EVALUATION AND DESIGN OF DOUBLE-SKIN FACADES FOR OFFICE BUILDINGS IN HOT CLIMATES

A Thesis

by

VIJAYA YELLAMRAJU

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2004

Major Subject: Architecture

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Approved as to style and content by:

Valerian Miranda (Chair of Committee)	Liliana Beltran (Member)
Ifte Choudhury (Member)	Phillip Tabb (Head of Department)

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ABSTRACT

Evaluation and Design of Double-Skin Façades for

Office Buildings in Hot Climates. (May 2004)

Vijaya Yellamraju, Dip. in Architecture, Sushant School of Art and Architecture

Chair of Advisory Committee: Dr. Valerian Miranda

The main objectives of this research are (a) to investigate the thermal effect of double skin facades in office buildings in hot climates and (b) to propose guidelines for their efficient design based on this evaluation. The study involves the energy performance analysis of two buildings in India. A base case with the existing building skin was simulated for both the cities. The main source for the high cooling loads was found to be heat gain through windows and walls. This led to the evolution of a series of façade strategies with the goals of reducing heat gain, providing ventilation and day-lighting. The buildings were then simulated for their energy performance with the proposed double-skin strategies. Each of these strategies was varied according to the layers constituting the façade, the transparency of the façade and the orientation of the façade to which it is applied. Final comparisons of energy consumption were made between the proposed options and the base case to find the most efficient strategy and also the factors that affected this efficiency. The simulations were done using the building simulation software, Ener-Win. The double skin was simulated as per an approximate and simplistic calculation of the u-value, solar heat gain coefficient and transmissivity properties of the layers constituting the façade. The model relied on

logically arrived at assumptions about the façade properties that were approximately within 10% range of measured values. Based on inferences drawn from these simulations, a set of design guidelines comprised of goals and parameters was generated for design of double-skin façades in hot climates typical to most of the Indian subcontinent. It was realized that the double-skin defined typically as a 'pair of glass skins separated by an air corridor' may not be an entirely energy efficient design strategy for hot climates. However, when used appropriately in combination with other materials, in the right orientation and with the right transparency, a double-layered façade turns out to be an energy efficient solution.

To my parents.

ACKNOWLEDGEMENTS

This thesis wouldn't have been possible without the continuous guidance and direction of Dr. Miranda. I truly appreciate his interest and association with this thesis.

I would like to thank Dr. Beltran and Dr. Choudhury for being on the committee and giving their valuable input to the thesis. I am also grateful to Dr. Degelman for providing me access to Ener-Win, for getting me started with the simulations and for patiently replying to all my email queries.

I also appreciate the timely help from my friends Umesh, Aparna and Divya during the course of the thesis.

I am indebted to my parents and my brother for encouraging me to pursue this degree; without their support I wouldn't be here.

And finally, my 'longhorn' husband, Kaushik, for his encouragement and support while I was studying… and for driving me to College Station from Austin more than a couple of times.

GLOSSARY

Cooling Load
Rate at which heat must be removed from a space to maintain the temperature and humidity at design values (comfort). Peak Cooling Load refers to the point when the cooling load is highest for the entire year on a particular day. Usually when the outside temperatures are at their peak, the cooling energy requirement also rises steeply. Annual Cooling Load is the total rate of cooling for an entire year for a building.

Daylight Transmissivity
The ratio of the daylight transmitted through a glazing to the total radiant energy falling on its surface. It is always affected by the thickness and composition of the substance, as well as by the incident angle.

Degree Days
A practical method for determining cumulative temperatures over the course of a season. Originally designed to evaluate energy demand and consumption, degree days are based on how far the average temperature departs from a human comfort level of 65℉. Each degree of temperature above 65℉ is counted as one cooling degree day, and each degree of temperature below 65℉ is counted as one heating degree day.

Emissivity
It is a surface characteristic of a material. It is the relative ability of a surface to absorb and emit energy in the form of radiation.

Energy Efficiency
The concept of utilizing less energy to perform the same functions in a building.

Façade
Exterior surface of a building envelope.

Simulation
The process of designing a model of a real system/building and conducting experiments with this model for the purpose of understanding its behavior and/or evaluating various strategies for the operation of the system/building. A simulation model is a representation of a real system.

Solar Heat Gain Coefficient (SHGC)
The SHGC is the fraction of solar radiation admitted through a window, both directly transmitted, and absorbed and subsequently released inward. The SHGC is needed to determine the solar radiant heat gain from a glazing.

Thermal Conduction
This is the mechanism of heat transfer whereby energy is transported between parts of a continuum by the transfer of kinetic energy between particles or groups of particles at the atomic level. Thermal energy transfer occurs in the direction of decreasing temperatures.

Thermal Convection
This form of heat transfer involves energy transfer by fluid movement and molecular conduction. When fluid currents are produced by external sources, the heat transfer is termed forced convection. If it is generated internally caused by temperature variation, the heat transfer is termed free or natural convection.

Thermal Radiation
In conduction and convection, heat transfer takes place through matter. In thermal radiation, there is a change in energy form from internal energy at the source to electromagnetic energy for transmission.

Thermal Resistance (R)
The measure of a material's ability to resist heat flow. The formula for Thermal Resistance is R = L / k where (L) is the material's thickness and (k) is the material's Thermal Conductivity constant. The higher a material's R-value, the better it insulates, and conversely. Also is defined as the mean temperature difference between two defined surfaces of material or construction that induces unit heat flow through a unit area under steady-state conditions. Units of R are h-ft^2-°F/Btu.

Total Annual Cooling Energy
This refers to the total amount of energy used for cooling by the building over a period of one year. It is expressed in Mbtu.

U-Value (Coefficient of Heat Transmission)
It is a measure of the rate of heat flow through any given combination of materials, air layers, and air spaces. It is equal to the reciprocal of the sum of all resistances (R). The lower the U-value, the lower the heat loss or the higher the insulating value. The units are Btu/hour/square foot/degree Fahrenheit.

Zones
For the purpose of simulation, a building is divided into a number of areas that that can be cooled or heated separately based on the nature, occupancy, orientation of that space. These areas are referred to as zones.

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CHAPTER I

INTRODUCTION

1.1 Background

The building envelope serves to separate the interior and the exterior environments and plays an important role in solar heat gain management, thermal load control, air infiltration and exfiltration, ventilation, noise control, design quality and aesthetic definition. Traditional envelope design regarded the external skin as a barrier between the variable outdoor climate and the highly controlled interior environment. Efficiency of the façade was measured by its ability to shield from the outdoor environment so that the air conditioning system could cool as efficiently as possible. However, newer concepts of facade design look at the building facade as a filter which moderates between the external and internal environment [15].

The façade design should be such that it achieves goals that are critical and important to the particular context it is being built in. The facades of buildings in hot climates would be different in their design, performance and appearance from the facades in the colder and temperate climates. Their design goals and needs would differ because of the extreme difference in the external climatic conditions and their appearance would vary because of the difference in the materials and construction technologies that are so different from country to country.

This thesis follows the style and format of Renewable and Sustainable Energy Reviews.

Unfortunately, contemporary building and façade design in developing countries like India is being based on 'western' concepts of façade design with curtain wall systems and completely glazed facades. There is very little concern shown for designing according to the climate, with indigenous materials, using passive design strategies to reduce energy consumption in buildings. The result is that the energy required for cooling these-high façade to floor ratio glazed-buildings is phenomenal, leading to a pressure on the overall energy resource.

There are a number of strategies that are being developed to use the potential of the façade as a major energy saving component in building design. The primary goals of a façade in a hot region should be to reduce solar heat gain and provide daylighting. There are a number of strategies like using external/internal shading devices, advanced glazing technology, passive/active ventilation systems, and double skin façade systems, by which these goals can be achieved.

Predominantly seen in the European countries, the concept of double skin facades or ventilated facades is now picking up in the USA and also other Australasian countries. Although double envelopes with cavities and other passive solar design ideas like the "trombe" wall have been around for a number of years, the concept of double skin design has now become analogous with explorations in transparent and glass architecture. It is becoming acclaimed as an environmentally responsible design strategy with major predicted savings in energy and life cycle costs. The double-skin façade essentially refers to a pair of glass skins separated by an air-corridor. The air space between the two skins acts as insulation against temperature extremes, wind and sound and may also have shading devices, which may be controlled [3]. This design is said to incorporate the passive strategies of natural ventilation, daylighting and solar heat gain into the fabric of a building which form the key components with respect to energy efficiency and comfort.

1.2 Problem Statement

Literature and data on performance of double skin façades in terms of thermal comfort, occupant control and energy efficiency is limited to the colder and temperate climates of Europe and North America. In these contexts, there are examples of efficient implementation. However, the efficiency or effectiveness of using double skin facades in hot climates is not known or documented. This study attempts to simulate the performance of double skin facades in hot climates. The data obtained would lead to a set of guidelines for design of energy efficient double skin facades in hot climates.

1.3 Objectives

The objectives of the research are:

a) To investigate the thermal effect of the double skin façade as an environmentally responsible and energy efficient design strategy especially in the context of hot climate of India.

b) To identify the various design issues and criteria based on the above evaluation for the physical application of the concept by designers.

1.4 Research Design

1.4.1 Hypothesis

In hot climates like most of the Indian subcontinent, double skin facades which are typically defined as 'a pair of glass skins separated by an air corridor' are more energy efficient than the conventional single skin facades. Cities like Hyderabad and New Delhi, representative of the Indian climate and also of the booming commercial activity in the country can use some energy efficient design strategies like double-skin facades to improve the building energy performance over their existing façade designs, which increasingly are more 'western' glazing technology oriented.

