A METHODOLOGY FOR AN ENERGY EFFICIENT

DAYLIGHTING DESIGN

A CASE STUDY

by

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DEDICATION

This thesis is dedicated to the memory of my grandmother, Laxmibai P. Dahanukar, for her love and strength throughout my growing up years.
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INTRODUCTION

In hot / dry regions, daylight is a desirable source of illumination while the thermal effect of solar radiation at most times is undesirable. As seen in traditional architecture common design solutions for controlling solar heat gain were smaller fenestration areas or the use of shading devices or openings that controlled or altered solar penetration.

As is evidenced by examples of traditional architecture of the world, the building envelope has always been the principle modulator of the external and internal environment.

It was only on the onset of the industrial revolution and the invention of the structural frame, that architects became fascinated by the ability of separating the structure and the envelope as seen in the Barcelona Pavilion in Spain. The "wall" thus lost its role as the principle building envelope. In the early twentieth century the "glass box" was born not as much as a direct product of the industrial revolution but as a symbol of technology - of the 'modern era', and the ability to unite the inside and the outside. A good example of this is the 'glass house' built by Philip Johnson in the 1950's. Also the advent of the mechanical Hyper Ventilating Air Conditioning system (HVAC) and breakthrough in artificial lighting systems made it possible to modulate the interior microclimate to acceptable levels of thermal comfort, which otherwise would not have been possible. Due to this fascination with the 'modernist' solution for a building that could be built anywhere with any orientation, the glass facade became very popular and was used for all building types ranging from residential to commercial. An idea greatly encouraged by the national competition sponsored by Westinghouse in the early 1950's. This competition was based on the premise that by designing around air-conditioning, the same house/building can be built anywhere with any orientation. [Lam, 1986]
Architects encouraged by industry and the marketplace thus started ignoring traditional practices of building construction, creating buildings that largely ignored actual climatic conditions prevailing in the area. The result was a high dependence on mechanical and electrical systems to control the indoor environment. A situation that provoked the consumption of large quantities of energy and thus resulted in high running costs for artificial lighting and air-conditioning associated with thermal and visual occupant discomfort. This is more accentuated in non-domestic buildings, which are characterized by daytime use patterns and long hours of electric lighting use.

Electric lighting thus loomed as the major energy consumer in commercial buildings.

The high consumption of electric energy for artificial lighting has been partly due to the fact that Daylighting has been ignored and many a times discarded as a suitable source of illumination and also because the spaces are overlit, a strategy promoted by power and lighting industries to increase the demand for more power plants. Thus high illumination levels were incorporated into codes. In some cases ‘required’ light levels were so high that artificial lights had to be used all the time, regardless of the external climate and availability of natural light. Such lights often heated buildings to the extent that air conditioning was needed throughout the year. This illusion of a limitless supply of cheap energy was to an great extent promoted not by public need but by the profit motives of privately owned utilities in the US. They created decreasing rate structures that encouraged waste by the largest users, whose very low rates were being subsidized by smaller users. [Lam, 1986]

Now that the idea of unlimited supply of cheap energy has been recognized as a myth, users are beginning to question the qualities of the totally artificial environment
produced by the architecture of technology. It seems to be time to reexamine the traditional architecture of the world, which evolved around climatic and human needs.

After introducing the problem of daylighting, one is made aware of the potential of daylighting design as an energy conscious approach. Daylighting does not ignore, nor seek to replace artificial lighting, but to integrate the two. So, if handled sensitively, Daylight should bring about an optimum blend of design and technology giving maximum human satisfaction, both physiological and psychological, with minimum expenditure of energy.

This research is focused on developing a new methodology for 'Energy Efficient Daylighting Design'. The method will integrate both daylighting and energy efficient strategies while maintaining visual and thermal occupant comfort. The report presents a brief review of the historic precedents of the use of sunlighting in architecture. Following is a brief chapter familiarizing the reader with some of the commonly used terms in daylight analysis calculations. The selection of the case study and the proposed/selected strategies and their impact on the same are discussed in detail in the following chapters. As the conclusion a methodology for arriving upon daylighting solutions that enhances the quality of the light as well as reduces the energy consumption by artificial lighting and air-conditioning is presented.
CHAPTER 1.

ROLE OF NATURAL LIGHT IN ARCHITECTURE.

Throughout history, throughout the world, the sun has been worshipped by mankind. Its benefits have been recognized, praised and prayed for. Because of its predictability it has affected the daily work, play and rest schedules and also the forms, materials, dress, and portable shelter of man. Sun lighting is thus the conscious design of a building to the use of sunlight for the illumination and thermal benefit, while Daylighting is the use of sky lighting to achieve a desirable illuminance level without the thermal load. These strategies have evolved slowly over the generations to suit visual and thermal need, within the restrictions of available construction materials and skills. The indigenous architecture of the world are primary examples of sunlight and upon analyses one notices an inherent logic in their use of forms, orientation, colors and materials. [Lam, 1986]

![Section showing pierced slabs of stone to filter light](a)

![Plan showing axial sequence through space](b)

Fig. 1.1. Great Temple of Ammon at Karnak, 1530-323 BC. (After Fletcher, 1975)

A study of Egyptian architecture especially Egyptian temples, reveals in its linearity the basis of its architecture. The Egyptians were a polytheistic society, with most of their gods represented by forces of nature, Amon the sun god being given special importance. Apart from this strong religious influence of the Sun, the presence of blinding sunlight and
A desert landscape also influenced the architecture. This is seen in the small size of the openings and the thick masonry walls which provided thermal storage thus reducing the diurnal swings characteristic of most desert climates. In temples, light was introduced in the interior through clerestory openings as in Temple of Ammon at Karnak, (see fig. 1.1.a). There the quantity of light was intentionally varied to reinforce the axial sequence through the great Hypostyle hall and finally to the darkest inner sanctum.(see fig. 1.1.b) Urban housing in ancient Egypt used an inner courtyard(atrium). In addition to providing light to inner rooms, it provided a primary work space, private social area for the family, and a sleeping area during summer. [ Moore, 1985 ]

Another geographic setting that profoundly affected its architecture and culture was that of Greece with its mild and sunny climate. It is seen in the myriad of public activities that were conducted outdoors in ancient times. The Greeks primarily built temples in stone facing east to illuminate the cult statue that it housed, (see fig. 1.2a). They were "object buildings" designed to be viewed from the exterior rather than inhabited. The offerings and prayer took place on a outside altar. Unlike the temples which were oriented for religious reasons, the ancient Greek towns seem to be laid out on a orthogonal grid that provided solar access to houses for lighting and heating. It may be likely that this was
intentional, as the Greeks were aware of the sun's movement as evident by their use of the Sundial. Houses were designed for winter solar gain through the pastas, a long shallow "room" or portico that opened onto a courtyard to the south. The court was surrounded on three or four sides by a colonnaded peristyle, (see fig. 1.2b).

Unlike the Greeks who conducted most public gatherings outside, the Romans focused on the interior space. Being prodigious builders they built many monumental buildings, palatial or civic and developed a variety of strategies for illuminating the interior. The development of the round arch, barrel vault, and dome allowed masonry materials (which are weak in bending) to be used in compression to span large spaces. The invention of concrete also made possible large uncolumned interiors and big wall openings that could admit abundant light. The Golden house of Nero employed skylight, through the oculus to illuminate the central octagonal wall and also a series of concealed clerestories to light the surrounding chambers, (see fig. 1.3). Another good example of solar consideration were the Roman Baths (thermae). These public buildings combined aspects of a modern health club with that of a public library and school. In the baths of Caracalla, the largest in Rome, show the logical placement of rooms. The Hot rooms (calderium) are on the south-west side facing the sun, the changing rooms (apodyteriums) are on the north-east side, the center is the cool, unheated room (frigidarium)

Fig. 1.3 The Golden House of Nero, Rome, A.D. 64-68. Section, Plan showing oculus and concealed clerestories.

(After Boethius and Ward - Perkins, 1970)
After the decline of Rome, the Basilican plan, used for court and commercial trade functions, was adopted for religious services by the Early Christians, (see fig. 1.4). The Roman vaulting was replaced by timber trusses, resulting in sloped side-aisle roofs that reduced the wall area available for clerestories. The reduced illumination helped enhance the mysticism of the new religious functions. It also enhanced the linear perspective with its convergence on the semi-circular apse which would be typically lit by windows that gave this area more visual emphasis.

The Byzantine use of the "dome" supported at four points by pendentives to cover a rectangular space, instead of the continuously supported dome of the Roman time made the "centralized" plan very popular with surrounding secondary spaces covered with half domes, (see fig. 1.5). [ Moore, 1986 ]. Light was usually admitted through many small stained-glass window at the base of the dome, creating a illusion of the dome floating. A return to barrel vaulting and arches of the Romans characterized the Romanesque. The linear basilican plan with an elevated dome at the intersection. Because of the barrel vaulting, windows in the load bearing walls were kept small. The non-bearing end walls could sustain larger openings, and therefore one saw the appearance of the Rose window.
Unlike the Romanesque architects who were struggling under the weight of load-bearing construction which curtailed the size and the number of openings, the Gothic period saw the highest level of structural sophistication in stone masonry. The development of the pointed arch and the rib vault which enabled the transmittance of the roof loads laterally to point locations on the walls. The flying buttress was another innovation to transmit vertical loads to the ground while resisting the outward thrust (see fig. 1.6). This freed the wall from its traditional role as the primary roof support and allowed for vast expanses of stained glass with the buttress extending beyond like fins, thus creating a lighter and a more visually transparent architecture. [Roth, 1993].

