QUANTIFYING ENVIRONMENTAL PERFORMANCE OF JALI SCREEN FAÇADES FOR CONTEMPORARY BUILDINGS IN LAHORE, PAKISTAN

by

AYESHA BATOOL

A THESIS

Presented to the Department of Architecture
and the Graduate School of the University of Oregon
in partial fulfillment of the requirements
for the degree of
Master of Architecture

March 2014

THESIS APPROVAL PAGE

Student: Ayesha Batool

Title: Quantifying Environmental Performance of Jali Screen Façades for Contemporary Buildings in Lahore, Pakistan

This thesis has been accepted and approved in partial fulfillment of the requirements for the Master of Architecture degree in the Department of Architecture by:

Ihab M. K. Elzeyadi	Chair
Mark Gillem	Member
Erin Moore	Member

and

Kimberly Andrews Espy	Vice President for Research and Innovation; Dean of the Graduate School

Original approval signatures are on file with the University of Oregon Graduate School.

Degree awarded March 2014

THESIS ABSTRACT

Ayesha Batool

Master of Architecture

Department of Architecture

March 2014

Title: Quantifying Environmental Performance of Jali Screen Façades for Contemporary Buildings in Lahore Pakistan

Jali screens are traditional window treatments in vernacular buildings throughout South Asia and the Middle East. Contemporary builders are starting to incorporate Jali screens as decorative façade elements; however, architects and scholars have largely ignored the impact of Jali screens on overall building energy and day-lighting performance. This research evaluates the effect of Jali screens, across a range of perforation ratios, on energy utilization and daylighting quality in contemporary office buildings. The data collection and analysis is through fieldwork in Lahore, Pakistan, as well as through computational energy modeling. Results demonstrate that Jali screens have a promising positive impact on cooling loads and may improve visual comfort. The findings suggest a holistic perspective combining traditional architecture and performance enhancement by architects and designers.

CURRICULUM VITAE

NAME OF AUTHOR: Ayesha Batool

GRADUATE AND UNDERGRADUATE SCHOOLS ATTENDED:

University of Oregon, Eugene
National College of Arts, Lahore, Pakistan

DEGREES AWARDED:

Master of Architecture, 2014, University of Oregon
Bachelor of Architecture, 2009, National College of Arts, Lahore, Pakistan

AREAS OF SPECIAL INTEREST:

High Performance Building

Vernacular Façades

Sustainable Design Research

PROFESSIONAL EXPERIENCE:

Associate Architect, Imtiaz Ali Associates, Lahore, Pakistan 2010-2012

Lecturer, Beaconhouse National University School of Architecture, Lahore, Pakistan. 2010-2012

Projects Director, Mian Muhammad Bukhsh Trust, Pakistan 2009 - Present

GRANTS, AWARDS, AND HONORS:

Fulbright Scholarship, Fulbright Flagship Program in Pakistan, Master of Architecture, University of Oregon, USA, 2012-2014

Student Scholar Award, Society of Building Science Educators, 2013

International Scholars Award, University of Oregon, USA 2012-2013

Gold Medal, National College of Arts, Pakistan 2009

Bhai Ram Singh Award, National College of Arts, Pakistan 2009

Mehdi Ali Mirza Award for Architectural Excellence, Institute of Architects Pakistan, 2010

Principal's Honors Award, National College of Arts, Pakistan 2008-2009

Travel Scholarship, Institute of Architects Pakistan Student Representative at Asian Congress of Architects, Busan Korea, 2008

ACKNOWLEDGMENTS

I would like to express the deepest appreciation to my committee chair, Professor Ihab Elzeyadi, without his guidance and persistent mentorship this thesis would not have been possible. I would like to thank my committee members, Professor Mark Gillem and Professor Erin Moore, whose support and supervision helped me focus throughout this thesis.

In addition, sincere gratitude is extended to Professor John Reynolds and Professor Judith Sheine for providing an external insight into the project and constant reassurance. I thank the faculty of School of Architecture and Allied Arts at University of Oregon for being available and opening up new avenues of research for me especially for providing access to the High Performance Environments Lab (HiPE).

I am indebted to my friends in Eugene for making a home for me. I thank Julie Zamost, Orestes, Dana and Sophie Yambouranis; Sahel Izadi and my colleagues in Studio 261 for their unwavering moral and emotional support. I offer special thanks to those who have been extra supportive in the writing of this thesis; Christina Bollo, Em Jackson and my husband Yasir Naseem for editing, proofing and helping me in putting it all together.

This research could not been conceived without the scholarship offered by the Fulbright Scholarship Program and International Scholars Award offered by the University of Oregon. I owe a big appreciation to my family, friends and colleagues in Lahore, Pakistan who helped me in my field research, including but not limited to Imtiaz Ali Associates for providing access to architectural drawings; Engineer Sheikh Farooq for helping me identify and access base case buildings; consultants at the Lahore Fort for providing approach to otherwise inaccessible zones for data collection; my family in expediting the data collection during a limited time in spring 2013.

I acknowledge and with utmost respect thank my family in Pakistan for their prayers and encouragement; my parents and my husband for being extremely patient and understanding in the difficult times and extended deadlines.

For my best friend, my counselor and husband in one, with whom I share a dream.

TABLE OF CONTENTS

Chapter Page

APPENDICES

LIST OF FIGURES

Figure Page

Figure Page

LIST OF TABLES

Table Page

CHAPTER I

INTRODUCTION

Pakistan occupies a geopolitically important location at the crossroads of South Asia, the Middle East and Central Asia. Lahore is the second largest city in Pakistan, with a population of 1,000,000 (in 2010). This city is the thirtieth largest city in the world by population (Wikipedia). With an ever-growing population, development is focused on this city. New buildings are built every month and the demand on infrastructure, especially electricity, is increasing. New commercial buildings in Lahore rely heavily on electricity for several reasons:

1. Excessive use of unprotected glass curtain wall
2. Dependence on mechanical systems for lighting and cooling.

Unprotected glass curtain walls are not very climate friendly in warm and hot-humid Lahore, and using blinds on the inside of the window is absolutely necessary. In commercial buildings, interior roller shades, blinds, and screens can attenuate heat gain, but they do not block sunlight. They significantly increase the total building energy when compared to external shading devices (Moeck et al.).

On the other hand, vernacular architecture[1] in Pakistan, in particular Lahore, is very climate friendly and respectful towards centuries old building culture. For example, the indigenous buildings in the Walled City perform very well, and do not rely heavily on electricity for cooling and lighting. Natural resources such as light and wind are used to decrease over all lighting and cooling loads of buildings. Architects today,

---

[1] Broadly defined, vernacular architecture is an area of architectural theory that studies the structures made by empirical buildings with the intervention of professional architects (vernaculararchitecture.com).

unaware of the true benefit of these strategies to the environment, tend to use traditional architectural elements in design merely to reflect a nostalgic view of the past. They do not understand their true value to the environment.

The designer must be aware of the possibilities to achieve thermal comfort for the occupant with minimal resources. Especially in Pakistan, reduced energy loads would mean more chances of thermally comfortable space; as the energy crisis gets worse, many hours of electricity are cut-off, buildings must provide necessary comfort conditions for operation through passive means, incorporating active resources only when in demand.

1.1. PROBLEM STATEMENT

Lahore, a modern financial center in Pakistan, is dominated with office buildings. These offices are air-conditioned throughout the year. Typically, in the US, the electricity consumption of air-conditioning equipment is around 40% of the total energy use of the whole building (Graham 2009). Heat flow via window is one major contributor to the air-conditioning load. The climate of Lahore is typically characterized by a high intensity of solar radiation. Heat avoidance is of primary concern as a means to reduce energy use and provide comfort to occupants (Boake 2014).

Excessive energy use does not only impact the building energy utilization but also the environment. In many places, building standards are incorporating minimal energy usage and concentrating on the potential of the building envelope to save energy. Certain envelope-design strategies have already proved to serve the purpose of energy saving in buildings (Olgay et al. 1957)(Brown 1985). There are several prescriptive sets of building criteria available to attain the thermal and comfort benefits, and ASHRAE has published several of them (Zhivov et al.)

However, such standards pertaining to thermal comfort are not available in Pakistan and the thermal construction in buildings is very poor, especially with regard to insulation, when using ASHRAE standards.

The role of the building envelope is also to achieve comfortable daylighting levels without causing glare. Typical shading devices include horizontal and vertical shades and louvers. Although, very commonly used, the literature shows that these do not help in visual comfort as compared with other shading devices. Fathy (1986) indicated that perforated screens, for example Mashrabiya in Egypt, affect the quality of space and improve visual comfort in spaces in comparison to Brise Soleil, shading device introduced by Le Corbusier in many building façades such as "Palace of Assembly" in Chandigarh, India. Several studies show that external screens reduce solar penetration as solar radiation is rejected before hitting the glazing (IESNA Lighting Handbook 2013) (Kwok et al. 2011).

Modern versions of perforated screen façades are becoming popular amongst architects with a focus on sustainable envelopes (ARUP). Recent commercial projects in the Gulf area, including Doha Tower by Ateliers Jean Nouvel, O-14 by RUR Architecture and Al Bahar Towers by Aedas Architects with Arup, are reinterpreting traditional screen façades, which claim to reduce solar gain and cooling loads. This is usually coupled with relatively high performing glazing in curtain wall skins to further limit heat transfer and solar gain (Boake 2014). However, in Pakistan single glazed curtain wall systems with low-performing envelope designs are still prevalent. In Pakistan, screens continue to be used as ornamental applications just for aesthetic value. Buildings in the Gulf area and in Pakistan have performance claims, which are not backed by any hard numerical evidence.

Jali Screen façades have been widely used as shading devices in the Lahore, Pakistan. This is due to their climatic adaptation and environmental performance. However, there is a lack in understanding of their performances in a quantitative manner and unavailability of scientific means that could be used for developing new efficient designs that suit the modern façades of office buildings. Studies conducted in other regions are lacking the context and research credibility as they are only based in simulated environment. Such research cannot be linked with the climate of Lahore as it is neither situated nor calibrated with an actual building. Therefore, not only do we need to understand the performance of Jali screens, but also how well they perform in the context of the climate of Lahore. Architectural practice in Lahore must be made aware of the current conditions of office buildings in the absence of any shading devices.

1.2. RESEARCH SCOPE

This study explores the performance of a range of Jali screen façades in terms of both daylighting and cooling (by shading). In the context of this research, the research is limited by:

1. Location: An existing office building in Lahore is documented for its environmental performance. This site is used as a base case and for further analysis of the impact of Jali screen façades. Traditional Jali screens are analyzed in Lahore for their visual performance and geometry.
2. Orientation: Shading devices, such as Jali screens, perform more efficiently on the south and west sides (Sherif et al. 2010). Thus, Jali screens are added in the simulation as external perforated shading for only south and west sides of the building.
3. Scale: Two offices (rooms) in the base case building are selected for detailed analysis. The existing window-to-wall ratio is kept constant for comparison.

4. Parameters: Out of the three Jali types documented in the field, one pattern was found to be the most prevalent and therefore selected. Furthermore, two basic parameters have had been documented as having significant to performance of Jali: Perforation Ratio and Depth Ratio (Sherif et al. 2012).
5. Designs: As a result of the field study, three perforation ratios, 30%, 40% and 50% are found to be useful for testing in the simulated model. Along with these three Jali screens, a common shading device, Brise Soleil, was also tested, with horizontal elements on the south and a combination of horizontal and vertical shading elements on the West façade.

1.3. RESEARCH OBJECTIVES

The objective of this research can be divided into three parts:

A. To determine the most efficient Jali screen, in energy conservation and visual comfort of office spaces.
B. To develop design parameters for Jali screens for buildings in Lahore that can be useful to architects and designers.
C. To provide a framework for further research on Jali screens in Lahore, Pakistan.

1.4. RESEARCH METHODS

The method of this study can be separated into three sections, including design, instrumentation and analysis.

1.4.1. Research Design

a. Research Design:

   Figure 1.1 shows a summary of Research Design. Study includes field measurements in Lahore and experimental research using various instruments including IES VE dynamic simulation software.

b. Shading Devices

Jali screens were tested for the predominant independent variable, i.e., perforation ratio. They were compared with other cases including common traditional devices and thermal constructions.

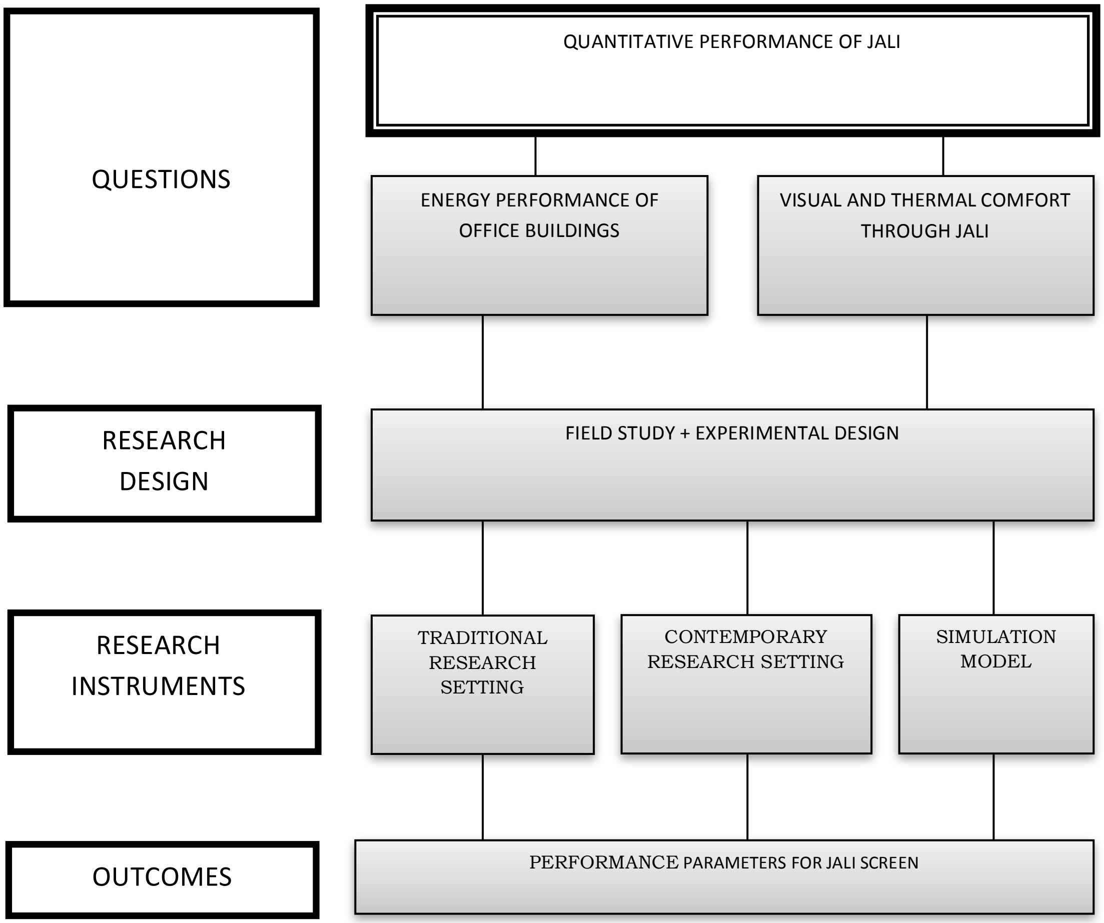


Figure 1.1. Research Design

1.4.2. Research Questions

The impact of Jali screens on energy conservation and visual comfort in office buildings in Lahore, Pakistan formed the core of this investigation. Details of variables, which affect the energy of building, cooling and lighting, were identified and form the sub-questions of the study. The results from the field study impact decisions taken during the experimental design stage. Table 1.1 shows the pattern of investigation guided by the research questions.

Table 1.1. Research Questions

RESEARCH PROBLEMS	RESEARCH QUESTION	SUB-QUESTIONS	RESEARCH INSTRUMENTS	RESEARCH OUTCOMES
<u>Main problem</u> **Energy conservation through façade design and shading through Jali.** **Gap in literature on the effect of Jali on visual comfort.**	What is the impact of Jali screen geometry on energy conservation in commercial buildings in Lahore Pakistan?	What is the impact of Jali screen on total building energy? What is the impact of Jali screen on visual comfort, including glare? How does it compare with other shading devices?	Field Study: How well does an average office building perform, visually and thermally? Experiment: How can the performance of office building be improved through Jali screens?	What are the quantifiable design attributes of Jali screens?
Gap in quantitative evaluation frameworks on Jali Screen façade		What are the variables and metrics for evaluation of comfort through Jali screens?	What is the difference of performance in varying shading parameters?	What are the assessment guidelines for Jali screens as shading devices?

CHAPTER II

FACTORS AFFECTING JALI SCREEN FAÇADES

2.1. FACTORS AFFECTING DESIGN IN LAHORE

Lying between 31°15′—31°45′ N and 74°01′—74°39′ E, Lahore has a population estimate for 2010 of more than 10,000,000, making it the second largest city in Pakistan after Karachi. With the rapid growth of the city, electricity demand has been on a rise.

2.1.1. Energy Crisis

Pakistan is currently meeting its energy needs derived from five main sources: oil (36%), natural gas (27%), hydroelectricity (32%), coal & nuclear power (5%) (Hasnain 2013). Energy consumption patterns show the building industry consumes a large part of the energy. Because of depleting oil and gas reserves and rising international oil prices, domestic prices are increasing and a huge gap between demand and supply of the both electricity and gas. As a consequence, consumers are facing the burden of the power and gas load shedding and are also paying huge bills.

Pakistan is the country third most-affected by climate change on the Global Climate Risk Index (CRI) developed by Germanwatch. The result for the citizens of Lahore is intentional power blackouts for up to 15 hours per day in the winter and up to 20 hours a day in the summer (Santana 2013). It is the same or worse in other parts of Pakistan (John 2009). At the same time, Lahore has been crippled by a raging energy crisis for the last few years (Waraich 2013). A large number of studies and policy recommendations have been produced on these issues without much visible impact (Afridi 2013)(Ahmed 2013).

2.1.2. Commercial Building Typology

Buildings consume almost 40% of the world's energy, 16% of the world's fresh water and 25% of the forest timber, while responsible for almost 70% of sulfur oxides and 50% of the CO_2 emissions (Ghiaus 2004). In Europe, about 41% of the total energy consumption is in buildings (Bosseboeuf 2012). In Malaysia, air conditioners are shown to be the major energy users (57%) in office buildings, followed by lighting (19%), lifts and pumps (18%) and other equipment (6%) (Saidur 2009).

Within the commercial sector, office buildings have the biggest energy consumption and CO_2 emissions. In the USA, offices account for 17% of total non-domestic area and about 18% of the energy use. In Spain, they account for a third of the commercial sector energy consumption while in the UK, the commercial sector account for 17% of the energy consumption. While no comparable data is available for Pakistan, this evidence drives the focus for this research.

In office and production buildings, solar heat gain is undesirable because high internal loads essentially heat the building indirectly (Daniels 2000, 147). It is quite common that such buildings require heating only when the temperatures outside fall below 0 ^{o}C (Daniels 2000). Power for lighting and fans represent the major energy input to most large, non-domestic buildings and must be provided constantly to area away from the perimeter (Baker et al. 2000). While mechanical shading systems respond to the fluctuations in solar transmission, energy and light requirements, they are often high-maintenance and therefore expensive solutions (Daniels 2000).

The passive zones in commercial zones can be day-lit and naturally ventilated and may make use of solar gains in winter; however, they are likely to suffer overheating be solar gains in summer. Passive zones are defined by orientation (Baker et al. 2000) and by the depth of building (distance from façade) that is twice the floor to ceiling height.

Thermal performance of the building envelope influences the energy demand of a building in two ways. It affects annual energy consumption; therefore, the operating costs for building heating, cooling, and humidity control. It also influences peak loads, which consequently determine the size of heating, cooling and energy generation equipment, and in this way has an impact on investment costs (Zhivov et al.).

2.1.3.Climate and Comfort

This research follows the latest research on climate in Pakistan (Zahid et al. 2011), which uses the Thornthwaite climate types. There are various classification methods including Ayoade, Nieuwolt, Runnels, Oakley, Koenigsberger, Lippsmeier, Koppen and ASHRAE, but Thornthwaite is deemed by Zahid and others as the most appropriate for Pakistan (Appendix A).

Figure 2.1 shows the climate zones of Pakistan where Lahore is shown in a red dot (Sourced from Zahid et al. 2011).

2.1.3.1. Lahore Climate

Lahore has overlapping climatic zones throughout the year. It is Tundra in mid-winter, (December to February), Meso-Thermal (March to April), Mega-Thermal (May – September), Micro-Thermal (October to November). Lahore has 9,753 cooling degree days and 3666 heating degree days. It is bracketed in the Mega-thermal zone. Over the course of a year, the temperature typically varies from 43°F to 104°F and is rarely below 36°F or above 112°F.

In Figure 2.2, the grey band marks the comfort range of temperature as determined by ASHRAE- 2005 Comfort Model (“Climate Consultant”).

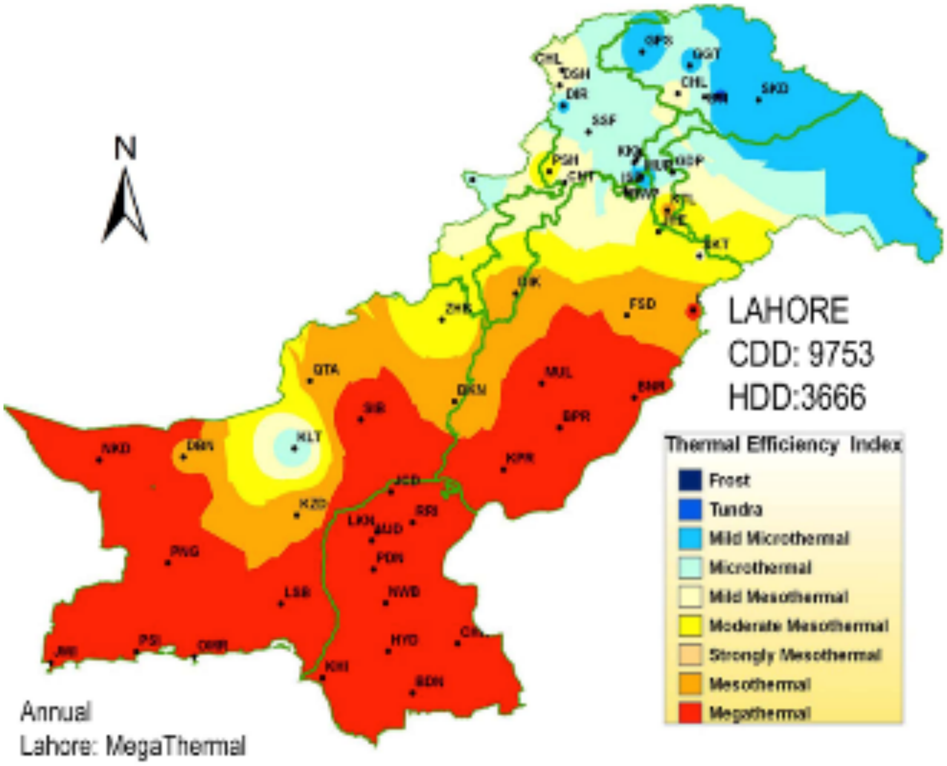


Figure 2.1. Annual Climate Zones in Pakistan

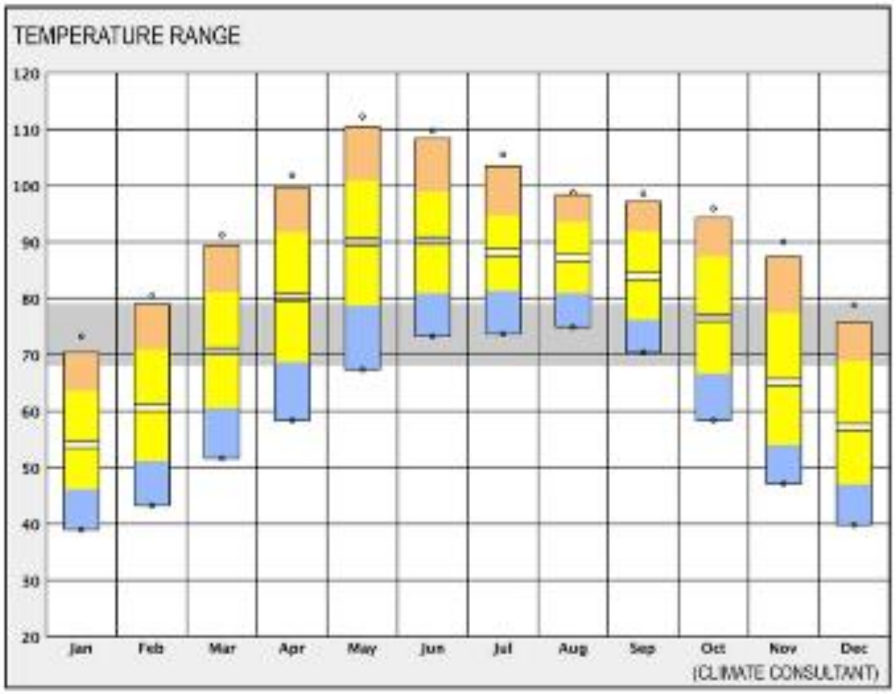


Figure 2.2. Temperature Range in Lahore

2.1.3.2. Comfort

Architectural responses to a particular climate require an understanding of the general problems and special conditions present in that climate. Some major concerns during hot-humid spells of Lahore are:
1. Uncomfortable hot weather requires active cooling to achieve comfort conditions.
2. Strong solar radiation, which is not only a source of heat but also light and glare in normal working conditions.

Figure 2.3 shows a Psychrometric Chart for Lahore, Pakistan (Climate Consultant) with each of 16 different building design strategies represented as different colored zones. This is an example of how three different attributes of climate can be displayed concurrently to show if humans will be comfortable in spaces with certain design strategies. Temperature (bottom scale) and absolute humidity (right scale) is plotted for every hour of the year, with the color indicating whether it is above the comfort zone (red) or below it (dark blue). The best single passive cooling design strategy is Sun Shading, which accounts for 24% of the time.

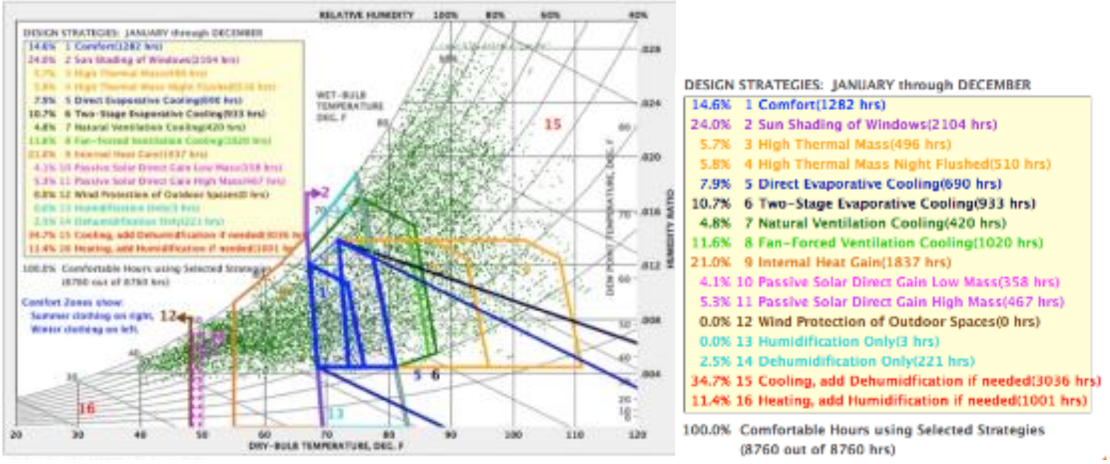


Figure 2.3. Psychrometric Chart for Lahore, Pakistan

2.1.3.2.1. Thermal Comfort

The American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) define thermal comfort as that condition of mind that expresses satisfaction with the thermal environment (ASHRAE 2010). Thermal comfort is one of the most essential aspects of user satisfaction and energy consumption in buildings (Nicol et al. 2012). In the case of office and work environments, productivity levels can be affected by thermal and visual comfort, and all steps should be taken to optimize ambient conditions and thermal comfort (Daniels 1994). It is not surprising that “man’s intellectual, manual and perceptual performance is in general highest when he is in thermal comfort” (Fanger 1972).

While Figure 2.3 shows that the amount of time spent in comfort without any strategies at work is only 14.6%, this idea corresponds with Figure 2.4, which shows the predominantly heating and cooling months in Lahore, along with heating-degree-days and cooling-degree-days figures at the top of each column. This shows how significant cooling is to achieve thermal comfort in Lahore. Figure 2.5 shows how much shading can contributing to the thermal comfort in buildings. Figure 2.6 shows the number of hours in thermal comfort defined by ASHRAE 2005, with the use of Sun Shading (Yellow) and Ventilation (Red) through the course of the year.

On the Sun Shading Chart for Lahore (Figure 2.7), the yellow dots indicate comfort conditions when the dry bulb temperature is within the comfort zone as defined on the Criteria Screen (Climate Consultant). Red dots indicate overheat conditions when the dry bulb temperature is above the top of the comfort range. Blue dots indicate under-heat conditions when dry bulb temperatures are below the bottom of the comfort zone. Ideally for a passive heated house, the windows should be fully exposed where there are blue dots, and to prevent overheating the windows should be fully shaded wherever there are red or yellow dots.

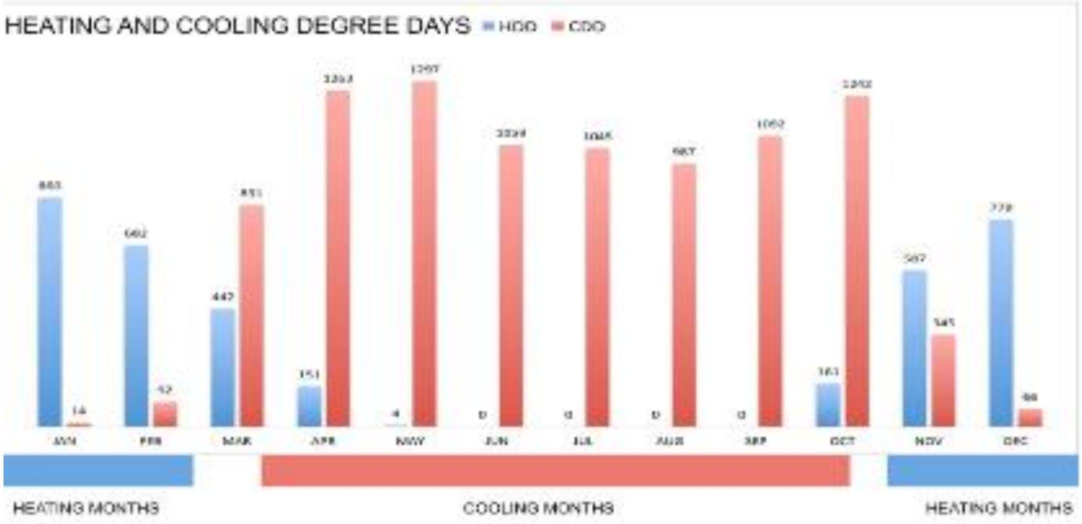


Figure 2.4. Heating and Cooling Months in Lahore, Pakistan

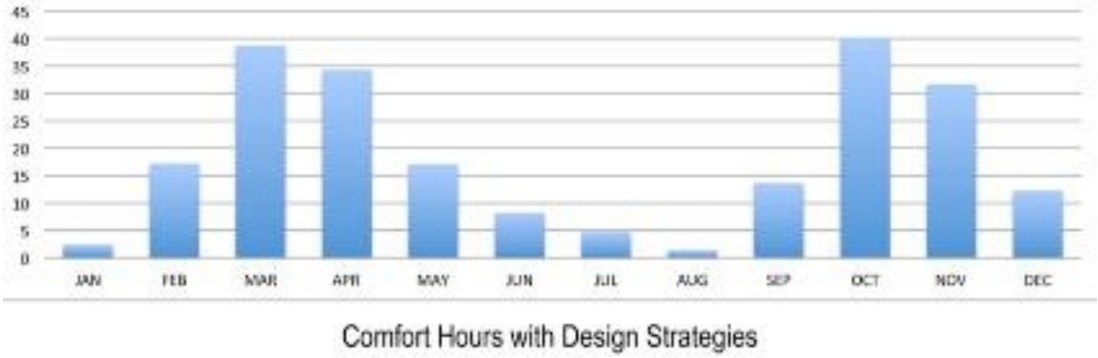


Figure 2.5. Thermal Comfort achieved through sun shading and natural ventilation

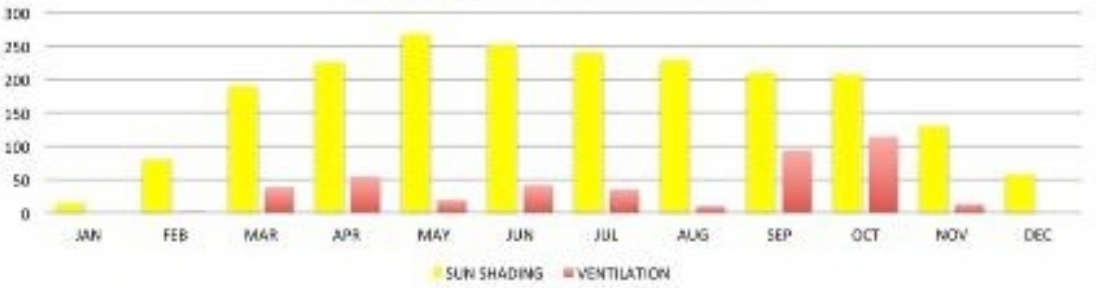


Figure 2.6. Number of hours spent in thermal comfort zone

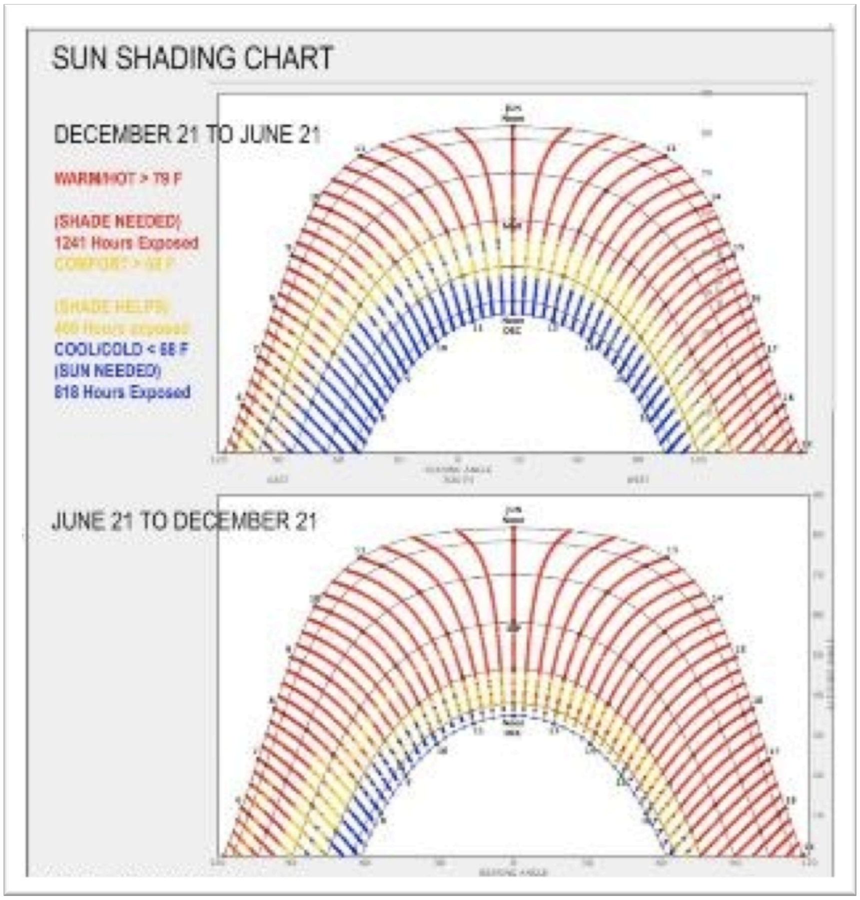


Figure 2.7. Sun Shading Chart for Lahore

2.1.3.2.2. Air Movement

Thermal comfort is greatly influenced by air movement within a space. In hot-humid climates, "physiological requirements for thermal comfort will not be satisfied unless there is some adequate fresh air ventilation and air movement in occupied rooms" (Crowden 1954). The limits of air movement in the comfort zone depend upon the air temperature and turbulences quotient of the airflow as shown in Figure 2.8 (Daniels 1994, 38). In the figure, values apply to activity level 1 and heat transmission resistance of clothing of approximately 0.12 M^2k/W.

