clothing, gender, age, and physical activity (ASHRAE, 2011). For analyzing the thermal performance, a building has to be considered as a system which is subject to unsteady climatic variations due to solar radiation and varying outdoor air temperature along with different operational loads due to lighting, air conditioning and heating, ventilation, occupancy and electric appliances within the building. However, literature review has revealed that for daylighting performance the most important factors are window to wall ratio and visual transmittance of the glazing.

This study is performed in three parts

1. Preliminary investigation: Assessment of various types of glazing by comparing their performances in various climate zones using simulation software- WinSel. The parameters like
solar energy transmittance (g-value), thermal leakage (u-value) and balance temperature are taken into account for analysis.

2. Parametric analysis- Daylighting and energy consumption simulation using the software IES Virtual Environment, based on the characteristics of typical office building. The parameters like Window to wall ratio (WWR), U-factor, SHGC, VT and aspect ratio are taken into account for the analysis.

3. Recommendations- Comparing the results with the current building envelop standards provided by ASHRAE 90.1 and recommending the fenestration guidelines.

**4.1 Preliminary Investigation**

For the preliminary investigation twelve window types (Table 4.1 and 4.2) were analyzed for their performance of energy efficiency with respect to heating and cooling loads in seven different climate zones of U.S (Fig 4.1). The simulation tool WinSel developed by Uppsala University (Karlsson, 2001) is used which is a simple energy rating tool for selection of windows based on their energy use performance. The glazing types for all climate zones are ranked according to their performances from energy point of view.

**4.1.1 Weather and Climate Zones**

Energy performance of the office building is analyzed for seven different climate zones based on ASHRAE classification. The cities which are densely developed or developing having commercial buildings are determined for each climate zones and the climate data for these cities is used in the study. Following are the cities identified from climate zones of ASHRAE (ASHRAE Fundamentals Handbook, 2009) -

1. Climate zone 1 – Very hot-humid – Miami, FL
2. Climate zone 2 – Hot-dry – Phoenix, AZ
In this study, twelve insulating glazing units consisting of two layers of glass with air gap are considered. The selected glazing types can be divided under two subgroups as follows:

<table>
<thead>
<tr>
<th>Insulating glazing unit</th>
<th>Insulating reflective glazing unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tinted</strong></td>
<td><strong>Low E</strong></td>
</tr>
<tr>
<td>Arctic Blue</td>
<td>Low E #1</td>
</tr>
<tr>
<td>Bronze</td>
<td>Low E #2</td>
</tr>
<tr>
<td>Ultrawhite</td>
<td>Low E #3</td>
</tr>
</tbody>
</table>

Table 4.1: Glazing Classification
Following table gives the detail characteristics of each glazing type- 

<table>
<thead>
<tr>
<th>Glazing Type</th>
<th>VT</th>
<th>U-Value</th>
<th>SC</th>
<th>SHGC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arctic Blue</td>
<td>0.50</td>
<td>0.49</td>
<td>0.47</td>
<td>0.41</td>
</tr>
<tr>
<td>Bronze</td>
<td>0.47</td>
<td>0.49</td>
<td>0.58</td>
<td>0.50</td>
</tr>
<tr>
<td>Ultrawhite</td>
<td>0.82</td>
<td>0.49</td>
<td>0.92</td>
<td>0.80</td>
</tr>
<tr>
<td>Low E #1</td>
<td>0.37</td>
<td>0.29</td>
<td>0.36</td>
<td>0.31</td>
</tr>
<tr>
<td>Low E #2</td>
<td>0.76</td>
<td>0.29</td>
<td>0.63</td>
<td>0.54</td>
</tr>
<tr>
<td>Low E #3</td>
<td>0.79</td>
<td>0.29</td>
<td>0.69</td>
<td>0.60</td>
</tr>
<tr>
<td>Stainless Steel window</td>
<td>0.08</td>
<td>0.39</td>
<td>0.16</td>
<td>0.13</td>
</tr>
<tr>
<td>Titanium Blue window</td>
<td>0.19</td>
<td>0.41</td>
<td>0.25</td>
<td>0.22</td>
</tr>
<tr>
<td>Crystal Chrome window</td>
<td>0.07</td>
<td>0.38</td>
<td>0.15</td>
<td>0.13</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>0.07</td>
<td>0.31</td>
<td>0.12</td>
<td>0.11</td>
</tr>
<tr>
<td>Superwindow</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Titanium Blue</td>
<td>0.18</td>
<td>0.31</td>
<td>0.21</td>
<td>0.18</td>
</tr>
<tr>
<td>Superwindow</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crystal Chrome</td>
<td>0.07</td>
<td>0.31</td>
<td>0.12</td>
<td>0.10</td>
</tr>
<tr>
<td>Superwindow</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2: Glazing types and related parameters

4.1.3 Simulation Software: WinSel

WinSel software is used for initial selecting of the windows with respect to their best performance as per the climate. The input required by the software are solar energy transmittance (SHGC), thermal transmittance (U-value) and the type of coating for the glazing. It takes into account the single parameter of balance temperature ($T_b$) to determine if the energy that flows through the window is useful or not for energy system of the building (Karlsson, 2001). Balance
temperature is defined as the outdoor temperature below which the building must be actively heated. It depends on the building envelope, internal gain, radiation and infiltration. Balance temperature can be stated by following equations-

\[ T_b = T_i - \frac{Q_i}{U_{A_{total}}} \] (Walter, 2010)

\[ T_b = \text{Balance temperature} \]

\[ T_i = \text{Avg indoor temp over 24 hrs, winter} \]

\[ Q_i = \text{internal gains+solar gains} \]

\[ U_{A_{total}} = \text{Total heat loss rate (Envelope+infiltration)} \]

It is important to know if the heat flows in the form of conductance and radiation are useful or not for the energy system of the building. J. Karlsson et al. have discussed in their paper regarding how balance temperature is of significant importance to determine when solar radiation and conductance are positive or negative for the building.