Fig. 1.5 The Byzantine use of the pendentive dome. (After Trachtenberg, 1986)

Fig. 1.6 Flying buttresses. (After J.H. Acland)
As one can see Gothic architecture was an assembly of parts worked out for each building individually. It was an architecture that could adapt to any situation, but it was not an architecture determined by universal norms that formed the basis of the Renaissance period. The Renaissance saw a revival of interest in visual harmony and systems of proportion. To the Italian of the fifteenth century, Gothic architecture was a symbol of an uncivilized period that separated the glories of ancient Greece and Rome from their own time. Thus the Renaissance architect set out to match intellectual and artistic achievements of the ancients. Classicism was the new architectural vocabulary. [Roth, 1993]. Daylight was typically used to emphasize architectural form and dramatize internal spaces. The important development of the renaissance was the thick wall and the dome supported on the drum. The thick walls and ceilings required deeply recessed daylight openings allowing a play of light and shadow.

Opposed to the Renaissance architects of the 15th and 16th century who endeavored to create new rational forms based on what they understood of the classical architecture of the ancients, the 17th century architect, who continued to develop the same, arrived at something different from what had been intended by Alberti and Brunelleschi, the Renaissance maestros. The nature of Baroque architecture was deliberately complex. They strived for ambiguity and contrast instead of Renaissance clarity and discipline. The aim was to create an emotional impact. The use of Frescoes and indirect lighting hallmark this period. Light was used to create a mood, a setting, to impress upon the viewer a mystical experience. It was rightly called the "architecture of the senses". [Roth, 1993]

The "architecture of the ancients" were largely influenced by religion and politics. This is evidenced in the numerous religious structures and palatial buildings built. The industrial revolution changed all that. Prior to the 1800's the builders simply could not afford to ignore the climate of the site and by necessity had to depend upon the building envelope to
admit light and to control other environmental conditions. [Chavez, 1989] The suitable response to the natural environment produced a well-lit and thermally comfortable shelter that common-sense builders developed to propagate traditional building. Thus traditional massive construction with limited window areas has the universal merit of thermal mass, minimum heat loss and gain through openings, and a reasonable thermal resistance of walls and roofs. Because of this the building envelope acted as the principle modulator between the internal and external environment. [Moore, 1985] The development of the structural frame and the availability of economical steel members permitted the building to be supported only on columns, and thus the wall was replaced as the main structural support system by the column, reducing its role to that of an element to exclude water, wind, and snow; minimizing its thickness and mass to reduce its weight on the columns. The temptation to cover the new structural frame with glass was natural. This approach provoked a number of environmental problems in buildings, such as excessive winter heat loss and summer heat gain, poor distribution of daylight and resulting in glare. The new structural capabilities of the buildings allowed for deeper internal spaces, in which daylight was badly distributed with over-illumination near the windows and gloomy areas in the depth of the plan, (see fig. 1.7). As a response to this, new artificial light sources were developed.

Fig. 1.7. Showing decreasing illumination levels in deep internal spaces
The development of the incandescent lamp in 1881 by Swan in England, and Edison in the U.S.A, made the gas mantle lamp obsolete. The incandescent lamp offered a double solution to the environmental problems posed by the gas lamps; it generated less heat and made no soot. However these lamps had low luminous efficacy (ratio of the total luminous flux emitted by the lamp to the total lamp power input, in lumens/watts power). [Chavez, 1989] Because of this Daylighting still strongly influenced building design, giving rise to buildings with central courtyards, narrow building configurations, high ceilings and above all large window areas. It was the availability of commercial fluorescent lighting in 1938, that really changed the situation. The fluorescent lamp offered a luminous efficacy from 4 to 6 times higher than the incandescent lamp (more effective light to heat ratio), longer life and apparent lack of glare. The use of Fluorescent lamp allowed the footprint of the building to become deeper, and soon windows, clerestories, skylights and light wells, started to be replaced as the primary source of illumination. The height to depth ratio of spaces which has been designed for natural ventilation, were no longer constraints, due to the advent of forced ventilation and air conditioning. Suspended ceiling thus came in to use, a necessity to conceal the upper part of the room volume occupied by ducts and conduits. Abundance of natural light was the main aim with no concern for its imposed thermal load on a building. This provoked a buildup of internal heat, increasing reliance on air-conditioning. The AC system required no admittance of external air flow, that is, windows should be kept closed at all times to avoid interference with the operation of the AC equipment. As a result the sealed building became prominent. The resultant buildings with fully glazed facades irrespective of orientation or latitude in conjunction with deeper and lower spaces, made the internal environment highly dependent on artificial control systems. [Chavez, 1989]
Parallel to the advent of interior lighting a "modern movement in architecture" was initiated at the beginning of the Twentieth century. This was more in reaction to the over-ornamentation of the classical revival of the 19th century and was supported by the technical developments of the Industrial revolution. One would think that advances in technology should have led to an more intelligent use of natural energy in buildings, but this unfortunately wasn't the case. After the second world war, the functionalist approach, with its resulting simple geometry, building forms, using vast areas of glazing gave rise to an "International Style of Architecture", where a design was built anywhere, irrespective of local climatic conditions. The propagation of this attitude was reinforced by the work of some European architects like Mies, Gropius, etc. who emigrated to the US. after 1940. Since then the industrially based, energy-dependent architectural style, has been widely accepted and adopted.

While the abundance of energy lasted and till it was relatively cheap, the excesses of the International Style were of little concern. The oil embargo in 1973 was a rude awakening that led to professional and public consciousness to the environmental and economical issues of the modern movement. As most professionals and decision makers were educated before the 1970's in a pro-technology, energy-abundant era, it was relatively easy for the clients and the lending institutions to be supportive of energy conservation. But for the architect it was a complex task, to rethink previously accepted design practices and strategies. It needed acquisition of fundamental technical knowledge to work with various systems and thus reclaim the role of an integrative designer. [Moore, 1985]

Concurrent to the energy conscious design movement, another unrelated architectural movement surfaced. The Post Modern Style was a reaction to the visual austerity of the modern movement. It is a movement that strives to revive color, ornament and spatial characteristics of the premodern style. It was to be an visual antidote to the sterility of the
International style. A commendable program but extensively misinterpreted. It was mostly surface articulation of the facades in various "styles" and resulted in being merely "pastiche". It was because of the styles prominent visual aspects that it has received extensive acclaim in both the public and professional spheres. But this beauty of the Postmodern is only skin deep. Devoid of the applied ornament, the style of the building is basically identical to the International Style it strived to replace. [Moore, 1985]
CHAPTER 2
PHYSICS OF LIGHT

2.1 Common Terms and Properties

The purpose of this section is to introduce the concepts and terms commonly employed in Daylight analysis.

Natural light:
Located in the visible portion of the electromagnetic radiation spectrum. It is a narrow wave-length band, (see fig. 2.1). The sun being the primary source of natural light, a large amount of thermal radiation in the near infra-red part of the spectrum is also received together with light. It is therefore very important to understand the distinction between the thermal and luminous qualities of sunlight for optimizing its use in building design.

The physical principles of light can be expressed by five luminous qualities:

Luminous Flux or Light Flux (measured in Lumens).
The Photometric term for the time rate of light flow is Luminous Flux. The unit of measurement of Luminous flux is the lumen.
A lumen is the luminous flux emitted within a unit solid angle (one steradian) by a point source having a uniform luminous intensity of one candela.

Fig. 2.1 The visible spectrum of the electro-magnetic radiation spectrum.
**Luminous Intensity:**

A light source emits luminous flux in various directions away from its surface. The luminous intensity is the amount of luminous flux in a given direction measured in lumens/solid angle and is measured in Candelas.

**Candela:** Is the SI unit of luminous intensity.

1 candela = 1 lumen/steradian in a given direction.

**Illuminance:**

When a luminous flux strikes a surface, that surface is said to be illuminated. Illuminance is thus the density of luminous flux on a surface. It is measured in Lumens/sq.m or Lux.

**Lux:** The SI unit of illuminance equal to one lumen per square meter.

**Foot candle:** The unit of Illuminance when the foot is taken as unit length.

**The Inverse Square Law:**

The direction of Luminous flux is divergent away from the point light source. Because the direction is not parallel, the luminous flux is spread over an even larger area as it travels further from its source (but the flux within the solid angle remains constant at all distances). Because of this, Illuminance is an inverse square function of the distance from source, (see fig. 2.2).