Previous studies of naturally ventilated buildings in hot–humid climates indicate that the temperature deemed comfortable increases with higher indoor air speeds (Cândido et al. 2011)(Khedari et al. 2000) (Mallick 1996) (Wijewardane et al. 2008).

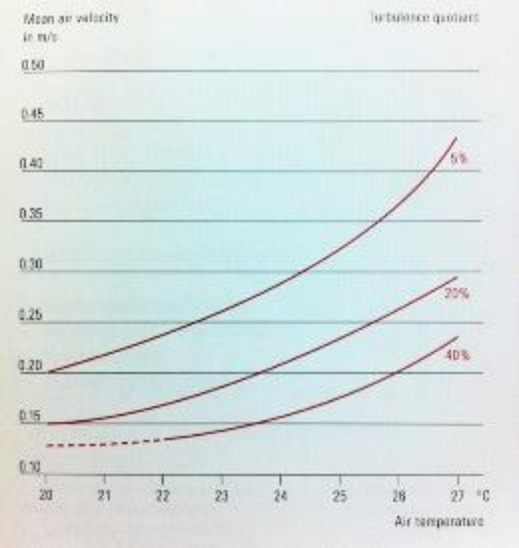


Figure 2.8. Comfort Average Air Velocities as a Function of Temperature and Turbulence Quotient in Air.

Therefore, as air movement is the only available relief from climatic stress in high humidity, buildings must be opened up to breezes. Openings must be placed strategically and responsively keeping the microclimate and predominant wind movements in mind.

Another way of representing detailed wind analysis is the Wind Rose Diagram. The Wind Rose Diagram (Figure 2.9) describes the prevailing wind direction and intensity in Lahore ("Climate Consultant").

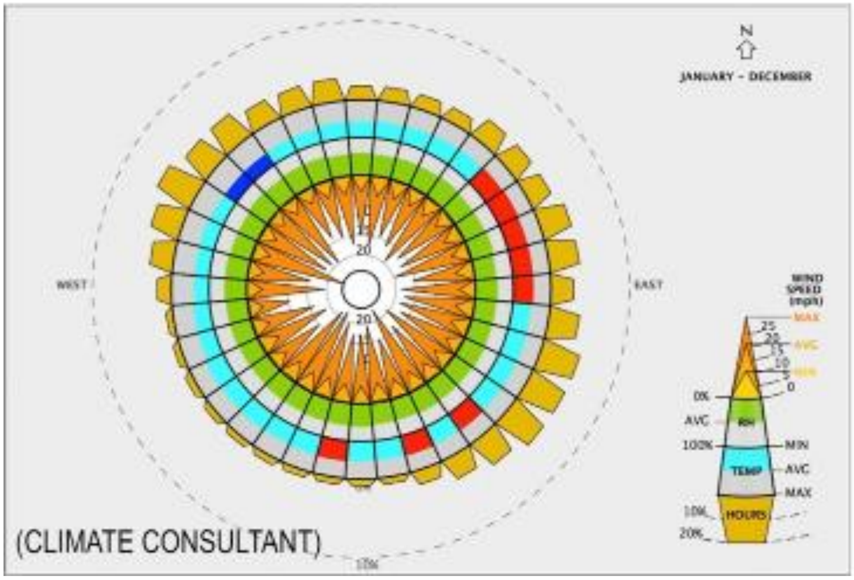


Figure 2.9. Wind Rose Diagram for Lahore Pakistan

2.1.3.2.3. Visual Comfort And Glare Protection

Daylighting is a crucial asset in office spaces; it increases the productivity of workers, enhances their morale, and maintains their health (Boubekri 2008). Despite its importance, sometimes designers do not accurately account for daylight during the design phase, which subsequently requires the use of more electric lighting and can lead to glare. On the other hand, some architects, like Alvar Aalto, Louis Kahn, and Le Corbusier, addressed daylight through architecture, emphasizing its importance.

The solar conditions in Lahore require protection from the sun, as evident in Figure 2.7. Responsive envelope design could mediate the extreme solar radiation on the exterior so as to provide comfortable interior. The sun in Lahore is the main source of heat and spaces have to be screened and protected against it. If windows are un-shaded they become radiation traps, allowing the short-wave solar radiation to enter, but allowing very little of the long-wave thermal radiation to pass back out. This is known as the Greenhouse Effect. However, this screening should be precisely designed so that daylight levels do not drop too low.

Achieving a balance in lighting conditions can be difficult and recent research in building science is focused on this subject. Reinhart defines this ideal condition of “daylighting” as “a space that is primarily lit with natural light and that combines high occupant satisfaction with the visual and thermal environment with low overall energy use for lighting, heating and cooling” (Reinhart et al. 2011).

A shading device may be able to protect the window in a sunny condition, but in a cloudy sky condition, such a device would be less useful. The main design problem is glare – discomfort caused due to contrast between bright outside and relatively darker interior of the room. Glare is a subjective human sensation (Hensen et al. 2011) that describes ‘light within the field of vision that is brighter than the brightness to which the eyes are adapted' (HarperCollins 2002). Ihab Elzeyadi posits that glare is not altogether subjective, it is well defined and quantifiable based on documented human response and physiological impacts (Elzeyadi 1996).

2.1.3.3. Traditional Passive Cooling And Day-Lighting Strategies In Lahore

The sunny, summer days of Lahore make the design of shade protection for windows very difficult. Traditionally, buildings protect the interiors using passive techniques and design elements, which include *Chajjas*, *Jharokas*, *Jalis*, Verandahs, Courtyards, amongst others techniques. An example of traditional building (Figure 2.10) is an ensemble of almost all existing passive design strategies. From basement cooling chambers, to courtyards, verandahs, Jharokas, Jali screens, Barsati, and Chajjas covering all windows, it stands in the dense fabric of the Walled City, with varying degree of opacity from ground up.


Figure 2.10. Façade of Haveli Naunehal Singh in Lahore

Figure 2.11 is a matrix of available vernacular architectural devices used for passive cooling and lighting of buildings in Lahore. The table is divided into elements, such as shades, to formal arrangements and the contextual settings. The scope of this research was focused on improving thermal comfort in office environments with shading façades.

2.2. CONTEMPORARY SHADING DEVICES

New commercial buildings in Lahore are divided into two kinds of façades. The first type do not use any shading devices and employ clear glazing systems; the second type uses shading devices with less-than-optimal designs, such as horizontal and vertical louvers. Sometimes, the Jali screen façades are used in traditional architecture, but only as a decorative use reminiscent of the rich historic past. Jali screens historically had many purposes, however, evolving with use and building typology.

Figure 2.12 shows three examples of contemporary façades in Lahore, shown from left to right in decreasing popularity. The most prevalent type, on the left, is the fully glazed façade (Photo Credit: Atif Rehman). The middle image shows a contemporary building with a so-called traditional façade. This treatment of a seemingly porous façade is merely decorative and neither light nor view is allowed through the windows.

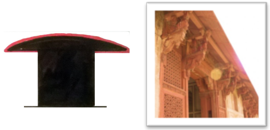
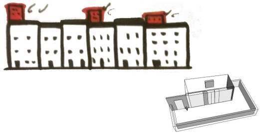
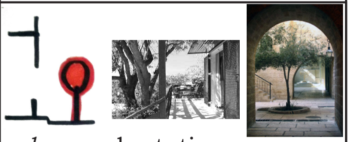
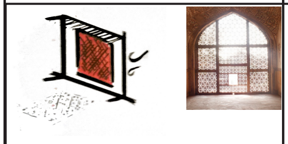
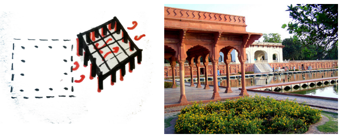
Element/Device	**Form/Space**	**Context/Environment**
 *Chajja* - Overhang Shading device wall + window	 *Courtyard* Shading + Cooling Living + open space	 *Favarah - fountain* Cooling Incoming air
 *Jharoka* - Overhang Shading + Living space window buffer zone ventilation + lighting	 *Barsati - Rain-room* Cooling + ventilation Living space	 *sabza* - plantation Shading+Evapotransipration Windows + Outdoor
 *Jali* - Screen Shading + Ventilation Window + space lighting	 *Beramda* - Veranda Shading + Ventilation buffer zone	 *Baradari* - Pavilion Shading + Ventilation Mediation between inside and outside

Figure 2.11. Traditional Passive Design in Lahore, Pakistan

The image on the right is a version of *Brise Soleil*, where the horizontal and vertical louvers cover the façade (Photo Credit: Atif Rehman). Although the thermal performance for these three examples is unknown, visual and daylighting performance is highly unsuitable for working conditions. Glass façades cause glare and use of blinds causes further lighting loads.

Figure 2.12. Examples of Contempory Façades in Lahore

2.3. JALI SCREEN AS FAÇADE

As Hassan Fathy points out, any traditional architectural solution must be understood implicitly in terms of its scientific, social and constructional aspects before any attempt can be made to apply it to a contemporary situation (Fathy 1986).

2.3.1. History and Use of the Jali

Jali has been used in architecture in Pakistan since the early Mughal period. The earliest forms of Jali are found in Gujrat. Over the years, architects and builders have acknowledged its benefits as a screen that filters light and air, while allowing selective privacy. Figure 2.13 shows a few examples of Jali use in buildings. When designed to suit particular climate and sun angles, the screens have a much more interesting surface than could have been obtained with identical patterns. (Fathy

1973, 35) (Fathy 1986). Architect V. S. Natraj has utilized this strategy with multi-story walls of concrete grillwork and the occupants chose opening the house to the breeze despite inherent problems of insects, security and privacy (Faris 1981).

Figure 2.13. Examples of Jali Screens in Lahore, Pakistan

When light filters through the screen, the patterns extend into the room, onto the walls behind and the floor beneath (Jones 1978), e.g. the tomb of Sheikh Salim Chisti, Fatehpur Sikri (Asher 1993, 350).

According to the literature, nearly all the geometric designs used in Jali screens can be reduced to a series of competitively simple geometric shapes (Grabar 1964). Figure 2.14 is an illustration derived from the Industrial Art Pattern book by Percy Brown, showing Jali screens (carving called Pinjra work in this text) from the 19th and 20th century art work in India.

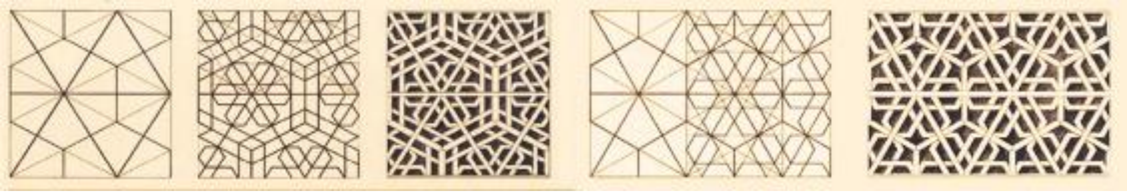


Figure 2.14. 'Pinjra Work' Drawing

Figure 2.15 is a matrix of issues associated with Jali use in the contemporary built environment, showing common materials, construction technologies and uses in certain climate zones and different building typologies.

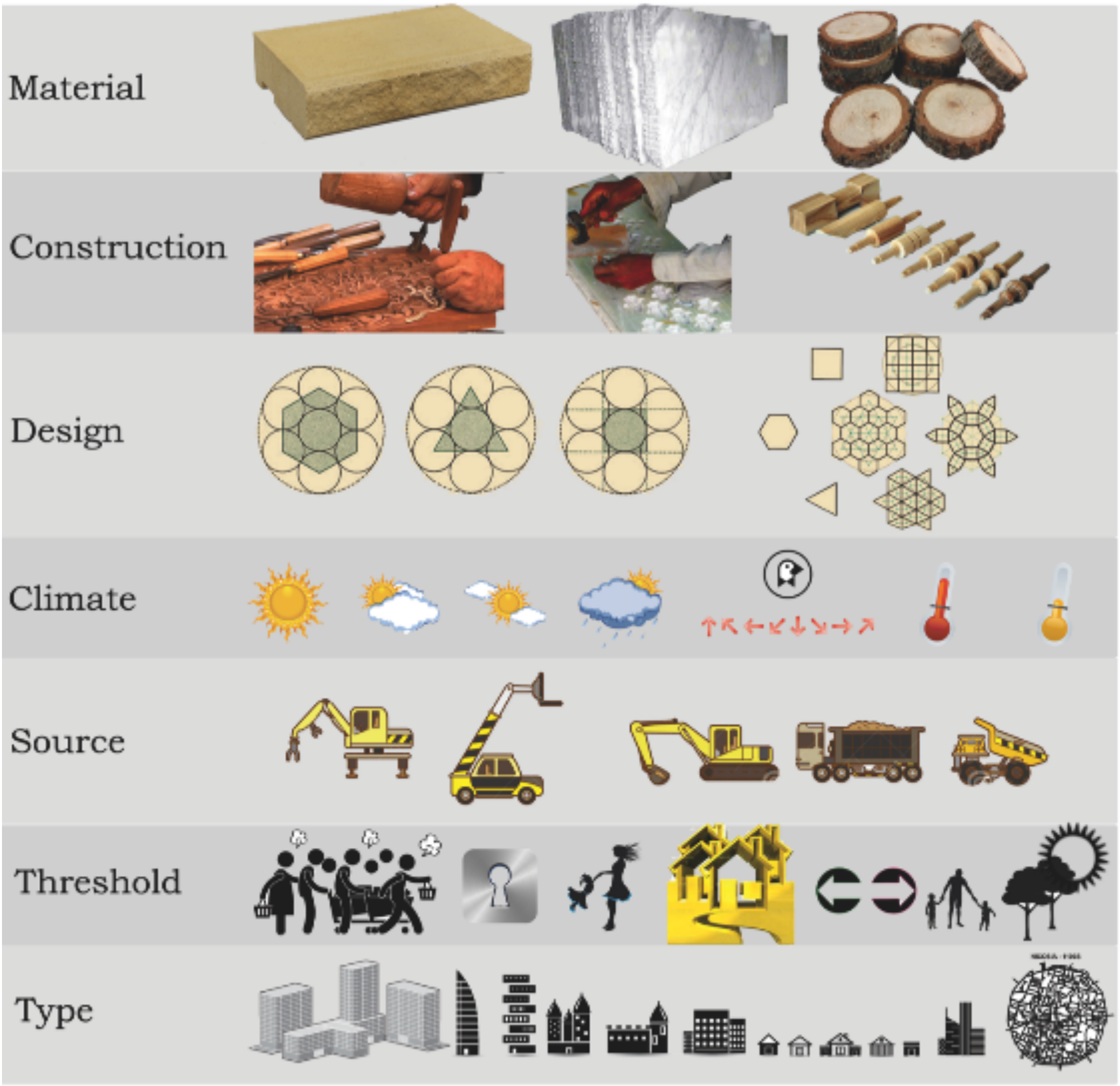


Figure 2.15. Matrix of Issues Related to Jali use in Lahore

2.3.2. Contemporary Issues

Jali screens are frequently used as merely decorative façade treatments without any understanding of their performance. Previous studies have identified issues associated with the decline of use in hot and humid climates (Fry 1982) and examined the economic and social problems with the application of intricate latticework in the contemporary city (Gelil

2005). Cost of labor as well as the cost and availability of local building materials vary widely and dynamically across the globe but are critical for assessing feasibility of integrating vernacular techniques into contemporary buildings (Zhai et al. 2010).

Construction of Jali Screens in marble continues today. Partial mechanization of the process through the use of drilling machines has made the process more time efficient. Masons use plant material to trace a pattern on the face of the marble. Figure 2.16 below shows the manufacturing process of Jali screens in Lahore today. Left to right: (1) A natural color is used so that the white marble can be washed without any remnants of the trace. (2) After the trace, a machine drills holes through the slab of stone. (3) Masons uses hand tools to chisel the remaining marble off the patterned screen. (4) Polishing is the final step, with electric polishing tools.

Figure 2.16. Manufacturing of Jali screens

2.4. FUNCTION OF JALI

2.4.1. Thermal Regulation

Jali Screens are not cooling devices. On their own they cannot cool buildings. Rather an intelligent ensemble of architectural features, each designed to reduce heat gains, creates a cool, steady internal environment in hot outside conditions.

2.4.1.1. Shading

The Jali screen acts as a mediator within the building envelope, regulating the external boundary layer by blocking any direct sunlight, reducing the Thermal Transmittance (U)[2] and the Diminution Factor[3]. The Jali screen allows for selective shading of windows, protecting in the summer and opening up to the sun in the winter.

External sun protection combined with sun protection glass is 15% more efficient than internal system (Hausladen et al. 2012). For a lightly constructed façade, a certain amount of thermal protection is required to reduce transmission heat gain. The outer wall's degree of absorption influences the cooling energy demand, and should therefore be as low as possible (Hausladen et al. 2012).

2.4.1.2. Cooling through Allied Strategies

Lowering the temperature of incoming air is made possible by adiabatic cooling, i.e. water evaporates onto or from a surface or is sprayed. Evaporation occurs when water with temperature well below 100°C (212°F) evaporates from the water surface or moistened surface. The evaporation increases in direct proportion to water and air temperature as well as air velocity.

By placing water sources (pond, fountain or sheet of water pouring over the Jali screen, soaked dampers made out of thatch) close to the Jali screens the temperature of air could be cooled as external air could be extremely hot and dry.

---

[2] The Thermal Transmittance U indicates how much energy is passed through the pane surface. The smaller value of U, the lesser the energy transfer.

[3] The Diminution Factor of a shading device (from DIN 4108) measures the percentage of incident radiant energy, which passes through a shading element and thus contributes to the warming of an interior space (Daniels 1994).

2.4.1.3. Airflow Regulation

The location, sizing and construction of Jali screen façades determine the internal thermal conditions of a space. The airflow rate is proportional to the perforation ratio of the screen (Samuels 2011). If airflow is looked at in conjunction with evaporative cooling techniques then criteria for determining the optimum dimensions of the Jali Screen Façades can be established.

2.4.2.Visual Comfort

Control of direct light is of critical importance in Lahore and similar climate zones. The heat caused by solar gain, internal daylight requirements and glare are three main issues that require that light be controlled carefully in such a climate.

In a hot climate, any shading device must be designed to control direct sun while allowing for diffused sky light to lighten up the space. With Jali screens, ambient light of the exterior can easily pass through the perforations, while providing shade from vertical (or almost vertical) solar rays. The control of glare and reflected ground light is effectively achieved through the use of Jali on façades. Unlike *Brise Soleil*, the light entering through Jali screens is dispersed on a fine scale. Hassan Fathy says that looking onto the open street from the inside was like “looking through a pane of darkened glass made of lace” (Fathy 1986). Often in the section of the Jali, the edges were rounded. Thus, the shadow gradient on the internal surface of each section consequently reduces the impact of the whole Jali façade.

2.4.3.Aesthetic and Social Role

Expectation of privacy is an embedded part of the culture of India-Pak Subcontinent. When the outside is bright, it is always visible as long as there is daylight: the exterior has the focus and the interior is outshined (Figure 2.17). By manipulating the perforation ratio and lighting conditions, it is possible to change the focus of the view. These screens have been a part of the society for a very long time, and the replacement for them, such as blinds, functions as a curtain barrier between inside and outside.

On the urban streetscape, Jali screens add vibrancy and life to the street life, adding a third dimension to the narrow streets shadowed by tall buildings. Historically, the decorative aspect of the screen was not only a social statement but also a signature by the master craftsman.

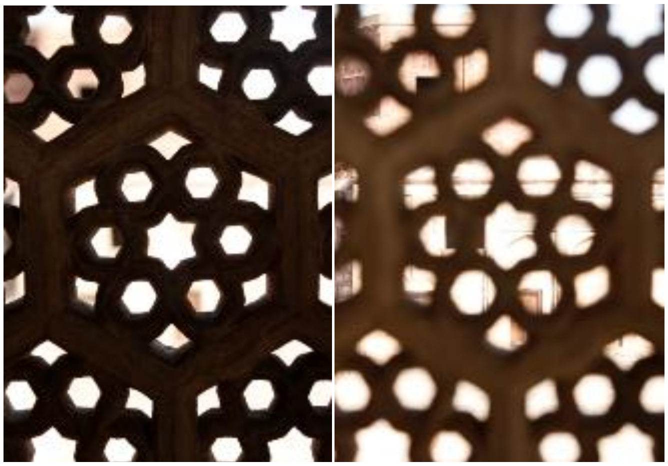


Figure 2.17 Jali viewed in varying focus of the eye

2.5. PHYSICAL PROPERTIES OF JALI

2.5.1.Geometry

2.5.1.1. Perforation Ratio

Perforation Ratio (PP) is the opening area to the whole area of the screen (Sherif et al. 2012).

2.5.1.2. Depth Ratio

The depth ratio (DR) is the ratio between the depth and the width of each perforation opening (Sherif et al. 2012).

2.5.1.3. Pattern

Several patterns exist for Jali screens. Research shows almost all patterns can be drawn to simple geometrical shapes, such as a hexagon, a triangle and a square.

2.5.2.Materiality

2.5.2.1. Thermal Mass

Conductivity of heat through the solar screens depends on the materiality of the screen. According to the physics of heat transfer, for the same thickness/mass, it mainly depends on the specific heat capacity of the material, as to how well it will perform as a heat barrier. The heat capacity of sandstone, marble and stone, is thrice that of wood.

2.6. ASSESSMENT OF JALI

It is important to assess the Jali screen parameters using current research available on other types of external screens. Table 2.1 provides a summary of existing literature. The impacts of screens or screen façades examined in research can be summed up into five broad categories: energy loads of building, daylighting loads, light intensity or glare, quality of light transmitted in patterns of screens, air movement and user perception.

2.6.1.Energy Performance

The use of external perforated solar screens in reducing energy consumption and achieving thermal comfort is documented in the literature (Harris 2006). However, articles that quantitatively address the issue of passive cooling through solar screens are difficult to find.

In the research on solar screens, there is evidence that external fixed deep perforated solar screens could effectively achieve energy savings up to 30% of the total energy consumption in the West and South orientations. Optimum range of depths and perforation percentages were recommended: 80–90% perforation rate and 1:1 depth/opening width ratio (Sherif et al. 2012). These lighter and deeper solar screen configurations were found to be more efficient in energy consumption in comparison with the traditional ones. Screen depth is cited as an important factor that affects energy savings

In a related study, using EnergyPlus simulation, researchers find that thermal loads quickly dropped when screens with high ratios (85%) of perforation are used (Sherif et al. 2010). Screens with perforations below this rate do not significantly reduce thermal load, according to the study Reduction of cooling energy was attributed to the substantial reduction of solar energy and the energy transmitted heat gain window. Sherif also explores the impact of external perforated solar screens on thermal performance in desert climates (2010) and finds that the use of perforated screens have a significant effect on reducing the cooling energy, especially in south, west and east orientations, with screens with a perforation range between 80% and 90% having the highest saving rate. Further studies by the same authors reveal that the most significant saving was achieved when using screens with depth to perforation ratio 0.75/0.75.

Research on a screening approach employing external cables shading provides evidence that they can reduce cooling loads while maintaining privacy at the same time (Raymond et al. 2008). In this study, decreasing the spacing between the cables achieved significant savings in cooling loads, while obstructing the view, while thinner cables provided dense shade and reinforced aspects for visual porosity.

Research using computer simulations shows that shading devices on south façades with horizontal, vertical and 45◦ tilted horizontal positions can decrease lighting energy consumption (Alzoubi et al. 2010). The study recommended the optimal orientation for shading devices that provides adequate internal illuminance level, while controlling solar heat gain.

External fixed horizontal shading devices of different slat lengths and tilts were examined using TRNSYS simulation (Datta 2001). It was found that optimizing the louver design decreased the cooling loads in summer achieving significant savings in the annual primary energy loads. Moreover, louver design varied in different locations and weather conditions.

Sherif cited a study on shading devices presented at the Passive Solar conference in 1984 (McCluney et al. 1984). In this study, the shading effect and heat gain reduction of several window treatments such as window tinting, reflective window films, screens, awnings, and overhangs are examined in Florida. McCluney found that changing the orientation slightly affected the potential shading. This could be attributed to the high average diffuse radiation component.

Another field study examined the perceived environmental quality and indoor comfort in two houses in Cairo, one with Jali screens and the other a contemporary Cairo villa. Recessed windows covered with wooden latticework in Fathy's Mit Rehan have similar thermal performance as flush windows shaded with overhangs in the Cairo Villa. This might suggest that both strategies are valid criteria in enhancing the building's thermal performance and should be viewed according to the suitability of the context and user's preferences (Elzeyadi 1996).

2.6.2.Daylight Performance

The daylighting aspects of external solar screens are analyzed in several other studies (Sabry 2011) (Tzempelikos 2008) (El-Zafarany 2011). The average illuminance levels resulting from use of solar screens on windows of a designed living room were measured for different window orientations over a range of day times in different seasons. The resultant quantity of room daylighting was investigated and recommendations for minimum screen perforation were presented. Conclusions were drawn stating the adequacy of these solar screens in terms of luminance values in different orientations, seasons and times (Rakha, et al., 2010).

Sherif et al. examined solar shading perforation where minimum perforation percentages for solar screens were presented for specific design cases that encompassed different orientations, seasons and time of the day. In addition, they developed a tool for architects based on required annual “Daylit” areas for the design of solar screens.

Traditional architecture devices, called Rawshans, were examined by Aljofi (2005). Experiments in the laboratory on a series of these screens, with varying screen cell typologies, are carried out and the effect of size of the solar screen gaps on reflected sunlight through screens was studied. Daylighting was found to be lower in rounded screens having larger cell diameters. This was attributed to the ratio of openings to solid parts of the screen panels.

2.6.2.1. Visual Comfort

Because of high intensity of atmosphere illuminance, screens act as a light filter to reduce the glare effect (Spencer 1990). Saini stated that screens not only diffuse sunlight but also distribute it uniformly through the internal space (Saini 1991).

In another study, minimum solar screen perforation percentages that provide sufficient daylighting in all-year round were demonstrated. Also, glare analysis was carried out in cases where illuminance levels were found very high. Results proved that using screens could significantly reduce glare and achieve visual comfort (Sherif, et al., 2012).

A detailed study by Tzempelikos (2008) discussed the impact of venetian blind geometry and tilt angle on view, direct transmission and interior illuminance. The analysis showed that the window effective reflectance could be significantly increased when the blinds rotate, especially with curved slats.

2.6.2.2. Patterns

Solar screens of circular openings design and analysis were examined algorithmically by using a generic optimization procedure to control daylighting levels (Lockyear 2010). Altering the openings arrangement of a couple of solar screens generated desirable light and shadow patterns. The study presented a variety of hourly and seasonally cast shadow patterns, and desired screens were fabricated and analyzed.

2.6.3.User Response

Other research work addressed users' response to the use of screens. In a pilot study on the use of shading systems, it appeared that office workers were consistent in the way they used their installed shading devices. It was found that users adjusted the tilt of the slats of the venetian blinds downwards towards the external ground in most of the time (Sutter et al., 2006). This explained the important of the external reflected daylight component on the behavior of users and the shading system used.

2.7. METRICS OF EVALUATION

Table 2.1 reiterates the fact that occupants' comfort conditions and the resulting use of lights, air-conditioning and shading devices are inseparably linked to the day light performance of a space and should not be ignored even during the earlier design stages (Reinhart et al. 2011).

Now that three performance categories for daylight – daylight availability, visual comfort and thermal loads – have been established, the reminder of this section reviews a series of metrics that can be used to evaluate these categories.

Table 2.1. Literature Review

SOURCE	**PARAMETERS**	**IMPACTS**
2012 Sherif et al.	- Orientation - Perforation Rate - Depth/Opening Ratio	- Cooling Energy - Heating Energy - Window Transmitted Solar Energy - Lighting Electricity
2010 Sherif et al.	- Orientation (south, west, east) - Perforation Rate	- Cooling energy
2011 Sherif et al. (PLEA)	- Location 14°N - 40°N - Depth – Perforation Ration 1:1, 0.75:0.75,	- Energy - Daylighting
2008 Raymond et al.	- Vertical spacing / perforation - Thickness / density	- Cooling load - Shading - Privacy
2001 Datta	- Slat length - Slat tilt / angles	- Cooling load - Heating load
2010 Alzoubi et al.	- Room geometry - Shading elements - Orientation	- Lighting energy - Illuminance level
2011 Borg	- Materiality (steel)	- Daylighting - Thermal performance
2006 Chow et al.	- Depth - Materiality - Air temperature	- Ventilation - Heat gain - Energy saving
1994 CIBSE	Wood (10 – 50% reflectance)	- Glare
2011 Sabry et al.	- Rotation angles Light shelves	- Daylighting

SOURCE	**PARAMETERS**	**IMPACTS**
1990 Spencer	- Light intensity - Geometry: Sahgiri (square grid) - Geometry: Musadass (hexagon)	- Glare - Pattern
1983 Ashraf	- Cress- Crossed - Diagonal crossed - Rounded strips	- Pattern
2010 Lockyear	- Algorithm/Generative - Layered screens / sectional study - Materiality - Opacity	- Pattern
2010 Sherif	- Materiality (wood) - Perforation ration - Screen geometry	- Daylighting (illuminance) - Privacy
2001 Al-Shareef et al.	- Parallel shading device - Position and tilt angles	- Daylighting - Venetian blinds
2002 Athienitis & Tzempelikenos	- Automated controlling (outdoor test room)	- Daylighting Transmission
2008 Tzempelikos	- Blind geometry / shape - Tilt angle / reflectance - Curved / rotation surface	- View - Direct light transmission - Illuminance
1990 Allyali	- Air velocity - Orientation - Wind speed	- Air movement
1988 Hassan	- Materiality (wood) - Geometry	- Humidity - Pattern

2.7.1.Energy Performance

2.7.1.1. Energy Utilization Intensity

The benchmark unit of Energy Use Intensity (EUI) is defined as follows: Annual Building Energy of all sources divided by the gross square footage of the building. This is expressed in KBtu/Sqft.Yr. Environmental Protection Agency's Target finder calculator defines the range of EUI values that a given project in a climate zone should have. Therefore, as an alternate to Lahore's climate zone, Climate zone 2A/B was used to find the median EUI for an office building.