<table>
<thead>
<tr>
<th>Outside temperature</th>
<th>Solar radiation influence on the energy system</th>
<th>Influence of conductance on the energy system</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_o &lt; T_b )</td>
<td>Positive, reduce heating load</td>
<td>Negative, increase heating load</td>
</tr>
<tr>
<td>( T_b &lt; T_o &lt; T_b + T_{dyn} )</td>
<td>Indifferent</td>
<td>Indifferent</td>
</tr>
<tr>
<td>( T_o + T_{dyn} &lt; T_o &lt; T_i )</td>
<td>Negative, increase cooling load</td>
<td>Positive, reduce cooling load</td>
</tr>
<tr>
<td>( T_o &gt; T_i )</td>
<td>Negative, increase cooling load</td>
<td>Negative, increase cooling load</td>
</tr>
</tbody>
</table>

Table 4.3: Solar radiation and thermal flow influence on the energy system depending on the outside temperature as assessed by the balance temperature (Karlsson, 2001).

\( T_o = \text{Outdoor temperature} \)

\( T_b = \text{Balance temperature} \)

\( T_{dyn} = \text{Dynamic temperature swing (Assumed as 5°C in this case)} \)
$T_i = \text{Constant indoor temperature (Assumed as 20°C in this case)}$

The energy balance equation for all hours of the year used in the simulation can be summarized as follows:

$$Q_{\text{tot}} = \sum (Q_{\text{rad}} \cdot g - \Delta T_i \cdot U) \quad (\text{Karlsson, 2001}).$$

$Q_{\text{tot}} = \text{Total energy balance}$

$Q_{\text{rad}} = \text{Solar irradiation during hour } i (i=1 \text{ to } 8760 \text{ hours, counted from first hour on January 1st to the last hour on 31st December})$

$g = \text{Solar heat gain coefficient (SHGC)}$

$\Delta T_i = \text{Temperature difference inside-outside during hour } i$

$U = \text{Thermal transmittance (U-value)}$

According to ASHRAE, the heat balance can be viewed as four distinct processes: Outside-face heat balance, wall conduction process, inside-face heat balance and air heat balance (Fig 4.3)
4.1.4 Glazing Selection

The best performing glazing types (Table 4.4) in all climate zones from tinted, low E and reflective were selected for the further study of optimization. Diversity in range of visual transmittance was an important criterion for the selection since the later study is about daylighting utilization and majorly depends on this parameter. Along with these three glazing types the clear glazing is selected as the base case to compare the results achieved.
4.2 Parametric Study

Along with being multifunctional, fenestration system needs varies widely with environmental conditions and occupant usage. This makes it difficult to make a completely optimal solution of a fenestration system. U-factor, solar heat gain coefficient, air leakage, etc. are the parameters which are typically used to compare fenestration systems under a fixed set of conditions. However, the absolute and relative effect of these parameters on a building’s heating and cooling load can fluctuate as environmental conditions change. As a result, these indices alone are not good indicators of the annual energy performance attributable to the fenestration. The four basic mechanisms of fenestration energy performance—thermal transfer, solar heat gains, air leakage, and daylighting should all be taken into account but are not independent of many other parameters that influence performance (ASHRAE, 2009).

This chapter describes the assumptions and considerations used for the simulations. It comprises of three sections—first section gives the overview of the simulation software IES Virtual Environments. Second section describes the design parameters related to the typical office buildings that are considered for this study. These include building form, lease span, building function, types of glazing and window to wall ratio assumed. Third section describes the building performance related parameters for daylight and energy simulations required by the simulation software are described.

4.2.1 Simulation Software: IES Virtual Environments

For studying the effects of daylighting and energy use in an office building using different windows, the simulation tool IES virtual Environments (IEVE) is used. This software uses the building simulation technology to evaluate a variety of envelop thermal characteristics in an integrated manner in order to assist the delivery of energy efficient design. The parameters
included are related to daylighting and window type. The daylighting calculations are performed by using the Radiance module implemented in IEVE.

Series of computer simulations are carried out on different types of office buildings by systematically changing the values of the selected glazing parameters along with varying window to wall ratio and aspect ratios for different building types and climate zones. The results generated thus formed the database from which results are generated for analysis.

4.2.2 Planning Consideration for Office Building Model

It is important to understand the basic planning factors in the initial stages of design to determine the strategies for tradeoff between the thermal and daylight performance to achieve maximum comfort with minimum energy utilization. The design for a typical office building is determined by design factors like building function, aspect ratio for building form and floor to ceiling height which are dependent on the planning decisions (Park et al., 2004). These factors are interdependent and affect the overall design of the building with respect to thermal and occupant comfort. The change in one planning consideration will generally result in variations of others resulting into varying comfort levels. The following sections will address the main parameters with respect to the design factors related to office building.

4.2.2.1 Building Form

The use of natural daylight is very beneficial in office buildings because of the energy reductions and enhanced working conditions. Traditionally, office buildings have deep plans to increase the floor plate area that rely almost completely on electric lighting. However, bringing daylight within the deep plan buildings is not easy. Also, most of the office buildings are occupied during day hours resulting in the situation where natural light is not utilized when it is available in abundance.
The form of the building plays an important role with respect to fenestration design for achieving energy conservation. Taking into consideration the geometry describing metrics such as aspect ratio and volume to surface area ratio, building form determines the size and the orientation of the exterior envelope exposed to the outdoor environment which in turn can affect building performance, energy efficiency and occupant comfort. Often, however, decisions on the building form are based on factors like site, aesthetics etc., which has the disadvantage of limiting the potential of performance improvement (Wang, 2006). Form optimization can help overcome the issue of building performance improvement by varying aspect ratio (defined as length/width) and surface to volume ratio resulting in design alternatives at the conceptual design stage for efficient performance with respect to energy saving and daylight utilization (Wang, 2006).

According to a survey in 2007 by Cho of Konkuk University, Seoul, Korea, out of 115 high rise buildings over 40-storeys tall, 28% were square, 47% were rectangular, 7% were circular and 5% were triangular. However, for buildings over 60 storeys, 30% were square and 25% were rectangular. This means that there has been a tendency of using a square plan when building height is increased. Also square plan resists loads equally in all direction and is more economical as compared with rectangular forms. Building with symmetrical plans are also less susceptible to wind impact than unsymmetrical buildings, and more efficient than curved or irregular shapes (Cho, 2007).