![Diagram of the Inverse Square Law](image)

Fig. 2.2. The Inverse Square effect - Illuminance as a function of distance. (After Moore, 1985)
Cosine Law of Illumination:

If a surface is perpendicular to the direction of light, it receives the greatest amount of light flux possible for its area. However if the surface relative to the direction of light, the area exposed to the source is less, and therefore fewer lumens are intercepted and therefore Illuminance is reduced. For surfaces that are not normal to the source, Illuminance is reduced by Cosine of angle of incidence.

Reflectance, Absorptance and Transmittance of Light:

Light incident on a surface can be distributed in three ways: by reflection, absorption, and transmission.

\[
\text{Reflectance} + \text{Absorptance} + \text{Transmission} = 1
\]

![Fig. 2.3 Light Reflectance, Absorption and Transmission. (After Moore, 1985) ]

Reflectance:

Is the ratio of reflected flux to incident flux. The reflective characteristics of a surface range from ideal matte to specular. The result of light reflected from a matte surface is diffuse light. If parallel incident rays remain parallel after reflection, specular reflection occurs and then, the surface is considered a plane mirror. Therefore the angle of incidence is congruent to the angle of reflection. In practice, most building materials will have some combination of specular and diffuse reflection (see fig.2.3)
Absorptance:
Is the ratio of absorbed flux to incident flux. Absorptance is the property of the material. Absorption is a general term for the process by which incident flux is converted to another form of energy, usually and ultimately to heat.

Transmittance:
Is the ratio of transmitted flux to incident flux. If the passage of light is blocked, the material is called "opaque". No glazing material is absolutely opaque or fully transparent. Transparency and thus Transmittance of a material also is dependent on thickness. Translucent materials refer to objects which transmit light, but break its straight path and scatter it in all directions, creating diffuse light.

Luminance and Subjective Brightness:
Illuminance evokes no visual stimuli. Light has to be reflected from a surface, and it is the brightness of such a surface, which results from the reflection of the light flux, that ultimately produces visual stimuli. Therefore the brightness of a reflecting surface depends on the Illuminance which it receives and the reflecting characteristics of the surface. The built-in sensitivity that the eye possesses allows that a given light flux stimulating the retina under a certain set of circumstances will produce a different sensation of brightness from the same amount of flux under another set of circumstances. That is, a certain brightness seen in dark surroundings will appear much brighter to the eye than the same brightness seen in lit surroundings. For this reason, it is necessary to distinguish between the physical brightness of an object, as measured by an photometer, which does not adapt as does the eye, and the subjective brightness of the object as seen by the adapted eye in a given surrounding. The term Luminance is thus used to specify the physical quantity of brightness(measured by an photometer). Therefore Reflected Luminance is the physical Photometric measure
of brightness of an illuminated opaque surface and is the product of Illuminance by reflectance of the surface, whereas **Subjective Brightness** is the visual sensation equivalent to luminance and is determined by factors such as the state of adaptation of the eye and the actual Illuminance of the space.

The term **Transmitted Luminance** refers to the product of surface Transmittance and Illuminance measured on the reverse side surface, and its unit is candelas/sq.m. For translucent surfaces, transmitted luminance depends on the angle of Transmittance and the diffusing qualities of the surface itself.

**Daylight Factor:**
Because interior Illuminance due to daylight changes as a function of sky conditions, absolute measurements of Illuminance are not directly indicative of actual building performance. The daylight factor is a ratio of interior and exterior Illuminance under an overcast, unobstructed sky (measured in a horizontal plane at both locations and expressed as percentage) and remains constant regardless of changes in absolute sky luminance. This is so because the relative luminance distribution of an overcast sky is constant and does not change with time. A daylight factor of 10% at a given interior location, for e.g., means that the location receives 10% of the Illuminance that would be received under an unobstructed sky. (the constancy of the daylight factor for a building applies only to the overcast sky conditions; under clear sky conditions, the daylight factor can vary as the sky luminance distribution changes with the position of the sun.)

**Graphic Representation of Illuminance:**
Daylight factor data from physical model studies, calculations, or building surveys can be represented graphically in the form of contours of equal daylight factors plotted over a building floor plan. This isolux contour method allows for ready assessment of Illuminance distribution throughout an area. (closely spaced contours represent a strong
Illuminance gradient, while widely and uniformly spaced contours represent a relatively even distribution.) Graphs of Illuminance levels are also frequently used for building sections. This is particularly useful for comparing data from physical model studies of alternate window configurations, (see fig.2.4).

![Floor plan with daylight factor isolux contours. (After Moore, 1985)](image)

2.2 Visual Comfort and Perception

Vision is the eye's ability to sense that portion of the radiation spectrum that is defined as light. Since evolution of man has occurred with daylight and sunlight as primary sources of terrestrial radiation, it seems that the limits of the human eye sensitivity approximate the limits of the solar spectrum.

Visual Adaptation:

The human eye is agile in adapting to various lighting conditions. All visual experience (of brightness, color, distance, perspective) is measured against some reference experience. This experience could be present (in form of surrounding luminous environment) or past (in form of expectations based on prior experience - an effect known as constancy). There are two visual effects of one's present environment that are particularly relevant to daylight illumination: General adaptation and Local Brightness Contrast.
**General Adaptation:**

Because of changing sky and sun conditions, absolute illumination levels are not predictable. The inability to predict absolute amounts is a source of concern for some, who are accustomed to the predictability of electric sources. The large variations inherent in daylight do not result in correspondingly large perceived changes in the interior. This is due to the wide range of adaptation of the eye to changing overall levels of illumination. Interior daylight illumination is usually expressed in terms of daylight factor. The daylight factor is thus a better measure of visibility than foot-candle. As the sky brightens, the eye adapts to an increase in interior illumination level so that the perceived effect is more closely related to the proportion of available light (the daylight factor) than to the measurable level. The physiological process of adaptation is a combination of rapid changing of the pupil diameter and a slower change in retinal sensitivity. Generally, changes in sky brightness conditions occur slowly enough to allow comfortable adaptation of the eye.

**Local Brightness Contrast:**

The eye generally adapts to the average of the various brightness within the field of view, being affected by most by brightness nearest the center of vision. If an area of high brightness is seen next to an area of much lower brightness, the eye tends to adapt to the average, making it difficult to discern detail in either area, especially in the low brightness area. While the eye could adapt to either of these brightness levels alone, the adjacency of the two levels in the field of view is the source of discomfort and reduced visual acuity. Local brightness contrast can be reduced by the use of similar reflectance on adjacent surfaces and (in case of windows and other Daylighting apertures) by ensuring that surfaces surrounding the opening have a relatively high luminance (i.e. receive light and are of high reflectance).
Brightness Constancy:
Constancy is the visual tendency to perceive the environment as it is remembered. Rarely noticed light constancy is always present in a lighted interior.
e.g. the amount of light reaching a white ceiling from side lit room may be, at the back of the room, only 1/20th of the light on the ceiling at the front. Yet the eye perceives the ceiling as white all over, rather than as white near the window and dark gray at the back of the room. The observer knows from experience that the ceiling is uniformly white and thus discounts the fact that not all areas of the ceiling receive the same illumination.

Visual Performance and Comfort:
Visual acuity is the ability of the observer to distinguish fine details. To a certain limit, visual acuity increases with increased illuminance of the task surface. Contrast sensitivity is the ability of the eye to distinguish differences in luminance and is also a function of task illumination. e.g. under poor illumination, it may not be possible to distinguish between a black card and an adjacent dark gray card; under better illumination, the difference is obvious.

Disability Glare:
results from areas in the field of view of such brilliance that they cause a scattering of light within optical matter of the eye, causing a veiling effect. this veiling effect reduces visual contrast to such a degree that seeing is reduced.

Veiling Reflections:
A veiling refection is a form of reflected glare that occurs when the source of illumination is reflected by a specular task surface. A familiar example is the image of an overhead skylight or electric lighting fixture reflected on the surface of a glossy magazine. Veiling reflections reduce visibility because the brightness of the reflected image causes an
increase in the brightness of both the light and dark features of the task surface. (e.g. if the brightness of both the black lettering and the white surrounding page are increased to very high levels, the contrast between the two will be eliminated.) Because veiling reflections are specular, they can be anticipated whenever concentrated light sources occur within the reflected field of view of the task surface.

**Discomfort Glare:**

Glare that produces discomfort, but does not necessarily interfere with visibility or visual performance, is termed discomfort glare. It may result from bright sources within the field of view that are not inherently distressing, but are seen in much darker surroundings.

**Direct and Reflected Glare:**

Glare can be categorized on the basis of the path of light. Direct glare is caused by sources directly visible within the field of view. Reflected glare is glare from a glossy surface that reflects an image of the light source. Disability Glare and Discomfort Glare can be caused by either direct or reflected light.