2.7.2.Daylight Performance

2.7.2.1. Illuminance

Different organizations, like the Illuminating Engineering Society (IES) and the National Research Council of Canada (NCR), recommend different light levels for office spaces. Many studies have shown ideal lighting levels for office spaces. However, research has shown that comfort in work environment varies from one culture to another. For the purpose of this study, it has been considered best to use 100-300 lux as the sufficient daylighting levels for office work in Lahore. Lighting levels above 1000 lux were taken as above the comfort range.

2.7.2.1.1. Daylight Factor

According to the Commission Internationale De L'Éclairage (CIE), the Daylight Factor is defined as the ratio of interior horizontal illuminance at a specific point to the exterior horizontal illuminance from the CIE standard overcast sky at the same time (IESNA Lighting Handbook 2013).

The daylight factor (DF) is a metric used to quantify the amount of diffuse daylight in a space (Otis et al.) It is usually measured at the height of the work plane. Table 2.2 describes recommended DF values

(Source: Millet and Bedrick (1980) in Mechanical and Electrical Equipment in Buildings).

Table 2.2. Recommended Daylight Factors

Task	**Daylight Factor**
Ordinary seeing tasks, such as reading, filing, and easy office work	1.5 – 2.5%
Moderately difficult tasks, such as prolonged reading, stenographic work, normal machine tool work	2.5 – 4.0%
Difficult, prolonged tasks, such as drafting, proofreading poor copy, fine machine work, and fine inspection	4.0 – 8.0%

2.7.2.1.2. Dynamic Daylight Metrics

Dynamic daylight performance metrics are based on time series of illuminances or luminances within a building. These time series usually extend over the whole calendar year and are based on external, annual solar radiation data for the building site. The key advantage of dynamic daylight performance metrics compared to static metrics is that they consider the quantity and character of daily and seasonal variations of daylight for a given building site together with irregular meteorological events.

2.7.2.1.2.1. Daylight Autonomy (DA)

The Daylight Autonomy metric is the percent or fraction of the occupied time (or analysis period) throughout the year when the target (or a criterion illuminance value) is met or exceeded at a specific point by daylight alone (IESNA Lighting Handbook 2013).

2.7.2.1.2.2. Useful Daylight Illuminance

The Useful Daylight Illuminance (UDI) metric is composed of three ranges, including the percent of occupied hours of the year when daylight illuminance at an interior point of interest is judged to be at “useful” levels (between 100 and 2000 lux (10 and 200 fc)), very low levels (below 100 lux (10fc)), and at high levels (above 2000 lux (200 fc)), which is more likely to cause glare or discomfort. These three levels are termed, “supplementary”, “useful”, and “exceedance.” Mardaljevic and Nabil introduced this climate-based metric in 2005 (IESNA Lighting Handbook 2013).

In Lahore, with the number sunshine hours, solar exposure also comes with solar gain. It has been found that for office environment, 100-300 lux is found useful range of lighting value, in order to keep the balance between daylighting and solar gain in Lahore.

2.7.2.1.2.3. Spatial Daylight Autonomy

The Spatial Daylight Autonomy (sDA) metric is a measure of the percent of area in a room or building that meets a given Daylight Autonomy (DA) value for a set of analysis period. For example, 250 lux (25 fc) for 50% of the year would be referred to as sDA250, 50%. Thus, the sDA value is the percentage or fraction of a space that reaches a DA250 value of 0.5 (or 50% when indicated as a percentage). sDA is expressed as a percentage of an area (IESNA Lighting Handbook 2013). For the purpose of this study, sDA 250 is considered optimum for office use in Lahore.

2.7.2.1.2.4. Annual Light Exposure Metrics

Annual Sunlight Exposure

The Annual Sunlight Exposure (ASE) metric refers to the total number of annual hours that illuminance from direct sunlight at a specific point of interest exceeds a certain value. It is intended for use with image preserving (clear) glazing and no operable shading devices in place (IESNA Lighting Handbook 2013). This is another reading of lighting quality and availability of direct sun into the space. While Jali is being used, the patterns and beams of light can also be associated with this metric. Another measure within the results of this metric is the highest and the lowest values of Lux. This can be symbolic of Luminous distribution in space as discussed ahead.

Average Annual Lux for Sunny Sky

The Average Annual Lux for Sunny Sky metric is a measure of the average lux value received at a certain point over the course of a year during the sunshine hours. IES VE dynamic simulation software runs this at multiple sensor points on a grid in the office. It is useful metric to compare the spatial characteristics in a very crude unit. Ranges of lux values are used to identify the availability of direct sun throughout the year. Colors represent the ranges where Red color is used for greater than 1000 lux, Yellow indicates 300-1000 lux, Green is the most useful for 100-300 lux and Blue is for under 100 lux values.

2.7.2.1.3. Luminous Distribution

For a better visual environment, the IESNA recommends that, within the occupant's field of view, the ratio between the maximum and minimum illuminance should not exceed 1:10 (IESNA Lighting Handbook 2013). However, the NRC Institute for Research in Construction recommendation exceeds that of IESNA, and goes up to 1:20 (National Research Council Canada), providing an acceptable argument for this high contrast, like highlighting certain objects on the working plane. Sometimes due to high contrast, the occupant perceives parts of the space as dark, which in reality have sufficient light levels. Maintaining a ratio of 1:10 prevents the false perception of light level inside spaces (Mansour El Sheikh 2011).

2.7.2.1.3.1. CIE Glare Index (CGI)

CGI was published by Einhorn in 1969 and adopted by the Commission Internationale de l'Eclairage (CIE) in metric calculations require both direct and diffuse illuminances. The scale is defined in a number value, where values greater than 28 are considered "Intolerable" and less than 13 are "Barely Perceptible." CGI predicts the highest likelihood of discomfort glare for diffuse day lit conditions as a worst-case scenario for comparison between designs (Jakubiec et al. 2010).

2.8. HYPOTHESIS

Jali envelope in Lahore will help in passive cooling and achieving visual comfort in office buildings.

2.9. RESEARCH MODEL

The research model (conceptual framework) (Figure 2.18) proposed for this investigation contains two categorizes: screen parameters and building parameters. These parameters are further analyzed to identify their independent and dependent variables. This model shows that visual comfort discussed in this study is a combination of energy use and daylight availability along with visual comfort.

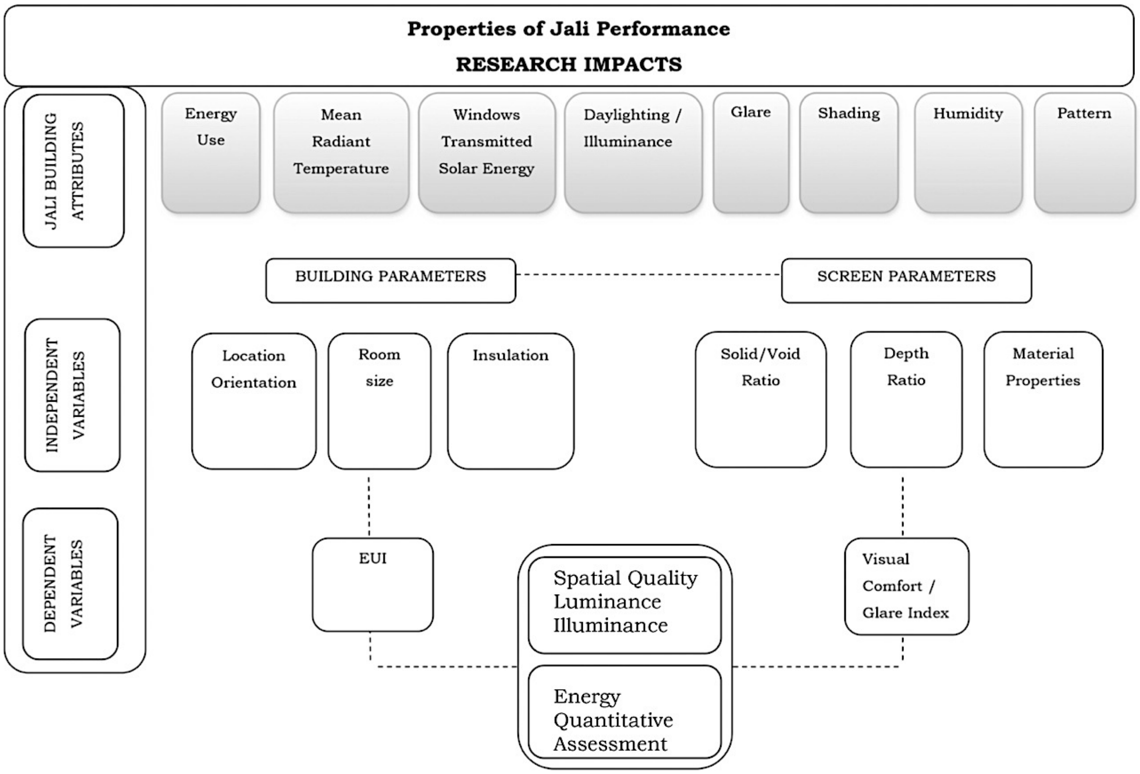


Figure 2.18 Conceptual Framework

CHAPTER III

METHODOLOGY

In Pakistan, despite the ongoing accreditation of regulations, methodological approaches for energy-efficient improvement of buildings are insufficient. In the absence of any data available on the existing building stock, it is important to record and measure a base measurement. Discrepancies between assessed and actual performance measures in office buildings are common and depend on various environmental conditions (Chidiac et al. 2011). In order to obtain close results to actual performance levels, it was pertinent to validate any assessment methodology with real data (Gücyeter et al. 2012).

In order to get performance levels as accurate as possible, this research employs dynamic energy simulation, starting with a building audit of the existing base case scenario, which was then fed into the simulation model to assess existing performance levels and create a calibrated model. Next, Jali screens defined from the traditional research setting (traditional building cases) and designed for this experiment were tested through the calibrated model. The calibrated model was further validated with Target finder and the EUI values in the base case were found to be too high for a balanced experiment. High performance thermal constructions were employed and verified as having a significant impact on performance. Furthermore, all shading devices are based on the optimized base case model (Figure 3.5). The steps of the methodology are described in the following sections.

3.1. FIELD STUDY

A field study was conducted in Lahore, Pakistan. A set of hand held, calibrated digital instruments were used to measure the indoor environment of two research settings. “Traditional Research Setting” is the series of existing Jali screens situated in various commercial and institutional buildings and “Contemporary Research Setting” is the base case office building in Lahore.

3.1.1. Research Settings

3.1.1.1. Traditional Research Setting

Three Jali screens were selected from institutional/commercial settings in vernacular architecture of Lahore. The Lahore Fort has the largest collection of Jali screens in place from the Mughal times. It is also a publicly accessible place, which allowed for the selection of pavilions and orientations. Data collected from these settings was compiled to give an idea of the parameters involved and their impact on the daylighting. All three cases are west facing.

3.1.1.2. Contemporary Research Setting

Outside Pakistan several environmental design practitioners have made significant contributions in to improve office building energy performance, and these include Arup (Cramer 2011 and Foster and Partners 2012) Norman Foster (Foster and Partners 2012), HOK (Beautyman 2006 and Cramer 2011) Ken Yeang (Greener Buildings 2004) and others. Apparently, many contemporary buildings do not perform very well (Leaman et al., 2010).

Base case Office Building for this study was located in the Commercial Area of Y-Block, Defence Housing Society, Lahore, Pakistan. This building is at the corner junction of two main roads and facing South and West. It consists of 5 floors including Basement, Ground, Mezzanine, first and second floors. The Real Estate building was selected for this study because it exemplified the trend of modern office design (Figure 3.1), 3-5 stories height, which had façades made of unprotected glass.

Figure 3.1. Commercial Buildings in Lahore, Pakistan

For the Contemporary Research Setting (base case building), information on building characteristics such as location, orientation, environmental factors, envelope characteristics, installation systems, comfort ranges, and schedules and occupancy were gathered (Caccavelli 2000) (Butala 1999) (Gücyeter et al. 2012). A total building energy audit is acquired for the whole year. However, to assess visual comfort, two rooms are selected shown in Figure 3.3 in which the two office used in this study for visual comfort are: South Facing (Left) and West Facing (Right).

Figure 3.2. Contemporary Research Setting – Base case building South Façade (left); West façade (right).

Figure 3.3. Plans of base case building.

3.2. EXPERIMENTAL DESIGN

Simulation techniques offer a more controlled environment in which each parameter can be individually manipulated, repeated and optimized. These techniques also require less time as the detailed data of months can be simulated in a short period; a few minutes to several hours depending on the size of the "virtual research space," level of details/accuracy required and the parameter(s) being considered. However, to carry out successful computerized building simulations, accurate and reasonable input data for the buildings and climate are essential (Guan 2006).

With this in mind, the simulation technique was selected for this research.

To enhance accuracy of the simulation, several studies suggested that simulated results must be compared with measured data and several input parameters affecting the simulation discrepancies were tuned (Haberl et. al 1998) (Sreshthaputra et. al. 2004). This procedure is usually known as the calibration of the simulation model.

3.2.1. Instruments of Research

Figure 3.4 shows an illustration of instruments used in the field measurements.

3.2.1.1. DataLoggers

These devices are used to measure and log temperature, relative humidity and light intensity and are sold as HOBO Meters.

3.2.1.2. Light Meters

The T-10 and T10M illuminance meters are Lux meters. These devices are used to evaluate the lux measurement (illumination strength) of light hitting a particular location. These devices further provide the ability to calculate illumination and average values making them viewable on the LED screen.

3.2.1.3. Kestrel: Pocket Weather Meter

Measures wind, temperature, and humidity quickly and accurately.

3.2.1.4. DSLR Camera + Photosphere

HDR photography was originally developed because a typical photograph could not capture a daylit scene without over or underexposure. This resulted in inconsistencies with different sections of photographs being either too bright or too dark (Bloch 2007). HDR images contain the entire range of lighting information including the light sources and light reflections from the surrounding environment. HDR imaging is also known as “an environment map, a radiance map, or a luminance map” (Cheney 2008). In order to accurately view a HDR image, two techniques can be used. These are “tone mapping” and “false colour rendering”. Tone mapping compresses the light values in the image so that the image can be viewed on the limited brightness range of a computer screen or printed page. False colour renderings use a range of colors that correspond to the luminance data contained in the underlying HDR image.

Christoph F. Reinhart and Jan Wienold have explored the effectiveness of simulation when it comes to daylighting and HDR images have been used to discover the “full dynamic range of a scene, from direct sunlight to deep shadow”. HDR images are currently used to “derive empirical sky models” (Inanici 2010, 26). Ihab M. K. Elzeyadi has analysed photographs by the using an image analysis and raster mapping procedure to create both a High Dynamic Range (HDR) photo, and a false-colour luminance map (Elzeyadi 2012). An HDR image can capture the lighting data of a physical scene accurately and can “match human perception” of a scene (Cheney 2008:26). The accuracy of this tool can provide HDR images to be used for daylight analysis within a space.

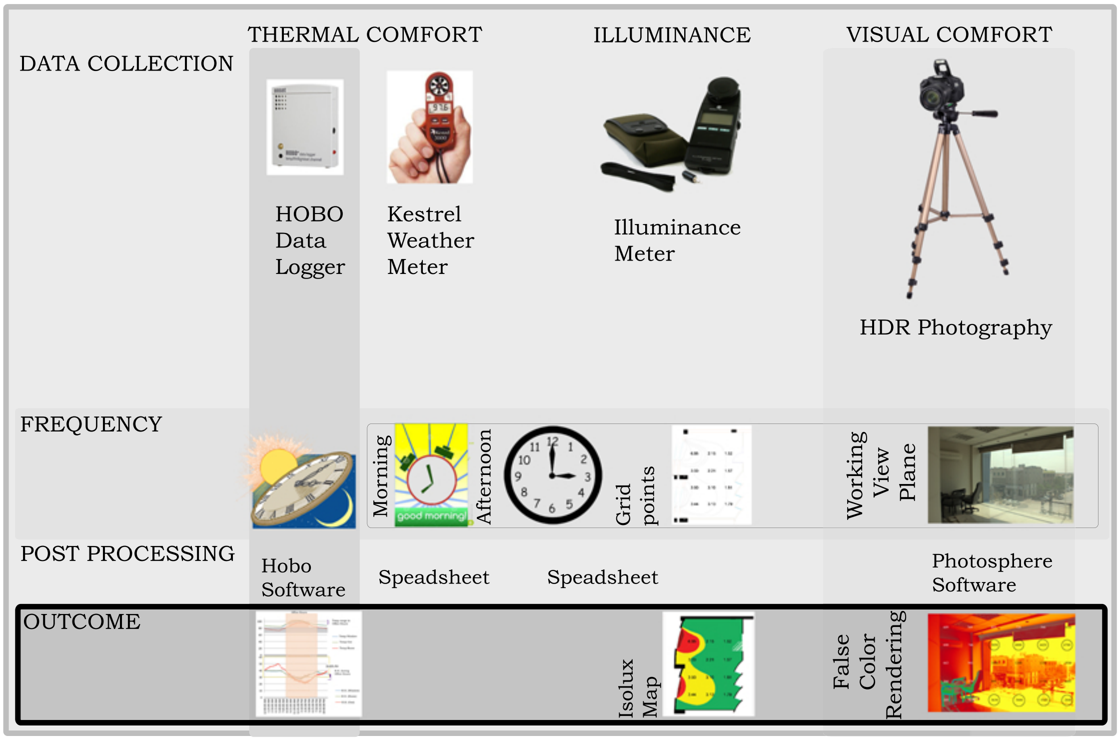


Figure 3.4. Instruments involved in Field Research

3.2.1.5. IES VE Simulation Software

The IES Virtual Environment (IES_VE) program is an integrated collection of applications linked by a common user interface and a single integrated data model (Kim et al. 2012). This means that the others can use the data input for one application. It consists of different modules, each of them performing specific calculations, such as “Apachesim” for thermal simulation, “Radiance” for dynamic lighting simulation and “SunCast” for solar shading analysis. Only three modules of the package were used to carry out this investigation, which are ModelIT, SunCast, and Apache (Muhaisen 2006) (Aldossary 2014).

3.3. EXTERNAL SHADING DEVICES

3.3.1. Brise Soleil

Typically the three basic types of shading devices (Kowitanupong 1999) are:

1. Horizontal shading devices;
2. Vertical shading devices;
3. Combination of horizontal and vertical shading devices.

To compare the impact of Jali screen geometry, an optimum combination of horizontal shades (for South side) and both horizontal and vertical shades (at 45^o) (for West) were design. Solar Tool in Autodesk was was used to derive the best design of these shades (Yang et al. 2014). In this investigation, this shading device is called Brise Soleil, from the work of famous architect Le Corbusier.

3.3.2. Jali Screens

a. Jali patterns were investigated and derived in the traditional research settings (Case A, B and C). It was found that most shapes were derived from a hexagon in the Jali screens. In order to simplify the process, therefore, basic shape of a hexagon was selected for the purpose of experiment. To find a screen configuration of highest energy saving potential, a range of solar screen designs was examined by performing computer simulation using IES VE dynamic simulation software.

b. Alternatives of void to solid ratios were determined by the cases from the traditional research setting, of 30%, 40% and 50% in windows facing south and west.

3.4. THERMAL CONSTRUCTIONS

After having calibrated the simulation model with the real base case scenario, it was also found beneficial to validate the efficiency of Jali screens with better thermal constructions. Envelope design in Lahore is very leaky and has low R-value. High performance buildings require not only good shading design but also thermal constructions with higher R-values. Research has shown that with bad thermal construction and leaky envelopes, shading devices cannot achieve the same effect as a good thermal construction (Sourced from GCT High Performance Template (Elzeyadi 2008). High performance materials were used for further final simulation for testing all shading devices (Table 3.1).

Table 3.1. High Performance Thermal Constructions used in Simulation Model

Roof	High Performance Roof [R40]
External Wall	High Performance Wall[R-30]
External Glazing	Low-e Triple Glazed [R-5]
Ground Floor	Super Insulated Floor [R-25]

Further optimization was achieved through the use of dimming profile for lighting controls (High performance Template) (Elzeyadi 2008). According to this template, a value of 360 lux was set on the work surface to optimize lighting controls such that maximum utilization of daylighting was achieved and electric lighting minimized during an ASHRAE work day of 8:00 am till 6:00 pm. Figure 3.5 shows the process through which the simulation model was calibrated and optimized to achieve the best results for assessment of Jali screen façades. While Figure 3.6 shows the parameters involved in the experiment once the simulation model was optimized.

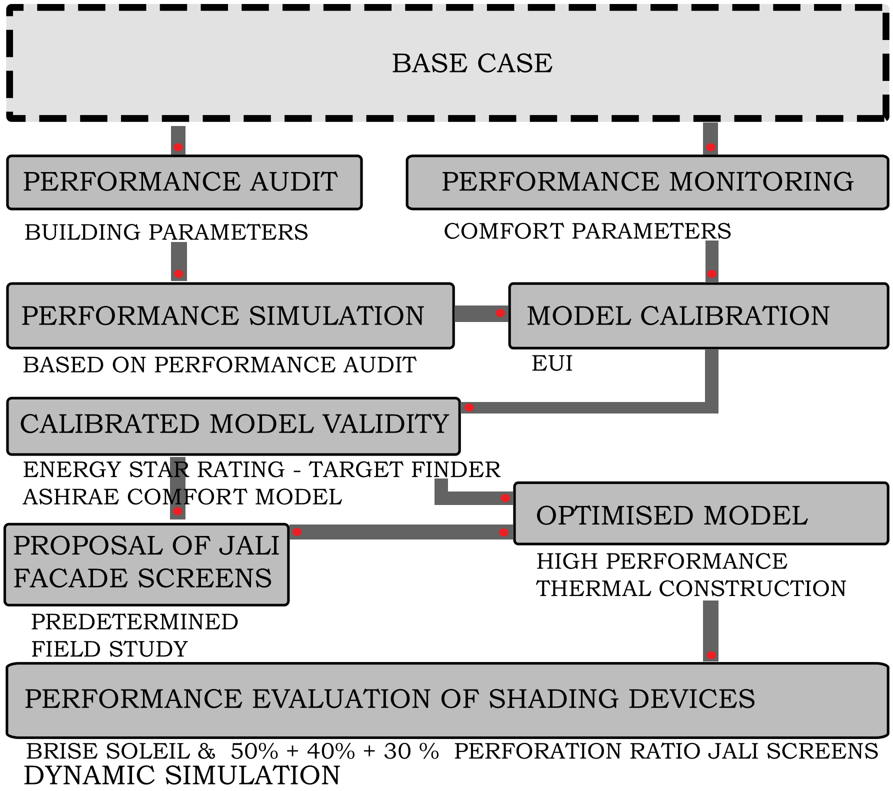


Figure 3.5. Flow Chart of Performance Monitoring, Calibration and Optimization of Simulation Model.

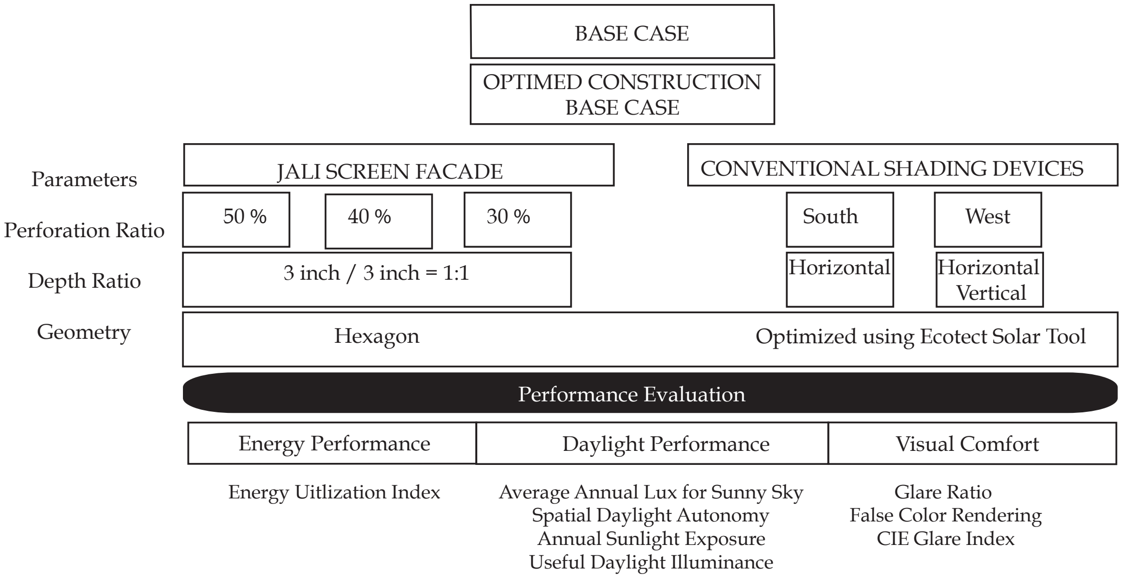


Figure 3.6. Experimental Design Parameters

CHAPTER IV

DATA ANALYSIS AND FINDINGS

This chapter covers the findings and results of field study and experimental methodology. Using the conceptual framework in Chapter 2, analysis of findings will be organized to including total energy performance, lighting analysis and visual comfort (glare analysis).

4.1. FIELD STUDY

Results of the field study can be divided into two main categories: Traditional Research Setting and Contemporary Research Setting. For each setting, data collected is analyzed in the order of Thermal Comfort and then Visual Comfort.

4.2. TRADITIONAL RESEARCH SETTING

Three cases for Jali screens were documented for visual comfort and screen geometry (Figure 4.1). The perforation ratios found were approximately 30%, 40% and 50%, which were used for the purpose of further analysis. As the depth of Jali screens was fairly in proportion to the minimum width of the shape of each module, the depth to width ratio of Jali was considered constant as 1.

Jali screen geometry was found to be fairly simple to read. When broken down to basic shapes, a hexagon was found to be the most common shape for use in Jali screen (Figure 4.2).

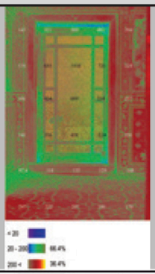
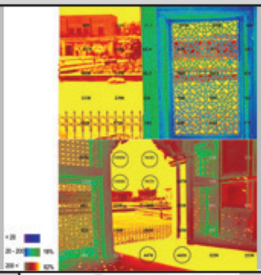
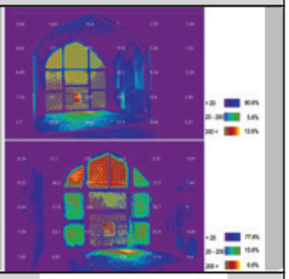
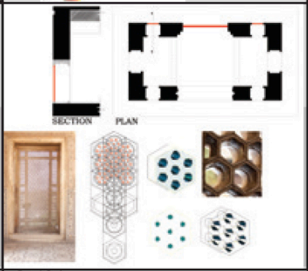
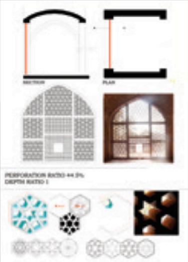
Traditional Research Setting	Naulakha Pavilion	Jehangir's Quadrangle	Underground Chambers
Visual Comfort Glare Anlysis			
Spatial Geometry			
Jali Geometry			
Perforation Ratio	35%	55%	45%
Depth	3”	3”	3”

Figure 4.1. Summary of Traditional Research Setting

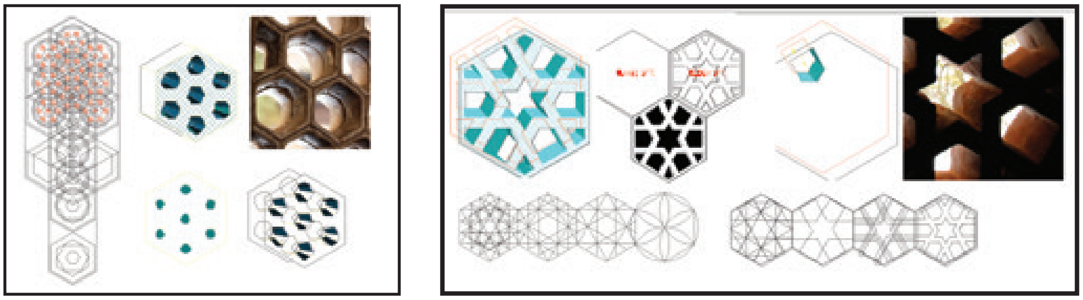


Figure 4.2. Jali Geometry Detail

4.3. CONTEMPORARY RESEARCH SETTING (CONTEMPORARY BUILDING CASE)

The major façades in the building were generally facing in the cardinal directions, while the two important façades, south and west were open and the other two façades were shared with adjacent buildings. Previous studies have shown that north-facing windows (in northern hemisphere) have lower impact than those facing other directions. Other studies have shown that south and west facing windows have major impact on lighting and energy consumption of buildings. Glare from south-facing windows can typically be controlled more easily than windows facing lower angles, such as those facing west. The actual glare value is most likely to be influenced by the site conditions present at the building location (Osterbaus 2005).

Figure 4.3 shows a summary of the field study conducted at the contemporary research setting, i.e., base case building.

4.3.1.Energy Performance

The total annual building energy for base case was found to be 254 EUI. This figure was based on the annual energy consumption readings of the building over the period of 2009-2011. This sum included lighting and cooling energy.

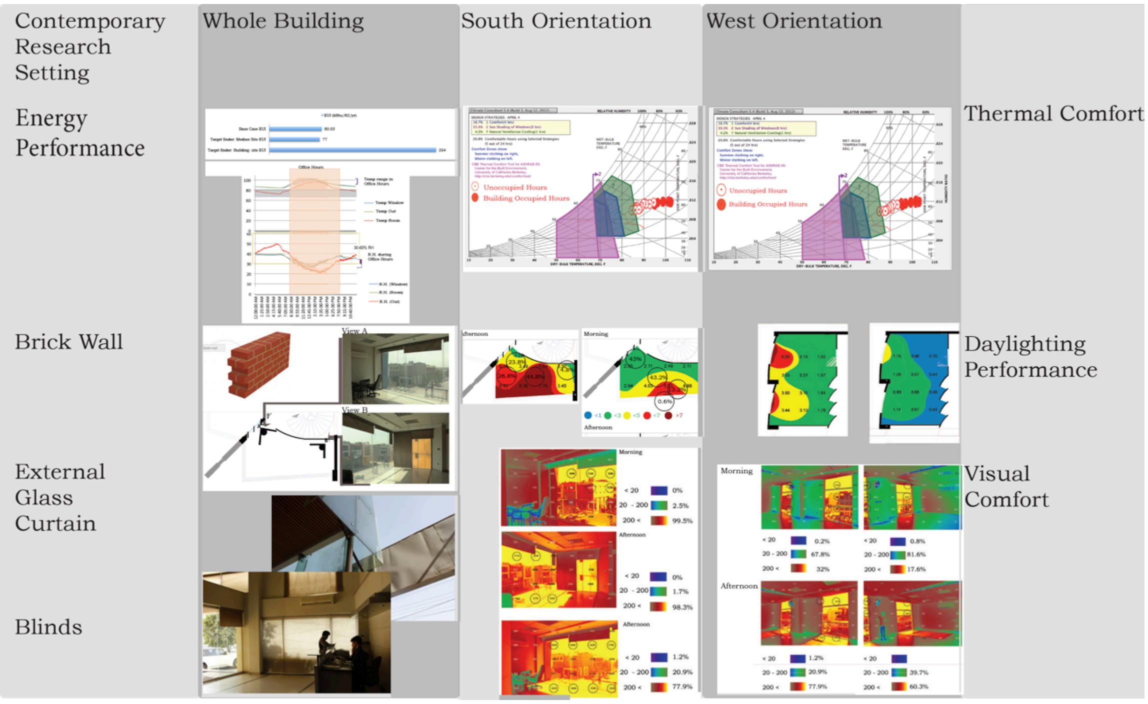


Figure 4.3. Summary of Contemporary Research Setting –Base Case Building

4.3.2.South Orientation

As noted in Chapter 3, the meeting room chosen on the South side was selected for an in-depth analysis of the thermal and visual comfort.

4.3.2.1. Thermal Comfort

Figures below plot the recordings from HOBO Dataloggers over a period of 24 hours in April 2013. These were plotted against the thermal comfort zones defined by ASHRAE Comfort Model 2005 and CBE Comfort Tool. The red dots in the Psychrometric Chart (Figure 4.4) show the readings per hour. Filled in dots are the occupied hours with the worst readings. In Figure 4.5 recorded temperature was plotted against time (top) with grey band showing comfort zone and the readings during occupied hours were outside the comfort range. Bottom graph shows relatively humidity recorded against time. Recordings near window, inside the room and outside were plotted to show a comparison of thermal comfort. Both diagrams showed how the temperature record in the room, was found to be out of the comfort zone defined by ASHRAE 2005 Comfort Model.