1.4.2 Variables

The façade type (single or double-skin) is the independent variable and energy efficiency is the dependant variable. The operational measure used to test the hypothesis is building energy performance.

1.5 Scope and Limitations

1.5.1 Scope

- The study tests the hypothesis for office buildings in two cities in India. This would give an insight into the variation, if any, in the energy performance of the same design in two different microclimates.

- Upon evaluation, the definition of the ‘double skin,’ may undergo a departure from just being restricted to glass skins to include a range of materials and other passive design strategies to reduce solar heat gain.
- Issues that are critical to the design of the double skin in hot climates will be identified, which can then be used to generate design guidelines.

1.5.2 Limitations

- Since the buildings are in India, actual measured data of the building energy performance is difficult to obtain. Therefore, the base case is essentially a simulated base case and there is no calibration with actual measured data.
- The double skin strategy, which is also simulated, is therefore compared with the simulated base case. Hence, the error factor in simulation would be the same for both the cases holding the comparison still valid.
- Since there is no exact method of calculations, the double skin has been modeled assuming the U-value and SHGC of the designed facade. These values are not exact and may involve deviation from measured data. However, they are acceptable approximations and are held consistent throughout all the calculations.

1.6 Significance

Designing buildings that are energy efficient and sustainable has become imperative and design strategies to achieve the same are the need of the hour. This research hopes to analyze the potential of a 'double skin façade' as a possible energy efficient design strategy and if it can be successfully implemented in hot climates. The evaluation would then generate a design resource for physical application of the strategy.

The significant contribution of this research would be that:

a) It tests the applicability of the concept in hot climates.

b) Puts forth a simplistic method for analysis of double skin façade through U-value and Solar Heat Gain Coefficient (SHGC) calculation of the layered façade

c) Identifies issues that affect or influence the functioning of these facades and then propose guidelines for their effective design.

d) Generates varying types of design alternatives unique to the context of the site, suggesting departure from the conventional concept of double skins.

1.7 Organization of the Research

The first chapter gives a basic introduction to the objectives, need and significance of the research.

The second chapter describes in detail the various aspects of double-skin facades through a review of existing body of literature in this field. It illustrates the history functioning and typologies of double-skins besides also citing some case examples.

The third chapter presents the detailed methodology followed to do the research, which includes collecting data, simulation of base case, identifying problem areas, suggesting alternatives, simulation of proposed alternatives, analysing these to finally arrive at conclusions and design guidelines.

The fourth chapter presents the analysis of the actual data, including the base case and proposed strategies for both the cities of Hyderabad and Delhi.

The last chapter is the chapter of conclusions which gives the inferences from all the simulations and analysis, to lead to a set of design guidelines.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

Double skin façade design is a system that has taken its present form over a number of years of its application. Predominantly seen in the European countries, the concept is now picking up in the USA and also other Australasian countries. Although double envelopes with cavities and other passive solar design ideas like the "trombe" wall have been around for a number of years, the concept of double skin design has again picked up new fervor and has now become analogous with explorations in transparent and glass architecture. It is becoming acclaimed as an environmentally responsible design strategy with predicted savings in energy and life cycle costs [3].

2.2 Definition

Double skin facades consist of an external façade, an intermediate air space and an inner façade. The outer layer provides protection against weather and acoustic insulation. The façade allows ventilation of intermediate space and also provides thermal insulation. An adjustable shading device is usually incorporated in the air cavity [16].

2.3 Context of Double-Skin Facades

The concept of 'polyvalent wall' (Fig.1) was first proposed by Mike Davies of Chrysalis architects and Richard Rogers Partners, in his article 'A Wall for all Seasons,' published in the RIBA journal in 1981. The article can be regarded as the first expression of the principle of intelligence being applied to building skins. Davies had suggested some, what were at that time, radical proposals for the way glass is used in buildings. Some of his ideas have now probably taken practical shape with the emerging technologies being developed these days. He proposed the need to 'develop a new integrated window wall where all elements are one, where multiple performance is integrated into one single element [9].' He urged the need for an 'environmental diode, a progressive thermal and spectral switching device, a dynamic interactive multi-capability processor acting as a building skin, based on the properties of glass [9].'

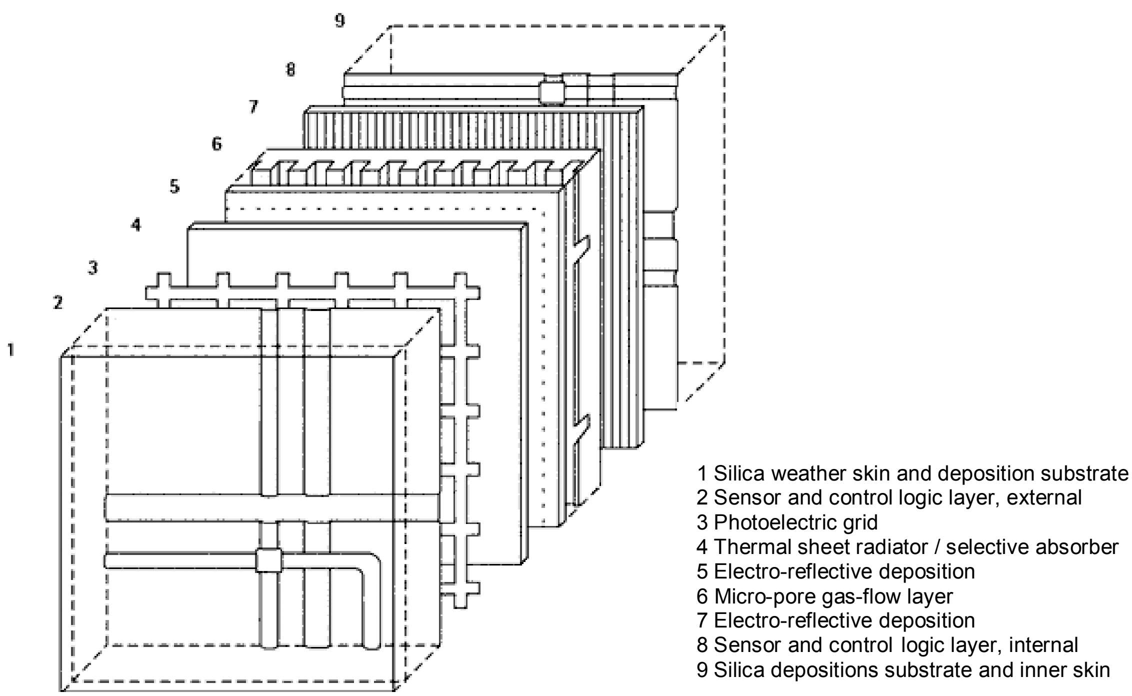


Fig. 1. Polyvalent Wall designed by Mike Davies [9]

2.3.1 Historical Evolution of the Double-Skin Façade

i) The double-skin façade can find its first precedents in the vernacular concepts of box windows, one of the oldest forms of a two-layered façade. It consists of a frame with inward-opening casements. 'Single-glazed external skin contains openings that allow the ingress of fresh air and the egress of vitiated air, thus serving to ventilate both the intermediate space and internal rooms [16].' The cavity may be divided vertically or horizontally to avoid transmission of sounds and smells from bay to bay and room to room. It was used commonly in situations where there are high external noise levels and where special requirements are made in respect of the sound insulation between adjoining rooms. Each box window element required its own air intake and extract openings [16].

ii) People have used thick walls of adobe or stone to trap the sun's heat during the day and release it slowly and evenly at night. 'A further advancement on this ancient technique was seen in a thermal storage and delivery system called a Trombe Wall (Fig.2) named after French inventor Felix Trombe in the late 1950s. The Trombe Wall continues to serve as an effective feature of passive solar design and basically 'consists of an 8- to 16-inch thick masonry wall coated with a dark, heat-absorbing material and faced with a single or double layer of glass. The glass is placed from about 3/4" to 6" away from the masonry wall to create a small airspace. Heat from sunlight passing through the glass is absorbed by the dark surface, stored in the wall, and conducted slowly inward through the masonry [6].'