(For more information see Moore, 1985 and Chavez, 1989)
Ch. 3  Analysis of the case study building

3.1  Introduction

The building selected for analysis, is located in Tucson, Arizona. This building is the school of Business and Public Administration on the campus of The University of Arizona. (see fig. 3.1.a) The actual "case study" is a medium size office space on the first floor of the said building facing south and looking out on a internal courtyard. (see fig. 3.1.b) The "office space" as we shall refer to it hereafter is 6.1 m wide and 6.12 m deep with a height of 3.606 m. It has for a window space all of its south wall facing the internal courtyard. (see fig 3.1.c)

This office space was selected for the following reasons:

a) It is representative of the 'glass box' modernist buildings that are being constructed to portray an image of Technical superiority and prosperity.

b) It also exemplifies a typical building with high running costs for artificial lighting and air-conditioning.

c) It represents, according to depth interviews and a conducted survey questionnaire with the occupants (see Appendix A), problems of thermal and visual discomfort, despite the air-conditioning, artificial lighting systems and an abundance of natural light.

d) The activities carried out in this office space are, general reception and word processing tasks with occasional prolonged tasks by part-time student employee on the two computer terminals. This office thus indicates a need for good general illumination (which can be provided by daylight) with artificial lighting at specific tasks. The office space is thus a good candidate for Daylight analysis.

e) It was felt that the findings from this experiment could be applied to a significant number of similar office spaces in the same building, and thus saving substantially on operating costs.
BPA Building: Overall plan showing location of case study 'office space'.

LOCATIONS MAP

BPA Building: VIEW

School of Business and Public Administration
The University of Arizona, Tucson

Fig. 3.1.a
Photograph showing internal courtyard.

Photograph showing inside of office space facing south.
3.2 Objective

The objective of this chapter is to analyze and assess the luminous conditions of the office space by two methods:

a) Actual Daylight measurements using LI-1000 photometer.

b) Using SUPERLITE 1.0 a Daylight analysis software developed by Berkeley Laboratory.

After validation of the outputs from both these methods of calculation, daylight design alternatives will be compared keeping in consideration their thermal impact. This will be done using a thermal analysis software called Calpas3.

3.3 Measurements of the Luminous Conditions in the Office Space.

3.3.1 Equipment used for measuring the luminous conditions of the Office Space

1 LI-1000 Datalogger
1 210SA Cosine corrected Photometric sensor.
2 Torpedo levels
1 Tripod
1 Measuring Tape
1 35/105 mm Pentax auto focus, autozoom camera.

Analysis Software used:
LI-1000 Data logger.
Calpas3
SUPERLITE 1.0
About LI-1000:

LI-1000 is manufactured by LI-COR, inc. in Lincoln, Nebraska. The LI-1000 Datalogger is a 10 channel datalogger that functions both as a data logging device and a multichannel, auto ranging meter. Each channel has 3 configurations viz.: LIGHT, THERM, GEN. They include a light sensor configuration for operation with LI-COR light sensors, a thermocouple configuration for operation with 1000-10 Thermocouple Terminal Block, and a general channel configuration for use with most other type of sensors. One can either get instantaneous readings (INSTantaneous mode) or the LI-1000 can be used as a Datalogger (LOG mode).

The LI-210SA Cosine corrected Photometric Sensor is designed to measure illumination in terms of Lux (1 fc = 10.764 Lux). This sensor may be handled or mounted at any angle. For the purpose of this experiment it was set on a level surface at a height of 75 cm. (For more information see LI-1000 DataLogger Instruction Manual, 1987)

About CALPAS3

Calpas3 is considered one of the most sophisticated energy design/simulation programs for houses and small commercial buildings. It is a useful design tool with a full 8760 hour simulation for predicting the energy performance. It calculates hourly air, surface, and mass temperatures throughout the building, as well as heat transfer among components, the contribution of natural energy to comfort levels, and the mechanical heating or cooling needed to maintain temperatures specified by the designer.

The program will model the heating and cooling loads of one or two-zone buildings, with air and storage temperatures (at up to 38 nodes), heat gains and losses, and all heat transfer within the building. Incident solar radiation on each surface is calculated in detail, as well as the exact values of transmittance for each window. Infiltration rates can vary.
with wind speed and temperature differences. Conduction from a slab or rockbed to an approximate ground temperature is also calculated.

The second zone can represent an attached sunspace or greenhouse, an envelope, vented or unvented attic, crawl-space, or basement. Thermal mass can be in the form of masonry or water wall (with or without vents), slab with or without covering, and other distributed or concentrated interior mass. The rockbed can be connected to any combination of house, sunspace, and outside air or evaporative cooler.

You can model any wall or window orientation or type, forced or natural convection between zones, and seasonally and monthly variable shading from shutters, overhangs, and side fins. Ground reflectance can also be specified monthly for each glazing section to represent a horizontal reflector or some special condition. Additionally, movable window insulation, thermal and wind-driven natural convection for cooling (with reduction to account for wind direction), and forced ventilation and evaporative cooling.

Calpas 3 was checked against data from test cell buildings at Los Alamos National Laboratories. The program was very accurate in the normal range of building temperatures (errors of 1° to 2 °F, up to 4 °F above 100 °F).

To use all the power in this sophisticated program, one needs an engineer's understanding of passive solar technology. But any designer can use Calpas 3 if he or she is familiar with heat loss/gain calculations. Hence, it can be used at many stages in the design process because it has an extensive set of default values which allows a simple building or preliminary run to be made with only 40 input values. But for more detailed and elaborate cases, these may be more than 500 parameters.
Weather data are available for about 250 locations in the United States and Canada, and about 22 international locations.

Calpas 3 is used primarily in four overlapping contexts:

First since Calpas 3 is certified by the California energy Commission for compliance with that state's Title 24 residential energy code, it is used extensively for predicting energy budgets as part of building permit applications.

Second It is used by designers to optimize buildings for good energy performance.

Third researchers use the program to find general energy conserving strategies or investigate other areas of interest.

Finally Calpas 3 is used in educational situations for student experimentation with passive and conservation approaches. (see Appendix B)


About SUPERLITE 1.0:

SUPERLITE 1.0 is a state-of-the-art computer program developed at Lawrence Berkeley Labs. It predicts daylight illumination in buildings. The program addresses the need to accurately model geometrically complex fenestration systems in architecturally complex building spaces. It enables a user to model interior daylight levels for any sun or sky conditions in non-rectangular spaces having windows and skylights, or other fenestration systems. The output is presented in numerical or graphic form.
The program SUPERLITE PC 1.0.1., was originally written to operate on a mainframe computer, now runs on a IBM PC microcomputers. The only algorithmic modification made to SUPERLITE PC 1.0.1. is that the maximum number of nodes on windows and interior surfaces was reduced from 400 to 200, for the Comprehensive Input format. For the Short Input version used for simple room geometries the number of surface nodes are limited in the horizontal direction to less than or equal to 12.

(For more information see SUPERLITE 1.0 Evaluation Manual, (1985). Windows and Daylighting Group, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720 U.S.A.)

3.3.2 Overview of the Input Process:

The current version of SUPERLITE is written in FORTRAN. The user does not directly control execution of the program, but rather submits a job file to be processed by the computer.

A typical SUPERLITE run includes 3 steps:

Step 1: Creation of an Input file. (see Appendix C)

This includes a geometric description of the subject building and the solar data to be used.

Step 2: Submission of the job file to the computer for processing.

Step 3: Retrieve output from the computer to either send it to the printer or view it at the terminal using a text editor. (see Appendix C)

One fine feature of the SUPERLITE program also has the ability to generate a graphic plotting file, for use with other graphics software.

3.3.3 Methodology and Data obtained.

The measurements of the luminous conditions of the office space were made on the third day of the month of October at 12 noon. The reason for choosing noon time being that
due to high insolation values and high ambient temperatures, air-conditioning loads are then closely at their maximum for that month.

**Procedure:**

Reflectance measurements of all significant room surfaces (walls, ceiling, floor, doors) were taken using the LI-1000 Data logger in the INSTantaneous mode. The photo sensor was placed about 15cm from the surface to be measured and the illuminance recorded, then the photo sensor was flipped around and the illuminance was measured again. The reflectivity of that surface was obtained by dividing the reflected illuminance by the incident illuminance value.

Internal illuminance readings with artificial lights turned off were taken and recorded at 17 points at a center to center distance of 0.68m on the centerlines dividing the office space into four equal quadrants, with the first point being at a distance of 0.34m from the window wall. (see fig. 3.2.a) Illuminance readings were taken at a height of 0.75m i.e. task level and the unit of measured illuminance was Lux. (see fig. 3.2.b)

Note: All graphs are taken in the depth of the office space.

Fig.3.2.a Diagram showing nodal distribution in office space with illuminance levels.
Photograph showing taking of illuminance measurements at 75 cm above floor level.

Photograph showing problem of glare in the 'office space'.
It is well known that in hot/dry regions, the ground reflectance plays a very important role in the thermal and lighting aspects of a building. As the ground in front of the window wall (courtyard) had three different types of ground cover viz.- dark green shrubs (6% reflectivity), gravel (11%), and concrete pathway (60%), reflectivity of these values were calculated in proportion to their respective areas and the total average reflectivity of 28% of the ground thus arrived upon.

The transmissivity of the glass was also calculated by taking an illuminance reading facing the center of the window and a subsequent reading at the same spot but from the inside of the room facing the window. The 'interior' value of 3250 fc then being divided by the 'exterior' value of 6720 fc and the Transmissivity of 48.36% was calculated.