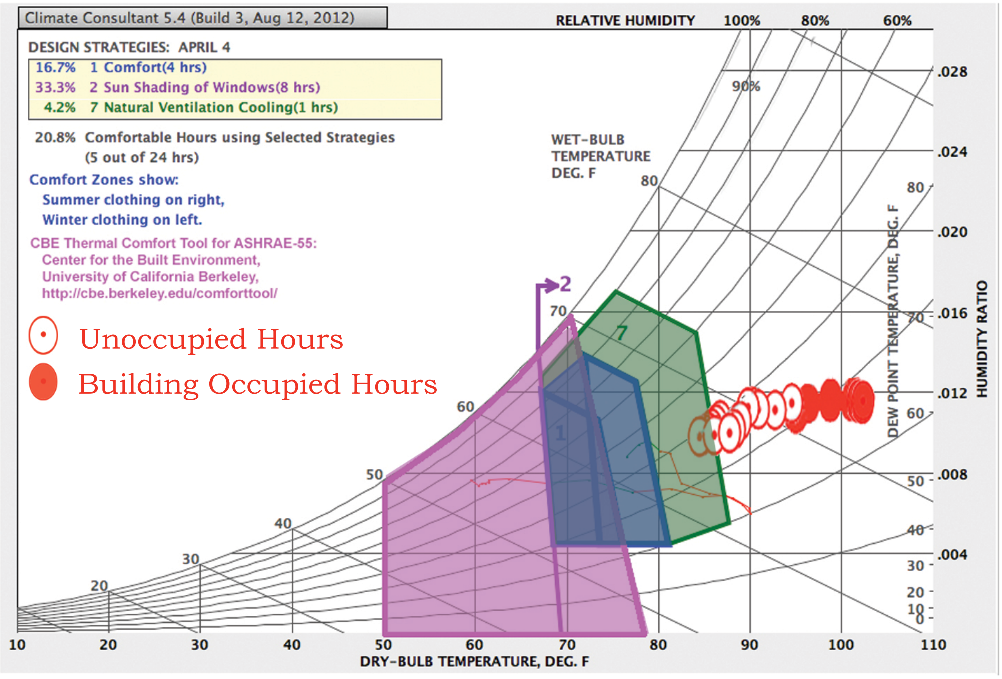


Figure 4.4. Psychrometric Chart (South)

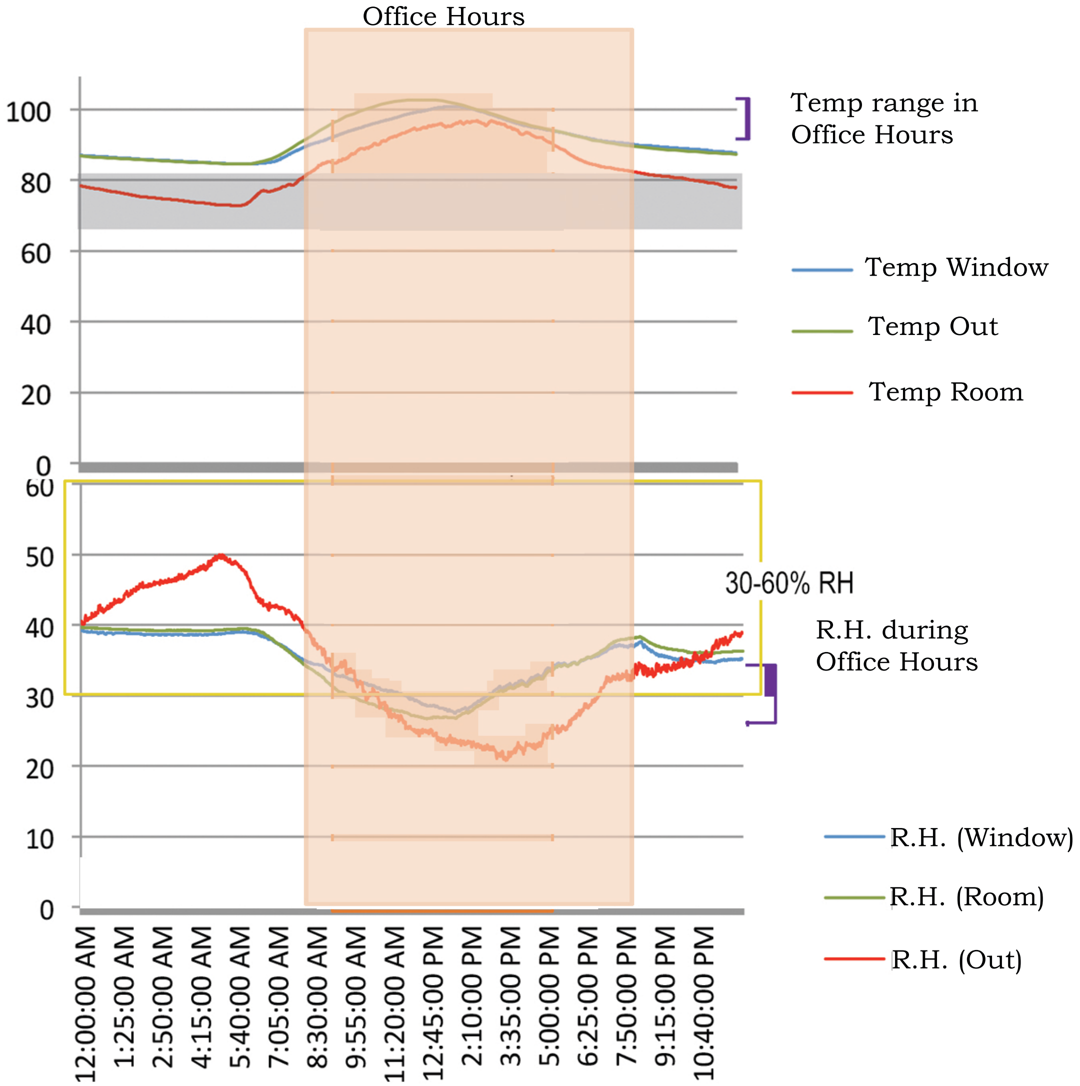


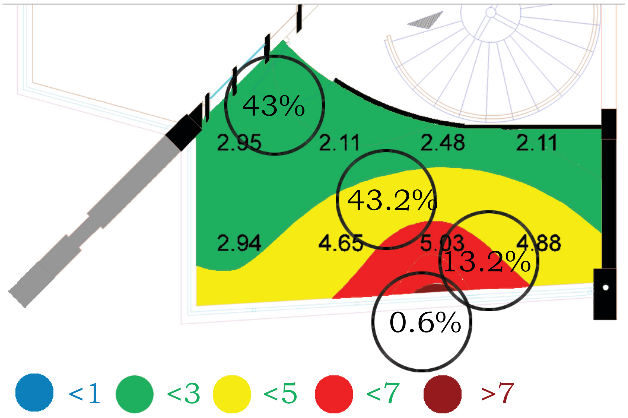
Figure 4.5. Temperature and Relative Humidity (South)

4.3.2.2. Daylight Performance

Illuminance

Recordings from light meter were processed to find the average daylight factor at the marked grid points. An isolux map was generated (Figure 4.6) where daylight factor was then plotted to show the lighting conditions in the room. The readings in the afternoon showed that the lighting level was unbearably high. Larger circles marked the percentage of area in that range of daylight factor (color).

Morning



Afternoon

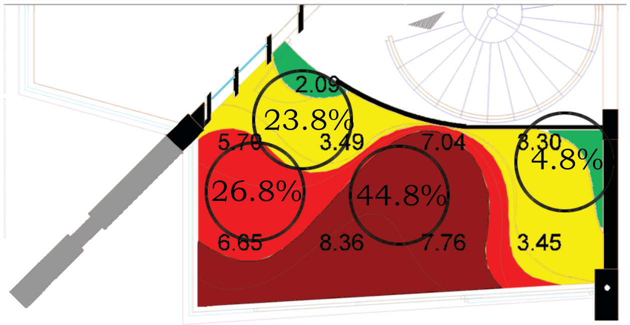


Figure 4.6. Isolux map (South)

4.3.2.3. Visual Comfort

Luminance

False color renders of the HDR Photography (Figure 4.7) showed that there were many areas where glare ratio was greater than 1:10. Those areas were circled in the view images. This was considered significant portion of time spent in discomfort glare conditions.

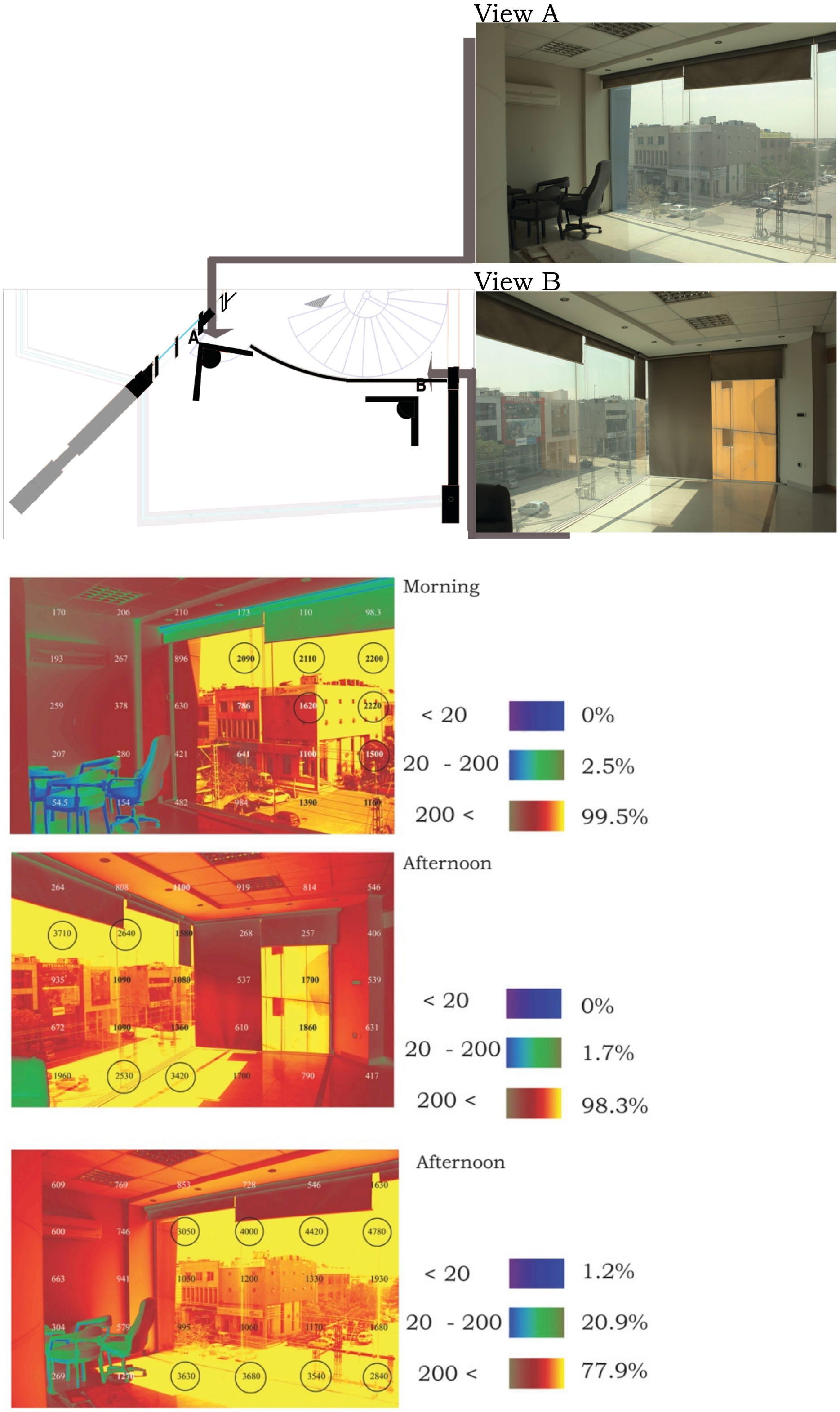


Figure 4.7. Luminance Map and Glare Analysis (South)

4.3.3.West Orientation

4.3.3.1. Thermal Comfort

Similar to South Orientation, the recorded temperatures and relatively humidity in west were also found to be outside the comfort zone on the psychometric chart (Figure 4.8) and graphs in Figure 4.9.

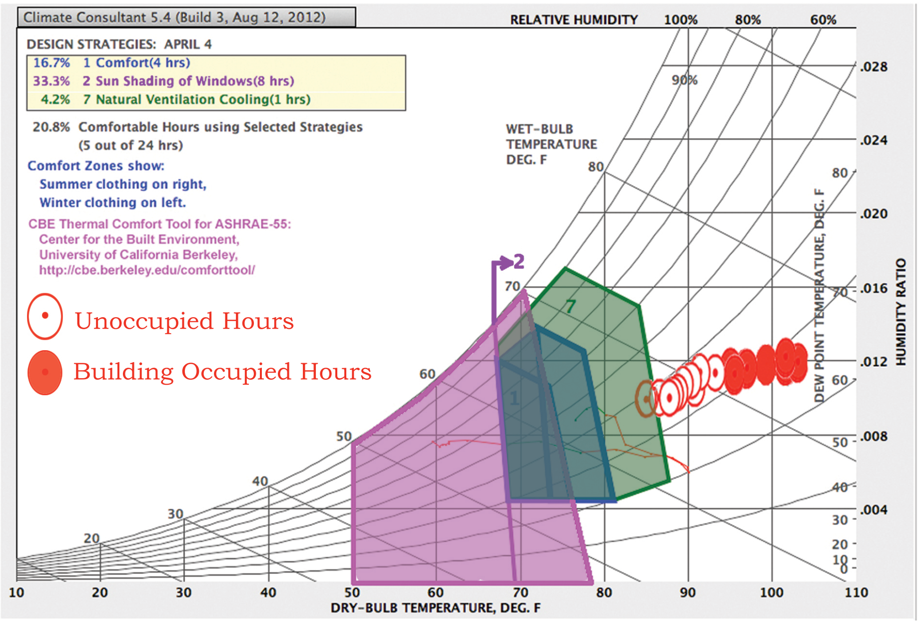


Figure 4.8. Psychrometric chart (West)

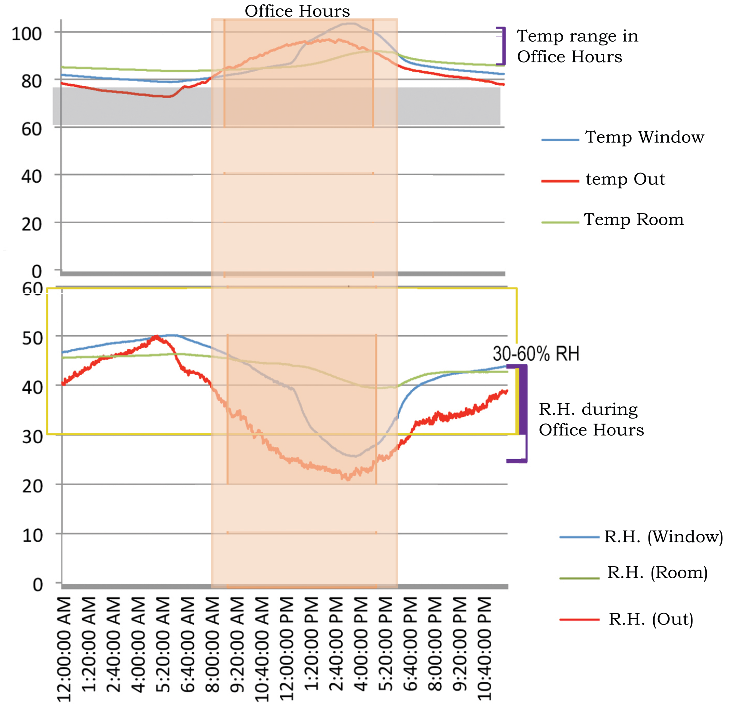


Figure 4.9. Temperature and Relative Humidity (West)

4.3.3.2. Daylight Performance

Illuminance

According to the Isolux Map, the lighting levels in west were not significant and only in afternoon lighting levels were found above comfortable range (Figure 4.10). Otherwise, the lighting levels required for working in the office would demand electric lighting in the room. In the figure, yellow color signifies 3-5% daylight factor, which is only 6.85% of the area in the afternoon.

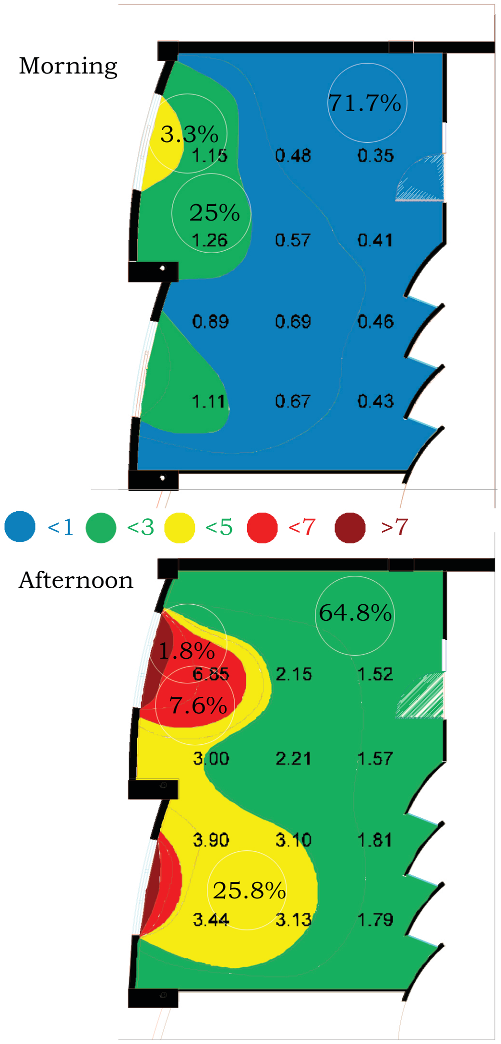


Figure 4.10. Isolux map (West)

4.3.3.3. Visual Comfort

Luminance

False color renders of the HDR Photography (Figure 4.11) showed that there were many areas in view where glare ratio was greater than 1:10. Those areas were circled in the images on the left. A significant portion of the working time was spent in discomfort glare conditions.

4.4. SIMULATION RESULTS

4.4.1. Whole Building Energy

Energy Utilization Index (EUI) was used in various studies to show the energy benchmarking of building and design strategies (Stoppel et al. 2014) (Wang 2012). Mean EUI of commercial buildings in the US was calculated from Target finder and used to compare with the base case EUI in Lahore as shown in Figure 4.12. EPA's online Target finder Calculator (EnergyStar[1]) was used to find the base case building Site EUI for a similar climate zone in the US. When compared to this value 77 kBtu/ft^2/yr, the value of Base Case building was found to be 88.03 kBtu/ft^2/yr.

The base case energy model was then modeled with the existing construction techniques in the building as built in Lahore, Pakistan. The results of this simulation showed a very high value of 80.3 kBtu/ft^2/yr. When using better construction, i.e. using GCT High Performance template, as shown in Table 4.1, studies have shown significant impact on the energy performance of buildings (Elzeyadi 2008). Introducing better thermal construction reduced the EUI to 67.68 kBtu/ft^2/yr. Furthermore, the existing conditions of base case were not optimized for lighting and solar gain. By introducing a dimming profile of ASHRAE 8:00 am – 6:00 pm workday, the EUI was further reduced to 55.01 kBtu/ft^2/yr.

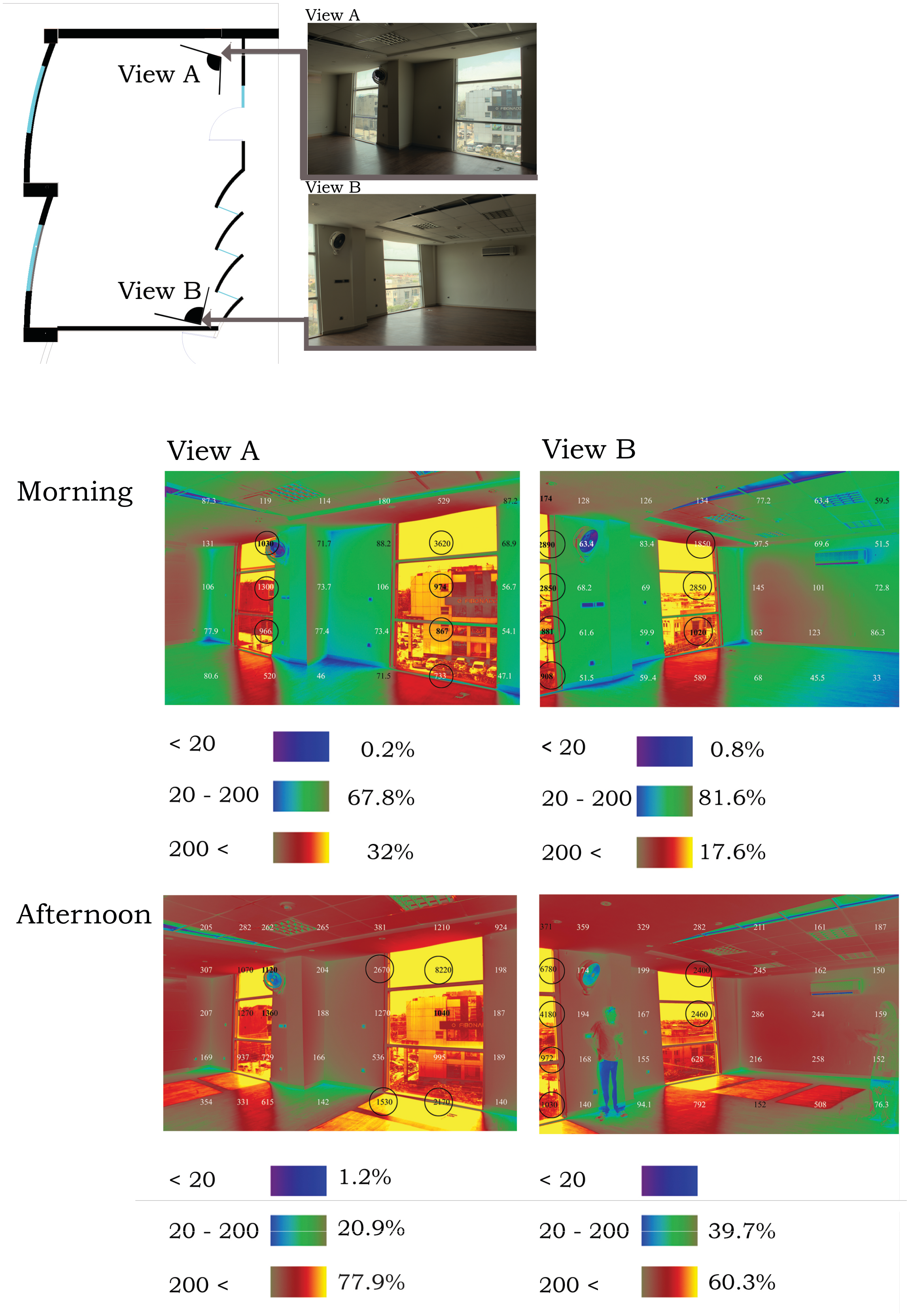


Figure 4.11. Luminance Map and Glare Analysis (West)

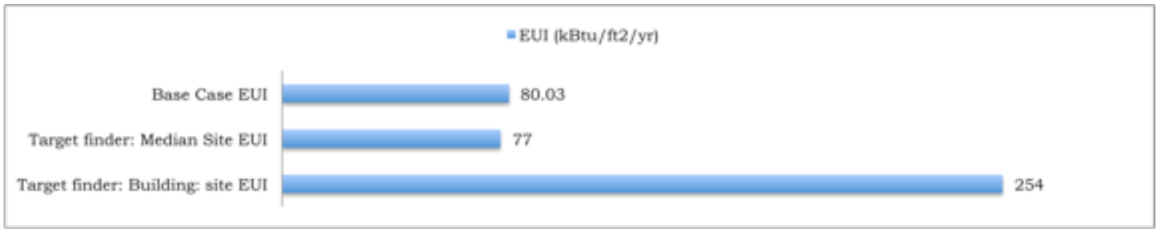


Figure 4.12 Building EUI comparison with Energy Star Rating

External shading devices, including Jali screens and Brise Soleil were then added to this computational building model. As shown in Figure 4.13, as the perforation ratio increased from 30% to 50% the EUI also improved. Brise Soleil outperformed Jali screen in the total energy consumption. This contradicted the results shown in Table 4.5, where the Brise Soleil was similar in quantity to the 40% perforation ratio of Jali screen. This was owing to the fact that although a lower perforation ratio reduced the solar gain (and the cooling loads), direct impact on lighting quality increased the lighting electricity loads as shown in Figure 4.14.

Table 4.1 R-Value of Existing and Optimized values of Construction.

R-Value	Existing Template	High Performance Template
Roof		R-40
External Wall		R-30
Floor		R-25
Ceiling		R-2

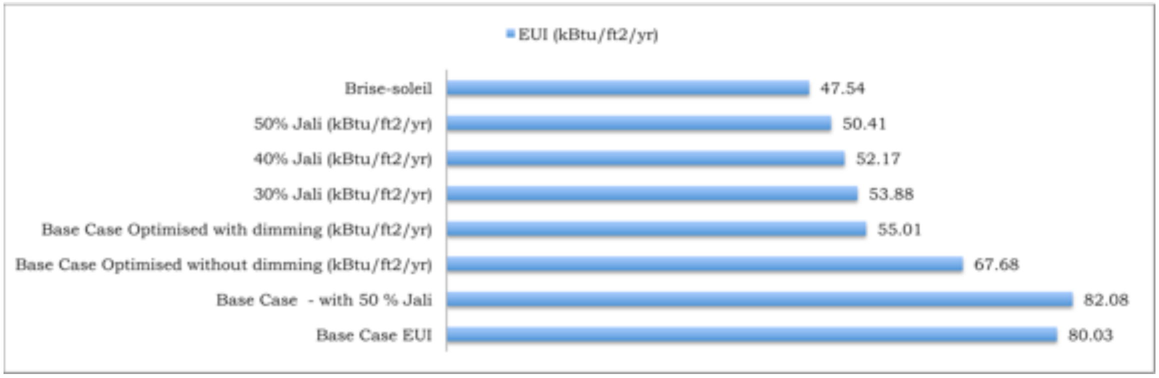


Figure 4.13. EUI Values derived through Dynamic Simulation Modelling

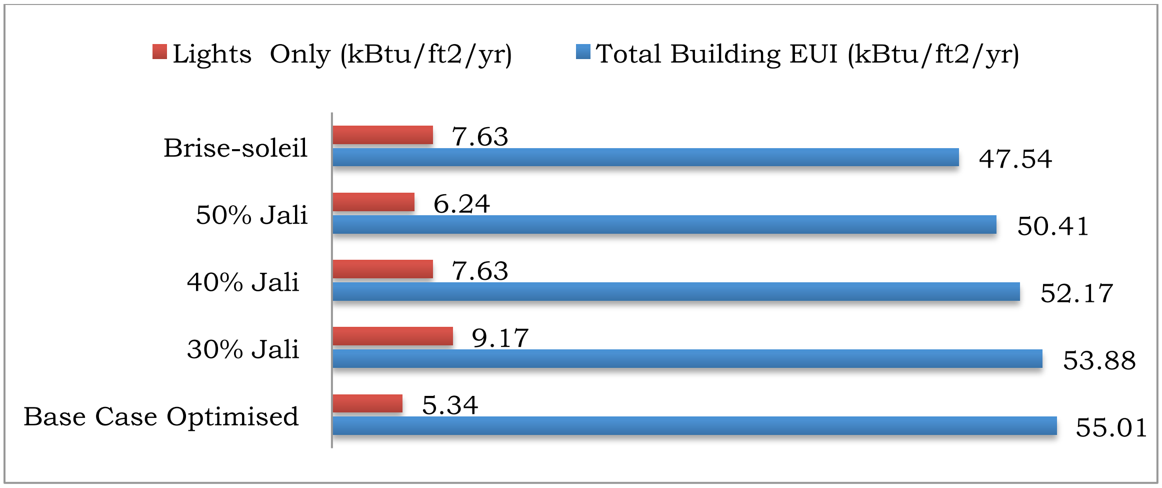


Figure 4.14. Correlation between Lights Energy and EUI.

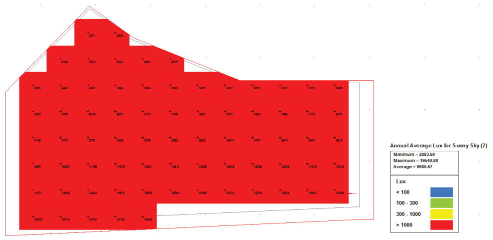
4.4.2.Daylight Performance

Experiments for the previous simulations were conducted in Radiance module of IES VE dynamic simulation software. The times of the day were set to the 8:00 am to 6:00 pm workday, per ASHRAE standard a given preset in IES VE dynamic simulation software. The reference plane on which daylighting performance was simulated contained sensors at a height of 1m. Dynamic daylight performance metrics were used to assess the illuminances or luminances within the building. These simulations extended over the whole calendar year and were based on external, annual solar radiation data for the building site. The key advantage of "dynamic daylight performance metrics compared to static metrics is that they consider the quantity and character of daily and seasonal variations of daylight for a given building site together with irregular meteorological events"(Reinhart et al. 2006). Some of the metrics utilized were Spatial Daylight Autonomy (sDA), Useful Daylight Illuminance (UDI), Annual Sunlight Exposure (ASE) and Average Annual Lux for Sunny Sky.

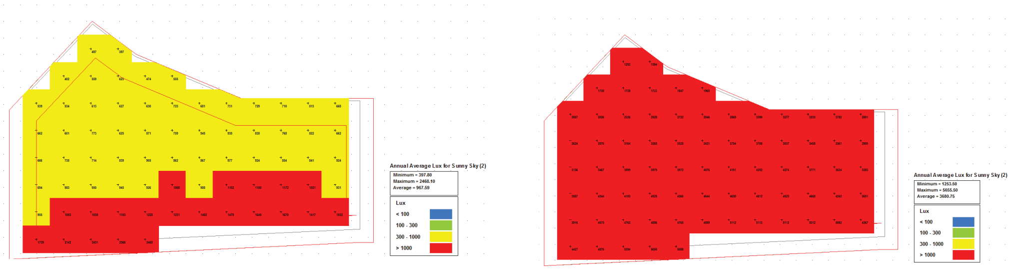
4.4.2.1. South Orientation

4.4.2.1.1. Average Annual Lux for Sunny Sky

Data indicated that the average lux for sunny sky condition was very high, i.e. above 1000 lux in most cases except 30% Jali façade. In the former case, majority of the area was between 300-1000 lux range (Red: >1000 lux, Yellow: 300-1000 lux, Green: 100-300 lux, Blue: <100 lux) (Figure 4.15). This meant that during sunny days, the room facing south was almost always getting more than the required lighting, except in 30% Jali façade. The maximum lux value increased with the perforation ratio, where the base case showed the highest value (Figure 4.16).

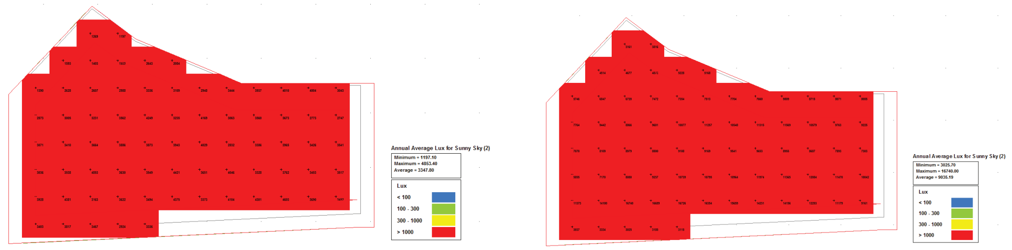


Base Case



30% Jali

50% Jali



40% Jali

Brise Soleil

Figure 4.15. Average Annual Lux for Sunny Sky (South)

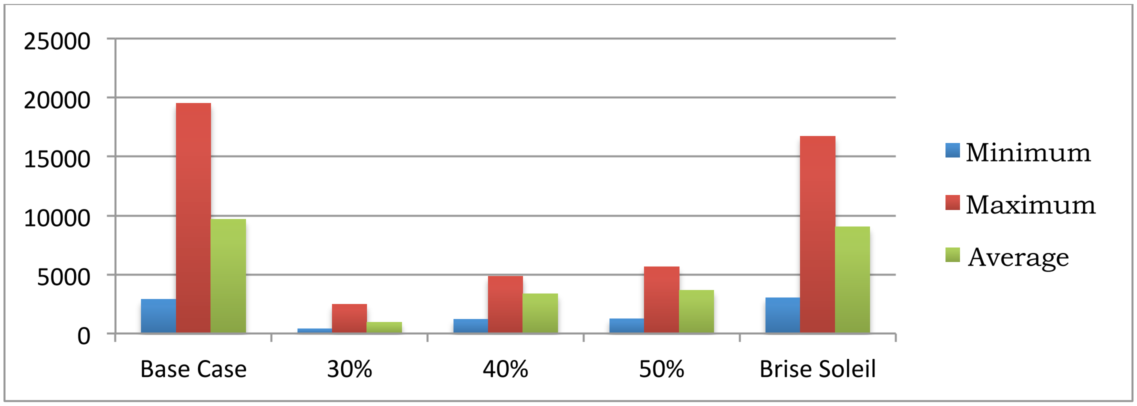
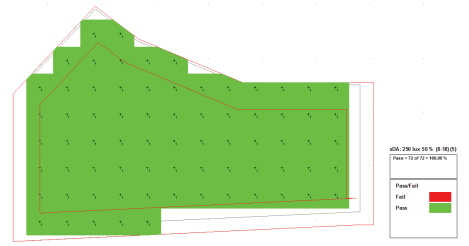


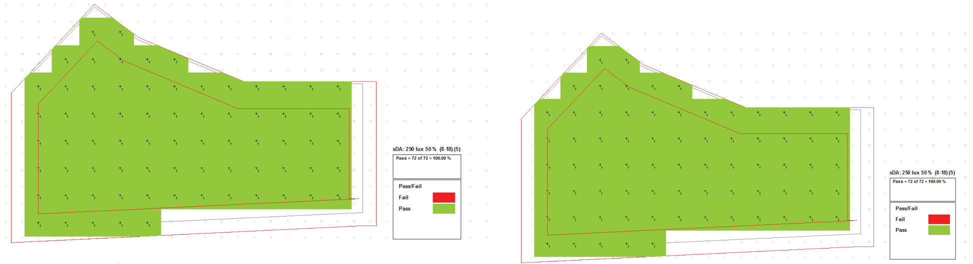
Figure 4.16. Minimum, Maximum and Average Lux Values (South).