Building form should be thermally optimized to allow the lowest heat losses in winter while allowing minimum summer heat gains. Though, square shaped buildings have many advantages with the least outside surface-to-volume ratio which might be the optimum for buildings with negligible radiation effects. However, when considering radiation effects in buildings with large window areas, orientation with the east-west as the major axis is often seen as optimization trend,
with different magnitudes of window area depending on the building type and location (Al Homoud, 1997).

The rectangular buildings are important with respect to the amount of daylighting with the longer axis oriented along E-W. In this configuration, east and west walls are minimized and thus receive less direct sun in summer, so excess heat gain is reduced. This same configuration works well for buildings in cold climates where passive solar heat gain on the south side during the winter is desired. A long, narrow building plan also facilitates daylighting and natural ventilation.

In order to investigate the impact of building form (aspect ratio and surface to volume ratio) on its performance, the office building module are optimized with two different forms- square (1:1) and rectangle (1:3), keeping the same gross floor area for each type of building in the analyses (Fig 4.4).

4.2.2.2 Lease Span
Lease span is a distance from a fixed interior element, such as building core, to an exterior window wall (Fig 4.3). This distance depends on the functional requirement and size of the floor and is very important consideration for overall building planning. Lease span is important requirement of providing the natural light and has considerable impact on the economic and environmental expectations, especially daylight performance (Dong-Hwan et al., 2008).

The buildings designed as a deep plan is considered as a building with an unobstructed open plan of more than 17m (Hansen, 2006). The depth creates a zone which needs the artificial lighting and ventilation and thus consumes more energy. In central business districts, the office buildings are built with the maximum site coverage, thus in case of square sites it results into deep plan with little perimeter zone that can acquire natural light.
Fig 4.3: Lease span

Although there are no international standards to determine the lease span depths, usually the depth of lease span for office buildings should be 33-46 ft (10 to 14m) (CTBUH, 1995). According to a recent research by Cho, of Konkuk University, Korea; 80% of the tall buildings use a lease span of 35ft to 50ft (Cho, 2007). Though, the longer lease span allows for flexible interior planning and an initial economic benefit, a small lease span is preferred by occupants when indoor environmental quality is considered. For instance, in Germany, the maximum allowable depth for office building is typically 18 ft (5.5m), whereas in United States as much as 50 ft is not a rarity (Jappsen 2002).

The study by Shpuza considered four types of the lease spans depending on the location of the core, major circulation routes and depth of office space. They are characterized as very deep 66 ft (20m), deep 36-62 ft (11-19m), medium 20-33 ft (6-10m) and shallow 13-16 ft (4-5m) deep. The narrow rectangular building can be divided only by shallow span while the square building can provide both shallow and medium depth (Shpuza, 2006).

Based on the lease span data provided by Shpuza the two office types with lease span ranging from 5m-11m are considered for the office building models. Following figures demonstrates the characteristics of the building models assumed for this study.
4.2.2.3 Simulation Parameters

In this study, the trade off strategies for optimization between thermal and daylighting performance will be tested against the existing codes and standards; in this case ASHRAE standard, to ensure the adherence to them. Thus most of the parameters considered for the office building model are considered in conjunction with ASHRAE standards.

As per ASHRAE, office buildings are categorized into three classes: A, B, and C. Class A is generally the most desirable building, located in the most desirable locations, and offering first-rate design, building systems, and amenities. Class B buildings are located in good locations, have little chance of functional obsolescence, and have reasonable management. Class C buildings are typically older, have not been modernized, are often functionally obsolete, and may contain asbestos (ASHRAE, 2011). Since this study is performed to provide the design guidelines for new buildings at initial design stage, class A category of office buildings will be assumed. A HVAC system appropriate for this class is denoted as variable-air-volume (VAV) systems and will be used while performing simulations.
As per ASHRAE HVAC applications 2011, the maximum density for offices can be approximately one person per 75 sq. ft. of floor area while in some private offices the density may be as little as one person per 200 sq. ft. For this study medium density office is considered and thus occupancy density is considered as 100 sq ft/person. As per ASHRAE fundamentals 2009, total internal gain per person is specified as 450 Btu/h (Sensible heat = 250 Btu/h W+ Latent Heat = 200 Btu/h). Lighting power density for the open plan is specified as 1.1 W/sq.ft while load factor for medium density office is specified 1 W/sq.ft. Also, most office buildings are occupied from approximately 8:00 AM to 6:00 PM (ASHRAE, 2011) and are considered as operating hours for this study, weekends and holidays being exceptions.

The daylight controls in the form of photosensors are used in each perimeter space of the office building model. The sensors are placed in the center of each room. The design illuminance considered is 500 lux (50 foot candles) at the work plane height during office hours (IESNA, 2000).

<table>
<thead>
<tr>
<th>Gain Reference</th>
<th>Maximum sensible gain</th>
<th>Maximum latent gain</th>
<th>Occupancy</th>
</tr>
</thead>
<tbody>
<tr>
<td>People</td>
<td>250 Btu/h</td>
<td>200 Btu/h</td>
<td>100 sq.ft./person</td>
</tr>
<tr>
<td>Computers</td>
<td>3 W/sq.ft.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluorescent Lighting</td>
<td>2 W/sq.ft.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.4: Assumed internal heat gains

4.2.3 Fenestration Parameters

Fenestration is a term which refers to the arrangement, proportion and design of window in a building. It affects building energy use through four basic mechanisms: thermal heat transfer, solar heat gain, air leakage, and daylighting (ASHRAE, 2011). Typically, a wide range of fenestration products are available that meet the specifications for a project. Refining the specifications to improve energy performance and enhance a living or work space can result in
lower energy costs, increased productivity, and improved thermal and visual comfort. Fenestration components include glazing material, either glass or plastic; framing, mullions, muntin bars, dividers, and opaque door slabs; and shading devices such as louvered blinds, drapes, roller shades, and awnings (ASHRAE, 2009).