Also to avoid errors the measured reflectivity and the Transmissivity values were checked against the recommended values by the IES Lighting Handbook. (see fig. 3.3), and the calculated values were found to closely match those in the table with a marginal error of 5.1%.

### Transmittance Data of Glass and Plastic Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Approximate Transmittance (per cent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polished Plate/Float Glass</td>
<td>80-90</td>
</tr>
<tr>
<td>Sheet Glass</td>
<td>85-91</td>
</tr>
<tr>
<td>Heat Absorbing Plate Glass</td>
<td>70-80</td>
</tr>
<tr>
<td>Heat Absorbing Sheet Glass</td>
<td>70-85</td>
</tr>
<tr>
<td>Tinted Polished Plate</td>
<td>40-50</td>
</tr>
<tr>
<td>Figure Glass</td>
<td>70-90</td>
</tr>
<tr>
<td>Corrugated Glass</td>
<td>60-85</td>
</tr>
<tr>
<td>Glass Block</td>
<td>60-80</td>
</tr>
<tr>
<td>Clear Plastic Sheet</td>
<td>80-92</td>
</tr>
<tr>
<td>Tinted Plastic Sheet</td>
<td>80-92</td>
</tr>
<tr>
<td>Colorless Patterned Plastic</td>
<td>80-90</td>
</tr>
<tr>
<td>White Translucent Plastic</td>
<td>10-80</td>
</tr>
<tr>
<td>Glass Fiber Reinforced Plastic</td>
<td>5-80</td>
</tr>
<tr>
<td>Double Glazed—2 Lights Clear Glass</td>
<td>37-45</td>
</tr>
</tbody>
</table>

### Reflectances of Building Materials and Outside Surfaces

<table>
<thead>
<tr>
<th>Material</th>
<th>Reflectance (per cent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bluestone, sandstone</td>
<td>18</td>
</tr>
<tr>
<td>Brick</td>
<td>48</td>
</tr>
<tr>
<td>light buff</td>
<td>40</td>
</tr>
<tr>
<td>dark buff</td>
<td>40</td>
</tr>
<tr>
<td>dark red glazed</td>
<td>30</td>
</tr>
<tr>
<td>Granulite pavement</td>
<td>30</td>
</tr>
<tr>
<td>Ceramic</td>
<td>27</td>
</tr>
<tr>
<td>Grass (dark green)</td>
<td>17</td>
</tr>
<tr>
<td>Concrete</td>
<td>40</td>
</tr>
<tr>
<td>Gravel</td>
<td>17</td>
</tr>
<tr>
<td>Marble (white)</td>
<td>45</td>
</tr>
<tr>
<td>Macadam</td>
<td>18</td>
</tr>
<tr>
<td>Paint (white)</td>
<td>5</td>
</tr>
<tr>
<td>Slate (dark clay)</td>
<td>8</td>
</tr>
<tr>
<td>new</td>
<td>75</td>
</tr>
<tr>
<td>Snow</td>
<td>74</td>
</tr>
<tr>
<td>old</td>
<td>64</td>
</tr>
<tr>
<td>Glass</td>
<td>7</td>
</tr>
<tr>
<td>reflective</td>
<td>7</td>
</tr>
<tr>
<td>Vegetation (mean)</td>
<td>25</td>
</tr>
<tr>
<td>tinted</td>
<td>7</td>
</tr>
</tbody>
</table>

* Includes single glass, double glazed units and laminated assemblies. Consult manufacturer's material for specific values.

Fig. 3.3. Reflectance and Transmittance data, IES Lighting Ready Reference, 1985.
Illuminance values have been graphically presented in the form of Illuminance gradient curves, (see fig. 3.4). These values were converted into foot-candles as the output generated by SUPERLITE 1.0 is in Foot-candles.

The equation: 1 footcandle = 10.76 Lux, was used.

Using the calculated reflectivity values and Transmissivity values, and geographic and atmospheric data for Tucson, Arizona an input file for SUPERLITE 1.0 was prepared. The output generated gave Illuminance values (in foot-candles) at a height of 0.75m (working surface) at a nodal distribution of .68m throughout the room. The measured illuminance values (fig 3.4) and the SUPERLITE 1.0 output showed an average marginal error of 2.1% in the rear of the office space which increased to an error of 33% in the front portion of the 'office space' near the aperture. This was thought acceptable as discomfort glare was identified with a illuminance level of 4510 fc (measured) and a illuminance level of 3377.91 fc (SUPERLITE 1.0). And the objective is to eliminate this glare and get a comfortable level of illuminance inside the office space (see fig. 3.5).

From hence onwards the output results of SUPERLITE 1.0 will be used for parametric analyses of different various daylighting strategies.
3.4 Interpretation of the Output file and conclusion.

Illuminance results for noon, October 3, the representative daylighting design day has shown a minimum value of 71.67 foot-candles registered at point 81 within the office space, was due to its location farthest from the source of light (window), (see fig. 3.2). Whereas the maximum illuminance reading was 3377.91 foot-candles registered at point 1, was due to its nearness to the window and the larger size area of daylight, direct sunlight and reflected sunlight from the ground that particular point 'sees' (see Appendix C). Taking into account the various visual tasks like reading, writing, word-processing, photocopying, conversation that are performed in the office space a minimum recommended value for general illumination of 500 Lux (approximately 46.45 foot-candles) was adopted (see fig. 3.6).
Upon analysis of the output generated by SUPERLITE 1.0, even point number 81 which is farthest away from the window shows an illuminance of 71.67 fc which is 55.8% more than the recommended value of 46 fc.

**In summary, the results obtained through SUPERLITE 1.0 revealed that, the office space is overlit. It has more than the necessary illumination with problems of glare occurring from the glass window to a depth of 2.38m in the front portion of the room. (see fig 3.2)**

Due to this there is a sharp contrast in illumination levels between the front of the office space and the rear. The situation shows a need for design alternatives that would eliminate glare at the front of the office space while maintaining the required illumination level of 46 fc in the rest of the office space.

With the optimum and correct choice of design strategies the conflict between heat and light would be solved if a general illumination of 45-50 fc was provided by daylight and only artificial lighting at tasks provided for. This would ultimately lead to a reduction in the energy consumption, while maintaining visual and thermal comfort for the occupants.
3.5 Selection of Daylighting Design Strategies.

3.5.1 Introduction
In selection, evaluation and performance of the most suitable Daylighting design strategies the following two approaches were considered:
1) The critical factors affecting the performance of such design alternatives within the existing luminance conditions of the office space.
2) The practicality of implementation of the said strategies and the ease of retrofit.

3.5.2 Brief analyses of Daylight design strategies.
a) Light Shelves:
A light shelf is essentially a flat element having a high reflectance finish (ranging from diffuse matte to white specular). This shelf can be used to collect sunlight and skylight, and then to reflect diffuse daylight onto the ceiling so that it can be distributed into the depth of the room.

![Light Shelf Configurations](image)

**Fig. 3.7 Diagram showing types of Light Shelves.**

There are three types of light shelves configurations. viz. internal, external and combined. The three types can have a single opening or a double opening. The single opening refers to a 'clerestory' situation while the double opening describes a situation where a shelf divides the aperture into two parts. (fig 3.7)
The typical combined light shelf is intended to provide shade, shading the occupants from direct glare, while reflecting sunlight and skylight off its surface onto the ceiling thus increasing the illuminance level at the rear of the space. (which is not needed with our existing situation of a illuminance value of 71.67 fc at the rear of the room).

b) Size of Opening:
The amount of light that reaches the interior of the room on a specific day is a function of wall and ceiling reflectance, window placement and its size, room proportion and size, and external obstructions. Illuminance levels in various locations within a room varies as a function of its proximity to the source of light (window). For sidelite spaces a optimum depth of the room is three times the height of the opening. A sidelite window may provide adequate light near it but the illuminance levels may drop in the depth of the room and vice versa a oversized window (similar to the one in the office space) may give adequate illumination at the back of the space but may produce disabling glare near the window. This shows us the importance of the correct sizing of the aperture in relation to the floor area it seeks to light. Given below is a graph that helps to determine the glazing area needed to achieve a certain level of recommended illuminance for a given floor area under overcast skies. (see fig. 3.8)

![Figure 3.8: Daylight factors for sideliteing and vertical monitors. (After Brown, 1985)](image-url)
c) Shading
Buildings that require shade are frequently also those buildings that need to reduce the internal heat gain due to direct glare. However shading devices though reducing glare at the same time reduce the illumination levels in the rest of the office space, because of which supplemental artificial lighting is needed, the heat generated by which adds up to the internal loads and thus increase air-conditioning costs.

But since the concerned office space has more than adequate illumination in the farthest point in the room (54% more than the recommended) a shading device like a properly sized overhang, opaque or perforated, or a deciduous tree seems suitable. It will significantly reduce the problem of glare at the front and slightly reduce the illumination at the back, and yet maintain a minimum daylight level of 45-50 fc throughout the office space.

d) Reflectivity:
If a surface is illuminated by a primary source of light such as sunlight or skylight, its resultant luminance makes it an indirect source of light. Due to the generally low brightness of the clear blue sky in hot/arid regions, sunlight reflected from the ground, surrounding building surfaces and elements of the building itself (interior walls) can become a more important light source than that received directly from the sky. [Chavez, 1989]

So one can vary the reflectance of the ground, exterior building surfaces, and interior surfaces as this would affect the illuminance inside the 'office space'.