4.4.2.1.2. Spatial Daylight Autonomy (sDA)

This is one metric in which all shading strategies fulfilled the criteria of being 100% as shown in Figure 4.17 (Green – pass; red – no pass) and Figure 4.18.

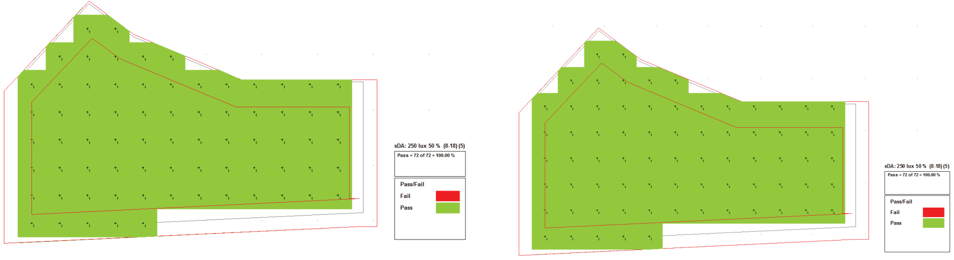


Base Case



30% Jali

50% Jali



40% Jali

Brise Soleil

Figure 4.17. Spatial Daylight Autonomy (South)

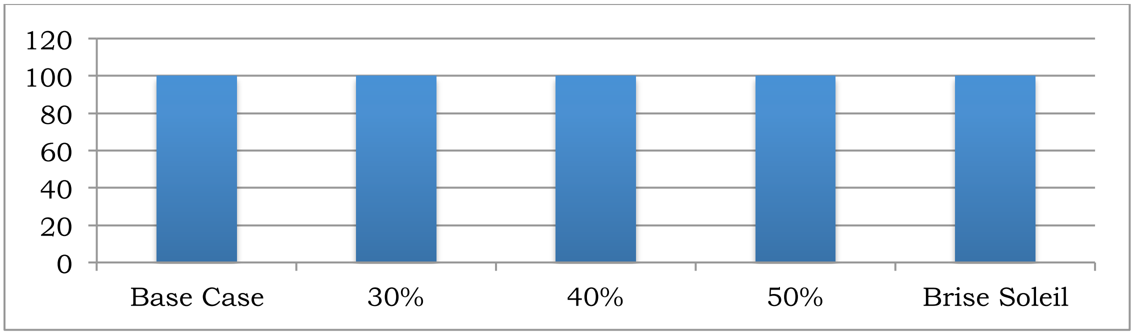
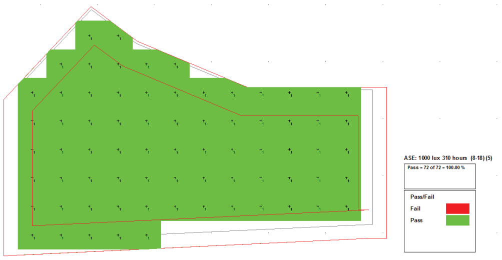


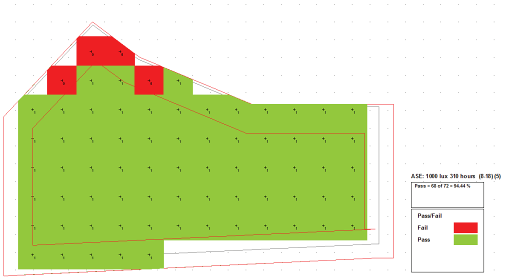
Figure 4.18. Percentage of Spatial Daylight Autonomy (South)

4.4.2.1.3. Annual Sunlight Exposure

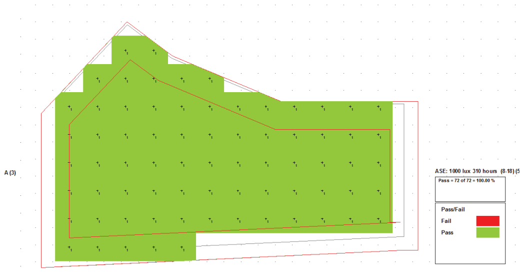
Brise Soleil did not pass this metric as shown in the following Figure 4.19 on South Side (Green – pass; red – no pass) and Figure 4.20.



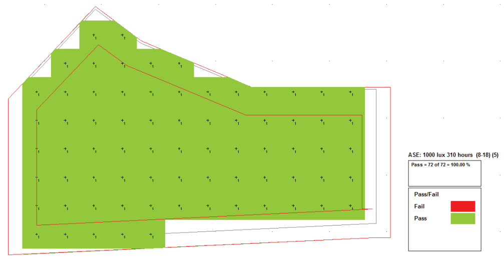
Base Case



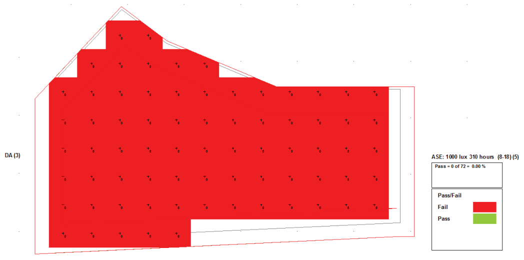
30% Jali



50% Jali



40% Jali



Brise Soleil

Figure 4.19. Annual Sunlight Exposure (South)

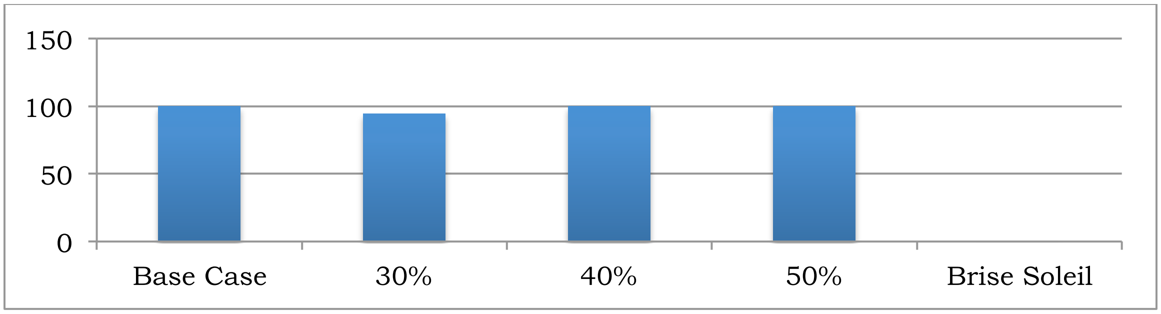
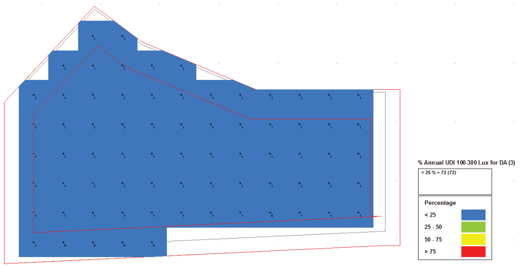


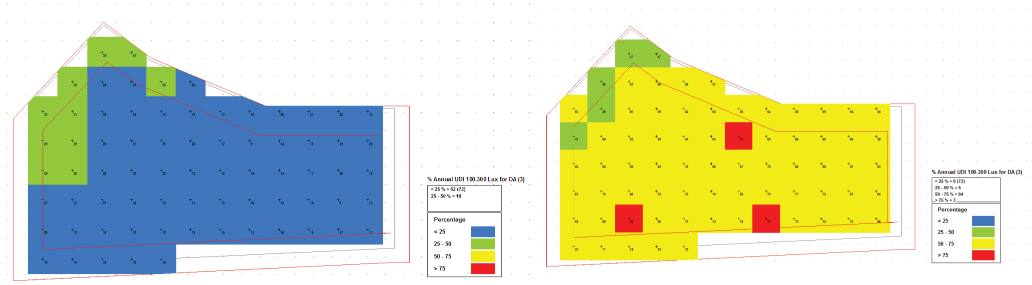
Figure 4.20. Percentage of Annual Sunlight Exposure (South)

4.4.2.1.4. Useful Daylight Illuminance (UDI)

50% Jali Screen Façade seemed to provide the maximum UDI of 100-300 Lux in office space in Figure 4.21 (Blue = <25%, Green = 25-50%, Yellow = 50-75%, Red = >75%) and in Figure 4.22.

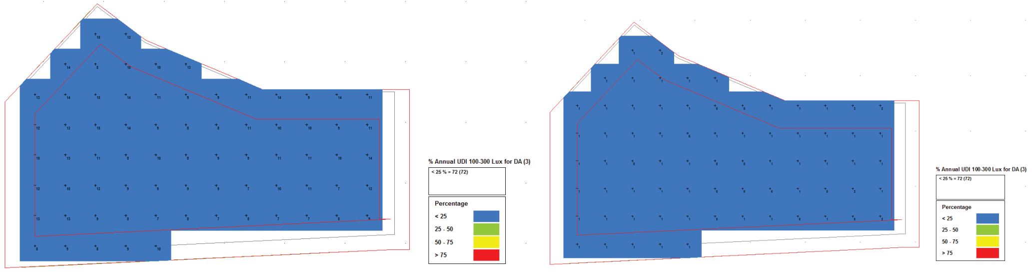


Base Case



30% Jali

50% Jali



40% Jali

Brise Soleil

Figure 4.21. Useful Daylight Illuminance (South)

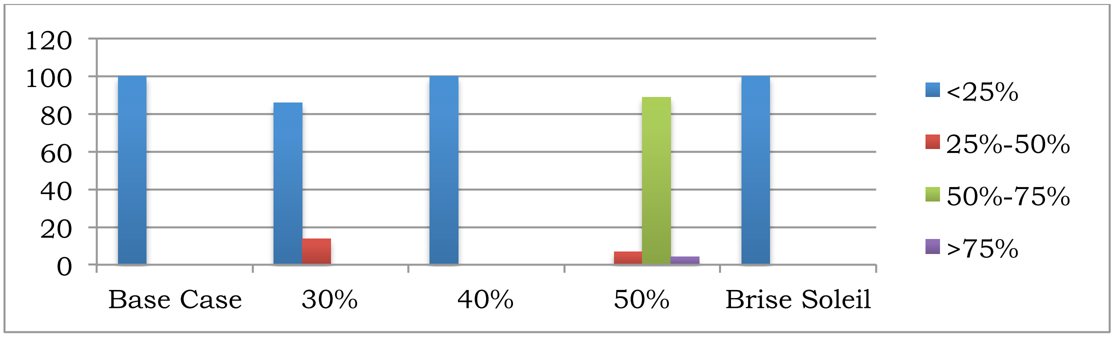
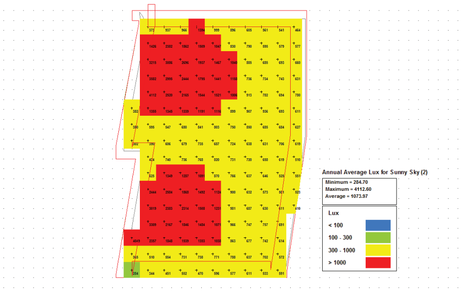


Table 4.22. UDI time for Value of 100-300 lux (South).

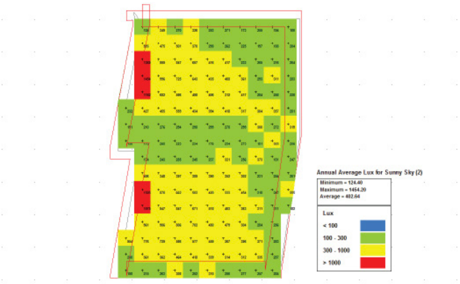
4.4.2.2. West Orientation

4.4.2.2.1. Average Annual Lux for Sunny Sky

In the simulation for the west room, shading devices did not make lighting level any better than the base case. In case of 50% screen façade, the conditions were worsened, i.e. the area with illumination values greater than 1000 lux was found significantly higher (Figures 4.23-4.24) (Red: >1000 lux, Yellow: 300-1000 lux, Green: 100-300 lux, Blue: <100 lux). Figure 4.25 illustrates the minimum, maximum and average lux values across strategies.

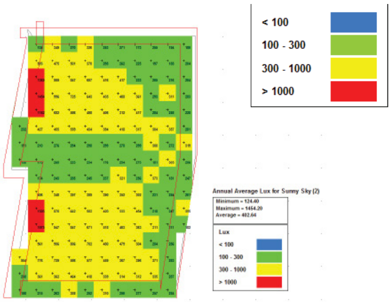


50% Jali

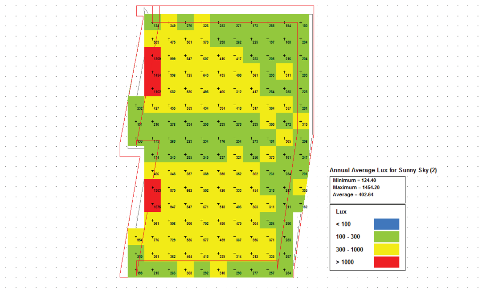


Brise Soleil

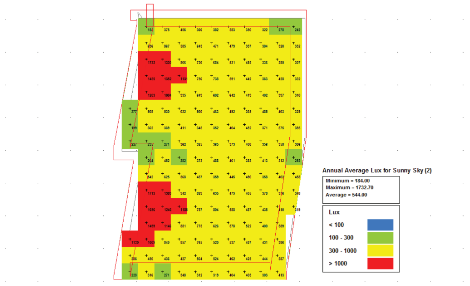
Figure 4.23. Average Annual Lux for Sunny Sky (West)



Base Case



30% Jali



40% Jali

Figure 4.24. Average Annual Lux for Sunny Sky (West)

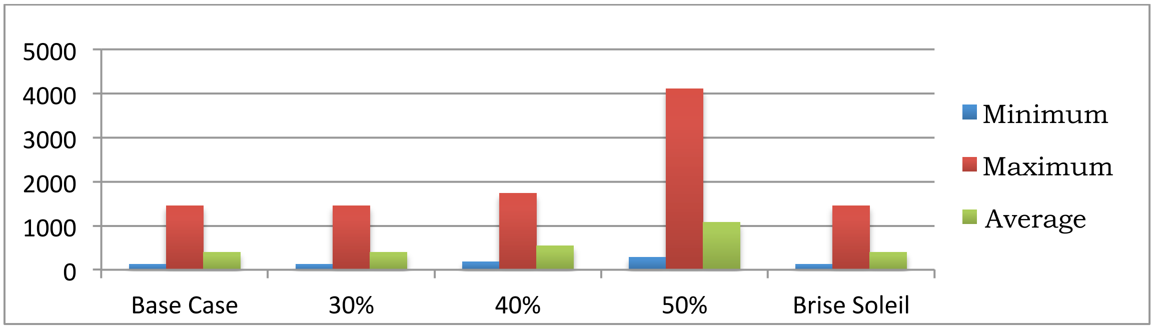
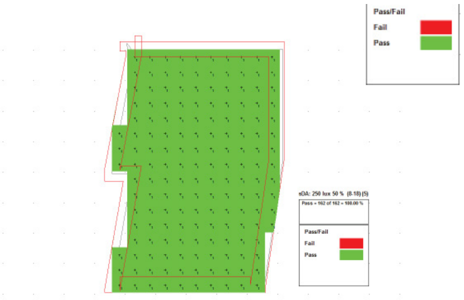


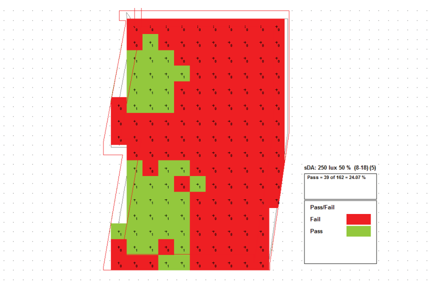
Figure 4.25. Minimum, Maximum and Average Lux values (West)

4.4.2.2.2. Spatial Daylight Autonomy (sDA)

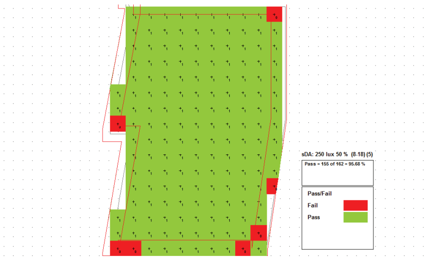
In the west room, the Spatial Daylight Autonomy worsened with the use of shading devices. Daylight dependence on electric lights increased. 30% Jali allowed the least amount of light in the room (Figure 4.26 and Figure 4.27).



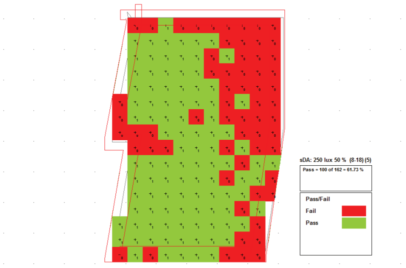
Base Case



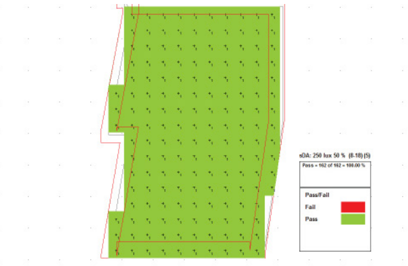
30% Jali



50% Jali



40% Jali



Brise Soleil

Figure 4.26. Spatial Daylight Autonomy (West)

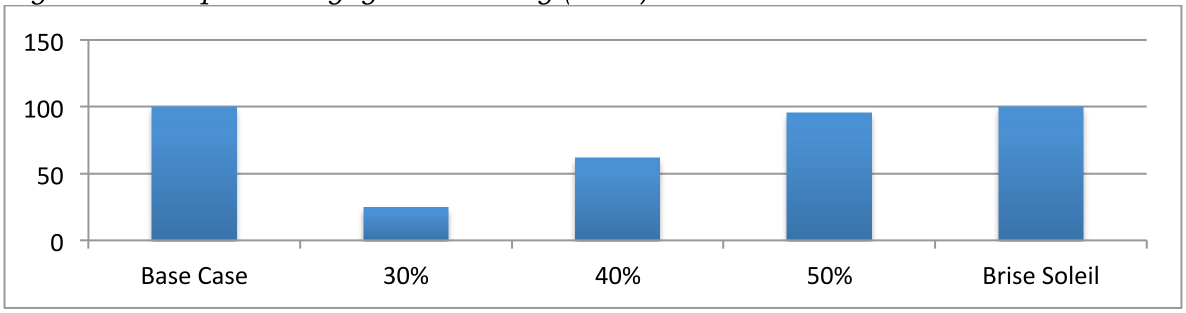
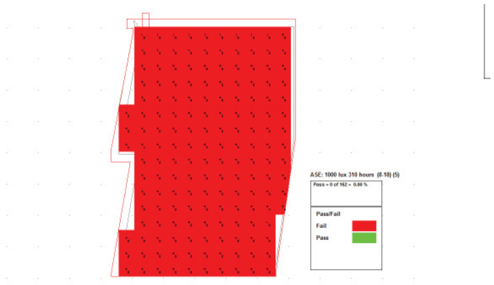


Figure 4.27. Percentage of Spatial Daylight Autonomy (West)

4.4.2.2.3. Annual Sunlight Exposure

The 50% Jali received maximum amount of sunlight in comparison to others (Figure 4.28 and Figure 4.29).



Base Case

30% Jali

50% Jali

40% Jali

Brise Soleil

Figure 4.28. Annual Sunlight Exposure (West)

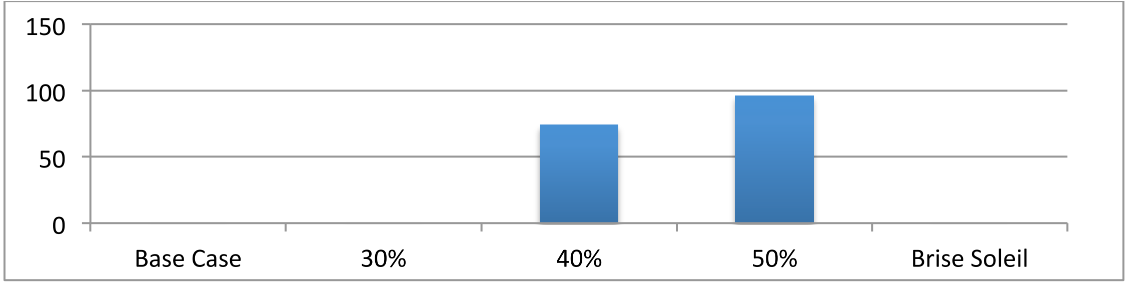
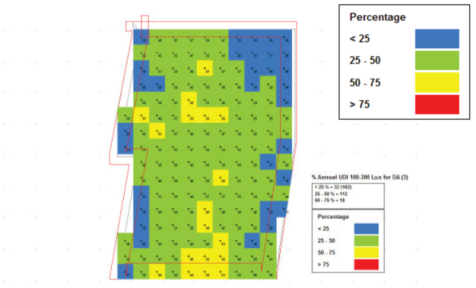


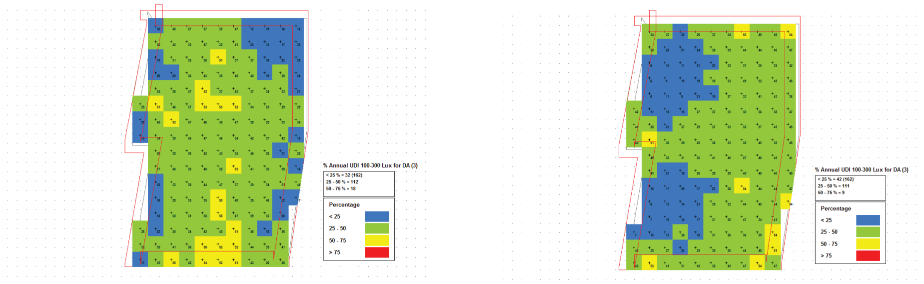
Figure 4.29. Percentage of Annual Sunlight Exposure (West)

4.4.2.2.4. Useful Daylight Illuminance (UDI)

Figure 4.30 and Figure 4.31 showed a comparison of percentage of the UDI Range (100 – 300 lux) achieved through various shading strategies on West. In this metric, 40% Jali exhibited a balanced lighting distribution.

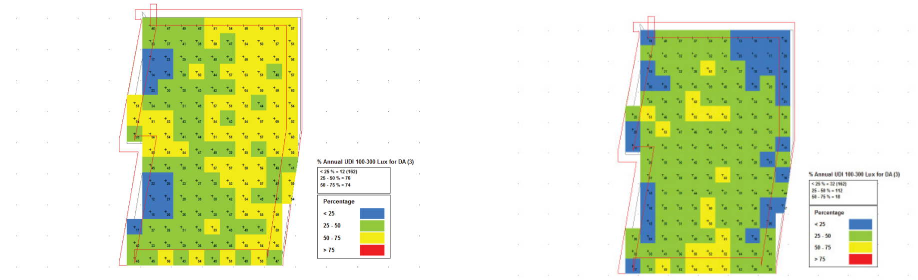


Base Case



30% Jali

50% Jali



40% Jali

Brise Soleil

Figure 4.30. Useful Daylight Illuminance (100-300 lux) (West)

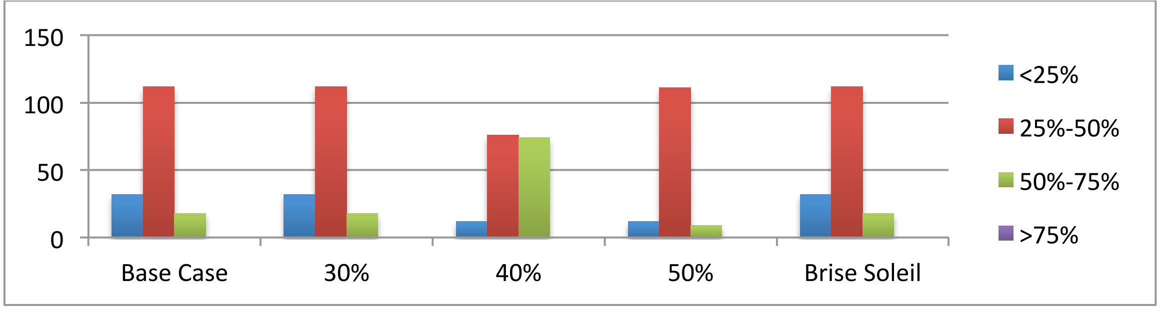


Figure 4.31. UDI time for Value of 100-300 lux (West)

4.4.3.Visual Comfort

This section analysed the visual comfort achieved through different shading strategies. For each orientation, south and west, the base case was analyzed and a specific time of the day was identified for detailed analysis. False Color Render was used to illustrate the glare ratio. For the purpose of comparison the scale was kept constant. The scale is defined as 0 (Purple) to 100 (Yellow). Furthermore, CIE Glare Indices showed the numerical value of glare in the same view as the images in this analysis.

4.4.3.1. South Orientation

4.4.3.1.1. Base Case

Figure 4.32 showed an array of views rendered in false color for base case without any shading device. In the three times of the day at solstices and the equinoxes, glare was analyzed using false color.

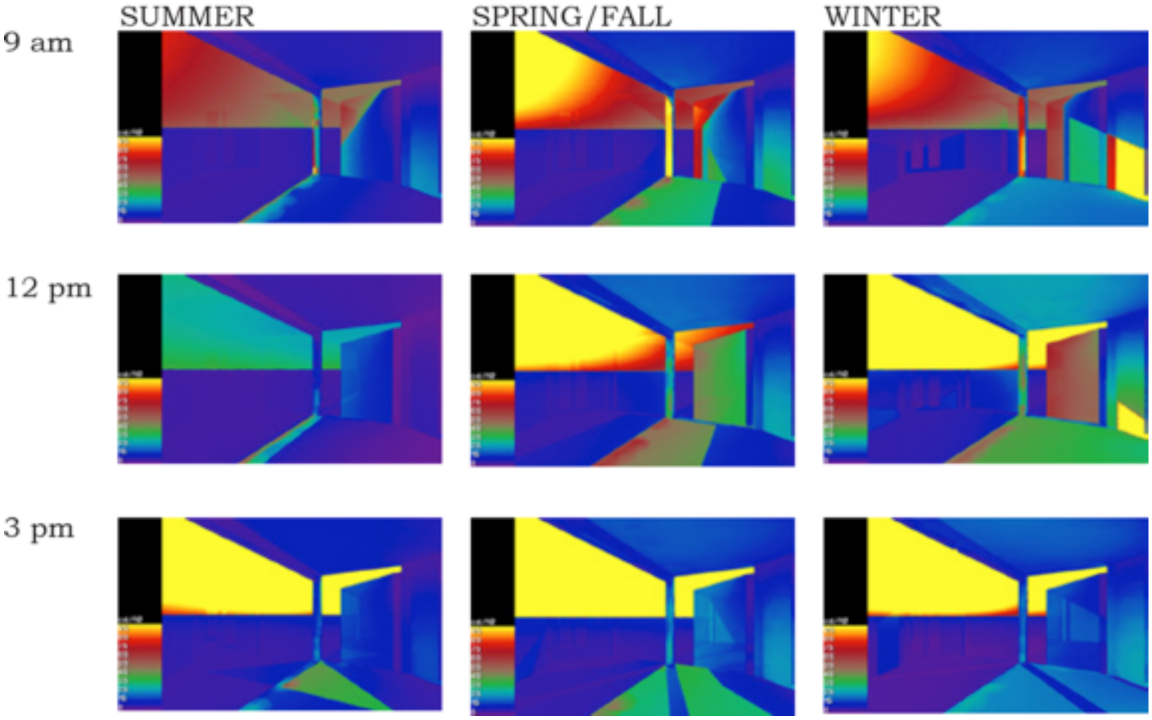


Figure 4.32. Comparison of False Color Render for Base case (South)

Summer sun is high altitude and caused lesser glare than at other times of the year. In all other times, solar altitude was lower and sunrays penetrated deep into the space, ranging from mild to very deep from fall through winter. Although winter sun was appreciated because of solar gain, and associated thermal comfort, it was still the cause of glare in work environments. The amount of glare caused in afternoon was also a result of the west-facing window. In order to eliminate the west glare, for a detailed analysis, only 12 pm was considered for the south room when the sun was facing south (Figure 4.33).

4.4.3.1.2. Shading Devices at 12 pm

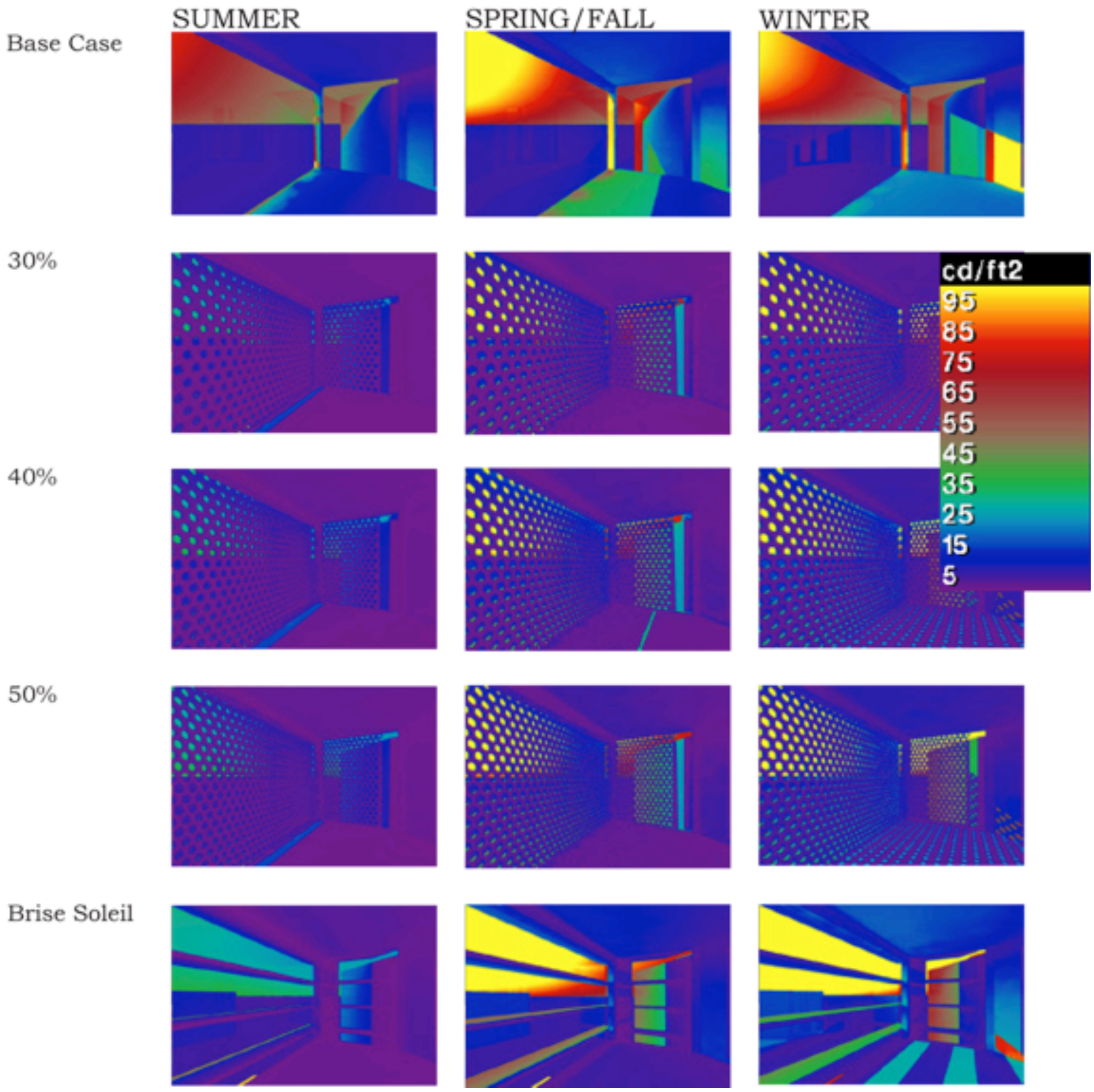
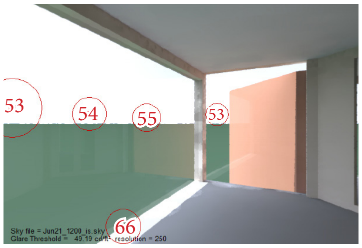
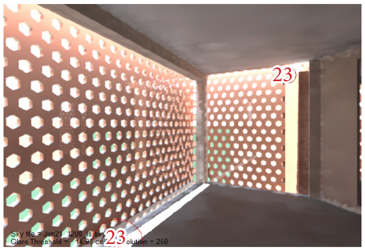


Figure 4.33. Comparison of False Color Render for Different Shading devices at 12 pm (South)

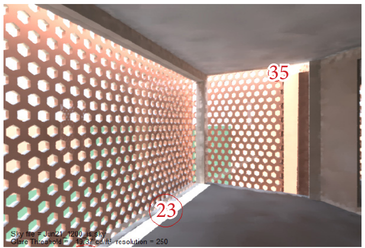
Figure 4.34 showed the impact of shading devices on glare in the south orientation on Summer Solstice. All views selected were for 12 pm as discussed in the previous section. Jali screen had a significant impact in glare reduction. The contrast of bands, in horizontal shading, was one of the main reasons for high discomfort glare levels in Brise Soleil.