In this research, fenestration and fenestration systems refer to the basic assemblies and components of exterior window system within the building. Based on the ASHRAE standard 90.1-2007, the two main window properties- the U-factor and the solar heat gain coefficient (SHGC) were considered.

### 4.2.3.1 Glazing Types

For this later study for optimization three glazing types from the preliminary investigation are selected on the basis of their performance with respect to energy usage.

<table>
<thead>
<tr>
<th>Glazing Type</th>
<th>VT</th>
<th>U-Value</th>
<th>SC</th>
<th>SHGC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear Glazing</td>
<td>0.79</td>
<td>0.49</td>
<td>0.81</td>
<td>0.7</td>
</tr>
<tr>
<td>Tinted Glazing</td>
<td>0.5</td>
<td>0.49</td>
<td>0.47</td>
<td>0.41</td>
</tr>
<tr>
<td>Low-E Glazing</td>
<td>0.37</td>
<td>0.29</td>
<td>0.36</td>
<td>0.31</td>
</tr>
<tr>
<td>Reflective Glazing</td>
<td>0.08</td>
<td>0.39</td>
<td>0.16</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Table 4.5: Selected glazing types and related parameters

### 4.2.3.2 Window to Wall Ratio

ASHRAE has defined window-to-wall area ratio (WWR) as the ratio of the transparent glazing area to the outdoor floor-to-floor wall area. The fenestration design that achieves an optimization between daylight admission and solar rejection can be determined by iterative calculations where the glazing area and/or glazing solar optical properties are varied parametrically. In the United States, a general rule has been that the fenestration area should be at least 20% of the floor area.
and maximum 50% of the wall area (ASHRAE, 2009) while the maximum window area is recommended as 40% of the wall area as per International Energy Conservation Code (IECC).

Considering the current trends in building facades which uses maximum glazed surfaces, in this research the window to wall ratio was considered in the range from 10%-90% with the increments of 15%.
5. DATA ANALYSIS AND APPLICATIONS

This section presents results of the simulations performed to examine the impact of utilizing daylight in office buildings. The study is intended to investigate the effect of window to wall ratio, visual transmittance and aspect ratio on different types of office buildings in seven climate zones identified by ASHRAE. The data sets developed are used to determine the trend of energy usage by varying window to wall ratio with respect to glazing types and climate zones and also to understand the effect of aspect ratio for the different building types.

Three different types of office buildings- small (1 floor), medium (3 floors) and large (12 floors) were selected for the optimization study, keeping the floor area for each type consistent (12,000 sq.ft.). Every building type was analyzed for two types of aspect ratio- 1:1 and 1:3, each having east-west as major axis. Four glazing types- clear, tinted, low-e and reflective are simulated for all types of building by varying the window to wall ratios from 15% to 90% with an increment of 15%. The results achieved are compared on the basis of the unit kBTU/sq.ft.yr, known as the energy use intensity (EUI). This common reference was used commonly for all offices at all selected locations in order to determine the optimum WWR and aspect ratio and their impact on corresponding building as size and climate vary.

Orientation, due to obvious reasons, was not an issue for the aspect ratio 1:1, however, the buildings for the aspect ratio 1:3 were analyzed by varying the orientation. The east-west major axis was changed to north-south and northeast-southwest to investigate the impact of orientation on thermal and daylighting performance. For all the building types, at all the locations, the buildings showed not more than 5 to 10% of difference in their performance. Since this was a minor difference, the study did not consider orientation as a major parameter of the study.
Finally, all the results gained from this study are compared to the current ASHRAE standards, which at present give WWR values based on thermal performance alone. The outcome achieved by daylight utilization shows substantial reduction of energy usage in office buildings and also an increase in overall efficiency. This study is thus intended to provide designers with optimum WWR values optimized for thermal and daylighting performance.

5.1 Daylight Performance Results

For each climate zone simulations were carried out by using different types of glazing under different WWR. Two sets of data are developed for each aspect ratio of the building- with daylight utilization and without daylight utilization. Every zone is further analyzed with following two ways-

i) Daylight performance by comparing to ASHRAE standards: For this, four types of glazing are simulated by varying the window to wall ratios for two aspect ratios. First column in each of these data sets shows the results of simulation without daylighting utilization and second column shows results with daylighting utilization. The trends of energy utilization for different glazing types are then compared to the present ASHRAE recommended glazing standards for each climate zone to understand the efficiency of daylighting. This study is thus used to determine the optimum WWR values optimized for thermal and daylighting performance.

ii) Daylight performance by comparing aspect ratios: This study focuses on the performance of specific glazing types with varying aspect ratios for the three types of office building. The results from these data sets help in determining the aspect ratio that allows for maximum energy optimum for different building types as per size and climate.
5.1.1. Climate Zone 1 (Very Hot-Humid), Miami, FL

For the hot and humid climate, the cooling demand is almost throughout the year while heating demand is negligible. This causes the increase in energy utilization due to cooling equipments. This energy use however can be seen offsetted by the daylighting utilization within the building which further reduces the electricity load caused by electric lighting.

The reduction in energy usage due to daylighting utilization can be clearly observed for the aspect ratio 1:3 as compared to 1:1. Also, the range of optimum WWR values (15%-45% for tinted and low-e glazing, 15%-30% for clear glazing while there is no trend observed for reflective glazing) can be clearly observed for 1:3, while no such range can be determined for 1:1 (Fig 5.1 and Fig 5.2). Also, the results achieved for 1:3 shows the higher efficiency of all the glazing types due to daylighting utilization as compared to the current ASHRAE standards while this is not true for 1:1. This can be observed because of the increased surface area in 1:3 as compared to 1:1, which allows for maximum daylight, however, still offsetting the cooling loads.