Upon analyses of the existing illumination conditions in the office space, the following strategies were chosen for parametric analyses.

a) Light Shelves

b) Shading
i) Horizontal Overhangs: opaque and perforated.
ii) Deciduous Tree
c) Reflectivity

i) Exterior ground reflectance.

ii) Interior surface reflectance: walls and ceiling.

The selection of these strategies was based on their promising approach in terms of good shading potential without sacrificing on light quality, relatively low cost and ease of implementation and maintenance, and expected low thermal impact and ease of maintenance.
3.5.3 PROCEDURE FOR A ENERGY EFFICIENT DAYLIGHTING DESIGN

Step 1: Physical measurements
Perform physical measurements and draft to scale, plans, sections, elevations of the selected ‘office space’ and its surrounding environment.

Step 2: Defining Nodes
Fix points (nodes) on plan, to take daylighting measurements. They should be uniformly distributed throughout the ‘office space’.

Step 3: Taking Daylight measurements
Daylight measurements (without artificial lights) are to be taken at the defined nodal distribution and to be taken at 75 cm above the finished floor level, (working surface).

Step 4: Taking Reflectance measurements
a) Take reflectance measurements (without artificial light) of the walls, ceiling, and the floor.
b) Reflectance of the exterior ground surfaces and the surrounding obstructions are to be taken.

Step 5: Transmissivity of glass is to be calculated and verified with glass manufacturers.

Step 6: Analysis of the ‘Basecase’.
Plot the measured illumination levels and superimpose on it the standard / recommended illumination values and thus identify areas of visual discomfort.

Step 7: Preparation of Superlite Input file
Creation of ‘basecase’ using the ‘short input’ format.

Step 8: Validation of Superlite input
Superimpose measured illumination values with the Superlite ‘basecase’ and thus validate the Superlite 1.0.

Step 9: Preparation of Calpas 3 input file
Creation of ‘basecase’ using Calpas 3.

Step 10: Basecase analyses
Analyses of both Superlite and Calpas ‘basecase’ and thus a selection of strategies that eliminate glare and yet maintain the minimum required illumination level inside the ‘office space’.

Step 11: Parametric analyses of the selected strategies
Selection of optimum dimensions and properties for the selected strategies that will reduce the thermal loads and give better illumination levels in the ‘office space’.

Instruments to be used:
(1) LI-COR 1000 DAtalogger, (1) 210SA Cosine corrected Photometric sensor, (2) torpedo levels, (1) tripod, (1) measuring tape, 1 35/105 mm Pentax auto focus, autozoom camera, Calpas 3.0, SUPERLITE 1.0.

Fig.3.9 Methodology for energy efficient daylight design.
Ch.4 Parametric Analyses of the selected Daylight design Alternatives.

4.1 Objective:
The objective of this chapter is to investigate and assess the performance of the daylight design alternatives. The main aspects investigated included:

a) Lighting Performance (using SUPERLITE 1.0).

b) Energy Efficiency (using CALPAS3).

4.2 Parametric Analyses

a) Light Shelves:
The light shelves were selected as one of the more suitable options for further parametric analyses. An external specular reflector (80% reflectance) was selected. Three different heights of the clerestory were investigated: 60cm, 75cm, 90cm. The three light shelf configurations (see fig.4.1) were simulated using SUPERLITE 1.0 and CALPAS3.

Fig. 4.1. Light shelf configurations tested.
Interpretation of the results:

The results show that the high illuminance values of 3500 fc (basecase) that were producing glare in the front portion of the office space were reduced to an average maximum illuminance value of 250 fc (93.1 % reduction) and the minimum average illuminance value predicted was 50fc in the back of the office space, a 46.2 % reduction in illuminance from the basecase. (see fig. 4.2a)

![SUPERLITE OUTPUT](image)

Fig. 4.2.a. SUPERLITE 1.0 Illumination levels using Light shelf

![CALPAS 3 RESULTS](image)

Fig. 4.2.b. Energy performance of Light shelf strategy.
Energy Efficiency of the Daylight Design Alternatives tested.

The energy performance of the various light shelf configurations (fig. 4.2b) were carried out using CALPAS3. The simulated runs show an increase of average 7 Kbtu in the heating load and a decrease of an average 2888 Kbtu in the cooling load, a total average reduction of an average 2888 Kbtu from the basecase.

b) Shading:

As evidenced by the SUPERLITE 1.0 basecase results, an illumination of 3500 fc is seen at the front portion of the office space resulting in disabling glare and an increase in the internal heat gain and hence a corresponding increase in the cooling loads. Shading was thus considered as a very promising strategy as it would not only eliminate glare but also produce a saving in the operating cost. However one is aware that shading devices though useful in reducing glare concurrently reduce the illumination levels in the back of the office space. For the purpose of the parametric analyses two types of shading strategies were investigated:

a) Overhangs:
   i) Opaque
   ii) Perforated (Ramadas as they are called).

b) Deciduous Trees.

Configurations were tested using SUPERLITE 1.0 for a variety of opaque overhang depths of 15 cm, 45 cm, 75 cm with a 40% reflectivity, and for a Ramada with the same geometry's but with a assumed transmittance value of 45%. (see fig.4.3)
The results show that an average maximum illuminance value of 140 fc was calculated against the basecase value of 3500 fc (a 96% reduction) and an average minimum illuminance value of 35.5 fc was calculated against the basecase value of 71 fc, (a 50% reduction), for the opaque overhang (see fig. 4.4). The results using the Ramada with a 45% transmissivity also produced an average maximum illuminance value of 405 fc was calculated against the basecase value of 3500 fc (a 88.43% reduction) and a minimum illuminance value of 47 fc was calculated against the basecase value of 71 fc, (a 33.81% reduction). (see fig. 4.5)
Another run was simulated by placing a deciduous tree with a transmittance of 45% in the month of October, the assigned design month, in front of the window wall. An average maximum illuminance of 405.5 fc against the basecase value of 3500 fc (a 88.43% reduction) and a minimum average illuminance of 49 fc against the basecase value of 71 fc (a 31% reduction) were produced by SUPERLITE 1.0.

![SUPERLITE 1.0 RESULTS](image)

Fig. 4.5 SUPERLITE 1.0 illumination levels using Ramada.

**Energy Efficiency:**

The energy analyses of the shading alternatives was carried out for configurations (see fig. 4.6) using CALPAS3. The simulated runs for the opaque overhang show an increase of 5.5 Kbtu in the heating loads and a decrease of 2341 Kbtu in the cooling loads resulting in a total savings of 2335.5 Kbtu.

The Ramada and the Deciduous tree strategy produced an 65 Kbtu increase in the heating loads and a 14442 Kbtu decrease in the cooling loads, with a total savings of 14377 Kbtu (see fig. 4.6).
c) Reflectivity:

Because of the clear sky conditions that dominate Tucson, Arizona, sunlight reflected from the ground plays a very important role in the Thermal and Lighting aspects of a building. At present the ground reflectivity in front of the window opening was measured and calculated to be 28%. For the sake of analyses and investigation ground reflectivity of 40% (dark buff brick), 48% (light buff brick) were investigated.

The results show that a maximum illuminance value of 190 fc and a minimum value of 48.4 fc. was calculated for the light buff brick (see fig. 4.7 a).

Another set of runs were simulated using SUPERLITE 1.0 but this time the reflectivity of the Interior walls were changed from an average interior reflectivity of 38% (excluding the floor) to reflectivity values of 40%, 45%, 50%, 55%.

The maximum average illuminance calculated was 152.36 fc and the minimum average illuminance 52.3 fc. for the interior reflectivity value of 55%, (see fig. 4.7 b).
Energy Efficiency:

When the ground reflectivity was changed to the preselected values of 40%, 48% the CALPAS3 output showed a decrease of 7 Kbtu in the heating load and a 4264 Kbtu
increase in the cooling load, (for the light buff brick) with an overall increase of 4257 Kbtu. Therefore this strategy did not prove to be energy efficient. (see fig. 4.8)

Changing the reflectance values of the interior surfaces enhances the lighting intensity in the back of the office space resulting in the reduction of electric energy usage of artificial lights and thus dependability on the same resulting in a corresponding reduction of the overall building internal load and thus a overall savings in utility bills.

![CALPAS 3 RESULTS](image)

Fig. 4.8. Energy performance of Ground Reflectivity

4.3 Comparison of Results of Daylighting Alternatives tested.

1) Light Shelves (specular Reflectors):

The results indicated an elimination of glare in the front portion of the office space and a comfortable illumination of 50.49 fc in the rear of the office space.

2) Shading:

a) Opaque overhang:

The results showed a lower illuminance of 35 fc in the rear of the office space, 24 % lower than the minimum illuminance required of 46 fc. (see fig.4.9)
b) Ramada:
The results showed an adequate illuminance of 48 fc in the rear of the office space (min. req. 46 fc). But there is a rapid fall in illuminance in the front of the office space and indicates a disadvantageous distribution of light. (see fig 4.9)

![Shading Results](chart1)

Fig. 4.9 Comparison of illuminance levels: Overhang and Ramada.