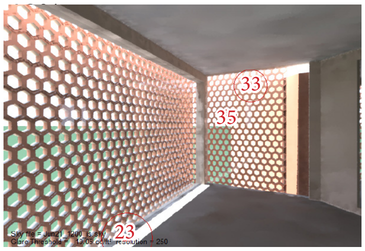
Base Case



30%



40%



50%

Brise Soleil

Figure 4.34. Glare and Shading devices (South)

4.4.3.1.3. CIE Glare Index

CIE glare index was found to be one of the important metrics for evaluation of luminance values in workspace. For the same view angle, when CIE glare was analyzed (Figure 4.35) in view angle (-60 to +60) three times a year at 12 pm on a given a design day (Acceptable range is 13 – 26). The maximum glare value showed up in December, when the sun angle was lower. For the base case, glare was highest in December. The only marked difference in the glare was when compared to Brise Soleil, where glare values for all months significantly worsened even from the base case. This is due to the increase in sharp contrast in the surface color on the façade. As for the comparison between Jali screen façade and Brise Soleil glare in months other than December was significantly reduced. On south side, Jali screen helped in reducing the glare effect within the comfort range of 13-26.

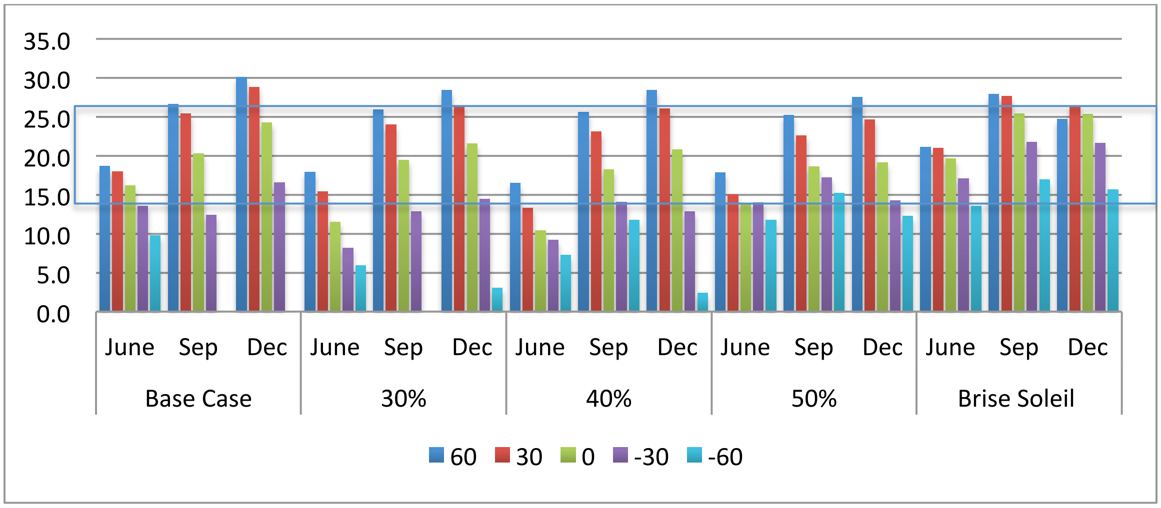


Figure 4.35. CIE Glare Indices (South)

4.4.3.2. West Orientation

Glare became an issue in the later half of the day when the sun is at a lower angle while setting in the west. This was a big cause of visual discomfort and controlling glare in the west was, therefore, a big challenge. Traditional shading devices designed to block the west sun incorporate vertical louvers, which in turn block any direct sunlight. This had previously been deemed appropriate, as the best way to avoid glare at low solar angles, while sacrificing on the daylight availability.

4.4.3.2.1. Base Case

Daylighting levels in the west were not sufficient in base case from morning till noon (Figure 4.36). Furthermore, a comparison of glare in summer months, during three times of the day (Figure 4.37) showed the increase in glare ratio through the day.

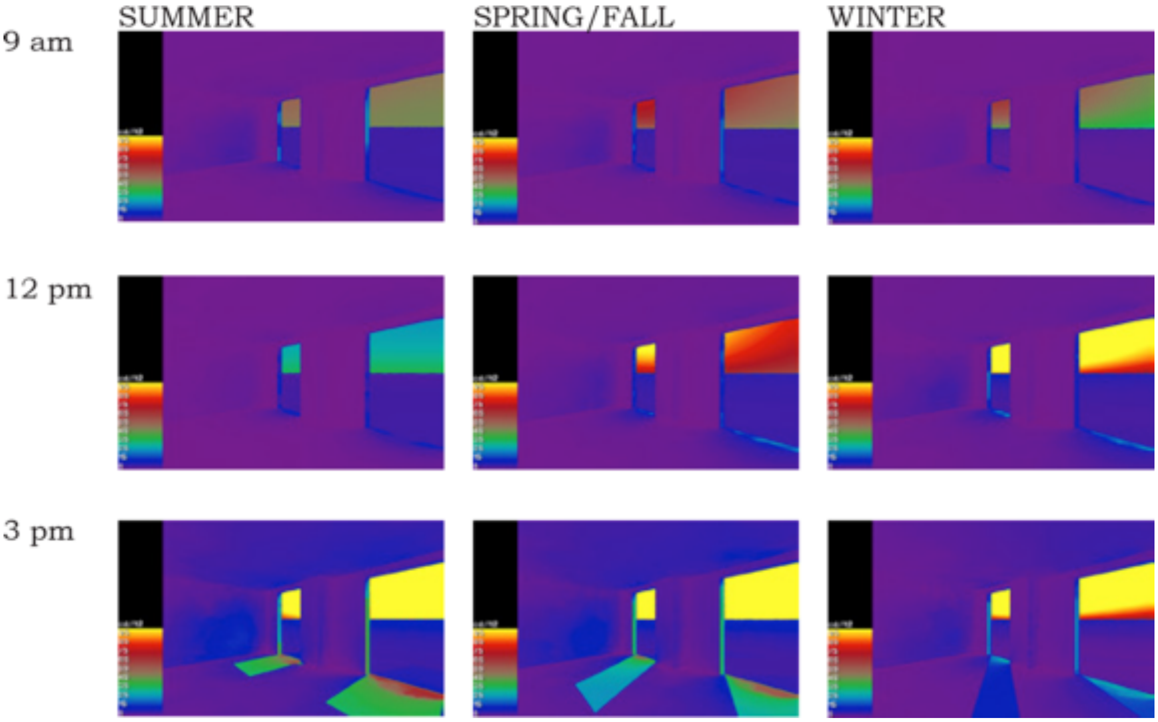
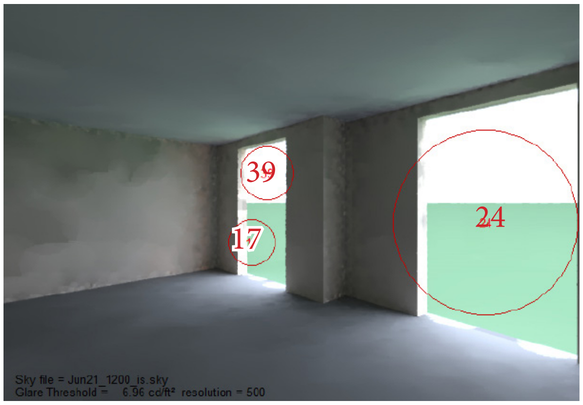


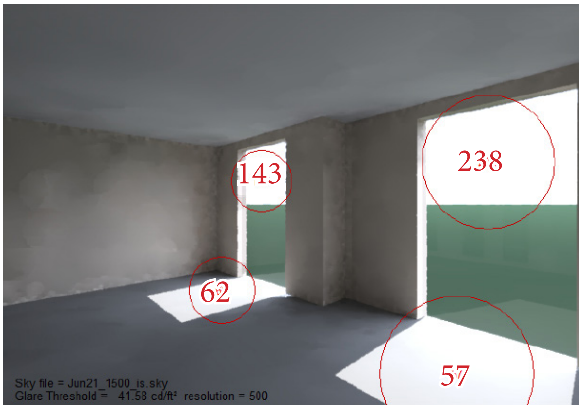
Figure 4.36. Comparison of False Color Render for Base Case (West)

SUMMER

9 am



12 pm



3 pm

Figure 4.37. Glare and Base Case on Summer Solstice (West)

For the purpose of comparison base case was looked into detail at 3 pm (Figure 4.38).

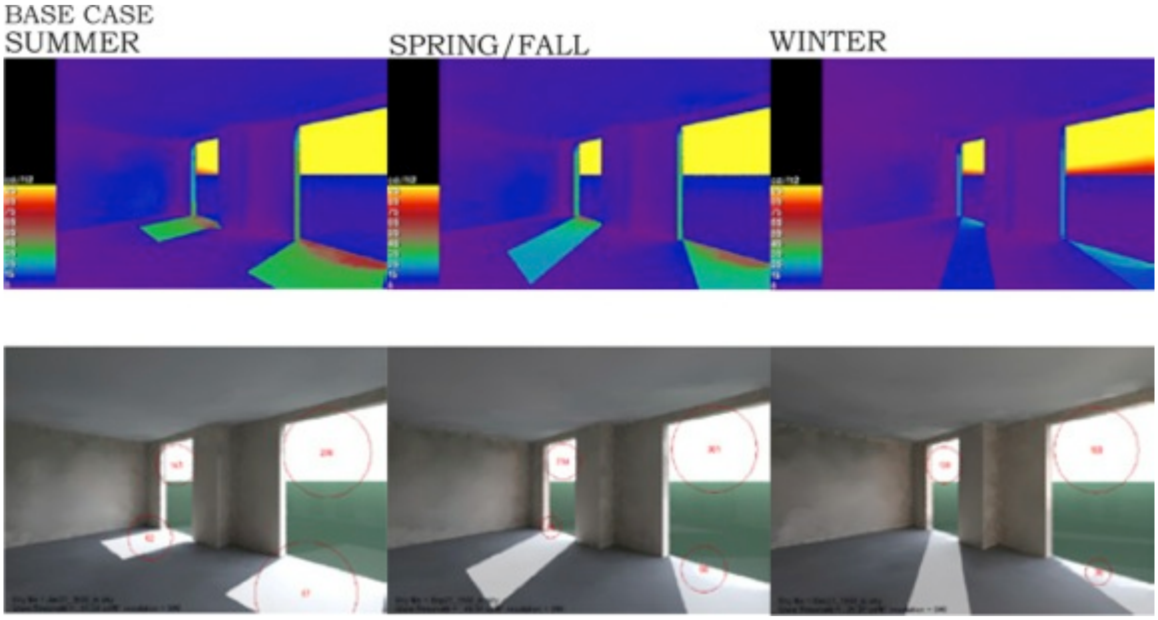


Figure 4.38. Comparison of False Color Render with Glare Analysis - Base case (West)

4.4.3.2.2. Shading Devices at 3 pm

The difference of glare values was most prominent at 3 pm. The perforated screen was able to reduce the contrast and spread the light in such way that it did not cause discomfort glare. Light pouring in through the Jali screens had a quality that was reminiscent of traditional architecture found in South-Asia. In many photographs, patterns formed through the Jali screens and were positively related to the quality and ambience of the space. However, as seen in Figure 4.39, perforation variation created a degree of variability in the light quality. Brise Soleil prevented any direct sun into space, but when compared to Jali screen, it drew no relationship to the traditional architectural practice in Lahore. This kind of relationship was considered very important in an architectural context, which is very rich historically and simultaneously very progressive. Figure 4.39 showed a detail of glare ratio, in summer solstice, for the west side at 3 pm. Low angle of sun in the west orientation maked it hard for almost all shading devices to reduce glare. While 30% Jali screen marked the best glare ratio, the angular vertical fins (Brise Soleil) block all sunrays making it the best strategy for glare ratio (Figure 4.40) when daylight availability and access to view were ignored.

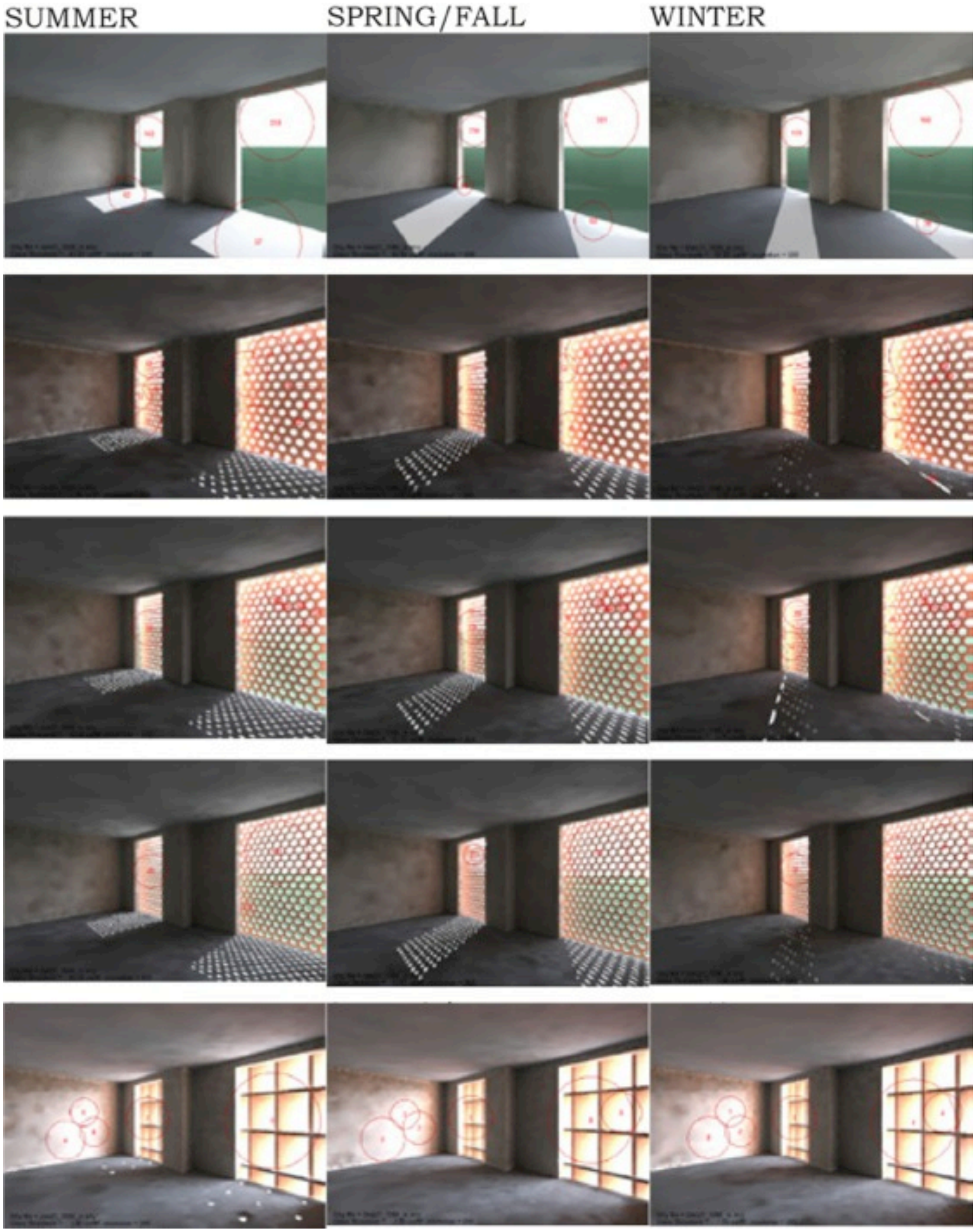
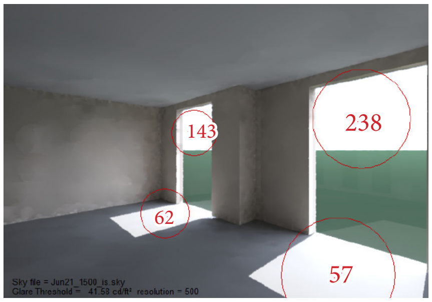
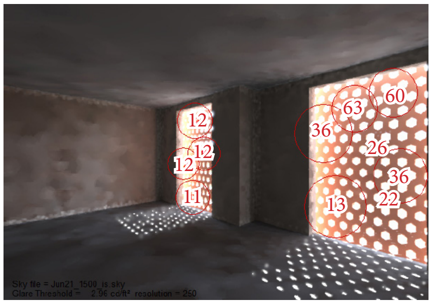


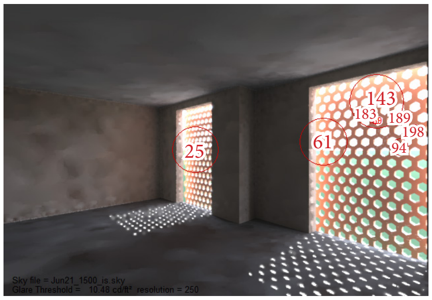
Figure 4.39. Comparison of Glare Analysis at 3 pm (West)



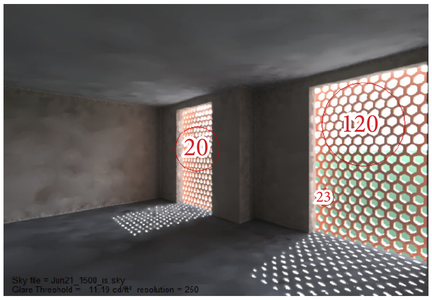
Base Case



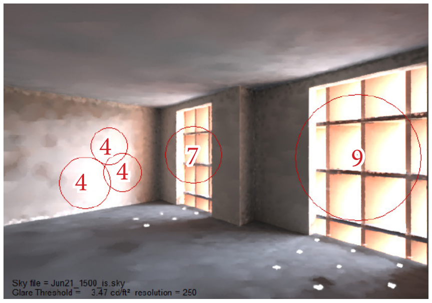
30%



40%



50%



Brise Soleil

Figure 4.40. Glare and Shading devices (West)

4.4.3.2.3. CIE Glare Index

Base case glare values were noted to be very high and almost always outside the tolerable zone of 13-26. The Brise Soleil, while covering the windows for direct solar exposure, reached the bare minimum of lighting levels in the room. While 30% Jali with its minimum perforation ratio caused the least amount of glare in the West. This was predictable as the contrast in surface was reduced along with perforation ratio as shown in Figure 4.41 where (in view angle -60 to +60) acceptable range is 13 to 26.

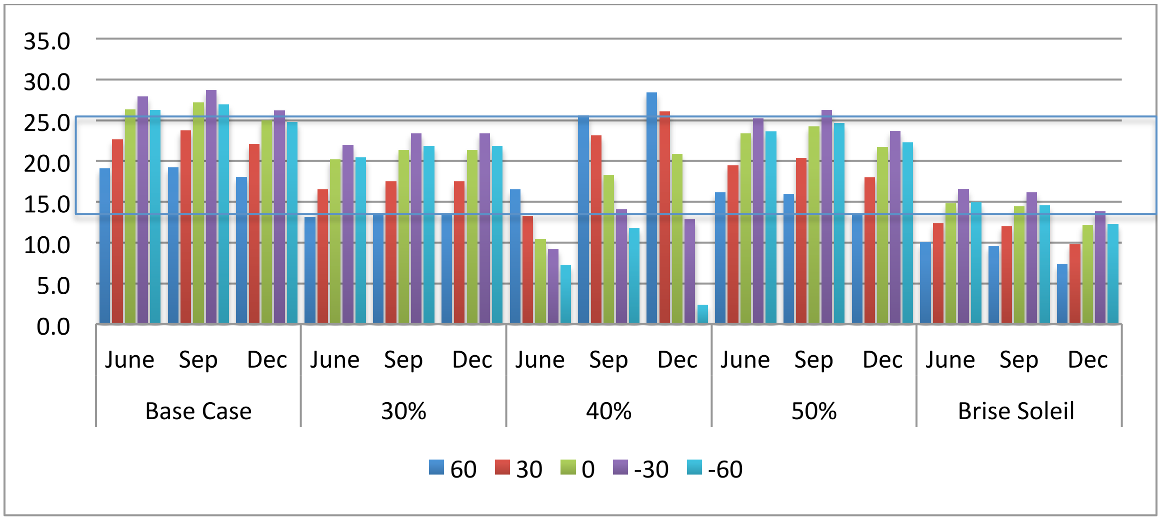


Figure 4.41. CIE Glare Indices (West)

CHAPTER V
CONCLUSION

This thesis examined the effect of Jali Screen façades on the year round energy performance; daylight performance and resultant glare phenomena. The conclusion is focused on the impact of shading devices; in particular, geometry of Jali screens façades on Energy Saving, Daylighting Performance and Visual Comfort in office spaces. For each of the two orientations, three Jali screens and Brise Soleil were designed and simulated. A holistic understanding of thermal and visual comfort is required to draw a conclusion for the best shading strategy in Lahore, Pakistan.

5.1. ENERGY PERFORMANCE

Energy was measured and assessed in EUI in Figure 4.12 and Figure 4.13. As pointed out in previous studies, the thermal construction of a building had a large impact on its energy performance. This study showed that by optimizing the thermal construction using Green Class Toolbox (Elzeyadi et al.) high total energy savings were made possible. Figure 5.1 showed how each of the three Jali screen façades affected the total energy of the building. It can be concluded from this study that the 50% perforation ratio performed best out of the three Jali screens. As the perforation ratio was increased from 30% to 50% energy performance also improved as the lighting energy decreased (Figure 4.14). When compared in terms of total energy, Brise Soleil out-performed all of the Jali screens, however, the lighting energy was higher for Brise Soleil than it was for Jali screen façade. This was due to the nature of vertical fins in Brise Soleil on the West side designed to cut out direct sun and cooling loads were reduced. In comparison, the 50% Jali was better option for the balanced energy approach for cooling and lighting.

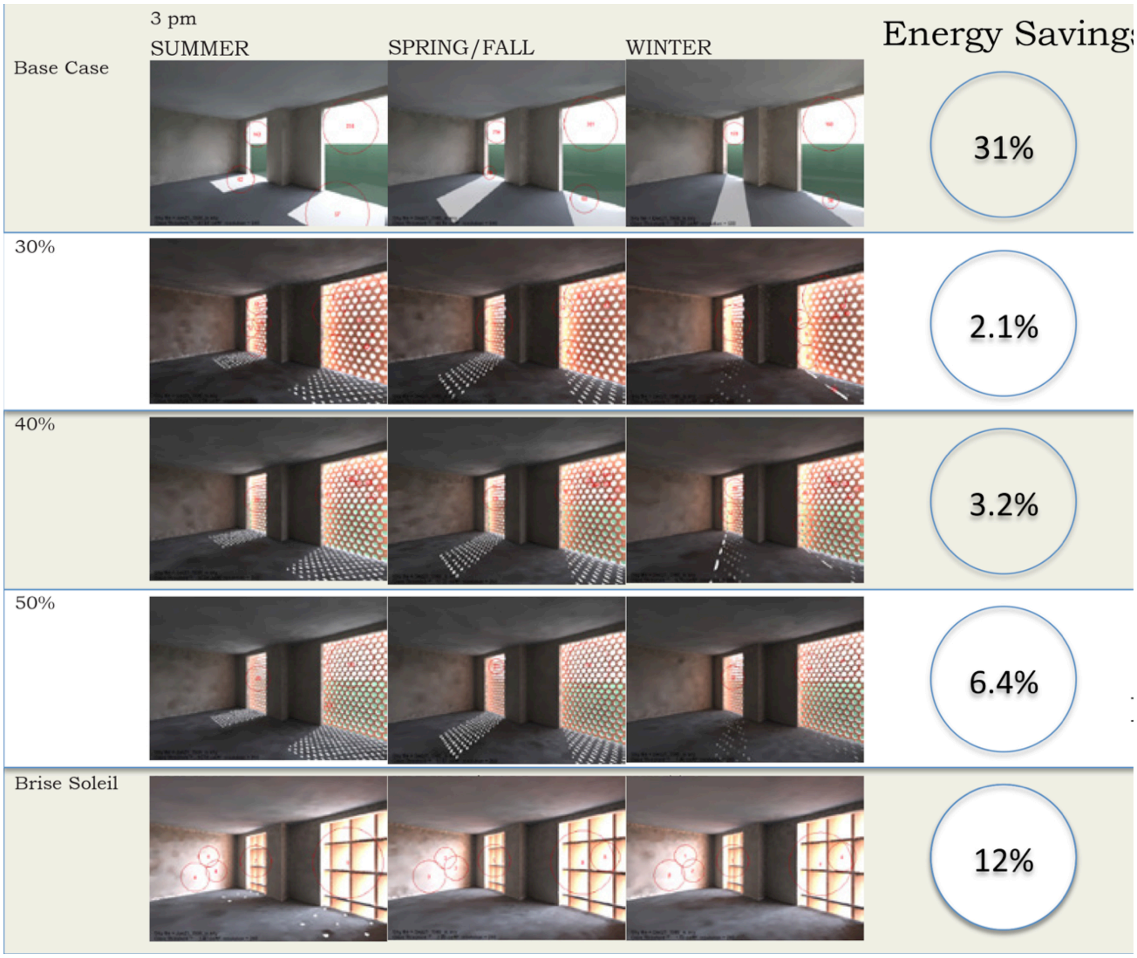


Figure 5.1. Energy Performance Comparison

5.2. DAYLIGHT PERFORMANCE

Each configuration of shading devices resulted in a different lighting performance, depending on each assessment criteria in the metrics used. Based on the results in Chapter 4, 50% Jali performed best out of the tested shading devices on the south side. Table 5.1 showed a comparison of daylighting and visual comfort metrics and the corresponding shading strategies. The only marked difference was seen for Useful Daylight Illuminance (UDI of 100-300 lux) required for office work. On the West side, 50% Jali screen also seemed the best option, except for under the UDI criteria of 100-300 Lux, where 40% Jali screen performed slightly better than 50% Jali screen

5.3. VISUAL COMFORT

In order to assess the visual comfort performance of Jali screens as shading devices, two main strategies were used. False color renderings of views in both rooms were assessed for glare ratios of 1:10. A second metric of evaluation used was CIE Glare Index. On the south side, the greater solar exposure led to an increase in glare probability. However, as pointed out in the earlier research (Fathy 1986) sharp bands of darkness and light caused further contrast when Brise Soleil was used. In Jali screens, the smallest perforation ratio had the least amount of glare. On the west side, the trend of Jali screen behavior continued. However, this time, for Brise Soleil vertical fins, which completely protected the glass from any direct sun, there was a very low glare value. These values were often lower than the accepted range of 12-36 in the CIE Glare Index. Better yet, all shading devices improved on the glare index when compared to the base case.

5.4. JALI VERSUS GLASS FAÇADE

The need for solar control and visual comfort has created opportunities for the development of new façade technologies and shading devices. In particular development of high efficiency glass and application of electrical generation through glass-based photovoltaic is a promising future with glass façades. However, in the developing economies, it is a far-fetched idea and simple shading strategies appropriated for function and building typology are deemed much suitable. Especially shading strategies such as Jali, proved to improve thermal and visual comfort, do not hinder the visual transparency of the building façade (Figure 5.2). When looking from the inside, Jali maintained a reasonable transparency without the need for blinds.

Figure 5.2. Jali Façade Exterior

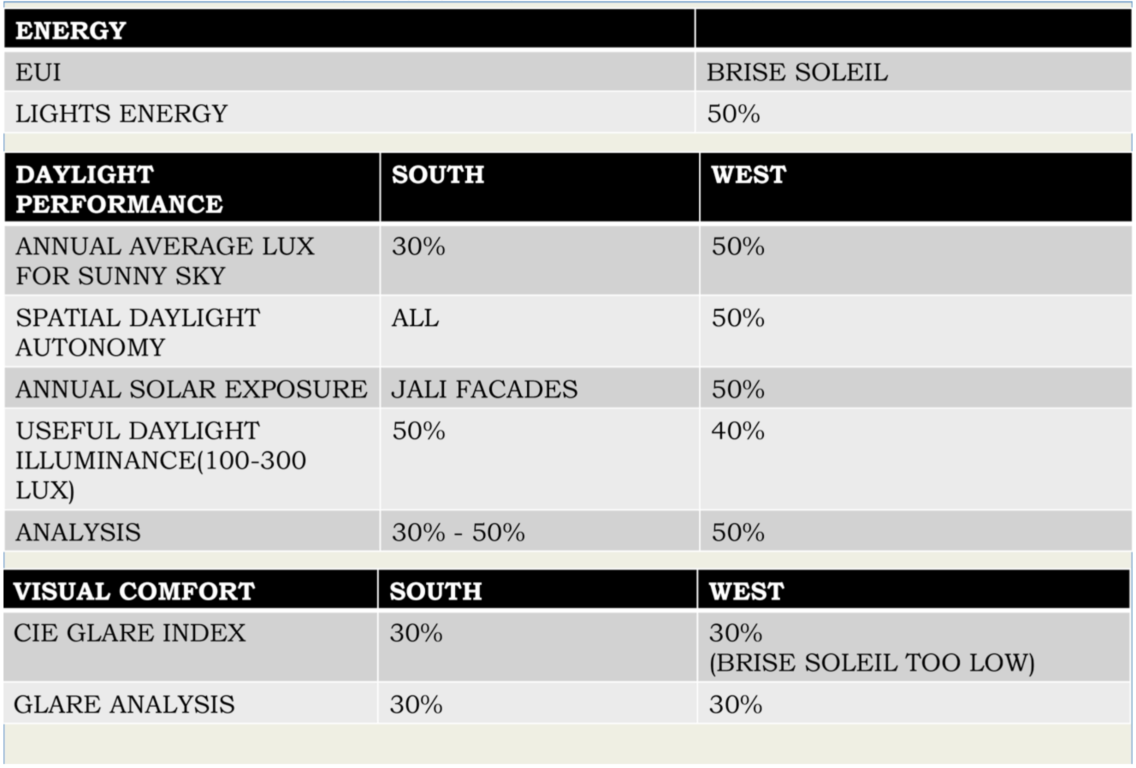
In addition to visual comfort Jali façade, therefore, enhances the transparency of glass façade. In the corporate sector where glass is used as a symbol of modernity, it further complements the idea of contemporary, without compromising on the performance.

5.5. RESEARCH VALIDITY

The base case energy audit was found to be very high in comparison to the worst-case scenario in the US. These figures were also compared to those in other countries and it was decided to optimize the thermal constructions through a high performance template, in order to truly understand the impact of shading (only) on the energy performance.

Images gathered from the field study were matched with the simulation view angles when testing the visual comfort and sensors were located on the same heights as the working plane in the office. These measures were conducted to ensure that the data collected from base case building matches the base case building in the simulation model.

Table 5.1. Comparison of Daylighting and Visual Comfort



ENERGY	
EUI	BRISE SOLEIL
LIGHTS ENERGY	50%

DAYLIGHT PERFORMANCE	**SOUTH**	**WEST**
ANNUAL AVERAGE LUX FOR SUNNY SKY	30%	50%
SPATIAL DAYLIGHT AUTONOMY	ALL	50%
ANNUAL SOLAR EXPOSURE	JALI FACADES	50%
USEFUL DAYLIGHT ILLUMINANCE(100-300 LUX)	50%	40%
ANALYSIS	30% - 50%	50%

VISUAL COMFORT	**SOUTH**	**WEST**
CIE GLARE INDEX	30%	30% (BRISE SOLEIL TOO LOW)
GLARE ANALYSIS	30%	30%

5.6. LIMITATIONS AND FUTURE RESEARCH

Although research framework illustrated in Chapter 2, laid out most of the aspects of research in Jali screen façades, this research was limited to variation in perforation ratio. Other aspects of Jali screen design that are recommended for future research are as follows:

Materiality of Jali Screen Façades

Sectional Depth.