Further, Fig 5.3, 5.4 and 5.5 shows that without daylight utilization, the energy use intensity for aspect ratio of 1:1 and 1:3 is nearly identical and depicts that the aspect ratio did not affect the envelope contribution to heating and cooling loads. However, with daylight utilization 1:3 form consume about 10-15% less energy for all building types as compared to 1:1. This is due to maximum reduction of the energy use for electric lighting in rectangular form, thus offsetting the cooling loads.
Fig 5.1 Results of Daylight Performance by comparing ASHRAE standards, Miami (1:1)

- **G1**: Clear Glazing (VT= 0.79, U-value= 0.49, SHGC= 0.70)
- **G2**: Tinted Glazing (VT= 0.50, U-value= 0.49, SHGC= 0.41)
- **G3**: Low-e Glazing (VT= 0.37, U-value= 0.29, SHGC= 0.31)
- **G4**: Reflective Glazing (VT= 0.18, U-value= 0.31, SHGC= 0.18)
- **G5**: ASHRAE recommended glazing
Fig 5.2 Results of Daylight Performance by comparing ASHRAE standards, Miami (1:3)

- G1: Clear Glazing (VT= 0.79, U-value= 0.49, SHGC= 0.70)
- G2: Tinted Glazing (VT= 0.50, U-value= 0.49, SHGC= 0.41)
- G3: Low-e Glazing (VT= 0.37, U-value= 0.29, SHGC= 0.31)
- G4: Reflective Glazing (VT= 0.18, U-value= 0.31, SHGC= 0.18)
- G5: ASHRAE recommended glazing
Fig 5.3 Results of Daylight Performance by comparing Aspect Ratios, Miami (Small Buildings)

Fig 5.4 Results of Daylight Performance by comparing Aspect Ratios, Miami (Medium Buildings)

Fig 5.5 Results of Daylight Performance by comparing Aspect Ratios, Miami (Large Buildings)
5.1.2. Climate Zone 2 (Hot-Dry), Phoenix, AZ

For the hot and dry climate of zone 2, the cooling demand is almost for nine months while heating demand is required for few days in months of Dec, Jan and Feb. This causes the increase in energy utilization due to cooling loads and to small extent by heating loads. This energy use however can be seen offsetted by utilization of the daylighting within the building which further reduces the electricity load by electric lighting.

The reduction in energy usage due to daylighting utilization can be clearly observed for the aspect ratio 1:3 as compared to 1:1. Also, the analysis of the daylighting performance for 1:3 gives optimum window to wall ratio values (15%-30% for all glazing types) while no optimum values can be determined for 1:1 (Fig 5.6 and Fig 5.7). This range is very low because of the very hot climate which absorbed maximum sun resulting in increased cooling loads with the increase in glazing area. Also, the data produced for 1:3 also shows the higher efficiency of all the glazing types due to daylighting utilization as compared to the current ASHRAE standards while this is not true for 1:1.

Further, in fig 5.8, 5.9 & 5.10, we can see that without daylight utilization, the energy use intensity for aspect ratio of 1:1 and 1:3 is nearly identical and depicts that the aspect ratio of the solid blocks did not affect the envelope contribution to heating and cooling loads. However, with daylight utilization, the 1:3 building form utilizes up to 15% less energy as compared to 1:1. Though the square building is efficient due to compactness and reduction in internal loads, the rectangular building is more desirable lowering the lighting loads and further reduces overall energy consumption.
Fig 5.6 Results of Daylight Performance by comparing ASHRAE standards, Phoenix (1:1)

- □ G1: Clear Glazing (VT = 0.79, U-value = 0.49, SHGC = 0.70)
- ○ G2: Tinted Glazing (VT = 0.50, U-value = 0.49, SHGC = 0.41)
- △ G3: Low-e Glazing (VT = 0.37, U-value = 0.29, SHGC = 0.31)
- × G4: Reflective Glazing (VT = 0.18, U-value = 0.31, SHGC = 0.18)
- ⋆ G5: ASHRAE recommended glazing
Fig 5.7 Results of Daylight Performance by comparing ASHRAE standards, Phoenix (1:3)

- G1: Clear Glazing (VT= 0.79, U-value= 0.49, SHGC= 0.70)
- G2: Tinted Glazing (VT= 0.50, U-value= 0.49, SHGC= 0.41)
- G3: Low-e Glazing (VT= 0.37, U-value= 0.29, SHGC= 0.31)
- G4: Reflective Glazing (VT= 0.18, U-value= 0.31, SHGC= 0.18)
- G5: ASHRAE recommended glazing
Fig 5.8 Results of Daylight Performance by comparing Aspect Ratios, Phoenix (Small Buildings)

Fig 5.9 Results of Daylight Performance by comparing Aspect Ratios, Phoenix (Medium Buildings)

Fig 5.10 Results of Daylight Performance by comparing Aspect Ratios, Phoenix (Large Buildings)

- X 1:1, No Daylighting
- 1:1, With Daylighting
- 1:3, No Daylighting
- 1:3, With Daylighting
5.1.3. Climate Zone 3 (Warm-Marine), San Francisco, CA

For the warm-marine climate of zone 3, most of the days are with moderate temperature making the cooling and heating demands negligible throughout the year. Though the energy demand for this climate type is much lower, it can be further reduced with the utilization of daylighting and further reducing the electric lighting loads.

The reduction in energy usage due to daylighting utilization can be clearly observed for the aspect ratio 1:3 as compared to 1:1. Also, the analysis of the daylighting performance for 1:3 gives optimum window to wall ratio values (15%-45% for tinted, low-e and reflective glazing and 15%-30% for clear glazing) while no optimum values can be determined for 1:1 (Fig 5.11 & Fig. 5.12). The data produced hardly show any efficiency as compared to the current ASHRAE standards neither shows any sensitivity in for the daylight utilization for the aspect ratio 1:1.