![Reflectivity Results](chart2)

Fig. 4.10. Comparison of illuminance levels: Ground reflectivity and Interior surface reflectivity.

c) Deciduous Tree:
Having a deciduous tree showed a similar lighting situation as the "Ramada". The only difference is the light penetration in the winter will be deeper and there could be problems of glare. But this strategy shows the highest amount of savings in operating costs.
3) Reflectivity:

a) Ground Reflectance:
This strategy shows an appreciable increase in illumination levels at the back of the room. Also, the illumination gradient drop in the depth of the room is shallower indicating an advantageous light distribution. (see fig. 4.10). But this strategy though satisfies the visual comfort level, increases the operating costs by 17%.

b) Interior Surface Reflectance:
Increasing the reflectance of the interior surfaces enhances the lighting situation. An optimum value of 50-55% reflectance (off-white) produced a minimum average illuminance of 49.6 fc, which satisfies the minimum recommended value of 46 fc. This cost of implementation (painting the room) could be subsidized by the projected savings in operating costs due to a reduction in usage of the artificial lights due to the lighting level enhancement in the office space and therefore a reduction in the internal load due to heat generated by the artificial lights.

**COMPARISON OF SUPERLITE 1.0 RESULTS**

---

**Fig. 4.11** Graph showing Illuminance values for tested strategies.
## Table Showing Parametric Analyses of the Selected Strategies

**Illuminance Levels**: Superlite 1.0 Output Reports

**Heating and Cooling Loads**: Calpas3 Output Reports

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Fig. 4.12 Parametric Analyses of the strategies tested
CONCLUSION

This selected case study building is the school of Business and Public administration on the campus of the University of Arizona. The actual case study is a medium size office space (37 sq. m) facing south and looking out on a internal courtyard. This specific selection of orientation resulted from a survey questionnaire that was given to all the people that had offices overlooking the courtyard, as it was the walls facing the courtyard that had almost 90% glass area with reported problems of glare resulting in visual discomfort and the heat gain due to the oversized openings resulting in thermal discomfort. (see Appendix A)

Utilizing the methodology using the measured illuminance levels of the office space and Calpas3 and SUPERLITE 1.0 described in Chapter.3 it was found that the Light Shelf is among one of the promising strategy that shows a beneficial distribution of light in the office space with a maximum illuminance of 250 fc (near the aperture) and a minimum illuminance of 50.49 fc (at the back of the room) resulting in a 11.45 % savings in operating costs.

Increasing the Interior reflectance to 40-55 % brings about an advantageous distribution of light.(see fig. 4.7.b) The implementation (painting the room) costs can be offset by projected savings in operation costs due to a reduction in usage of artificial light because of better illumination levels in the office space and therefore a reduction in the internal load which is partly due to the heat generated by the artificial lights

The perforated shading strategies using the ramada and a deciduous tree were the most advantageous in energy savings but show a steep drop in illuminance level in the office space indicating an disadvantageous distribution of light.(see fig. 4.5)
Increasing the Ground reflectance though produces better illumination, increases the operating costs and therefore is not considered as a suitable energy conserving strategy.(see fig. 4.8)

The opaque overhang shows a better distribution of light but the minimum calculated illuminance level at the rear of the office space is 35 fc, 23 % lower than the minimum recommended value of 46 fc. If combined with general artificial illumination at the rear of the office space or luminaries on specific task locations will compensate for the deficiency and result in more balanced illumination levels. Such integrated lighting strategies should be considered especially when dealing with retrofit design.

As evidenced by the parametric analyses of the various strategies (see table fig.4.12), introduction of natural light can reduce the energy costs through reduction in electric lighting. This subsequently affects the cooling loads, as the artificial light generate heat.

This report does not presume to tackle the entire realm of Daylight design, but seeks to address its energy conserving potential. Handled with sensitivity and care and many a times intuitively "Daylighting" has the ability to transform a space. Its introduction in the otherwise sterile office environment is a much welcome and a much needed relief. Neither does this report propose a general guideline or criteria for optimum selection of the tested strategies. That is left unto the users of the 'office space', and also because this report does not cover the Design economics and/or life cycle costs as this went beyond the scope of this research.

Since the experiment and subsequent parametric analyses were carried out for a particular day for a given time, results of this experiment cannot be generalized. The strategies need to be tested for at least four different times of the day (10 a.m., 12 noon, 2 p.m., and 4 p.m.) and for both winter and summer, as the altitude of the sun plays a
tremendous role in deciding on overhang depths, ceiling reflectance, ground reflectance, etc.

What this report proposes is a new approach or a step by step method to guide the user into an energy efficient daylighting design. This method can be used to analyze the visual and thermal qualities of an interior space and daylighting strategies can be tested for as many combinations as needed. This is not as time consuming as it would be if one was conducting this experiment using physical scale models. Also steps 2 to 6 (see fig. 3.9) can be skipped as these steps were to validate the SUPERLITE 1.0 output. Now that this daylighting software is validated actual physical daylight measurements need not be taken. Steps 7 to 11 which need an good understanding of both SUPERLITE 1.0 and CALPAS 3 will guide one through an visual and thermal analyses of a given space. Thus one can arrive upon the most daylight effective and the most energy conserving strategy for a given space and certain climatic and geographic conditions.

The designer in the hot/arid regions should thus take advantage of the daylight availability and try to integrate the existing lighting system with the daylighting system. To get optimum rewards from this integration, the occupant needs to be educated in the operation of the existing lighting systems. These measures would lead not only to significant energy savings but also to cost-effectiveness of integrating daylighting systems with the existing ones.

Finally it is important to bear in mind that not all the benefits are concerned with the savings in electricity. In fact some other subjective benefits evaluated (see appendix A), have to be considered as well when making the final decision about the most suitable strategy for energy efficiency, and it is the occupant of this building who should ultimately decide its suitability.
METHODOLOGY FOR AN ENERGY CONSCIOUS DAYLIGHTING DESIGN

Phase I

- Take Physical measurements of the selected case study
  - Take Daylight measurements
  - Take Reflectance measurements: Interior surfaces & Exterior ground and obstruction/s.
  - Define nodes. They should be uniformly distributed throughout the selected space.
  - Calculate Transmissivity of glass

- Preparation of SUPERLITE 1.0 input file
- Preparation of CALPAS3 input file

- Plot measured illuminance graph

Phase II

- Validation of SUPERLITE 1.0

Analyses of both SUPERLITE 1.0 & CALPAS3 'basecase' files

Selection of Strategies that will alleviate the problem identified in 'basecase' results

- Parametric Analyses of Selected strategies
  - Using SUPERLITE 1.0
  - Using CALPAS3

Selection of strategy that shows optimum performance with CALPAS3 and SUPERLITE 1.0
REFERENCES

APPENDIX A

SURVEY QUESTIONNAIRE

INTRODUCTION:

The Business and Public Administration Building in The University of Arizona was chosen as the case study as it represented the 'modern' prototype for an office building. To analyze the office spaces around the courtyard I had broadly categorized my research into two parts.

a) To address the physical properties of light - its quality and the amount of light and the problems if any due to the same. Attached to this would be some qualitative data regarding preferences of the user group towards artificial or natural light.

b) The other part of the experiment would be to take actual daylight measurements inside the office space and plot the illuminance levels and identify the problems due to the natural light in the office space.

A new 'methodology' would be drawn up and problems of glare, gloom, etc. will be identified and localized strategies to alleviate the same would be suggested. The energy conserving potential of the strategies will play a major role in their selection and implementation.
RESEARCH SURVEY

CASE STUDY: The School of Business and Public Administration, University of Arizona, Tucson.

TARGET GROUP: Students and Administrative staff and Faculty in office spaces facing the courtyard.

MODE OF QUESTIONING: Personal interview with a questionnaire.

METHODOLOGY:

A questionnaire was developed and reviewed by three Architecture faculty members, myself and a fellow student studying in the School of Business and Public Administration at the U of A. The questionnaire was tested on the teaching and administrative faculty here in the school of Architecture before it was presented to the target group at the Department of Business and Public Administration.

It was thought best that the mode of questioning would be a ‘personal interview’. This was thought appropriate as the questionnaire was a mix of ‘open ended’ questions that were qualitative and some ‘quantitative’ questions that asked the respondents to rate on a scale of 1 - 10 (1 being low and 10 being high). The ‘Target group’ was restricted to those who had office spaces overlooking the courtyard as their responses would be more pertinent to analyzing the daylighting qualities in the office spaces as a result of the courtyard.

END PRODUCT:

The survey would generate information on the physical problems of glare, gloom, veiling reflections, bright spots in the surrounding office spaces that are a result of the courtyard.
SURVEY RESULTS

Of the 68 work areas identified overlooking the courtyard, 39 were being used in full time capacity. Twelve were empty, eighteen were being used sporadically for purposes ranging from conference rooms, mail rooms, graduate students study areas, faculty and staff lounges etc.