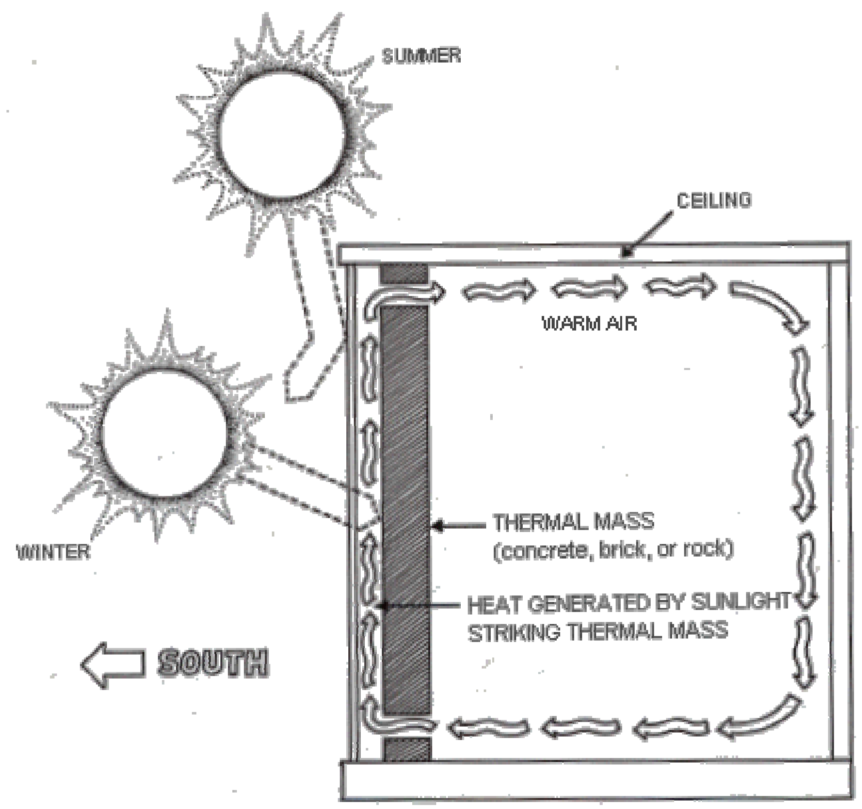


Fig. 2. Trombe Wall Section [12]

iii) In 1903, the Steiff Factory in Giengen, Germany was designed by Richard Steiff, the factory owner's son. 'The main priorities were to maximize daylighting while taking into account the cold weather and strong winds of the region.' For this purpose, a three-storey structure supporting a framework of welded T-sections fixed with cleats to the internal and external sides of each column was built. The framework supported the two layers of the double-skin, leaving a void of 25 cm. The building was regarded a success and along with later double-skin systems, it is still in use [7].

iv) Le Corbusier had used a second skin glazing system in his Villa Schwob in his home town of La Chaux de Fonds in Switzerland in 1916. He designed very large windows (one of them two storeys high) in two layers, with heating pipes between them to prevent down draughts. Later he even envisioned two complimentary building systems: one to produce “respiration exacte”, which was a carefully controlled mechanical ventilation system and the other “murs neutralisants” which would have ‘walls envisaged in glass, stone or mixed forms, consisting of a double membrane with a space of a few centimetres between them...a space that surrounds the building underneath, up the walls, over the roof terrace. In the space between the membranes depending on the external climate, hot or cold air is blown so that the surface of the interior air is maintained at 18 C [25].’ Although these concepts were tested for good performance, they could not be implemented because of budgetary and other constraints [25].

v) In 1978, Cannon design in association with HOK designed the Occidental Chemical Centre, also called the Hooker Office building. It can be regarded as the first modern instance of a glazed double skin façade incorporating Le Corbusier’s ideas in ventilation. ‘The 8- inch cavity houses a system of louvers, grouped in banks. On each bank, a louver has a solar cell that registers when the sun hits it and reacts by tilting the whole bank out of the sun [5].' The louvers collect radiative energy as the bank bounces the sunlight back. This results in a stack effect where warm air rises to the top where it is collected in cold weather and discarded on warm weather [5].

2.4 Functions of Double-Skin Facades

The three key functions of the double skin façade with respect to energy efficiency and comfort are the passive design strategies of natural ventilation, daylighting and solar heat gain control.

2.4.1 Natural Ventilation

The exterior glazing of the double skin creates a buffer zone of air next to the exterior wall of the building that is not affected by high velocity wind. This zone is accessible by the inhabitants for natural ventilation. In some cases the external glazing is also opened out for natural ventilation. This may not be suitable for extremely hot climates where it may not be appropriate to let high temperature winds into the building. The operability of the façade can be used for providing night time ventilation though [2].

2.4.2 Solar Heat Gain

To better understand the functioning of a glass façade, it is important to understand the mechanism of how glass responds to solar heat gain. The main heat bearing components of the light spectrum are infra red and visible light, referred to as short wave or high frequency solar radiation. A general rule is that longer the wavelength, the lower energy it carries [23].

Normal clear glass is almost transparent to high frequency solar radiation, but is a barrier to low frequency or long wave radiation. The solar heat energy passing through the glazing warms up the various internal surfaces by absorption and these internal surfaces become heat radiators. This re-emitted heat is, however, low frequency and therefore is trapped within the room causing the temperatures to rise (Fig. 3). Commercial buildings, often glass clad, are dominated by cooling loads especially because of the large floor area to glass façade area. The trapped solar heat in a room can be dissipated by natural or mechanical ventilation or air-conditioning or radiant cooling by chilled surfaces/building thermal mass [23].

The control of solar heat gain with the double skin façade is achieved through the shading devices and the ability of the cavity to absorb some of the solar radiation. The intermediate blind reflects some short wave/high frequency radiation back through the glass and absorbs the remaining high frequency solar radiation and re-radiates it back as ‘sensible’ low frequency heat. Since clear glass is a barrier to low frequency heat, there is no heat gain through the inner glass unit into the space. Thus, the instantaneous cooling loads are not increased. The air plenum serves to continuously extract the sensible heat gain (Fig. 4). This extracted heat gain can be recovered to be used in a heat exchange system to offset cooling and heating loads. Also, with the use of improved solar heat transmission values for glazing, the absorption and reflection of heat can be manipulated to minimize solar heat gain. For instance, now various advanced glazing types like spectrally selective glazing are available which respond differently to different wavelengths of solar energy [23].

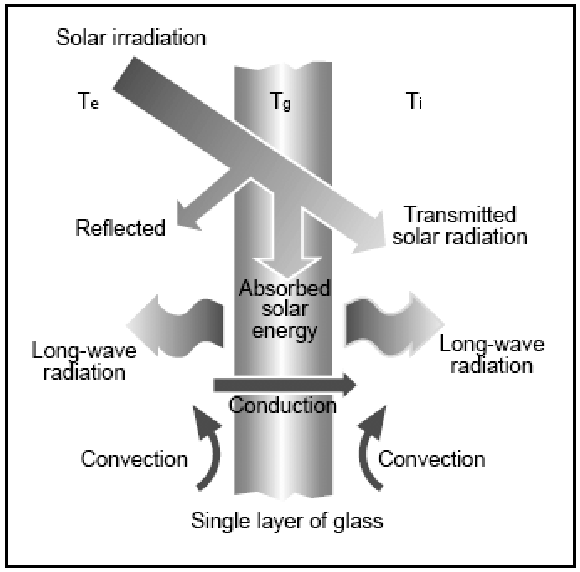


Fig. 3. Heat Transfer through a Single Pane of Glass [23]

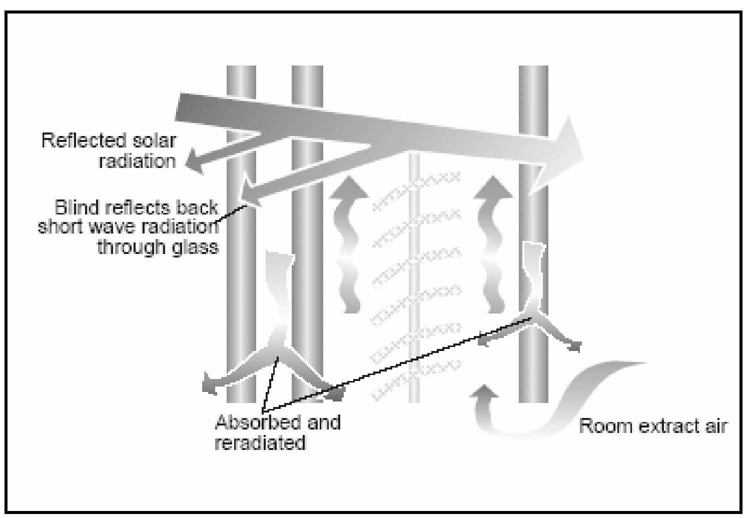


Fig. 4. Heat Transfer through a Double-Skin Facade [23]

2.4.3 Daylighting

The double skin façade with its increased glazing coverage improves the access to daylighting in the space [2]. Daylighting is important as it reduces the amount of electrical lighting and also its quality is preferred over electrical lighting. However, due to the double skin, the amount of light transmitted reduces and the problems of glare and heat need to be addressed.

2.5 Functioning of Double-Skin Facades

2.5.1 Cooling Season

Air is introduced into the cavity to carry away heat that would be otherwise accumulated in the cavity and be partially transferred into the adjacent occupied space. Temperature of the inner membrane is kept lower than without the airflow. This reduces conduction, convection and radiation from the occupied space within. Thus, less heat is transferred from outside to the inside, and less energy is required to cool the space. Solar shading devices placed between the skins absorb or reflect unwanted solar radiation. The heat absorbed by the sun-shading device can be removed by convection if air is moved along the surface of the blinds and then removed from the cavity [2].

2.5.2 Heating Season

Two possibilities exist for the heating season:

a) The system is closed with no air movement through the cavity. Cavity is allowed to heat up, increasing the temperature of the inner pane, reducing conductive, convective and radiant losses.

b) Warm air is introduced into the cavity from the interior to warm the inner pane of glass and achieve the same result. This air is then ducted to the building systems plant where it may be run through a heat exchanger to pre-heat the incoming air [2].

2.6 Goals of Double-Skin Facades

Arons [2] in his thesis has presented the following as the chief goals of double-skin facades.

2.6.1 Energy Savings and Ecological Responsibility

Energy savings are achieved by minimizing solar loads at the perimeter of the buildings. Providing a low solar factor and low U-value minimizes the load of adjacent spaces. It is claimed that double-skin facades (DSF) save natural resources by reducing energy consumption during the operational life of the building. No study has been seen on the relationship of operational costs to construction/embodied energy impacts [2].