Further, in fig 5.13, 5.14 & 5.15 we can see that without daylight utilization, the aspect ratio of 1:1 is optimum and consumes 10-15% of less energy for small and large building types while the energy use for both the aspect ratio is identical for medium buildings. However with daylight utilization, 1:3 form is more desirable for all building types, reducing the overall energy consumption by 10-15%. For large buildings, though the benefits of daylight utilization can be observed, the energy efficiency of 1:1 form without daylight utilization still surpasses the daylight benefits, thus making 1:1 form the most desirable in any condition.
Fig 5.11 Results of Daylight Performance by comparing ASHRAE standards, San Francisco (1:1)

San Francisco, Small Office, 1:1: No Daylighting

San Francisco, Small Office, 1:1: With Daylighting

San Francisco, Medium Office, 1:1: No Daylighting

San Francisco, Medium Office, 1:1: With Daylighting

San Francisco, Large Office, 1:1: No Daylighting

San Francisco, Large Office, 1:1: With Daylighting

G1: Clear Glazing (VT= 0.79, U-value= 0.49, SHGC= 0.70)
G2: Tinted Glazing (VT= 0.50, U-value= 0.49, SHGC= 0.41)
G3: Low-e Glazing (VT= 0.37, U-value= 0.29, SHGC= 0.31)
G4: Reflective Glazing (VT= 0.18, U-value= 0.31, SHGC= 0.18)
G5: ASHRAE recommended glazing
Fig 5.12 Results of Daylight Performance by comparing ASHRAE standards, San Francisco (1:3)

San Francisco, Small Office, 1:3: No Daylighting

- G1: Clear Glazing (VT= 0.79, U-value= 0.49, SHGC= 0.70)
- G2: Tinted Glazing (VT= 0.50, U-value= 0.49, SHGC= 0.41)
- G3: Low-e Glazing (VT= 0.37, U-value= 0.29, SHGC= 0.31)
- G4: Reflective Glazing (VT= 0.18, U-value= 0.31, SHGC= 0.18)
- G5: ASHRAE recommended glazing

San Francisco, Small Office, 1:3: With Daylighting

San Francisco, Medium Office, 1:3: No Daylighting

San Francisco, Medium Office, 1:3: With Daylighting

San Francisco, Large Office, 1:3: No Daylighting

San Francisco, Large Office, 1:3: With Daylighting
Fig 5.13 Results of Daylight Performance by comparing Aspect Ratios, San Francisco (Small Buildings)

Fig 5.14 Results of Daylight Performance by comparing Aspect Ratios, San Francisco (Medium Buildings)

Fig 5.15 Results of Daylight Performance by comparing Aspect Ratios, San Francisco (Large Buildings)

---

- **Clear Glazing**
- **Tinted Glazing**
- **Low-E Glazing**
- **Reflective Glazing**

---

- 1:1, No Daylighting
- 1:1, With Daylighting
- 1:3, No Daylighting
- 1:3, With Daylighting
5.1.4. Climate Zone 4 (Mixed-Humid), Baltimore, MD

For the mixed-humid climate of zone 3, the cooling demand is for four months i.e. May, Jun, July and August. April and September are pleasant months while heating demand is for remaining six months. The energy use however can be seen offsetted by utilization of the daylighting within the building which further reduces the electricity load caused by electric lighting.

The reduction in energy usage due to daylighting utilization can be clearly observed for the aspect ratio 1:3 as compared to 1:1. Also, the analysis of the daylighting performance for 1:3 gives optimum window to wall ratio values (15%-45% for tinted and low-e glazing, 15%-30% for clear glazing) while no optimum values can be determined for 1:1 (Fig 5.16 & Fig 5.17). The data produced for 1:3 also shows the higher efficiency of all the glazing types due to daylighting utilization as compared to the current ASHRAE standards while this is not true for 1:1.

Further, in fig 5.18, 5.19 & 5.20 we can see that the without daylight utilization, the energy use intensity for aspect ratio of 1:1 and 1:3 is nearly identical and depicts that the aspect ratio did not affect the envelope contribution to heating and cooling loads. However, with daylight utilization the 1:3 form is more desirable for all building types with 10-15% reduction in energy consumption.
Fig 5.16 Results of Daylight Performance by comparing ASHRAE standards, Baltimore (1:1)

Baltimore, Small Office, 1:1: No Daylighting

Baltimore, Small Office, 1:1: With Daylighting

Baltimore, Medium Office, 1:1: No Daylighting

Baltimore, Medium Office, 1:1: With Daylighting

Baltimore, Large Office, 1:1: No Daylighting

Baltimore, Large Office, 1:1: With Daylighting

G1: Clear Glazing (VT= 0.79, U-value= 0.49, SHGC= 0.70)
G2: Tinted Glazing (VT= 0.50, U-value= 0.49, SHGC= 0.41)
G3: Low-e Glazing (VT= 0.37, U-value= 0.29, SHGC= 0.31)
G4: Reflective Glazing (VT= 0.18, U-value= 0.31, SHGC= 0.18)
G5: ASHRAE recommended glazing
Fig 5.17 Results of Daylight Performance by comparing ASHRAE standards, Baltimore (1:3)

- **G1**: Clear Glazing (VT= 0.79, U-value= 0.49, SHGC= 0.70)
- **G2**: Tinted Glazing (VT= 0.50, U-value= 0.49, SHGC= 0.41)
- **G3**: Low-e Glazing (VT= 0.37, U-value= 0.29, SHGC= 0.31)
- **G4**: Reflective Glazing (VT= 0.18, U-value= 0.31, SHGC= 0.18)
- **G5**: ASHRAE recommended glazing
Fig 5.18 Results of Daylight Performance by comparing Aspect Ratios, Baltimore (Small Buildings)

Fig 5.19 Results of Daylight Performance by comparing Aspect Ratios, Baltimore (Medium Buildings)

Fig 5.20 Results of Daylight Performance by comparing Aspect Ratios, Baltimore (Large Buildings)
5.1.5. Climate Zone 5 (Cool-Humid), Chicago, IL

For the cool-humid climate of zone 3, the cooling demand is for four months i.e. May, Jun, July and August. April and September are pleasant months while heating demand is for remaining six months. The overall energy use however can be seen offsetted by utilization of the daylighting within the building which further reduces the electricity load caused by electric lighting.

The reduction in energy usage due to daylighting utilization can be clearly observed for the aspect ratio 1:3 as compared to 1:1. Also, the analysis of the daylighting performance for 1:3 gives optimum window to wall ratio values (15%-30% for tinted and clear glazing, 15%-45% for low-e glazing while there is no trend observed for reflective glazing) while no optimum values can be determined for 1:1 (Fig 5.21 and Fig 5.22). The data produced for 1:3 and 1:1 both show the higher efficiency of all the glazing type (except for clear glazing in 1:1) due to daylighting utilization as compared to the current ASHRAE standard.