The sample group was thus forty six who were using the work areas for a minimum of 5 - 6 hours a day and have been using their office space for a period of more than twelve months. This was thought necessary so as the user having been in their respective office spaces over summer, winter, spring. Twenty eight people were interviewed. Eighteen were unavailable due to end of semester workload. The effective sample thus collected was therefore 61%.

Since the problems of natural light are mostly due to the orientation, I decided to categorize the office spaces and their responses and group them according to their orientation.

OFFICES FACING NORTH :

19 Total
2 empty
12 constantly used
5 sporadically used
6 interviewed (50 %)

There was a consensus among all interviewed that there office spaces had no problems of glare and were bright enough. All used artificial light, the reasons ranging from habit to people visiting being more comfortable with brightly lit spaces.

Observations: Need supplemental artificial lighting on overcast days.
OFFICES FACING SOUTH:

24 Total
5 Empty
15 constantly used
4 Sporadically used
13 interviewed (86.66%)

75% of the sample interviewed responded that it was too bright in summer and reported problems due to glare. The use of blinds is seen to alleviate this. During winter it was reported to be dull in the mornings but had better light through remainder of the day. The offices in the west corner reported afternoon glare in the winter. People working on Computer terminals preferred dark surroundings and said that the office spaces were too bright. People on the upper floors said they would prefer deeper overhangs so they would not have glare on the upper part of the windows. There was consensus in the preference of natural light to artificial light, as they feel that natural light was more soothing to the eye.

Observation: Overhang necessary to block high summer sun, though the depth of the overhang is crucial. A light shelf would be a worthwhile strategy to test for these south facing offices. Another solution could be to vary the courtyard landscape. Having Deciduous trees tall enough and with dense foliage (the existing ones have very sparse foliage) to block the high afternoon sun, and the shedding of their leaves in winter will allow in the low winter sun.

OFFICES FACING EAST:

18 Total
2 empty
11 constantly used
5 sporadically used
5 interviewed (45.45 %)

Summer glare in the morning. The use of blinds is seen. Two office spaces have overhangs and report lack of glare. Winter morning glare, so use blinds.

Observations: Problems appears to be for early mornings, so use of blinds for those hours seem most economical.

OFFICES FACING WEST:
7 Total
4 empty
0 constantly used
3 sporadically used

Conclusion: From the responses that were generated because of the questionnaire, it was found that the offices facing west portrayed more problems of glare throughout the year. Also user responses indicated a desire for a much more permanent solution to the problem of glare and overlit spaces. Keeping in mind all the information generated by the survey and also some of my own observations it was thought best to choose as the 'case study' an office space facing south and one which showed a mix-use pattern of work.
APPENDIX B
CALPAS3 SAMPLE INPUT FILE

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MAYGR=0.28 JUNGR=0.28 JULGR=0.28 AUGGR=0.28 &
SEPGR=0.28 OCTGR=0.28 NOVGR=0.28 DECGR=0.28 &
reflectivity value for courtyard landscape
HOUT 4.00; average outside film coeff. 7.5 mph in Tucson

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ABSRP=0.6 INSIDE=AIR
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TILT=90 UVAL=0.37 ABSRP=0.01 INSIDE=AIR
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MAYGR=0.28 JUNGR=0.28 JULGR=0.28 AUGGR=0.28 &
OCTGR=0.28 NOVGR=0.28 DECGR=0.28 &
landscaping in the courtyard
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TIMEDOWN=17 TIMEDUP=7
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TIMEDOWN=17 TIMEDUP=7
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adjusted for a semi-open site
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DAYTIMES WDBEG=7 WDEND=18 SDBEG=5 SDEND=19
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HEATING=ELECTRIC HTCOP=1.94 \&
Electric heating and cooling system
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SOLARCALC FREQ=MONTHLY
*END
CALPAS3 SAMPLE OUTPUT REPORT

Bpa basecase  CALPAS3 V3.12 License: PC0201

School of Business and Public Administration Weather: TUCSON.AZ

SUMMARY  Run period: JAN-01 - DEC-31  Conditioned floor area: 402 sf

SPACE CONDITIONING LOADS  Run totals  Peaks

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Note:  CALPAS3 is the property of and is licensed by Berkeley Solar Group, 3140 , Martin Luther King Jr. Way, Berkeley, CA 94703 (415 843-7600). Correct application and operation of CALPAS3 is the responsibility of the user. Actual building performance may deviate from CALPAS3 predictions due to differences between actual and assumed weather, construction, or occupancy. CALPAS3 is certified for California energy code compliance when used in accordance with the BSG publication "Using CALPAS3 with the California Residential Building Standards."
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**TEMPERATURES (F)**  
**WTHR (F; Btu/sf)**  
**PEAKS (kBtu)**
APPENDIX C

SUPERLITE 1.0 SAMPLE INPUT FILE

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SUPERLITE 1.0 SAMPLE OUTPUT REPORT

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
* *
* DAYLIGHT ILLUMINATION IN A RECTANGULAR ROOM *
* *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

ROOM HAS A WIDTH (WINDOW WALL) OF 6.1 UNITS
A DEPTH OF 6.1 UNITS
AND A HEIGHT OF 3.6 UNITS
ROOM ORIENTATION (FROM OUTWARD WINDOW NORMAL) = .0 DEG. OFF SOUTH

ROOM HAS 1 WINDOW(S) IN THE FRONT WALL

WINDOW NO. 1 IS 6.10 UNITS WIDE BY 3.61 UNITS HIGH
WINDOW CENTER IS .00 UNITS TO RIGHT OF WALL CENTER
1.80 UNITS FROM FLOOR
WINDOW DISCRETIZATION IS 9 BY 5
WINDOW TYPE IS "1" (CLEAR WINDOW)
MAINTENANCE FACTOR =1.00
WINDOW THICKNESS = .05
WINDOW TRANSMISSIVITY = .46
WINDOW REFLECTANCE = .54
FRONT WALL. DISCRETIZATION 1 BY 1, REFLECTANCE = .40
LEFT SIDE. DISCRETIZATION 9 BY 5, REFLECTANCE = .37
REAR WALL. DISCRETIZATION 9 BY 5, REFLECTANCE = .36
RIGHT SIDE. DISCRETIZATION 9 BY 5, REFLECTANCE = .37
CEILING. DISCRETIZATION 9 BY 9, REFLECTANCE = .40
FLOOR. DISCRETIZATION 9 BY 9, REFLECTANCE = .28
WORKING SURFACE. DISCRETIZATION 9 BY 9, ELEVATION = .75 UNITS

SUBJECT BUILDING.
BUILDING WIDTH (FRONT WALL) = 35.2 UNITS
BUILDING HEIGHT = 16.3 UNITS
OFFSET TO RIGHT OF ROOM CENTER = -10.6 UNITS
REFLECTANCE = .54

OBSTRUCTION.
OBSTRUCTION WIDTH = 35.2 UNITS
OBSTRUCTION HEIGHT = 16.3 UNITS
OFFSET TO RIGHT OF ROOM CENTER = -10.6 UNITS
DISTANCE FROM SUBJECT BUILDING = 15.9 UNITS
OBSTRUCTION REFLECTANCE = .54

SKY LUMINANCE DETERMINED BY GEOGRAPHICAL DATA
LATITUDE 32.1 DEG.
LONGITUDE 111.0 DEG.
TIME ZONE 7
ALTITUDE 787.6 METERS
SKY MODEL 2
GROUND REFLECTANCE .28
FIRST MONTH 10
LAST MONTH 10
INCREMENT BETWEEN MONTHS 1
DAY OF MONTH 3
FIRST TIME OF DAY 12.5 HRS.
LAST TIME OF DAY 12.5 HRS.
TIME INCREMENT 1.0 HRS.
MONTHLY VALUES FOR TURBIDITY AND COND.WATER..
MONTH C.W. TURB.
10 1.6000 .0600

MONTH = 10 TIME = 12.5 HRS.
**SUN ALTITUDE ANGLE = 47.1**  
**SUN AZIMUTH ANGLE = -7.7 DEG. OFF SOUTH TOWARDS EAST**  
**DIRECT-SUN TRANSMISSION FRACTION, ALPHA**  
WINDOW 1 ALPHA=1.000

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**DATA FOR WORKING SURFACE NODES; I=SURFACE, K=NODE-NO.**

* X,Y,Z=COORDINATES,
* S=ILLUMINANCE FROM EXTERNAL SOURCES (FOOT-CANDLE)
* R=INTERNAL REFLECTED COMPONENT (FOOT-CANDLE)
* T=TOTAL ILLUMINANCE (FOOT-CANDLE) D=DAYLIGHT FACTOR (PERCENT)

**X = DISTANCE FROM FRONT WALL (PARALLEL TO FRONT WALL)**
**Y = DISTANCE FROM ROOM CENTER LINE (PERPENDICULAR TO FRONT WALL)**
**POSITIVE VALUES (LEFT OF CENTER LINE)**
**NEGATIVE VALUES (RIGHT OF CENTER LINE)**
**Z = HEIGHT OF WORK PLANE**

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