2.6.2 Natural Ventilation

DSF is a common solution for allowing windows to be operable in a windy zone because of the buffering effect of placing a fixed plane of glass outside the operable window. However, this is not a very appropriate solution for very hot climates, where it would not be desirable to allow hot air inside. But these operable windows could be used for night time ventilation [2].

2.6.3 Cost Savings

DSFs are more expensive to install than conventional curtain wall systems considering only the cost of the installed façade. Additional costs have ranged significantly from 20%-300%. Facades that may come pre-assembled to the site will tend to be more cost effective than facades that require site assembly. DSFs with inner skins being something other than glass may be less costly like fabric, flexible metallic screens. One should look at costs and benefits on a project-wide capital basis and also on a life-cycle basis besides looking at capital costs of the façade alone. Also operational and maintenance costs need to be looked at. By reducing the heating and cooling loads of the envelope at the source, the overall size of the HVAC systems can be reduced [2].

2.6.4 Noise Reduction

DSFs are now specifically being used for reduction of noise in urban settings. The degree of noise reduction increases with use of glazing that reflects sound and varies with specific details and operation of the facades [2].

2.6.5 User Control and Comfort

The temperature of the inside surface of glazing systems needs to be taken into consideration, as this surface is a source of infrared radiation during summer and a heat sink during winter. Saelens states that DSF's can solve this problem, as the surface temperature of the inner pane is leveled with the room temperature, improving the thermal comfort near the window [18]. However, this may not be always true especially when the façade is not inside ventilated, or when the glass temperature rises due to the re-radiated heat absorbed by the shading devices. User comfort is also linked with the aspect of being able to control the light with louvers/shades and the ability to control air movement with operable windows [2].

2.6.6 Security

The additional skin of the façade makes it almost a transparent physical barrier increasing the feeling of security psychologically. Also it allows the windows being open in the inner skin, which also improves the security of the building in comparison to directly exposed operable windows.

2.6.7 Aesthetics

The double skin facades offer tremendous opportunity to designers as it enhances the qualities of transparency, depth, layering and movement in a building, in comparison to conventional masonry facades, which appear as massive and bulky.

2.7 Forms of Heat Transfer through a Facade

i) Direct radiation through windows is described by the solar heat gain coefficient (SHGC). 'The SHGC is the fraction of solar radiation admitted through a window, both directly transmitted, and absorbed and subsequently released inward. The SHGC is needed to determine the solar radiant heat gain from a glazing. It should be included, along with U-value and other properties, in any description of a window's energy performance [23].'

ii) Conductive and convective transfer due to a difference in temperatures from inside to outside measured by U value (coefficient of thermal transmission). 'The U-value expresses the heat flux (in $W.m^2$) through a building component (or a combination thereof) with a temperature difference of one degree across the components under steady state conditions. It is evaluated by first calculating the R-value (thermal resistance in m^2K/W) and then computing its reciprocal. A low U-value indicates that the building component has a high thermal resistance [23].'

2.8 Classifications

The exact definition of a double skin varies with different situations and these can be classified according to the form in which the intermediate space is divided and the nature of air flow within the space.

a) According to Dirk Saelens [18], double skin facades can be classified into various categories based on the major working principles:

i) Based on the origin of the air flow into the intermediate space:

- Supply: fresh outside air flows into the cavity (Fig.5).

- Exhaust: inside air flows through the cavity to outside.

- Air curtain: air leaves the cavity the same side it came in; there is no exchange between the air outside and inside (exterior and interior air curtain).

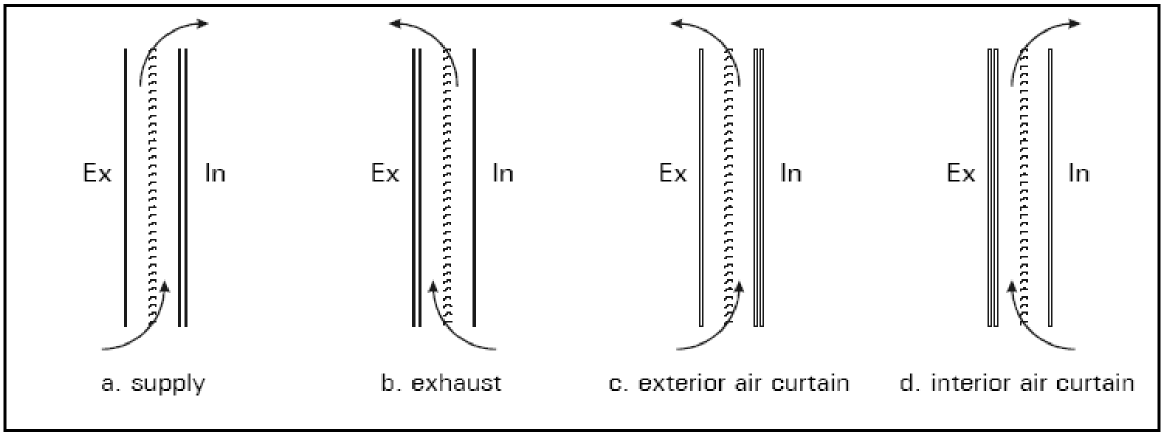


Fig. 5. Types of Double-Skin Based on Air Flow [18]

ii) Based on the driving force of the air flow of the façade:

- Mechanically ventilated systems: In these systems air flow is generated by fans, making it much more controllable.

- Naturally ventilated systems: Here, the driving forces are thermal buoyancy and wind pressure differences. Air flow rate is not a known quantity but depends on climatic conditions. This may not be very suitable for extremely hot climates and also where the temperature difference between the outside pane and inside space is not great enough to allow the stack effect to take place.

iii) Based on compartmentalization of the cavity along the façade:

- Façade: If the air space is along the entire height of the building with no intermediate divisions (Fig.6).

- Shaft: If the air space is divided into vertical compartments along the height of the façade.

- Corridor: If the cavity is divided into horizontal components, usually at the level of every story, with gaps to facilitate movement of air.

- Window: If the air space is both horizontally and vertically subdivided, with windows as multiple-skins.

- Box: If the façade is horizontally and vertically subdivided, with entirely transparent envelopes.

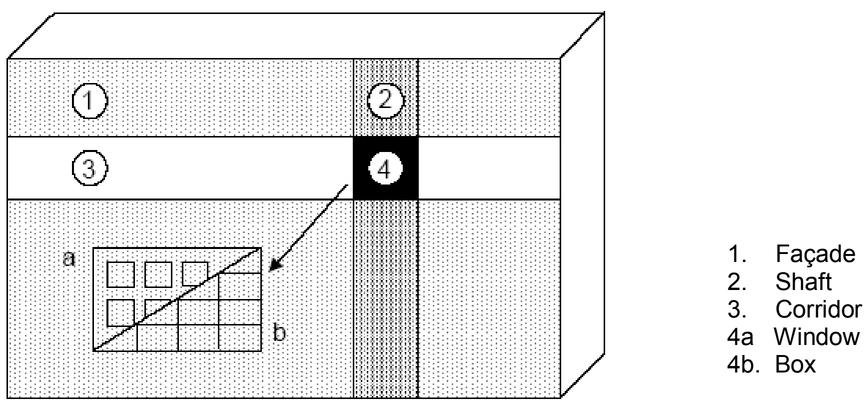


Fig. 6. Types of Facade Based on Compartmentalization [18]

b) The European countries follow the classification system described by the Battle McCarthy [25] engineers in London who categorize double skin facades into five categories:

i) Sealed Inner Skin:

- Mechanically ventilated cavity with controlled flue intake
- Ventilated and serviced thermal flue

ii) Openable Inner and Outer Skins:

- Single storey cavity height
- Full building cavity height

iii) Openable Inner Skin with mechanically ventilated cavity with controlled flue intake.

iv) Sealed Cavity, either zoned floor by floor or with a full height cavity.

v) Acoustic Barrier with either a massive exterior envelope or a lightweight exterior envelope.

c) While the five category classification of double skins is more prevalent in the European countries, in American typology; three types of general systems are recognized. Originally coined by Werner Lang and Thomas Herzog, this classification has also been used by Terri Meyer Boake of University of Waterloo in her research articles [3-5]. The three types of systems (Fig. 7) generally applicable and accepted by the American community are:

i) Buffer system: In this system, two layers of single glazing spaced 250 to 900 mm apart ,sealed, allow fresh air into the building through additional controlled means-either a separate HVAC system or box type windows which cut through the overall double skin. Shading devices may be included in the cavity.

ii) Extract air system: This comprises of a second single layer of glazing placed on the interior of a main façade of double-glazing. Air space between the two layers of glazing becomes a part of the HVAC system. The heated used air between the glazing layers is extracted through the cavity with the use of fans and thereby tempers the inner layer of glazing while the outer layer of insulating glass minimizes heat transmission loss.

iii) Twin face system: Consists of a conventional curtain wall or thermal mass wall system inside a single glazed building skin. Interior space of at least 500-600 mm is needed to permit cleaning. Openings in the skin allows for natural ventilation.

The outer skin protects the air cavity contents from weather, blocks wind in high-rise situations allowing interior openings an access to fresh air without associated noise or turbulence. Ventilation openings in outer skin also moderate temperature extremes within the façade. For sound control, the openings in the outer skin can be staggered or placed remotely from the windows in the interior façade. Internal skin offers the insulating properties to minimize heat loss. Use of windows allows for night-time cooling of the interior thereby lessening the cooling loads of the building's HVAC system.