Further, in Fig 5.23, 5.24 & 5.25 we can see that without daylight utilization, the energy use intensity for aspect ratio of 1:1 and 1:3 is nearly identical and depicts that the aspect ratio of the did not affect the envelope contribution to heating and cooling loads. With daylight utilization, however, the 1:3 aspect ratio is more desirable with reduction of 8-10% of energy use. The daylight gained during the summer months reduces the electric lighting use and impacts the overall annual energy use within the building.
Fig 5.21 Results of Daylight Performance by comparing ASHRAE standards, Chicago (1:1)

G1: Clear Glazing (VT= 0.79, U-value= 0.49, SHGC= 0.70)
G2: Tinted Glazing (VT= 0.50, U-value= 0.49, SHGC= 0.41)
G3: Low-e Glazing (VT= 0.37, U-value= 0.29, SHGC= 0.31)
G4: Reflective Glazing (VT= 0.18, U-value= 0.31, SHGC= 0.18)
G5: ASHRAE recommended glazing
Fig 5.22 Results of Daylight Performance by comparing ASHRAE standards, Chicago (1:3)

- G1: Clear Glazing (VT= 0.79, U-value= 0.49, SHGC= 0.70)
- G2: Tinted Glazing (VT= 0.50, U-value= 0.49, SHGC= 0.41)
- G3: Low-e Glazing (VT= 0.37, U-value= 0.29, SHGC= 0.31)
- G4: Reflective Glazing (VT= 0.18, U-value= 0.31, SHGC= 0.18)
- G5: ASHRAE recommended glazing
Fig 5.23 Results of Daylight Performance by comparing Aspect Ratios, Chicago (Small Buildings)

Fig 5.24 Results of Daylight Performance by comparing Aspect Ratios, Chicago (Medium Buildings)

Fig 5.25 Results of Daylight Performance by comparing Aspect Ratios, Chicago (Large Buildings)
5.1.6. Climate Zone 6 (Cool-Dry), Helena, MO

For the cool-dry climate of zone 3, the cooling demand is only for two months i.e. June and July. May and August are pleasant months while heating demand is almost for eight months. The overall energy use however can be seen offsetted by utilization of the daylighting within the building which further reduces the electricity load caused by electric lighting.

The reduction in energy usage due to daylighting utilization can be clearly observed for the aspect ratio 1:3 as compared to 1:1. Also, the analysis of the daylighting performance for 1:3 gives optimum window to wall ratio values (15%-30% for all glazing types) while no optimum values can be determined for 1:1 (Fig 5.26 and Fig 5.27). The data produced for 1:3 and 1:1 both show the higher efficiency of all the glazing type (except for clear glazing in 1:1) due to daylighting utilization as compared to the current ASHRAE standards.

Further, in Fig 5.28, 5.29 & 5.30 we can see that without daylight utilization, aspect ratio of 1:1 is optimum for all building types. In typical scenario, more external surface area allows more sun exposure and further reduces the heating loads by allowing the sun rays. However, in this climate type the cloud cover is much more in winter months, thus desiring the lesser external surface area to minimize the harsh winter effect, and further lowering the heating loads. With daylight utilization, however, the 1:3 aspect ratio is more desirable with reduction of 8-5% of energy use. The daylight gained during the summer months reduces the electric lighting use and impacts the overall annual energy use within the building.
Fig 5.26 Results of Daylight Performance by comparing ASHRAE standards, Helena (1:1)

G1: Clear Glazing (VT= 0.79, U-value= 0.49, SHGC= 0.70)
G2: Tinted Glazing (VT= 0.50, U-value= 0.49, SHGC= 0.41)
G3: Low-e Glazing (VT= 0.37, U-value= 0.29, SHGC= 0.31)
G4: Reflective Glazing (VT= 0.18, U-value= 0.31, SHGC= 0.18)
G5: ASHRAE recommended glazing
Fig 5.27 Results of Daylight Performance by comparing ASHRAE standards, Helena (1:3)

- **G1**: Clear Glazing (VT= 0.79, U-value= 0.49, SHGC= 0.70)
- **G2**: Tinted Glazing (VT= 0.50, U-value= 0.49, SHGC= 0.41)
- **G3**: Low-e Glazing (VT= 0.37, U-value= 0.29, SHGC= 0.31)
- **G4**: Reflective Glazing (VT= 0.18, U-value= 0.31, SHGC= 0.18)
- **G5**: ASHRAE recommended glazing
Fig 5.28 Results of Daylight Performance by comparing Aspect Ratios, Helena (Small Buildings)

Fig 5.29 Results of Daylight Performance by comparing Aspect Ratios, Helena (Medium Buildings)

Fig 5.30 Results of Daylight Performance by comparing Aspect Ratios, Helena (Large Buildings)

- ·-·-· 1:1, No Daylighting
- ·-·-·-·-·-· 1:1, With Daylighting
- -·-·-· 1:3, No Daylighting
- ·-·-·-·-·-· 1:3, With Daylighting
5.1.7. Climate Zone 7 (Very Cold), Duluth, MN

For the very cold climate of zone 3, the cooling demand is only for three months i.e. June, July and August. May and September are pleasant months while heating demand is almost for seven months. The overall energy use however can be seen offsetted by utilization of the daylighting within the further reduces the electricity load caused by electric lighting.

The reduction in energy usage due to daylighting utilization can be clearly observed for the aspect ratio 1:3 as compared to 1:1. Also, the analysis of the daylighting performance for 1:3 gives optimum window to wall ratio values (15%-30% for all glazing types) while no optimum values can be determined for 1:1 (Fig 5.31 and Fig 5.32). The data produced for 1:3 and 1:1 both show the higher efficiency of all the glazing type (except for clear and tinted glazing in 1:1) due to daylighting utilization as compared to the current ASHRAE standards.