Sectional Geometry

Impact of Ventilation

Distance of façades screen from the building

Window to wall ratio

Building height and size

5.7. DESIGN RECOMMENDATIONS

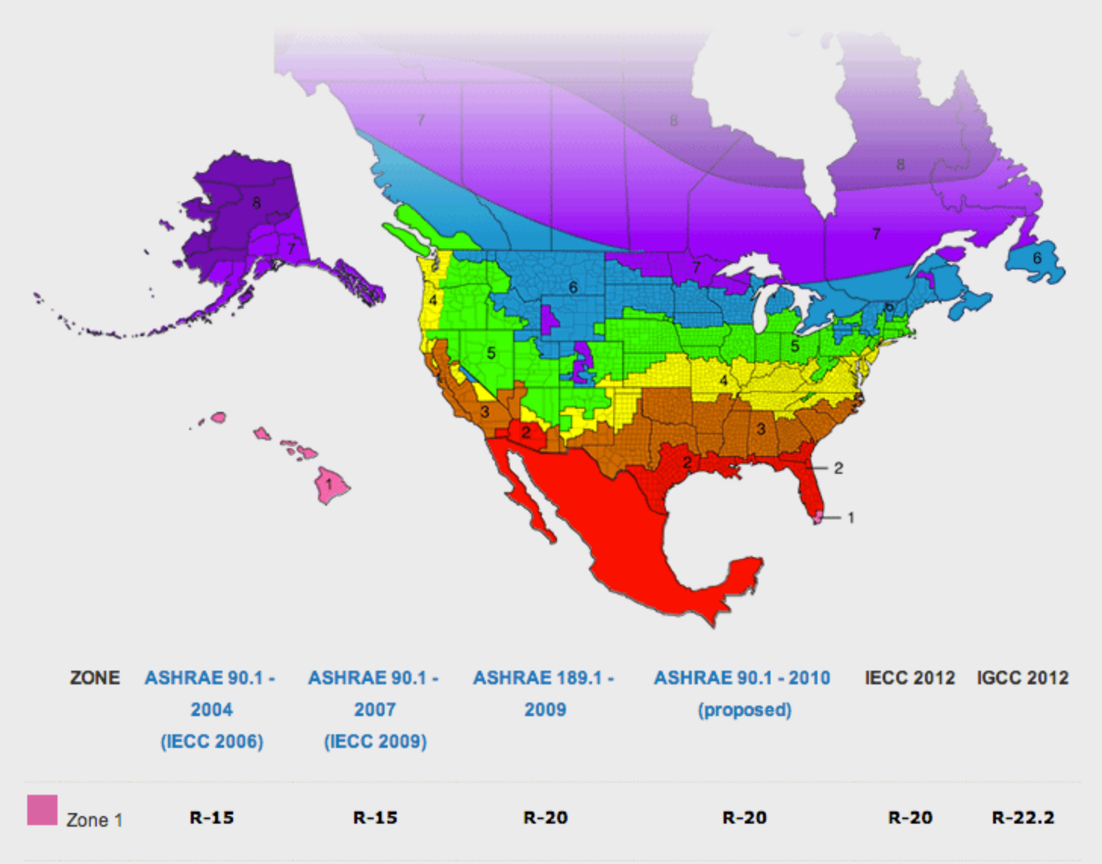
Buildings today must be concerned with both energy and visual comfort of the occupants. Jali screen façades help in energy performance, achieve daylight autonomy and improve visual comfort of office spaces. This relationship is very unique to the porous screens, in which they are scaled such that the distribution of light is not causing further glare such as in the Brise Soleil.

Jali screen façades encourage sensitivity to exterior relationships within the interior space. An architect can insulate a building, can isolate it from the exterior and place it anywhere in the world, but Jali breaks the spatial confinement while allowing for energy efficiency and thermal and visual comfort. In creation of the relationship between exterior and interior, Jali attenuates the relationship of a building with its context. Therefore, Jali is not only a façade element, which connects the architectural context with the history, but also engages the building, with its particular context.

APPENDIX A

CLIMATE CLASSIFICATION

ASHRAE CLIMATE ZONES IN THE US AND R-RATINGS FOR ZONE 1



ZONE	ASHRAE 90.1 - 2004 (IECC 2006)	ASHRAE 90.1 - 2007 (IECC 2009)	ASHRAE 189.1 - 2009	ASHRAE 90.1 - 2010 (proposed)	IECC 2012	IGCC 2012
■ Zone 1	R-15	R-15	R-20	R-20	R-20	R-22.2

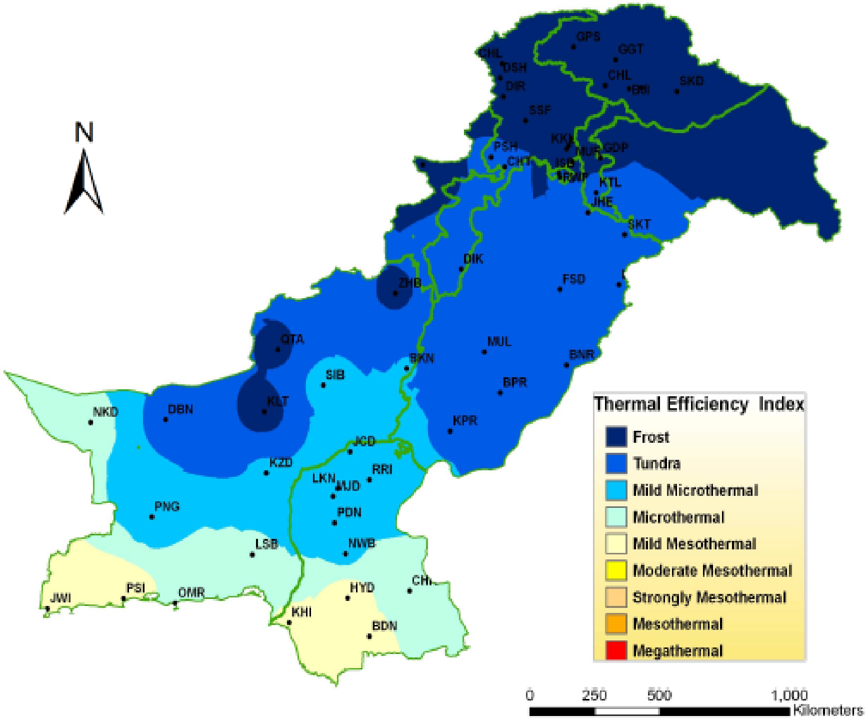
Source: GreenZone (http://www.greenzone.com/general.php?section_url=12)

CLIMATE TYPES BASED ON THORNTHWAITE'S THERMAL EFFICIENCY INDEX

Table 1. Thermal climate types based on Thornthwaite's Thermal Efficiency Index

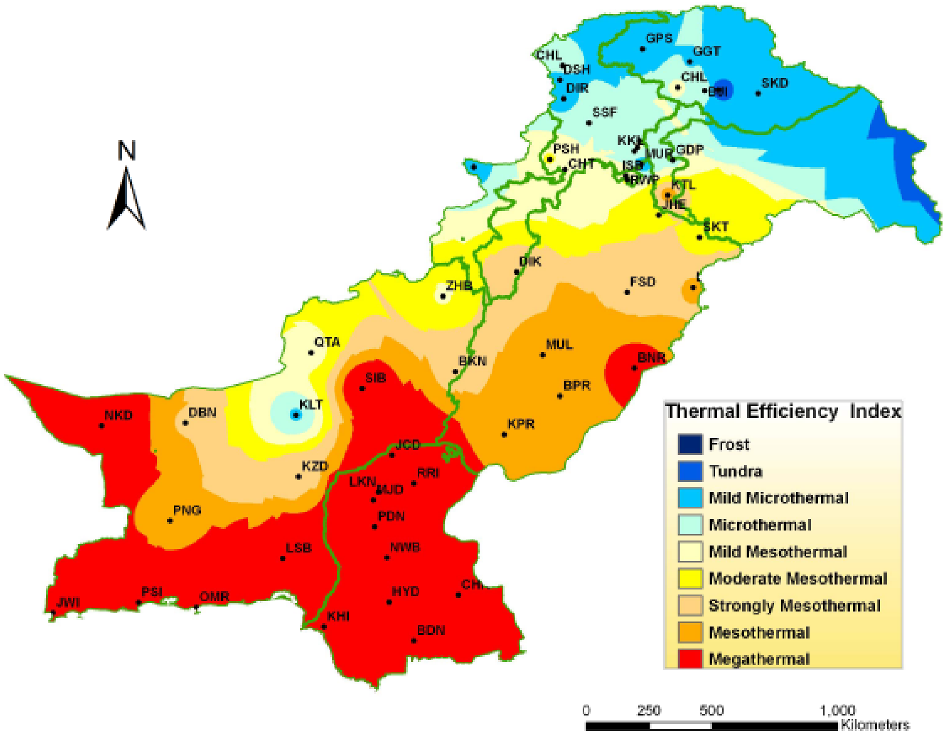
TE index	Climate	Type	Redefined types for simplification
14.2	E'	Frost/Ice	Frost
28.5	D'	Tundra	Tundra
42.7	C_1'	Microthermal	Mild Microthermal
57	C_2'	Microthermal	Microthermal
71.2	B_1'	Mesothermal	Mild Mesothermal
85.5	B_2'	Mesothermal	Moderate Mesothermal
99.7	B_3'	Mesothermal	Strongly Mesothermal
114	B_4'	Mesothermal	Mesothermal
> 114	A'	Megathermal	Megathermal

CLIMATE CLASSIFICATION OF LAHORE



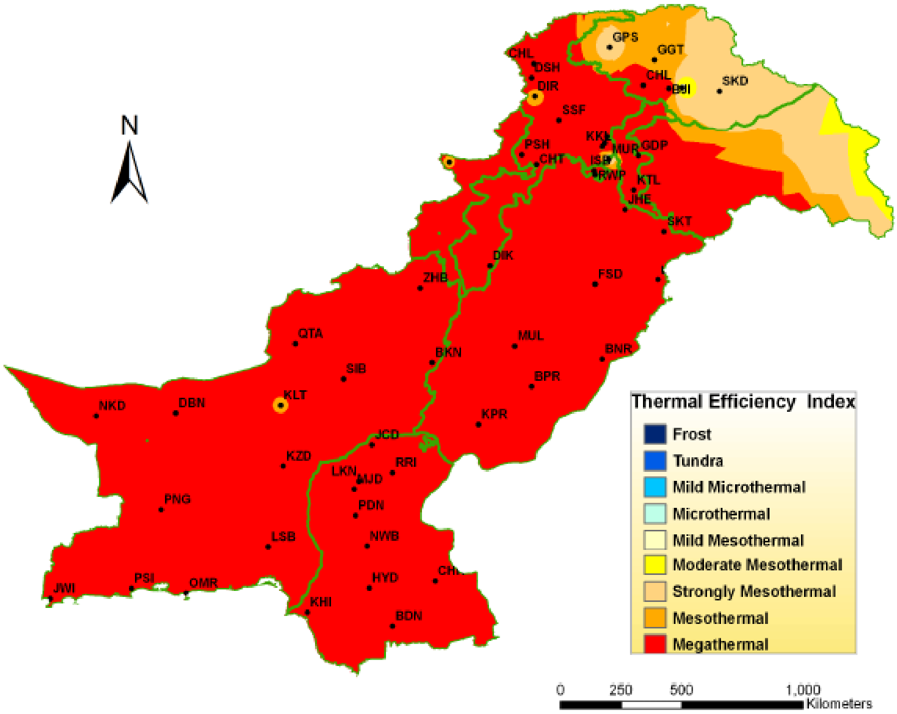
Thermal Classification of Winter (Dec - Feb) in Pakistan; Lahore is under Tundra Classification (Zahid et al. 2011)

From December till February, Lahore falls under the category of Tundra climate with temperature close to freezing and dry air, which necessitates the usage of closed environments.



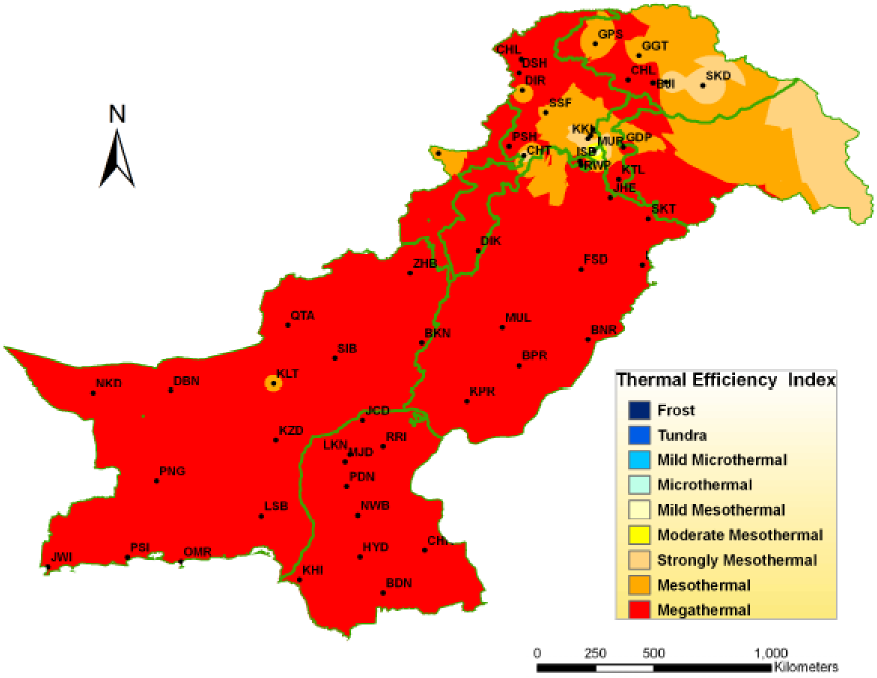
Thermal Classification of Spring (Mar-Apr) in Pakistan; Lahore is under Mesothermal classification (Zahid et al. 2011)

In March-April, Lahore’s climate becomes Mesothermal, specified with mild temperature and spring season. This is much appreciated by the locals, as the mild cold air makes possible to enjoy outdoors.



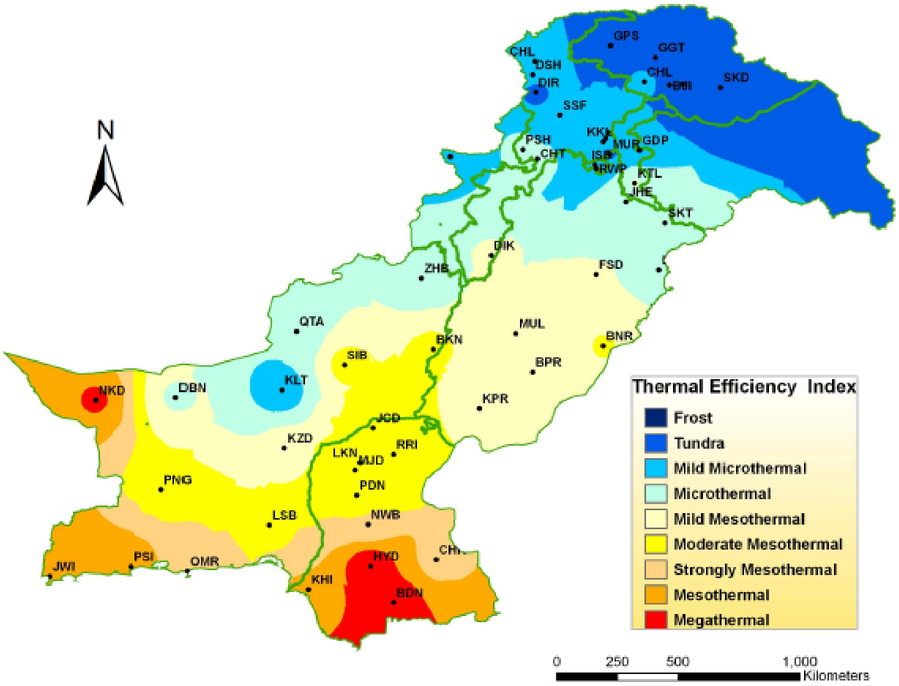
Thermal Classification of Summer (May - June) in Pakistan; Lahore is under Megathermal Classification (Zahid et al. 2011)

The climate changes to Megathermal in summer from May to June. It is extremely hot and dry with low relative humidity. Once again, the indoor environment is preferred, with the maximum amount of expenditure on cooling systems.



Thermal Classification of Monsoon (Jul - Sep) in Pakistan; Lahore is under Megathermal Classification (Zahid et al. 2011)

July brings Monsoon and lasts till September. Although the rain brings a lot of water but temperature still remains high and humid. Outdoors would be preferred, but in shade and ventilated zones.

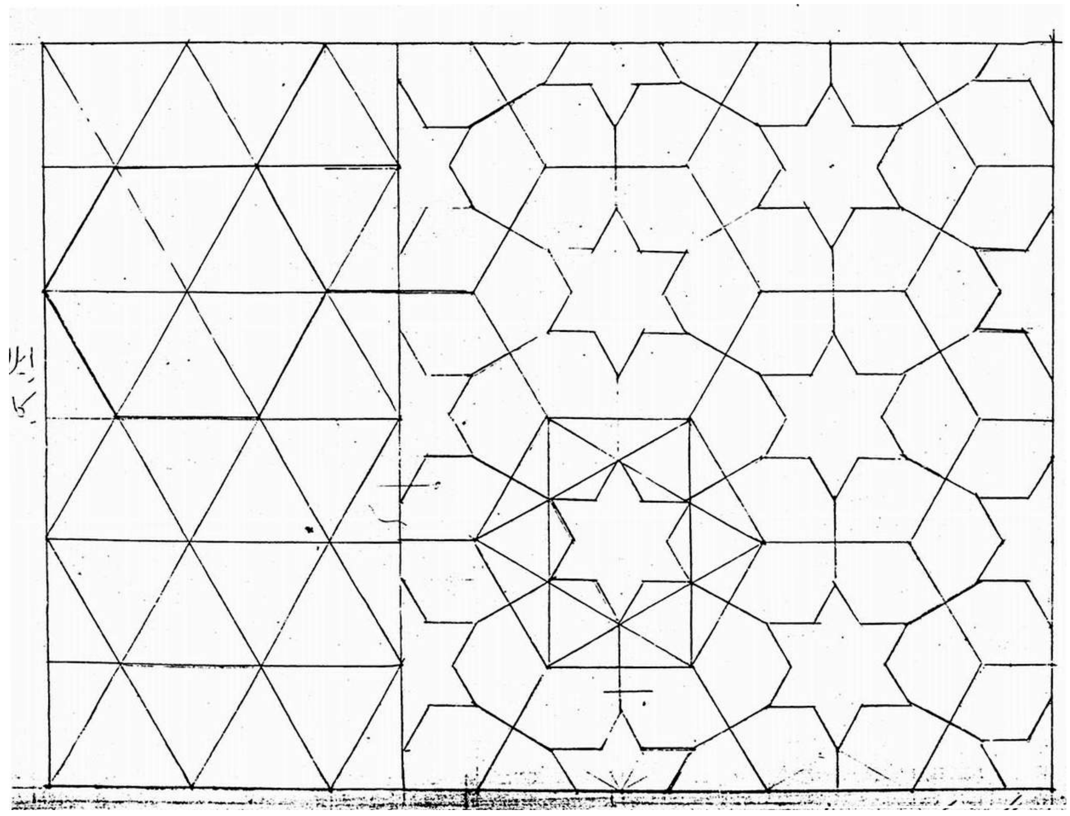


Thermal Classification of Autumn (Oct - Nov) in Pakistan; Lahore is under Microthermal Classification (Zahid et al. 2011)

In Autumn, Lahore faces a change in climate to Microthermal. From October through November, cool dry air starts and signals the arrival of Autumn. People go outside or enjoy sitting in well-lit and ventilated places at home.

APPENDIX B

JALI PATTERNS



Drawing by: Ustad Rahim Bukhsh of Multan
1970s.
(Anjuman Mimaran Library)

Original drawings by Ustad Rahim Bukhsh of Multan Pakistan, 1970s

Retrieved from and cited with permission from National College of Arts, Archives (http://www.nca.edu.pk/Res-Archives.html).

Poster submission (next page) titled “Misaal-e-Mulk-e-Abad” at the International Conference on Islamic Art and Architecture, National College of Arts Lahore, Pakistan. 2008. Cited with permission from Taimur Khan Mumtaz.

Architecture: Methods

Geometric Patterns

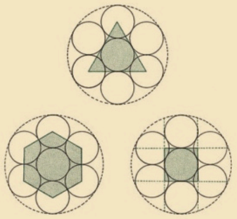
Basis

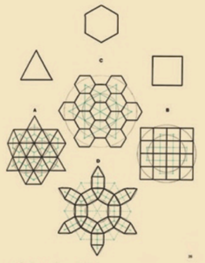
The most natural division of the circumference, by its radius, gives the hexagon, while the first polygon is the triangle. The third shape to emerge is the square. 'The equilateral triangle, the hexagon and the square are the three primary shapes, which will independently fill a surface without leaving any gaps.

(Critchlow, Keith, *Islamic Patterns*, 1995).

The faces of the five regular solids are made-up of the triangle in three cases - tetrahedron, octahedron and icosahedron - and the square and the pentagon in one case each. Thus the three basic planar figures which form the basis of geometric patterns are rooted in the fundamental divisions of a sphere's surface. Also, 2, 3, and 5 are the only numbers required for the division of the octave into musical scales. We can then accept these three as a trinity of generative principles.'

(Lawlor, Robert, *Sacred Geometry philosophy and practice*.)


▲ *Geometric basis: Triangle, Square, hexagon.*



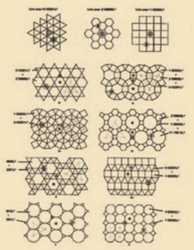
▲ *3 Regular Grids*

Three Types of Grids:

3 Regular

8 Semi-regular

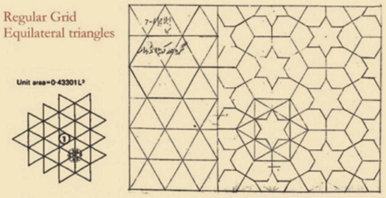
14 demi-regular


▲ *8 Semi-regular*

Examples

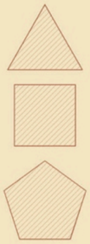
Patterns based on Grids:

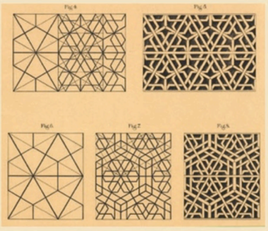
Regular Grid
Equilateral triangles



▲ *Drawing from Ustad Rahim Bukhsh M/s. 1970s, Multan.*

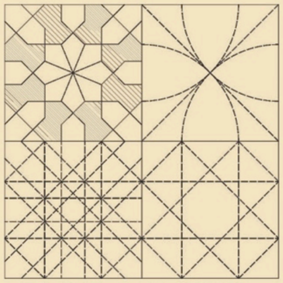
Triangular / Hexagonal Grids

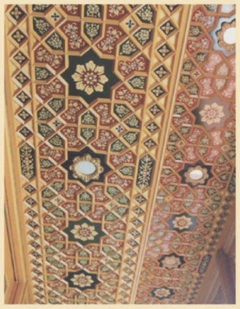


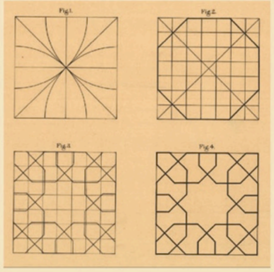


▲ *'Pinjra' work drawing from Industrial Art Pattern Book,*
▼ *Mayo School of Art.*

Square & Octagonal Grids


▲ *'Hasht Kharan' - 8-clog design, Haji Abdul Aziz's method.*


▲ *Wooden Ceiling design based on Haji Abdul Aziz's method.*



١١

'Misaal-e-Mulk-e-Abad'

The Time-less message of Islamic Architecture -
An Exhibition exploring its Philosophy, Meaning & Methods.

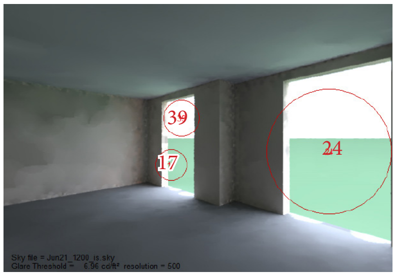
APPENDIX C

SIMULATION RESULTS
VISUAL COMFORT AND DAYLIGHTING ANALYSIS

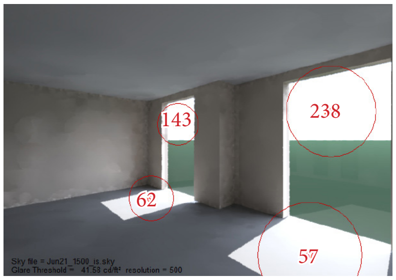
Visual Comfort
Base Case
Glare Analysis
West

SUMMER

9 am



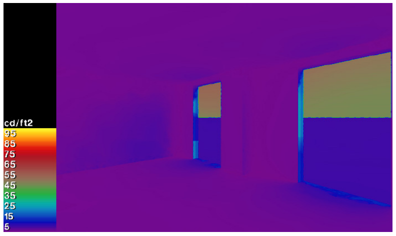
12 pm



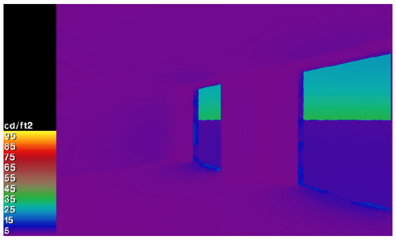
3 pm

Visual Comfort
Base Case
False Color Render
West

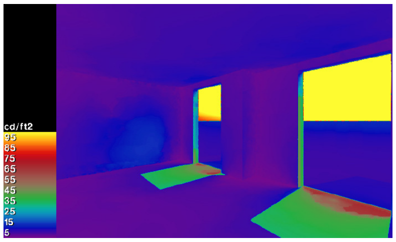
SUMMER



9 am



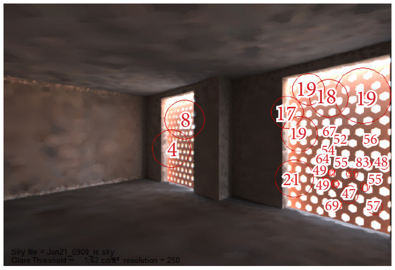
12 pm



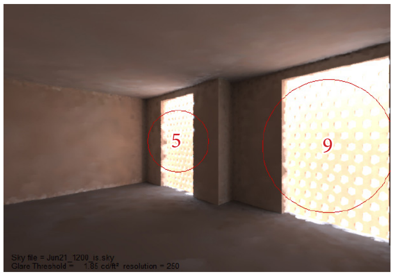
3 pm

Visual Comfort
30%
Glare Analysis
West

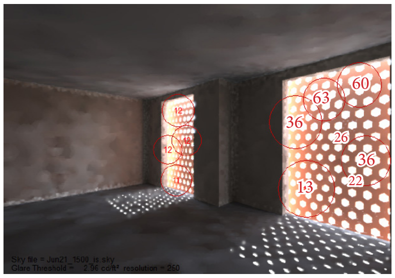
SUMMER



9 am



12 pm

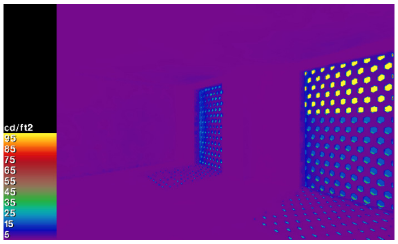


3 pm

Visual Comfort
30%
False Color Render
West
SUMMER

9 am

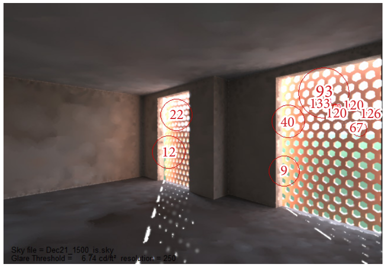
12 pm



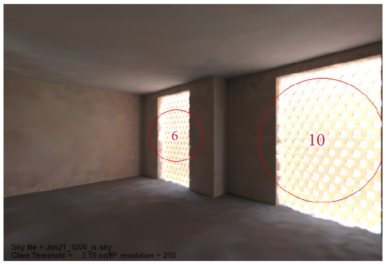
3 pm

Visual Comfort
40% JALI
Glare Analysis
West

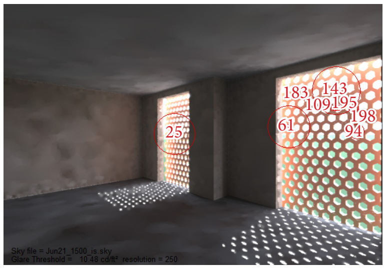
SUMMER



9 am



12 pm



3 pm

Visual Comfort
40% JALI
False Color Render
West

SUMMER

9 am

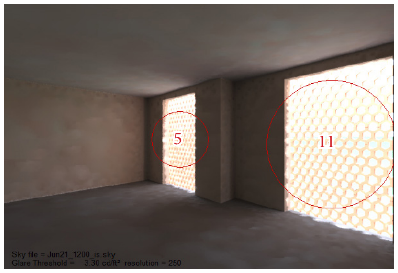
12 pm

3 pm

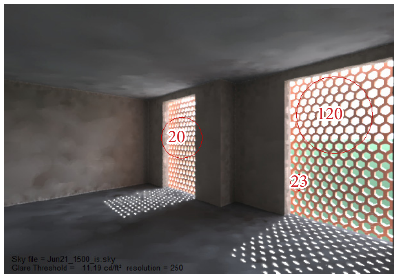
Visual Comfort
50% JALI
Glare Analysis
West

SUMMER

9 am



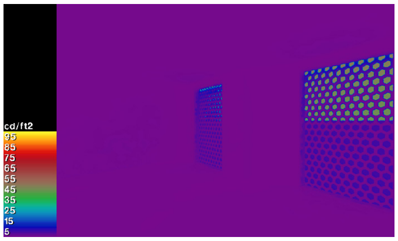
12 pm



3 pm

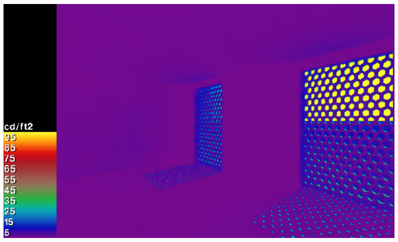
Visual Comfort
50% JALI
False Color Render
West

SUMMER



9 am

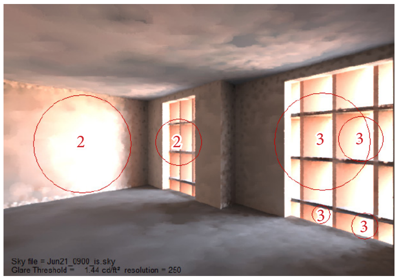
12 pm



3 pm

Visual Comfort
Brise Soleil
Glare Analysis
West

SUMMER



9 am

12 pm

3 pm

Visual Comfort
Brise Soleil
False Color Render
West

SUMMER

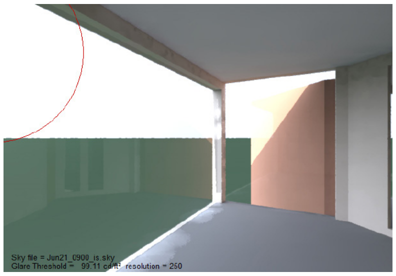
9 am

12 pm

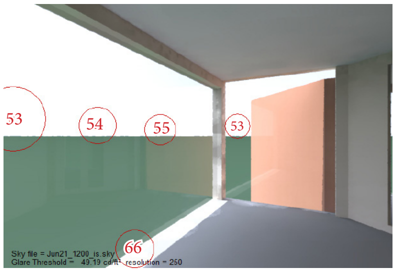
3 pm

Visual Comfort
Base Case
Glare Analysis
South

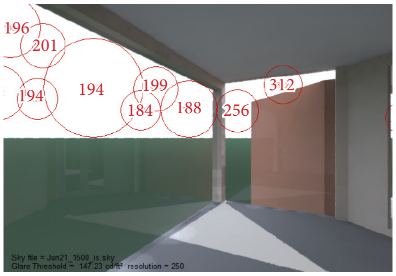
SUMMER



9 am



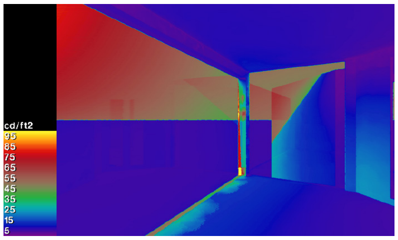
12 pm



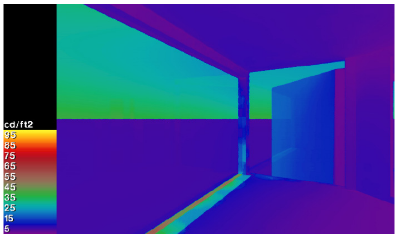
3 pm

Visual Comfort
Base Case
False Color Render
South

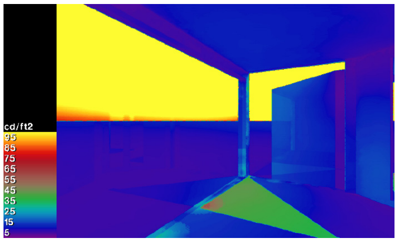
SUMMER



9 am



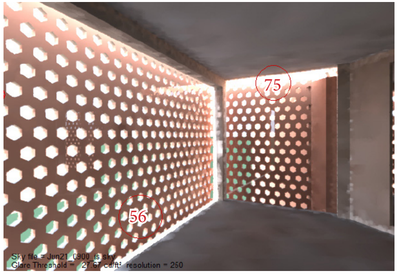
12 pm



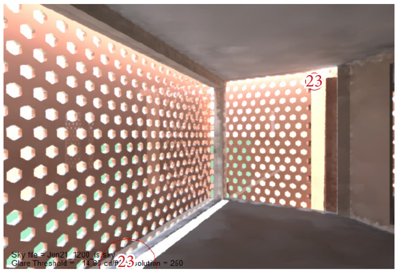
3 pm

Visual Comfort
30% JALI
Glare Analysis
South

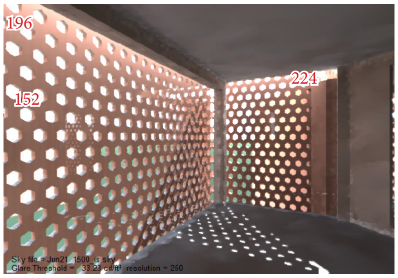
SUMMER



9 am



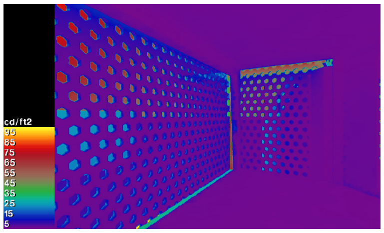
12 pm



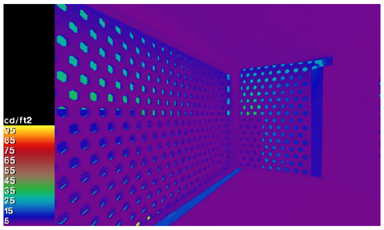
3 pm

Visual Comfort
30% JALI
False Color Render
South

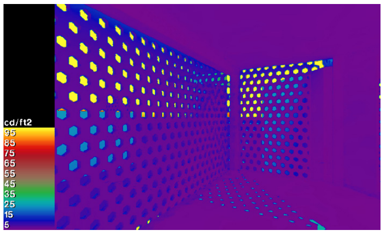
SUMMER



9 am

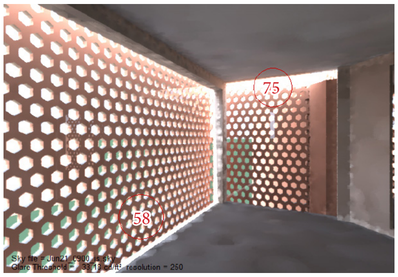


12 pm

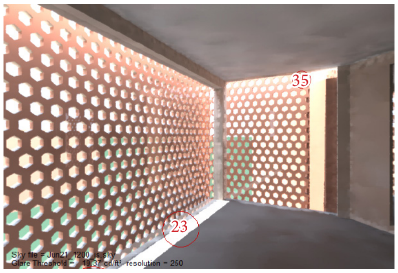


3 pm

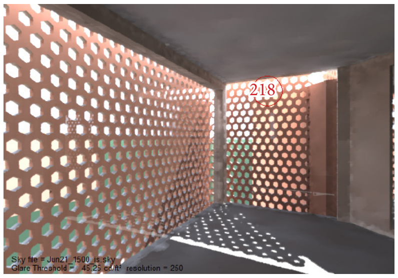
Visual Comfort
40% JALI
Glare Analysis
South
SUMMER