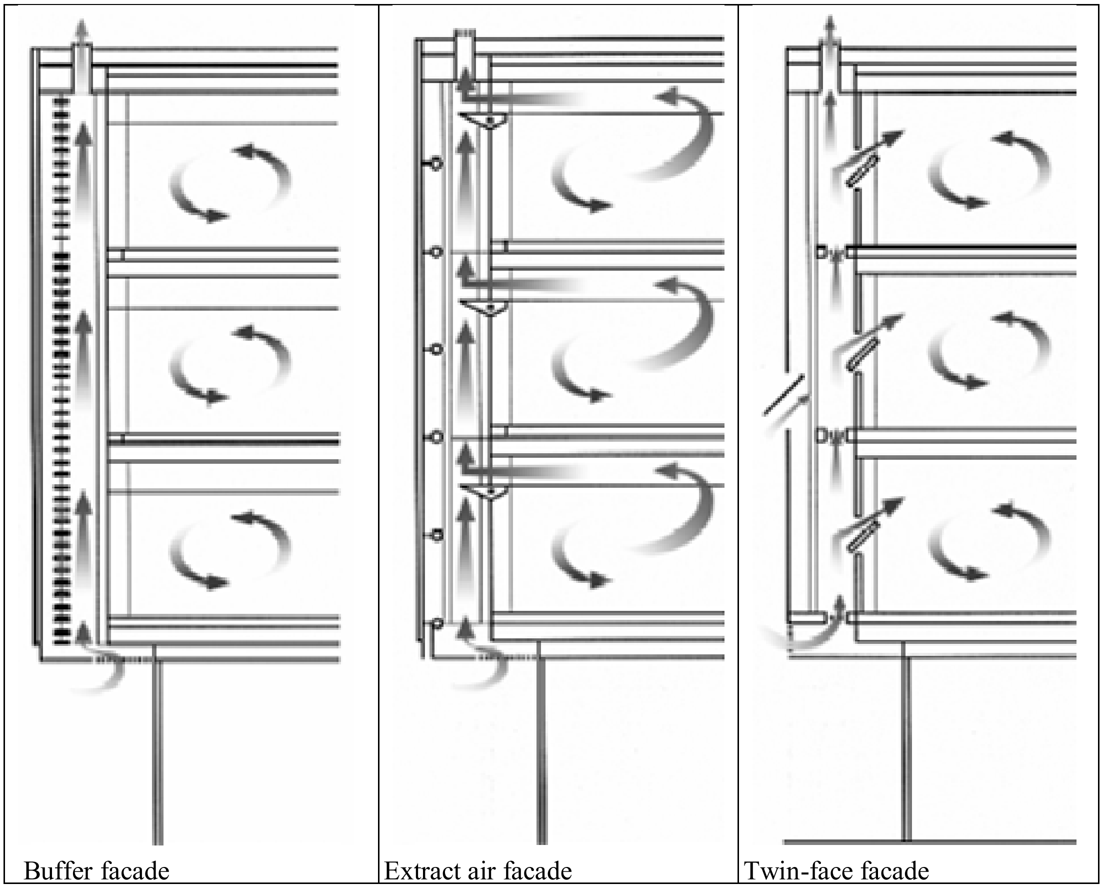


Fig. 7. Types of Facades [4]

2.9 Other Parameters and Physical Properties

Though the double skin facades can be classified according to the above mentioned principles of air flow and façade compartmentalization, each façade has its own set of physical parameters and properties which make the façade unique to the context of its location [2]. Some of these parameters are:

i) Spatial aspects: This includes the depth of the cavity and the height of the window, which may affect the thermal insulation quality of the façade.

ii) Glazing properties: The emissivity, transmissivity, reflectivity and absorptivity of each pane of glass used affect the overall solar heat gain coefficient and the U-value.

iii) Blind properties: Location dimensions and spacing of the blinds and their emissivity, absorptivity and reflectivity would also affect the amount of solar radiation absorbed and re-radiated into the cavity.

iv) Air movement path: Inlet to the inside or outside

Forced or natural convection

v) Controls: Individual control of blinds and operable windows and building control of blinds, windows and fans.

vi) Interaction with other systems such as mass storage and air supply/exhaust.

vii) Configuration and interrelationship of other mechanical components-ducts, fans and controls.

viii) Overall color and visual reflectivity of the system.

2.10 Simulation Research

A lot of research activity is being carried out on the specific task of evaluating double skin façade systems. The analysis of energy performance of buildings especially air conditioned office and commercial buildings is highly complex because of the interactions between the climate and the building and the air-conditioning system and user interactions. The energy performance depends on the building fabric design, occupancy pattern, operating schedules and prevailing climatic conditions [10].

Simulation of a double skin façade is not a trivial exercise as it involves a number of temperature and airflow fluctuations as illustrated by Hensen et al. in their studies. A lot of design support is required for simulating a double façade and a comparative simulation for different situations to identify the advantages of double-skin façade construction especially in terms of reducing the cooling loads has been done through the simulation software ESP-r [13].

The concept of double skins is often found combined with photovoltaic technology where the outer skin has photovoltaic elements to provide energy to operate ventilation devices within the façade or other purposes in the building. Olaf Gutschker and Harold Rogab describe in their article, a procedure to simulate a photovoltaic hybrid façade. The U-value (heat loss coefficient) can be applied to double skin facades without much difficulty, whereas the definition and determination of the g-value (total heat or solar transmittance) causes problems. The g-value, which can also be defined as the fraction of the incident radiation energy that can be used for the heating of the building, can strongly depend on the ambient air temperature [11].

Double skin envelopes are becoming an increasingly exercised option of integrating advanced facades into high performance buildings. Stephen Selkowitz [20] argues that an appropriately designed façade system not only creates comfort conditions for the inhabitants but also reduces the overall energy it uses. Advanced glazing systems can be incorporated into responsive facades to enhance sun protection and air quality, reduce cooling loads and operating costs. There is a conflict between certain issues when designing these facades; while one needs to provide view, glare needs to be controlled. Similarly, the provision of daylight conflicts with controlling solar transmittance and resultant cooling load. Providing natural ventilation leads to other control issues of air leakage and acoustics. These issues become important considerations while designing double skin facades as also understanding the limitations of costs, lack of appropriate design tools and complex commissioning and operation systems [20].

2.11 Efficiency

Double skin facades are also referred to as 'environmental second skins' by Wigginton Michael and Battle McCarthy who in their research carried out for the UK Department of Environmental Transport and the Regions describe the role of double skins in reducing energy consumption drastically in comparison with conventional single skin facades. The study establishes that 'double skin buildings are able to reduce energy consumption by 65%, running costs by 65% and CO_2 emissions by 50% in the cold temperate climate prevalent in the UK when compared to a single skin building [25].' Besides tracing the history of double skins and describing their effects on various comfort factors, the authors classify the double skin facades into various categories. These different categories are further subdivided and facilitate easy understanding of the dynamics of double skins. A detailed analysis and cost exercise led them to the conclusion that 'buildings employing a double skin may cost as little as 2.5 % based on the gross internal floor area [25].'

The University of Waterloo is presently engaged in an extensive research in this area and has presented their investigations and analysis in a series of articles available on a website. The web- articles foster a discussion of the benefits, short-comings and legitimacy of double skin systems as an environmentally 'sustainable' building technology. In another article compiled by Kate Harrison, various environmental and economic issues that need to be considered when designing these systems are highlighted. These issues include effectiveness in controlling solar gain, insulating value of the system, access to fresh air, daylighting, maintenance issues, embodied energy, aesthetics and climatic considerations among other commercial aspects including initial, running and life cycle costs. The absence of a benchmark or a base case against which the performance of a double façade can be compared with is also brought to light [4].

The actual technical merit of double skin facades is questioned in an article by John F Straube and Randy van Straaten, also of the University of Waterloo. Through a comparative analysis with other types of façade systems, the authors conclude that double facades are merely one approach in overcoming the large energy consumption and comfort problems that are created by the use of excessive glazing areas of inferior performance. They even propose other technically valid and less expensive solutions to solve the same problems and argue that the most environmentally sound solution would be to reduce glazing areas and improve the qualities of the glazing product [21]. This article leads to the possible redefinition of double skin facades from being restricted to transparent glazing skins to include a range of materials as desired by a particular context and climate.

2.12 Façade Design

An important issue in designing any kind of energy efficient sustainable building is response to climate and local context. In principle, the design concept may remain the same. However, its physical application will essentially vary with changes in climate. John Perry and Maurya McClintokk [15] façade engineers in Arup identify the possibilities and challenges of applying 'green' strategies to cooling dominated high-rise office buildings in the more tropical climates of Australasia. This study is important as it gives a good review of the external climate conditions in Asia, along with the internal requirements and possible moderations between the exterior and interior through the building envelope.

2.13 Case Examples

2.13.1 Buffer Façades

2.13.1.1 The Hooker Office Building, Occidental Chemical Center, NY

Built in 1980, the building (Fig. 8) is important because it is claimed to be the first North American example of a double-skin building. The original intention was to build a highly energy efficient and transparent building that would capitalize on its location and views of the wonderful Niagara falls [5].