Further, in Fig 5.33, 5.34 & 5.35 we can see that without daylight utilization, aspect ratio of 1:1 is optimum for all building types. In typical scenario, more external surface area allows more sun exposure and further reduces the heating loads by allowing the sun rays. However, in this climate type the cloud cover is much more in winter months, thus desiring the lesser external surface area to minimize the harsh winter effect, and further lowering the heating loads. Benefits with daylight utilization can hardly be observed in small and medium buildings, however, for large buildings, upto 15% reduction in energy use can be obtained through 1:3 aspect ratio. This is because of the lower impact of the weather factors on internal load dominated nature of large buildings, which is further offsetted by daylight gained during the summer months reducing electric lighting loads.
Fig 5.31 Results of Daylight Performance by comparing ASHRAE standards, Duluth (1:1)

- G1: Clear Glazing (VT= 0.79, U-value= 0.49, SHGC= 0.70)
- G2: Tinted Glazing (VT= 0.50, U-value= 0.49, SHGC= 0.41)
- G3: Low-e Glazing (VT= 0.37, U-value= 0.29, SHGC= 0.31)
- G4: Reflective Glazing (VT= 0.18, U-value= 0.31, SHGC= 0.18)
- G5: ASHRAE recommended glazing
Fig 5.32 Results of Daylight Performance by comparing ASHRAE standards, Duluth (1:3)

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- **G1**: Clear Glazing (VT= 0.79, U-value= 0.49, SHGC= 0.70)
- **G2**: Tinted Glazing (VT= 0.50, U-value= 0.49, SHGC= 0.41)
- **G3**: Low-e Glazing (VT= 0.37, U-value= 0.29, SHGC= 0.31)
- **G4**: Reflective Glazing (VT= 0.18, U-value= 0.31, SHGC= 0.18)
- **G5**: ASHRAE recommended glazing
Fig 5.33 Results of Daylight Performance by comparing Aspect Ratios, Duluth (Small Buildings)

Fig 5.34 Results of Daylight Performance by comparing Aspect Ratios, Duluth (Medium Buildings)

Fig 5.35 Results of Daylight Performance by comparing Aspect Ratios, Duluth (Large Buildings)

- 1:1, No Daylighting
- 1:1, With Daylighting
- 1:3, No Daylighting
- 1:3, With Daylighting
## 5.2 Proposed Fenestration Standards for Commercial Buildings
(Modified ASHRAE 90.1 Tables 5.5-1 – 5.5-8)

### MODIFIED TABLE 5.5-1 FENESTRATION REQUIREMENTS FOR CLIMATE ZONE 1

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6. CONCLUSIONS

The responsibility of designing buildings with high standards of energy efficiency, performance and comfort is increasing with the growing concern for depletion of resources. Computers are seen as important design tools that can assist designers to evaluate the impact of their design on building performance. However, because of the time consuming nature of the process involved and expertise needed for data input; these tools are not widely used, as a result leading to non integrated methods in building design. This study is thus performed considering an integrated approach through optimization strategies to reduce the energy consumption and to increase the overall efficiency of the buildings with the help of optimized fenestration design.

This study is focused on identifying the problems in the current fenestration standards (ASHRAE 90.1) and developing modified guidelines for fenestration design by overcoming drawbacks in the existing standards. This is achieved by determining the fenestration parameters which can be optimized for thermal and daylight performance of the buildings. By performing simulations with and without daylight utilizations for different office building types in all climates of U.S, the data is produced which is further used to develop modified tables 5.5-1 – 5.5-7 of ASHRAE 90.1. The modification is to provide the values for additional fenestration parameters such as VT and WWR which are currently not a part of existing guidelines. The summary of the optimization results achieved is as follows-

- The energy loads for HVAC may be offsetted by the daylight utilization due to reduction in the electricity load caused by electric lighting. This phenomenon is most evident in hot climates with estimated energy saving of 10-15%. However, in mild and cold climates, the energy savings is not more than 5-8%.
• Aspect ratio 1:3 performs better in utilizing daylight because of the increased outer surface area as compared to aspect ratio 1:1.

• Optimum ranges for WWR could be determined for aspect ratio 1:3 because it facilitates the balance between thermal and daylighting performance. However, aspect ratio 1:1 is not observed to be efficient in utilizing daylighting and thus can be evaluated based on thermal performance alone.

• Without daylighting, the EUI for both the aspect ratios is almost identical, while with daylight utilization 10-15% of energy saving can be observed for aspect ratio 1:3 as compared to aspect ratio 1:1.

The modifications proposed for the prescriptive model for fenestration design will provide the designers an ease to select optimum fenestration related parameters in the initial design stage for all climate zones of the U.S. By initiating optimization strategies early in the design process can assist the designers in following ways-

• For prioritizing envelope based energy efficiency strategies so as to provide daylighting within the building without the penalty of unwanted solar heat gain.

• For maximizing daylight and reducing the electric lighting loads by selection of the glazing properties and window size optimized for daylight performance.

• For minimizing solar gains when the building is in cooling mode and utilizing passive solar gain when the building is in heating mode by selection of glazing properties and window to wall ratio values optimized for thermal performance.

Site planning, building configuration and massing are the most important factors that need to be addressed during the conceptual stage of an architectural design. These factors finally influence the interior design, the HVAC design and the electric lighting design through the building
orientation, building form and configuration of window design. For example, the compact form such as square would have least solar losses and gains through building envelope but utilizes minimum daylighting. This can result in reduced HVAC equipment sizes but increased requirement for electric lighting. However, in rectangular building, though the solar losses and gains are higher, it utilizes maximum daylighting which can result in increased HVAC equipment sizes and reduced requirement for electric lighting.

With the help of computer simulation techniques, it is possible to derive the most energy efficient building form and size with respect to the thermal and daylighting performance for typical climatic condition. However, in most of the cases the building size and shape depends on the shape of the site and the client requirements. Thus, providing the designers with an optimum shape and size of the building, peculiar to climate zone will not be useful in practicality. However, facilitating the envelope design parameters optimized for different shapes and sizes of the buildings is thought to be more reasonable and thus achieved in this study in order to provide flexibility of architectural design for designers.

The applications of the guidelines recommended in this study can assist designers in predicting energy and daylight performance of the building and can help to plan in advance the interior design, the HVAC design and the electric lighting design to achieve better performing buildings.
7. BIBLIOGRAPHY