9 am



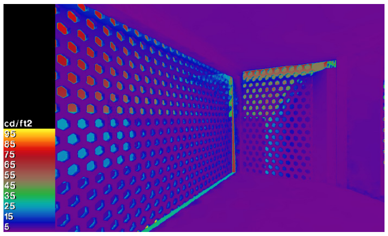
12 pm



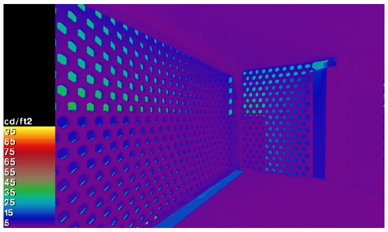
3 pm

Visual Comfort
40% JALI
False Color Render
South

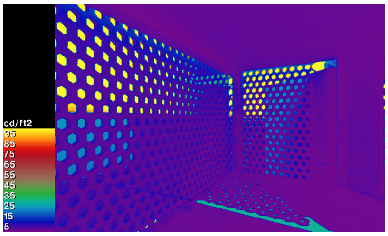
SUMMER



9 am



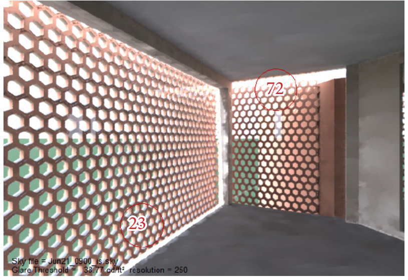
12 pm



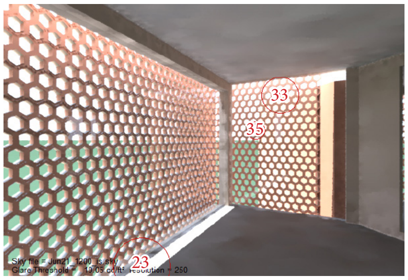
3 pm

Visual Comfort
50% JALI
Glare Analysis
South

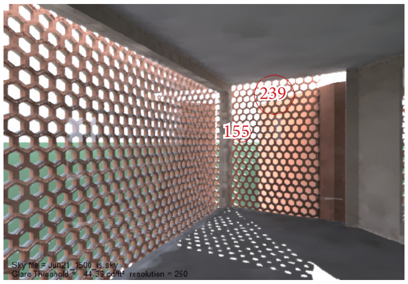
SUMMER



9 am



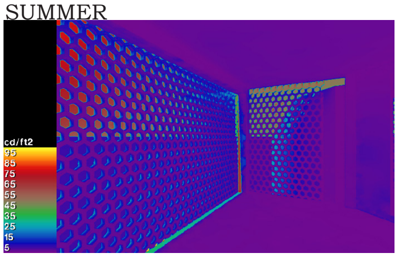
12 pm



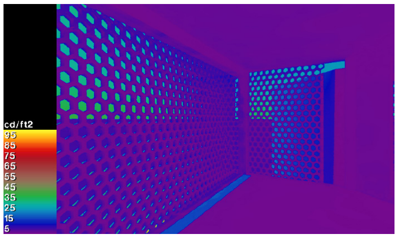
3 pm

Visual Comfort
50% JALI
False Color Render
South

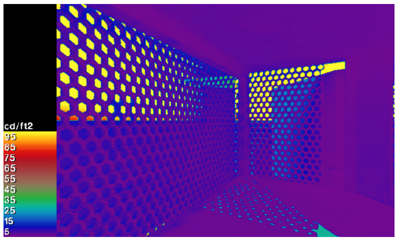
SUMMER



9 am



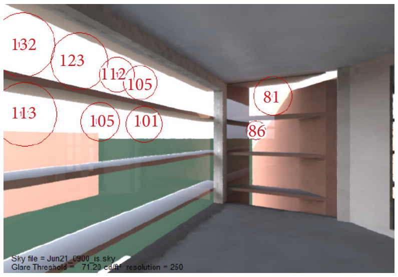
12 pm



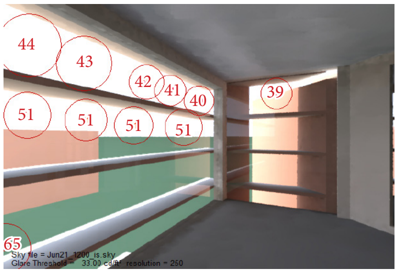
3 pm

Visual Comfort
Brise Soleil
Glare Analysis
South

SUMMER



9 am

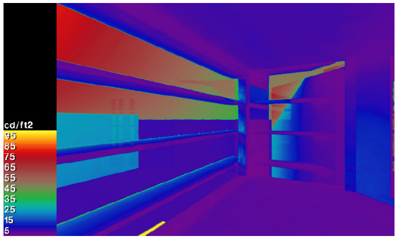


12 pm

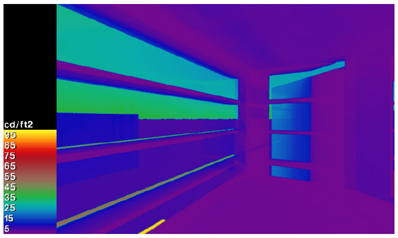
3 pm

Visual Comfort
Brise Soleil
False Color Render
South

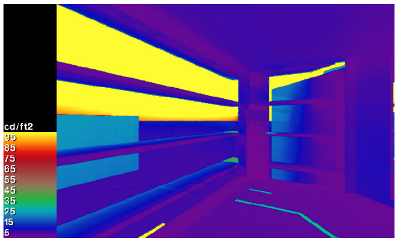
SUMMER



9 am



12 pm



3 pm

APPENDIX D

SUPPLEMENTAL SOURCES

Jali Screens – Photographs and Visuals

http://mini-site.louvre.fr/trois-empires/en/sculptures-incrustations-7-z1.php
http://www.metmuseum.org/learn/for-educators/publications-for-educators/art-of-the-islamic-world/unit-three/featured-works-of-art/image-15
http://cs.nga.gov.au/Detail.cfm?IRN=129691
http://www.artgallery.nsw.gov.au/collection/works/220.1998/
http://www.pinterest.com/watidesign/jali-mughal-screens/

Energy and Comfort

Energy Star – Target finder
http://www.energystar.gov/buildings/service-providers/design/step-step-process/evaluate-target/epa%E2%80%99s-target-finder-calculator

Energy Design Tools – Climate Consultant
http://www.energy-design-tools.aud.ucla.edu/

CBE Comfort Tool
http://smap.cbe.berkeley.edu/comforttool

Historical Weather For The Last Twelve Months in Lahore, Pakistan
Pakistanhttp://weatherspark.com/history/32865/2014/Lahore-Punjab-Pakistan

REFERENCES CITED

Afridi, Aamir. "Energy Crisis in Pakistan." *Pakistan Renewable Energy Society* (blog), September 22, 2013. http://www.pres.org.pk/2013/energy-crisis-in-pakistan/ (accessed December 19, 2013).

Aldossary, Naief A., Yacine Rezgui, and Alan Kwan. "Domestic energy consumption patterns in a hot and arid climate: A multiple-case study analysis."*Renewable Energy*. (2014): 369-378. http://www.sciencedirect.com/science/article/pii/S0960148113003972?via=ihub (accessed February 22, 2014).

Aljofi, E. "The potentiality of reflected sunlight through Rawshan screens." *International Conference “Passive and Low Energy Cooling for the Built Environment”*, 2005. http://www.inive.org/members_area/medias/pdf/Inive/palenc/2005/Aljofi.pdf (accessed April 13, 2013).

Alzoubi, Hussain H., and Amneh H. Al-Zoubi. "Energy Conservation and Management." *Assessment of building façade performance in terms of daylighting and the associated energy consumption in architectural spaces: Vertical and horizontal shading devices for southern exposure facades*. no. 8 (2010): 1592-1599. http://www.sciencedirect.com/science/article/pii/S0196890409004762 (accessed March 13, 2013).

Asher, Catherine B. *Architecture of Mughal India*. London.1992. p. 133

ASHRAE. “ANSI/ASHRAE Standard 55-2010: Thermal Environmental Conditions for Human Occupancy.” American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta. 2010

Baker, Nick, and Koen Steemers. *Energy and Environment in Architecture: A Technical Design Guide*. London: E & FN SPON, 2000.

Bloch, C. “The HDRI Handbook.” 2007. Rocky Nook Inc.: Canada

Boake, Terri Meyer. "HOT CLIMATE DOUBLE FAÇADES: Avoiding Solar Gain." FACADE TECTONICS Journal. (2014).

Bosseboeuf , Didier. ADEME, "Energy Efficiency Trends in Buildings in the EU." Last modified September 2012. Accessed October 22, 2013. http://www.odyssee-indicators.org/publications/PDF/Buildings-brochure-2012.pdf.

Borg, Karl. Buhagiar, Vincent. "Solar Control Mechanisms: Effects on Daylight & Thermal Performance- An experimental Study on a Public Library." *Plea 2011 – 27th Conference on Passive and Low Energy Architecture. Louvain-la-Neuve, Belgium*. 13-15 July 2011.

Boubekri, Mohamed. *Daylighting, Architecture and Health: Building Design Strategies*. Routledge, 2008.

Brown, G. *Sun, Wind, and Light: Architectural Design Strategies*. New York: John Wiley & Sons, Inc. 1985.

Butala, Vincenc, and Peter Novak. "Energy consumption and potential energy savings in old school buildings." *Energy and Buildings*. no. 3 (1999): 241-246. http://www.sciencedirect.com/science/article/pii/S0378778898000620 (accessed January 19, 2013).

Caccavelli, Dominique, and Jean-Louis Genre. "Diagnosis of the degradation state of building and cost evaluation of induced refurbishment works." *Energy and Buildings*. no. 2 (2000): 159-165. http://www.sciencedirect.com/science/article/pii/S0378778899000304 (accessed January 20, 2013).

Cândido, C.,R. de Dear, R. Lamberts. "Combined thermal acceptability and air movement assessments in a hot humid climate." *Building and Environment*. no. 2. (2011): 379–385.

Centre for Natural Resources and Environmental Studies, "VNU Center For Natural Resources & Environmental Studies." Accessed December 2, 2014. http://www.vnu.edu.vn/eng/?C2249/N12733/VNU-Center-for-Natural-Resources-&-Environmental-Studies.htm.

Cheney, K. “Image based rendering: Using high dynamic range photography to light architectural scenes.” 2008. University of Washington: Washington.

Chidiac, S.E., E.J.C. Catania, E. Morofsky, and S. Foo. "A screening methodology for implementing cost effective energy retrofit measures in Canadian office buildings." *Energy and Buildings*. no. 2-3 (2011): 614-620. http://www.sciencedirect.com/science/article/pii/S0378778810003993 (accessed January 21, 2013).

Chow, T.T, Z Lin, W He, A.L.S Chan, and K.F Fong. "Use of ventilated solar screen window in warm climate." *Applied Thermal Engineering*. no. 16 (2006): 1910-1918. http://www.sciencedirect.com/science/article/pii/S1359431106000251 (accessed March 13, 2014).

CRES. “Center for Natural Resources & Environmental Studies. 2000. http://www.vnu.edu.vn/eng/?C2249/N12733/VNU-Center-for-Natural-Resources-&-Environmental-Studies.htm

Creswell, K. A. C., and James W. Allan. *A Short Account of Early Muslim Architecture*. Aldershot: Scolar Press, 1989. 69-71

Crounch, Dora P., and June G. Johnson. *Traditions in Architecture - Africa, America, Asia and Oceania*. New York: Oxford University Press, 2001.

Crowden, G. P. “Indoor climate and thermal comfort in the tropics.“ *Proceedings of the Conference on Tropical Architecture*. University College, London. (1953): 27-35.

Daniels, Klaus. *Low-Tech Light-Tech High-Tech*. Basel.Boston.Berlin: Birkhauser Publishers, 2000.

Daniels, Klaus. *The Technology of ecological building: basic principles and measures, examples and ideas.* Berlin: Birkhäuser Verlag, 1994.

Datta, Gouri. "Effect of fixed horizontal louver shading devices on thermal perfomance of building by TRNSYS simulation." *Renewable Energy*. no. 3-4 (2001): 497-507. http://www.sciencedirect.com/science/article/pii/S0960148100001312 (accessed March 13, 2013).

Doyle, Shelby, and Christoph Reinhart. Harvard Graduate School of Design, "High Dynamic Range Imaging & Glare Analysis High Dynamic Range Imaging & Glare Analysis." Accessed October 23, 2013. http://www.gsd.harvard.edu/research/gsdsquare/Publications/HDR_I_Definitions.pdf.

Einhorn, H. D. "A new method for the assessment of discomfort glare." *Lighting Research and Technology*. no. 4 (1969): 235-247. http://lrt.sagepub.com/content/1/4/235.abstract (accessed December 2, 2013)

Einhorn, H. D. "Discomfort glare: a formula to bridge differences." *Lighting Research and Technology*. no. 2 (1979): 90-94. http://lrt.sagepub.com/content/11/2/90.abstract (accessed December 13, 2013).

El-Zafarany, A., Sherif, A., Sabry, H., Arafa, R., Rakha, T. and Anees, M. “Balancing the Energy Savings and Daylighting Performance of External Perforated Solar Screens - Evaluation of Screen Opening Proportions.” *PLEA 2011 - Architecture and Sustainable Development. 27th Conference on Passive and Low Energy Architecture*. Presses universitaires de Louvain: Belgium. 2011.

Elzeyadi, Ihab. “Vital Signs Project: A Tale of Two Houses - Sustainability, and Indoor Comfort Inside Hassan Fat'hy's Mit Rehan and a Contemporary Villa in Cairo, Egypt.” *Vital Signs Building Case Studies Competition.* 1996. http://www.arch.ced.berkeley.edu/vitalsigns/workup/two_houses/two_conc.html (accessed November 1, 2012)

Elzeyadi, Ihab M. K. "Post-occupancy evaluation: A design, operations and performance assessment of a LEED Platinum building." *World Health Design.* (2012): 60-69. http://www.worldhealthdesign.com/uploaded/documents/WHDJan2012Ads.pdf (accessed October 21, 2013).

Elzeyadi, Ihab M.K. The American Institute of Architects, "Green Classroom Retrofit Toolbox (GCRT): Evidence-Based Design Guidelines to Adapt K-12 School Facilities for Climate Change." Last modified 2008. Accessed September 12, 2013. http://www.aia.org/aiaucmp/groups/aia/documents/pdf/aiab079900.pdf.

EnergyStar, "EPA's Target Finder calculator." Accessed April 22, 2013. http://www.energystar.gov/buildings/service-providers/design/step-step-process/evaluate-target/epa's-target-finder-calculator.

Fanger P.O. *Thermal Comfort: Analysis and Applications in Environmental Engineering.* McGraw-Hill Book Company: New York. 1972.

Fathy, Hassan. *Architecture For the Poor.* Chicago: The University of Chicago Press, 1973.

Fathy, Hassan. *Natural Energy and Vernacular Architecture: Principles and Examples with Reference to Hot Arid Climates.* University Of Chicago Press, 1986.

Foster and Partners. "Norman Foster." 2012. Accessed March 20 2012. http://www.fosterandpartners.com/Team/SeniorPartners/11/Default.aspx.

Fry, Maxwell, and Jane Drew. *Tropical Architecture in the dry and humid zones.* Malabar: Robert E. Kreiger Publishing Company, 1982.

Gelil, Nermine Abdel. "A New Mashrabiyya for Contemporary Cairo: Integrating Traditional Latticework from Islamic and Japanese Cultures."*Journal of Asian Architecture and Building Engineering.* 5. no. 1 (2005): 37-44. http://dx.doi.org/10.3130/jaabe.5.37 (accessed October 19, 2012).

Ghiaus, C. and Inard, C. “Energy and environmental issues of smart buildings.” *A Handbook for Intelligent Building. (*2004):26–51. Accessed 26 September 2013 http://www.ibuilding.gr/handbook/

Grabar, Oleg, and Derek Hill . *Islamic Architecture And Its Decoration A.D. 800-1500*. Glasgow: R. MacLehose and Company Limited, 1964.

Graham, Carl Ian. "High-Performance HVAC." *Whole Building Design Guide*. (2009). http://www.wbdg.org/resources/hvac.php (accessed March 5, 2013).

GreenerBuildings. 2004. http://www.greenerbuildings.eu/

Güçyeter, Başak, and H. Murat Günaydın. "Optimization of an envelope retrofit strategy for an existing office building." *Energy and Buildings*. (2012): 647-659. http://www.sciencedirect.com/science/article/pii/S0378778812004847 (accessed January 21, 2013).

Haberl, J.S. and T.E. Bou-Saada. “Procedure for calibrating hourly simulation models to measured building energy and environmental data.” *Journal of Solar Energy Engineering.* no. 1 *(*1998): 193–208.

HarperCollins. *Collins Thesaurus of the English Language*. (2nd ed.). HarperCollins Publishers: 2002

Harris, C.M. *Dictionary of Architecture and Construction*. fourth ed., McGraw-Hill: New York. 2006. 908.

Hasnain, Tahir. EnviroCivil.com, "Climate Change, Governance and Energy Discourse in Pakistan." Last modified January 24, 2013. Accessed October 7, 2013. http://envirocivil.com/climate/climate-change-governance-and-energy-discourse-in-pakistan/.

Hausladen, Gerhard, Petra Liedl, and Mike de Saldanha. *Building to Suit the Climate - A handbook*. Basel: Birkhauser Publishers, 2012. 106

Hensen, Jan L.M., and Roberto Lamberts. *Building Performance Simulation for Design and Operation*. Routledge, 2012.

Inanici M. “Dynamic Daylighting Simulations from Static High Dynamic Range Imagery using Extrapolation and Daylight Coefficient Methodologies,” *International Building Performance Simulation Association (IBPSA) 2013. Conference,* Chambery, France, August 25-28, 2013.

IESNA Lighting Handbook 2013. *Recommended Practice for Daylighting Buildings.* 2013. https://www.ies.org/store/product/recommended-practice-for-daylighting-buildings-1305.cfm

Jones, Dalu. *Surface, Pattern and Light. Architecture of the Islamic World - Its History and Social Meaning.* Edited by George Michell. London: Thames and Hudson, 1978.

Khan, Masood A., Saif ur Rehman Dar, Rashid A. Makhdum, and PEPAC. *A Haveli, Lahori Mandi Bazar. The Walled City of Lahore.* Edited by Margaret B. Sevcenko, Rashid Makhdom, Donald Hankey, S.M. Irfan, Shaukat J. Khawaja. Lahore: Pack Art Press , 1993.

Khedari, J., Yamtraipat, N. Pratintong, N. Hirunlabh, J. “Thailand ventilation comfort chart.” *Energy and Buildings.* no. 3. *(*2000): 245–249

Koita, Yahya. “Comfort Attainment in Moghul Architecture.” *Passive Cooling.* Edited by Arthur Bowen, Eugene Clark, Kenneth Labs. Newark: Publication Office of the American Section of the International Solar Energy Society, 1981.

Kwok, Alison G., Grondzik, Walter T. *The Green Studio Handbook.* Elsevier: 2011

Laumer, John. Treehugger.com, "Climate Contributes To Lahore Pakistan's Daily Power Blackouts - Australian Coal To The Rescue?" Last modified January 7, 2009. Accessed October 7, 2013. http://www.treehugger.com/corporate-responsibility/climate-contributes-to-lahore-pakistans-daily-power-blackouts-australian-coal-to-the-rescue.html.

"Largest Cities of the World." Accessed October 23, 2013. http://www.worldatlas.com/citypops.htm

Leaman, A., Stevenson, F., Bordass, B. “Building Evaluation: Practice and Principles.” Building Research and Information. 2010. Volume 38, Issue 5, 2010. Special Issue: Housing occupancy feedback: linking behaviours and performance. 564–577

Lewcock, Ronald. *Materials and Techniques.Architecture of the Islamic World - Its History and Social Meaning*. Edited by George Michell. London: Thames and Hudson, 1978.

Lockyear, B.E. “Generative design and analysis of solar screens.” *Proceedings of ASES National Conference: Solar 2010 Conference*. Arizona. The United States of America. 2010. http://studiognarly.com/Docs/GenerativeSolarScreens.pdf

Mallick, F.H.“Thermal comfort and building design in the tropical climates.” *Energy and Buildings*. no. 3. (1996):161–167

Mansour El Sheikh , Mohamed. Faculty Of The USC School Of Architecture University Of Southern California, "Intelligent Building Skins: Parametric-Based Algorithm For Kinetic Facades Design And Daylighting Performance Integration." Last modified May 2011. Accessed October 27, 2013. http://cdm15799.contentdm.oclc.org/utils/getfile/collection/p15799coll127/id/15574/filename/15590.pdf.

Mccluney, R. and Chandra, S. “Comparison of window shading strategies.” *Proceedings of the 9th National Passive Solar Conference*. Columbus, OH. The United States of America. (1984): 414–419.

Miguel, António F. “Airflow through porous screens: From theory to practical considerations.” *Energy and Buildings*. no. 1. (1998): 63-69, http://www.sciencedirect.com/science/article/pii/S0378778897000650

Moeck Martin, Younju Yoon, William Bahnfleth, and Richard Mistrick. Lighting Research Center, "How Much Energy Do Sidelighting Strategies Save?" Accessed March 5, 2013. http://www.lrc.rpi.edu/programs/daylighting/pdf/sidelighting.pdf.

Muhaisen, Ahmed S., and Mohamed B Gadi. "Effect of courtyard proportions on solar heat gain and energy requirement in the temperate climate of Rome." *Building and Environment*. no. 3 (2006): 245–253. http://www.sciencedirect.com/science/article/pii/S0360132305000491 (accessed December 22, 2012).

Nasim, Samina. “Decorative Elements of the Faisal Mosque, Islamabad.” Thesis presented to Department of Fine Arts, Lahore College for Women University, Lahore. http://eprints.hec.gov.pk/6312/1/321S.htm. 2009

Nath, R. *History of Muhal, Architecture*. Vol. ii, New Delhi. 1985. pl ccxii)

Necipoglu. *The Topkapi Scroll -- Geometry and Ornament in Islamic Architecture*. (1996): 111

Nicol, F. and Humphreys, M. and Roaf. S. “*Adaptive Thermal Comfort: Principles and Practice*.” Routledge, London. 2012

Olgyay, Victor, and Aladar Olgyay. *Solar Control and Shading Devices*. Princeton: Princeton U.P., 1957.

Osterhaus, Werner K.E. "Discomfort glare assessment and prevention for daylight applications in office environments." *Solar Energy*. no. 2 (2005): 140–158. http://www.sciencedirect.com/science/article/pii/S0038092X04003536 (accessed April 12, 2013).

Otis, Tiffany, and Christoph Reinhart. Harvard Graduate School of Design, "A Design Sequence for Diffuse Daylighting - 'Daylighting Rules of Thumb'." Accessed October 24, 2013. http://www.gsd.harvard.edu/research/gsdsquare/Publications/DiffuseDaylightingDesignSequenceTutorial.pdf.

Palmero-Marrero, Ana I., and Armando C. Oliveira. "Effect of louver shading devices on building energy requirements." *Applied Energy*. no. 6 (2010): 2040-2049. http://www.sciencedirect.com/science/article/pii/S0306261909005078 (accessed January 1, 2013).

Petersen, Andrew. “Mashrabiyya.” *Dictionary of Islamic Architecture*. New York: Routledge, 1996.

Petherbridge, Guy T. *The House and Society.Architecture of the Islamic World - Its History and Social Meaning*. Edited by George Michell. London: Thames and Hudson, 1978.

Radhi, Hassan, Stephen Sharples, and Fayze Fikiry. "Will multi-facade systems reduce cooling energy in fully glazed buildings? A scoping study of UAE buildings." *Energy and Buildings*. (2013): 179-188. http://www.sciencedirect.com/science/article/pii/S0378778812004343 (accessed November 21, 2013).

Rakha, Tarek and Sherif, A. and Sabry, H. “Daylighting for privacy: evaluating external perforated solar screens in desert clear sky conditions.” *Proceedings of Renewable Energy 2010, Joint with the 4th International Solar Energy Society Conference.* Asia Pacific Region, Yokohama, Japan, 2010. http://eeersociety.wikispaces.com/file/view/Sherif_et_al.2010-Daylighting_for_privacy__evaluating_external_perforated_solar_screens_in_desert_clear_sky_conditions.pdf

Raymond, J. Clark and Hattice, Solzer. “Cultural Response and Sustainability in the Design of a High-Rise Tower in the Middle East.” *CTBUH 8th World Congress*. Dubai. March 2008

Reinhart, Christoph F., and Jan Wienold. "The daylighting dashboard – A simulation-based design analysis for daylit spaces." *Building and Environment*. 46: no. 2 (2011): 386-396. http://www.sciencedirect.com/science/article/pii/S0360132310002441 (accessed October 23, 2013).

Reinhart, Christoph F., John Mardaljevic, and Zack Rogers. "Dynamic Daylight Performance Metrics for Sustainable Building Design." *LEUKOS*. no. 1 (2006): 7-31. http://www.arch.mcgill.ca/prof/sampson/arch447/fall2007/Readings/2-Dynamic Daylight Metrics.pdf (accessed November 1, 2013).

Sabry, H. and Sherif, A. and Rakha, T. “Daylighting Efficiency of External Perforated Solar Screens: Effect of Screen Axial Rotation under Clear Skies.” *ICSDC 2011.* 35: 283-291. http://ascelibrary.org/doi/abs/10.1061/41204(426)36 (accessed on October 20, 2012).

Saidur, R. Energy Policy, "Energy consumption, energy savings, and emission analysis in Malaysian office buildings." Last modified October 2009. Accessed October 22, 2013. http://ideas.repec.org/a/eee/enepol/v37y2009i10p4104-4113.html.

Saini, Balwant Singh. *Building in hot dry climates*. J. Wile & Sons, 1991.

Samuels, William. *Performance and Permeability An investigation of the mashrabiya for use within the Gibson Desert*. Victoria University of Wellington School of Architecture and Design: Master of Architecture Thesis, 2011.

Santana, Rebecca. Huffingtonpost.com, "Pakistan's Power Shortage Problem Is Countr'ys Biggest Threat." Last modified June 15, 2013. Accessed October 7, 2013. http://www.huffingtonpost.com/2013/06/15/pakistan-power-shortage_n_3447599.html.

Saranti, K. . "Air moving in and through building: historical prototypes and contemporary applications." *International Workshop on Energy Performance and Environmental Quality of Buildings*. no. July (2006): 1-6. http://www.inive.org/members_area/medias/pdf/Inive\Milos2006\40_Saranti_6P.pdf (accessed October 27, 2012).

Sherif, A., Faggal, A., & Arafa, R. “External perforated solar screens for thermal control in desert environments: the effect of perforation percentage on energy loads.” *Renewable Energy 2010 Conference Proceedings*. Yokohama: Japan. 2010

Sherif, Ahmed. Hanan, Sabry. Abbas, El-Zafarany, Rasha, Arafa. Tarek, Rakha and Mohamed Anees. “Balancing the Energy Savings and Daylighting Performance of External Perforated Solar Screens - Evaluation of Screen Opening Proportions.” *PLEA 2011- 27 Conference on Passive and Low Energy Architecture*. Belgium: 2011.

Sherif, Ahmed, El-Zafarany, A. and Rasha, Arafa. "External perforated window Solar Screens: The effect of screen depth and perforation ratio on energy performance in extreme desert environments." *Energy and Buildings*. 52. (2012): 1-10. http://dx.doi.org/10.1016/j.enbuild.2012.05.025 (accessed October 01, 2012).

Sherif, Ahmed, Hanan Sabry, and Tareq Rakha. "External perforated Solar Screens for daylighting in residential desert buildings: Identification of minimum perforation percentages." *Solar Energy*. 86. No. 6 (2012): 1929-1940. http://dx.doi.org/10.1016/j.solener.2012.02.029 (accessed October 19, 2012).

Spencer, J. “Mashrabeya, an architectural language.” *Art & the Islamic World.* 1990

Sreshthaputra A, J Haberl, and MJ Andrews. “Improving building design and operation of a Thai Buddhist temple.” *Energy and Buildings.* no. 6 *(*2004)**:** 481–494.

Stoppel, Christopher M., and Fernanda Leite. "Integrating probabilistic methods for describing occupant presence with building energy simulation models." *Energy and Buildings*. no. A (2014): 99-107. http://www.sciencedirect.com/science/article/pii/S0378778813005392 (accessed February 12, 2014).

Sutter, Yannick, Dominique Dumortier, and Marc Fontoynont. "The use of shading systems in VDU task offices: A pilot study." *Energy and Buildings*. no. 7 (2006): 780-789. http://www.sciencedirect.com/science/article/pii/S0378778806000582 (accessed January 21, 2013).

The Engineering Tool-Box, "Specific Heat Capacity." Accessed October 22, 2013. http://www.engineeringtoolbox.com/specific-heat-solids-d_154.html.

Tzempelikos, Athanassios. "Solar Energy." *The impact of venetian blind geometry and tilt angle on view, direct light transmission and interior illuminance*. no. 12 (2008): 1172-1191. http://www.sciencedirect.com/science/article/pii/S0038092X08001345 (accessed May 1, 2013).

Umnuakov, I. *Samarkand, A Guide*. Moscow. 1972. pl. 270a.

Utzinger, Dennis M. "Millet Method." *[Sbse]* (blog), April 3, 2013. https://lists.uidaho.edu/pipermail/sbse/2013-April/000686.html (accessed October 23, 2013).

Vandal, Sajida H., Nasrullah Nasir, Saba Samee, and Aisha Imdad. UNESCO, "Cultural Expressions of South Punjab." Accessed October 19, 2012. http://unesco.org.pk/culture/documents/publications/Cultural_Expressions.pdf.

Wang, Jen Chun. "A study on the energy performance of hotel buildings in Taiwan." *Energy and Buildings*. (2012): 268–275. http://www.sciencedirect.com/science/article/pii/S037877881200093X (accessed September 10, 2013).

Waraich, Omar. Time, "Pakistan’s Biggest Challenge Is Not the Taliban — It’s Electricity." Last modified June 25, 2013. Accessed October 7, 2013. http://world.time.com/2013/06/25/pakistans-biggest-challenge-is-not-the-taliban-its-electricity/.

Wijewardane, S. and Jayasinghe, M.T.R. “Thermal comfort temperature range for factory workers in warm humid tropical climates.” *Renewable Energy*, 2008. 33:9. pp. 2057–2063

Yang, Li, Bao-Jie He, and Miao Ye. "Application research of ECOTECT in residential estate planning." *Energy and Buildings*. (2014): 195-202. http://www.sciencedirect.com/science/article/pii/S0378778813008578 (accessed March 1, 2014).

Zahid, Maida, and Ghulam Rasul. "Thermal Classification of Pakistan." *Atmospheric and Climate Sciences*. (2011): http://www.SciRP.org/journal/ac.

Zhai, Zhiqiang John, Jonathan M. Previtali. "Ancient Vernacular Architecture: Characteristics Categorization And Energy Performance Evaluation." *Energy and Buildings*. 42. No. 3 (2010): 357-365. http://dx.doi.org/10.1016/j.enbuild.2009.10.002 (accessed October 28, 2012).

Zhivov, Alexander, Dale Herron, and Richard Liesen. USACE Engineer Research and Development Center, "BUILDING ENVELOPE." Accessed October 21, 2013. http://www.wbdg.org/pdfs/usace_buildingenvelope.pdf.