Referred to as "dynamic" skin system because of it ability to change as a function of the time of the year and day, the building was constructed with a straightforward square plan with a central core and suspended ceilings. All four sides a 4-foot (1.2 m) cavity allows for maintenance of the movable daylight controlling louvers, window washing and ventilation of the cavity by stack effect. The louver system was designed to automatically rotate to control daylight entering the building. The outer skin was double glazed with blue-green glass as the outer pane and clear glass as the inner pane. The inner skin is floor to ceiling single glazing. The cavity was fitted with motorized dampers at the base and the top to assist in controlling the flow of air through the cavity [5]. Fig. 9 describes the wall section through the façade of the building.

A performance analysis in 2001 revealed that a number of the original design intentions and systems of the façade system were no longer functioning either in whole or in part. The coating on the interior surface of the exterior glazed skin was disintegrating or delaminating and there was a lack of proper maintenance and cleaning of louvers. In fact, a user survey also revealed that the occupants were not comfortable as the building was either too hot or too cold [5].

Fig. 8. View of the Hooker Building [5]

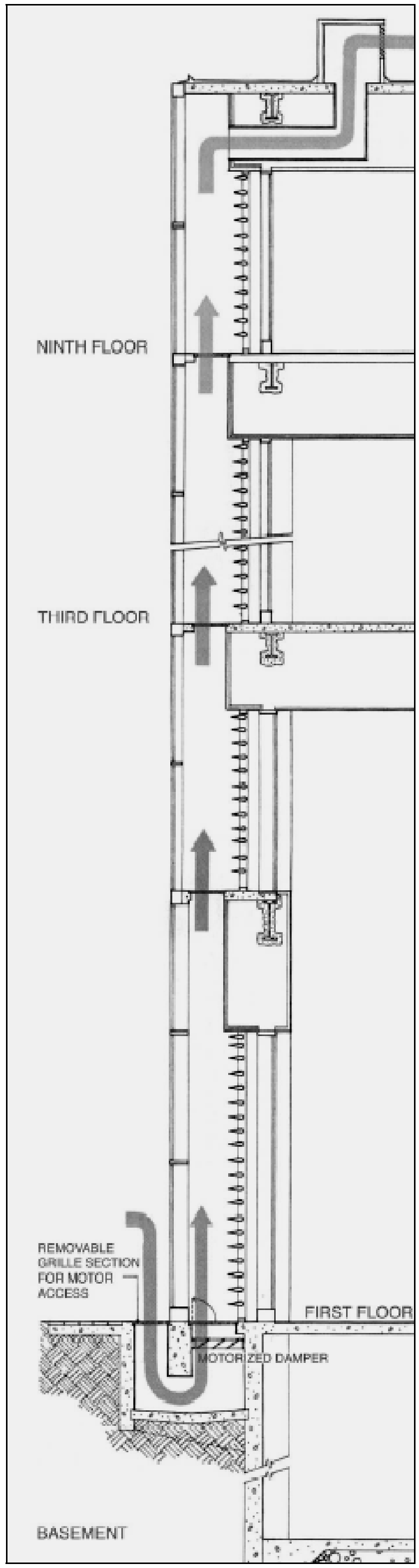


Fig. 9. Wall Section through the Facade of the Hooker Building [5]

2.13.2 Extract Air Facades

2.13.2.1 The 'Helicon' Finsbury Pavement, London (UK)

The architects desired maximum transparency for the building, while realizing the requirement for adequate solar control. They relied on the control of solar energy through the façade to reduce the need to import energy to maintain internal comfort. 'The double skin consists of an outer pane of frameless single glazing (12mm) and inner double-glazed panels. It acts as a thermal flue with automatically controlled vents and tilted blinds for solar control. This void of the double skin glazing can be naturally ventilated with automatic openings, which induce a stack effect to dispel unwanted solar gain. Blinds in the cavity can be lowered and tilted automatically in response to outside light and solar intensity, and inside light levels and inside temperature. Timed sweeps, occupancy detectors and photocell sensors automatically control lighting [26].'

Winter heating is provided by a perimeter heating system and the double skin on the east and west can be kept closed to act as a thermal buffer, reducing winter time heat loss. Summer cooling is provided by a chilled ceiling system where chilled ceiling panels are integrated with the perforated metal ceiling tiles. The double skin on the east and west facades are opened with low and high level openings that produce a stack effect to remove unwanted solar build-up [26].

Daylighting is provided to the relatively deep floor plate of the building because of the full height glazing. Maintenance walkways within the double skin void provide a degree of solar protection at each floor level. Fig. 10 presents photographic views of the Helicon Building.

Fig. 10. Photographs of the Helicon Finsbury Building [24]
Details of the facade and shading devices can be seen.

2.13.3 Twin Face Systems

2.13.3.1 Telus/ Farrel Building, Vancouver, BC

Opened in about 2001, one of the few double skin facades built in North America, this building employs the ‘twin-face’ type of double-skin strategy. This system provides natural ventilation through operable windows in both the exterior and interior facades. Originally made to house the company's analog telephone switching gear, much of the space in the building became redundant for its intended use after the introduction of digital operating equipment. Instead of demolishing the building, the architects decided to retrofit the structure and the building was proposed to be covered with a double glazed aluminium framed curtain wall (Fig. 11). The cavity acts as a greenhouse that stores heat in winter and provides shade, diverting heat from the building in the summer (Fig. 12). The cavity is controlled by louvers at the base of the cavity and dampers at the top to flush the air as required. Photovoltaic cells are linked to the ventilation fans and dampers on the roof [5].

'Embodied energy is low due to the reused materials and, together with the operating energy reduction; there is a significant reduction in life-cycle energy use compared to standard practice. Operating energy is reduced by the tempering effect of the new external glazed skin. The skin and horizontal shading devices reduce the solar load during summer and provide solar gain during winter [5].'

Fig. 11. View Showing the Old and New Facades [1]

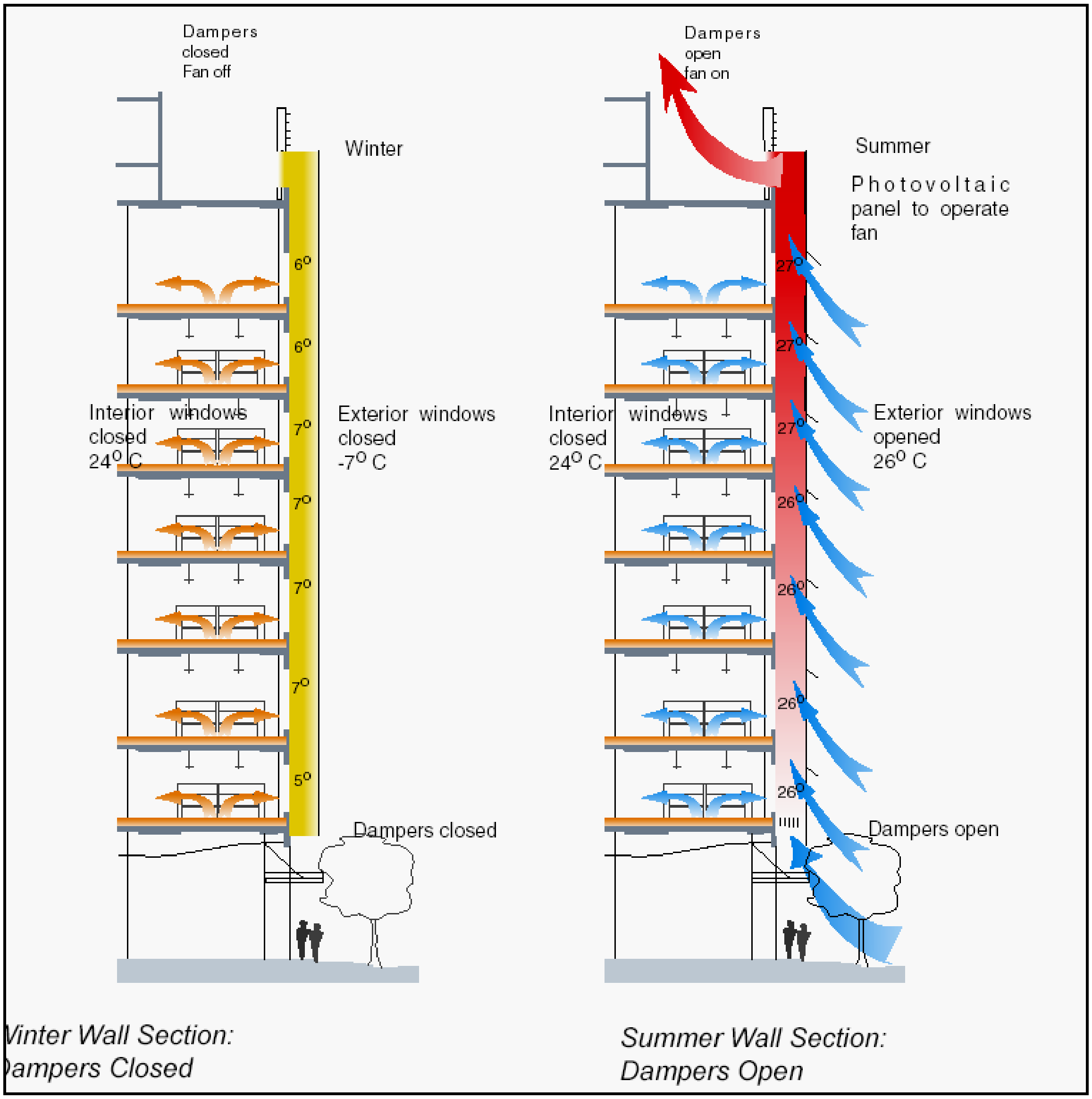


Fig. 12. Wall Section through the Facade of the Telus Farrel Building [5]

2.13.3.2 Das dusseldorfer Stattdor, Dusseldorf, Germany

The Stadttor project (Fig. 13) is an office building composed of two separate rhomboid towers, connected at the top of a huge atrium void, 50 m high. The 20-storey building is supported by two vertical triangular trusses that are connected by the top three floors forming a structural bridge [26].

'A double skin cavity envelops the three sides of the office floors creating a ventilated perimeter zone, varying between 1.4 and 0.9 m in depth. The outer face of the double skin is 15 mm toughened planar glazing which is a low iron glass for maximum transparency. The inner skin is made of vertically pivoted high performance windows [26].' The building is said to be mostly naturally ventilated through computer-controlled ventilation flaps that run in horizontal bands at each floor level.

'There are sensors for wind, temperature, rain and sun to exercise optimum control strategies for heating, cooling and fresh air supply. It has been predicted that natural ventilation would be available for 70% of the year when the temperatures would be between 5 C and 22 C. Pre-heated mechanical ventilation would be provided for 25 % of the year when the temperatures would be below 5 C and pre-cooled ventilation would be provided for the remaining 5% of the year when the temperature would be above 22C [26].'

Full height glazing ensures maximum daylight and views over the city. Blinds situated within the cavity are lowered automatically in response to photocell detectors on each façade, which indicate if the sun is shining on a particular face. Their tilt can be further adjusted to let daylight enter but to reduce glare.

The performance tests of the façade apparently showed that the air leaving the cavity is 6 C hotter than incoming air, suggesting that it is performing a useful cooling effect on the blinds.

Fig. 13. Photographic Views of the Stadttor Building [17]

2.13.4 Hybrid Systems

2.13.4.1 Debis Headquarters, Potsdamer Platz, Berlin, Germany

This building was required to house the headquarters of the property, financial services, information technology and media services of Daimler-Benz in Germany. The form of the building (Fig. 14), rises from a six-storey broad lower end to a narrow 21-storey narrow end. An atrium of about 14 m runs north to south down the center [26].

‘The east, south and west elevations, with the highest exposure to solar gain, incorporate a glass wall, about 700 mm outside the main window wall. This wall comprises of glass panels which can open to 70 degrees, controlled by sensors to allow for ventilation in warm weather. In cold weather, these close to create an insulating layer. The inner skin incorporates upper and lower panels of insulating glazing: the upper windows open automatically at night in warm weather, to ventilate the interior and thus remove much of the heat build up during the day. The outer layer of glass louvers reduces wind pressure, keeps rain away and also provides protection to the retractable blinds within the cavity [26].'

Comfort cooling is provided in the form of chilled ceilings and heating is provided from the district heating system.

As long as the temperature does not rise above 30 C, the natural ventilation is designed to produce better conditions than the mechanical ventilation and is said to be adequate for about 40-55% of the year. This is said to reduce the energy loads of the building by about 40%. Daylighting is ample and the German standard of a 2% daylight factor is easily achieved through all the office spaces [26].

Fig. 14. Views of the Debis Building [14]

CHAPTER III

METHODOLOGY

3.1 Data Collection

The first step in the procedure of the research was to collect data about the two case study buildings in India, one building in Delhi and one building in Hyderabad. This data related to information about the building and the weather data of the cities.

3.1.1 Building Information

The detailed drawings of each building were obtained which included plans, sections and elevations. Basic information about the building mechanical systems was also obtained. All the building information was obtained from the respective architects of each building in India.

3.1.2 Weather Data

The weather data of each city was available in the weather database of Ener-Win, the software used for the simulation.

3.2 Simulation of Base Case

After obtaining basic building and weather data, this information was used to simulate the energy performance of the existing buildings in their current state. This was the base case simulation for each city. The simulation software used for this research was Ener-Win 2002, developed by Degelman Engineering Group, Inc and copyright property of College of Architecture, Texas A&M University. This basic energy simulation software can be used for quick design decisions regarding building energy performance. It provides a user friendly interface and has the capacity to simulate energy consumptions and costs from basic input of the building shell, thermal zones, climate data and economic parameters.

Fig. 15 describes the entire methodology followed in conducting this research.

3.2.1 Input

3.2.1.1 Basic Building Information

This was input in terms of its name, location, type and period of evaluation.

3.2.1.2 Zone Identification /Building Sketch

Each building was then divided into a number of thermal zones based on orientation and nature of space. These were offices on north-east, offices on north-west, offices on south-east, offices on south-west and electrical, toilets, elevator and corridor zones. These zones were described by means of a sketch in Ener-Win. With the sketch, a zone properties dialogue box is arrived at which has the specific properties of each zone. Depending on the building information, the zone properties were changed.

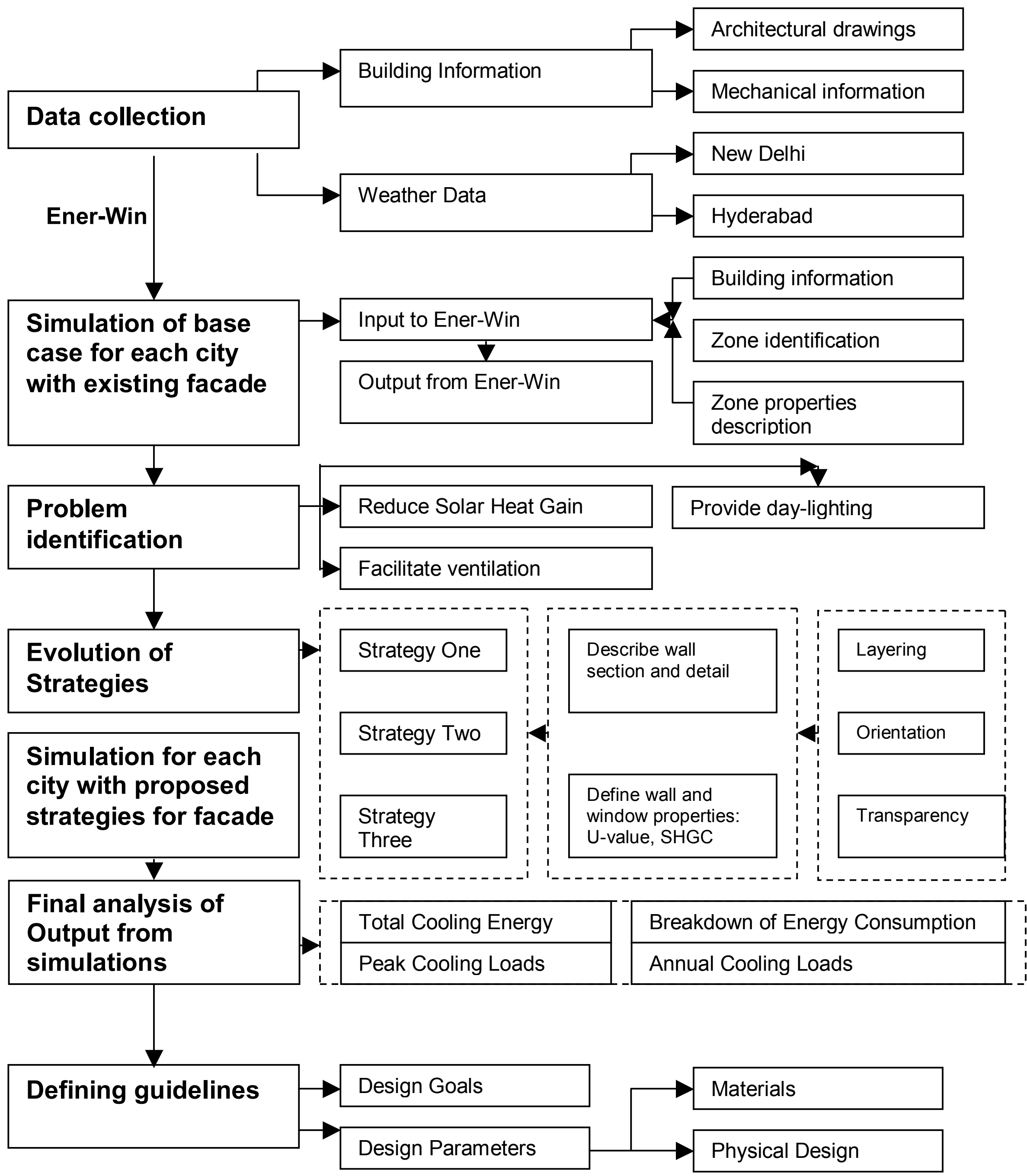


Fig. 15. Methodology of the Research

3.2.1.3 Zone Properties Description

Ener-Win input to describe the properties of each zone can be divided into two sub categories:

a) The first set defines the broad parameters of each zone like occupancy, hot water system used, temperature profiles, ventilation, lighting and equipment, type of HVAC system, use of natural ventilation and daylighting. For all these values, defaults were used for office buildings except for the HVAC system which was obtained from each building's data. The base case was simulated with no natural ventilation and no daylighting.

b) The second set shows the specific properties of each zone in terms of the wall properties (area, orientation, exposure, and wall id), shading, window properties (type, glazing area, size).The wall area is calculated by the program and one does not need to change it. The only values to be entered are:

i) Wall type: The typical wall section of the existing building in each case was studied and its U-value was calculated. A new wall type specific to the building was created in the program with the calculated U-value and approximate assumed values of time lag and solar absorption coefficient. The U-value was calculated as a simple sum of resistances across the layers of each façade.

The general equation used to calculate the U-value was: $U_{total} = 1/R_{total}$

Where $R_{total} = R_o + R_{wall} + R_i$

R_o= Resistance of outside air

R_{wall}= Sum of resistances of each component constituting the wall

R_i= Resistance of inside air

These U-values were used to create three new wall types with new wall id's and these were used in the simulation runs.

ii) Wall area, orientation and surface exposure were calculated by the program.

iii) Window type was identified according to each building's respective available information.

iv) Glass area: The glass area was manually calculated and entered based on information from building drawings.

v) Other parameters: The other parameters used were defaults and only the window sill and window height were changed according to the drawing data.

3.2.2 Output

After all the appropriate input to best define the existing buildings was entered, the base case was simulated for the annual performance for the year 2002. Ener-Win generates a detailed report of the heating/cooling energies, peak and annual cooling/heating loads, costs and annual breakdown of energy consumption.

For this thesis, only some of the output graphs were analyzed because they seemed to be most relevant in the context of the simulation. The number of 'Cooling Degree Days' far exceeds the number of 'Heating Degree Days' clearly showing the dominance of the cooling season. (Refer to detailed weather data for both cities in the Appendix D).It was noticed that because of the hot conditions, the most significant loads were the cooling loads and maximum energy was used for cooling. In terms of break-up of annual energy consumption, the major consumers were space cooling and lighting. A cost analysis of the building was omitted, as the major objective of the research is to study the thermal effect of facades, and also because of practical difficulty in obtaining the exact prices and costs of materials and construction practices in India. Therefore, the major focus of the analysis was on the following four output graphs:

a) Total Annual Cooling Energy
b) Peak Cooling Loads
c) Annual Cooling Loads
d) Breakdown of Energy Consumption

3.3 Problem Identification

The information obtained from this output was then used to identify the major problem sources for heat gain and high cooling loads. Both Base Case simulations showed that maximum heat gain was through window transmission and solar radiation, followed by the heat gain by walls. Thus a need was felt to reduce heat gain through these sources, which are actually the constituents of the building envelope, more specifically the façade. Therefore, changing the properties of the façade seemed to be beneficial in cutting down the cooling loads.

3.4 Evolution of Strategies

Based on the output obtained from the Base Case simulations, the goals for the façade to be designed for the buildings were identified. The main goals of the double skin façade in this particular context with mostly cooling dominated loads would be to:

a) Reduce solar heat gain: This can be achieved by ample use of shading devices and also by increasing the thermal mass and U-value of the façade. The use of extensive glass, 100 % transparent facades, similar to the European countries does not seem appropriate. Therefore, the façade needs to be designed with brick cavity walls in combination with double skinned glazing.

b) Facilitate ventilation: The façade should be able to allow for ventilation through its cavity to remove/ extract hot air continuously from the cavity. This vent could be sealed in the winter, to allow for some heating. The nature of the gap could vary from being compartmentalized horizontally, vertically or be continuous. Natural ventilation for the interior space may not be very desirable because of the extremely hot temperatures. The operability of the inner façade can be controlled according to the outside temperatures during day time and for night time ventilation to cool down the heat absorbed by the building fabric during the day.

c) Facilitate daylighting: Daylighting can be notably achieved with the use of the double skin, to avoid extreme electric lighting loads.

3.5 Methodology for Simulation of Strategies

Ener-Win has the capacity to calculate energy consumption for summer and winter months individually. Since the functioning of the double skin is different in the summer and winter months, Enerwin's feature of different set of calculation procedures has been used.

The actual physical or mathematical calculation of the U-value of a double skin façade is tedious and involves a number of factors like radiation and convection coefficients. Therefore, for simplicity of simulation, the double skin has been simulated through a series of logically arrived-at assumptions. Though, the U-values assumed are not exact, they are within 10% range of actual measured U-values of existing double skins.

In summer, the double skin is designed with open vents allowing outside air inside, so the properties of inner skin are taken as the properties of the double-skin. The façade is treated as a large window and the window properties are changed. Based on the nature of the façade, the transparency is adjusted. The U-factor of the inner skin is increased by 10% to take into account the heat from the outside air. The SHGC and daylight transmissivity of the skin is calculated by multiplying the individual SHGC and transmissivity properties of both the layers of the skin. The emissivity of the skin is taken to be a constant equal to the inner skin emissivity.

In winter, the double skin is sealed (the vents are closed), to allow heat to get trapped within the skin, providing heating. In this situation the U-factor of the combined layers is assumed to be close to the U-factor of a double glazed unit, with e=0.10 and half inch air space. This value is obtained from the tables provided in the 2001 Ashrae Fundamentals Handbook. The SHGC and transmissivity are again calculated in a similar manner as explained above.

The following parameters are varied in each of the simulation runs to study the affect each of these have on the efficiency of the building. This would help in arriving at a set of design criteria for an efficient design of a double-skin façade in a hot climate.

1. Layering of the skin.
2. Transparency of façade
3. Orientation

Each of the strategies was then also simulated with an option of including shading on the transparent facades to study the effect of shading on the energy performance of the building. In the first set of simulations no extra shading devices are used. Then the simulations are done incorporating shading on the various facades. The shading is calculated as fractions in Ener-Win based on the location of the shading device. The following were assumed as the shading fractions for each orientation of the façade based on Sunpath diagrams (refer Appendix C).

i) The northern façade being the least exposed to direct and prolonged periods of sun is treated with an overhang of 1' depth at each floor level (10' height).

This is calculated as a top shade T= depth of overhang/ height of window

Therefore, T= 0.1

ii) The eastern and western facades are exposed to direct sun for almost 4 hours each in the morning and evening respectively. Vertical shading on these facades would help cut off direct sunlight. Therefore these are incorporated as devices to the right of the window (R) and devices to the left (L). Both the fractions are calculated as angles they subtend at the end of the window. Assuming, a 1' deep fin at every 5' interval on the façade, it can be seen that the angle it describes is about 12 degrees. In Ener-Win, a 45 deg angular description implies an R1. or L1. Therefore, a 12 deg angular description would mean an R .2 and L .2.

iii) The southern façade is most exposed to low angle direct sunlight in the afternoon. To shade this façade all the three above mentioned devices: overhang, left and right fins are used. This gives shading fractions of R .2, L.2 and T.1.

To summarize, the following were the steps followed for the simulation:

1. Decide layering of each strategy.
2. Calculate/arrive at window properties of the composition based on above method for both summer and winter.
3. Define the window and wall properties
4. Decide on transparency and orientation. Where 100% transparency of façade is assumed, wall properties are not changed, only glazing fraction was changed. When transparency is different then, wall properties were also changed. In these cases, the wall composition was also decided and its U-value was calculated.
5. The first set of simulations was done.
6. Then, the shading values as explained above were incorporated and another set of simulations were done.

3.6 Strategies

Three strategies were evolved for the façade treatment. Each of these strategies was further varied by changing certain parameters. The following is a description of each of the three strategies in detail with their description and input properties.

3.6.1 Strategy One

3.6.1.1 Description

The proposed double skin strategy (Fig. 16) consists of an outer layer of ¼' gray tint glass- aluminum (al.) fixed and an inner layer of ¼' clear (al. operable) glass separated by an air cavity of 2 feet. In summer, the façade is vented open from the bottom to facilitate removal of heat trapped within the glass skins. In winter, the façade is sealed to allow heating the space and keeping the inner pane at a comfortable temperature (Fig. 17).

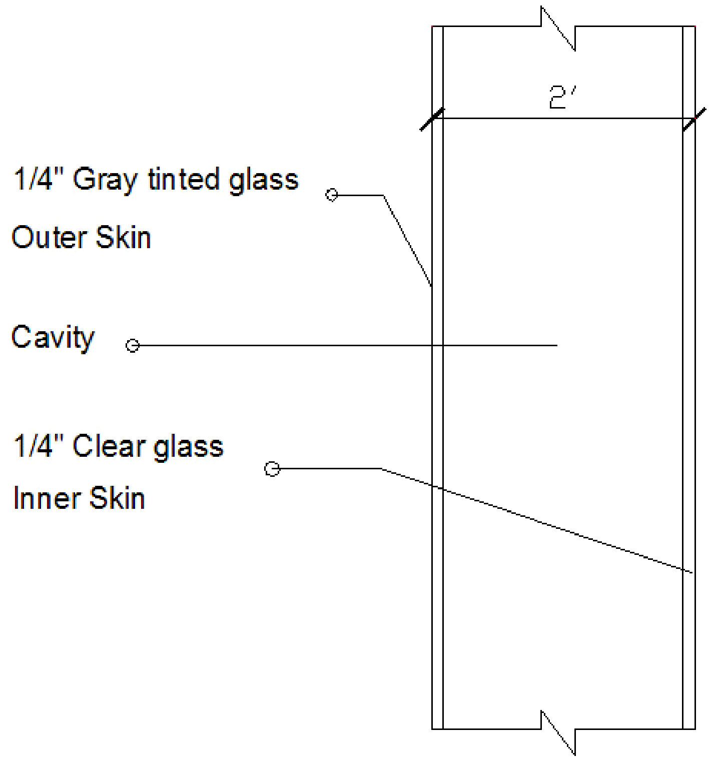


Fig. 16. Detail of Wall Section for Strategy One

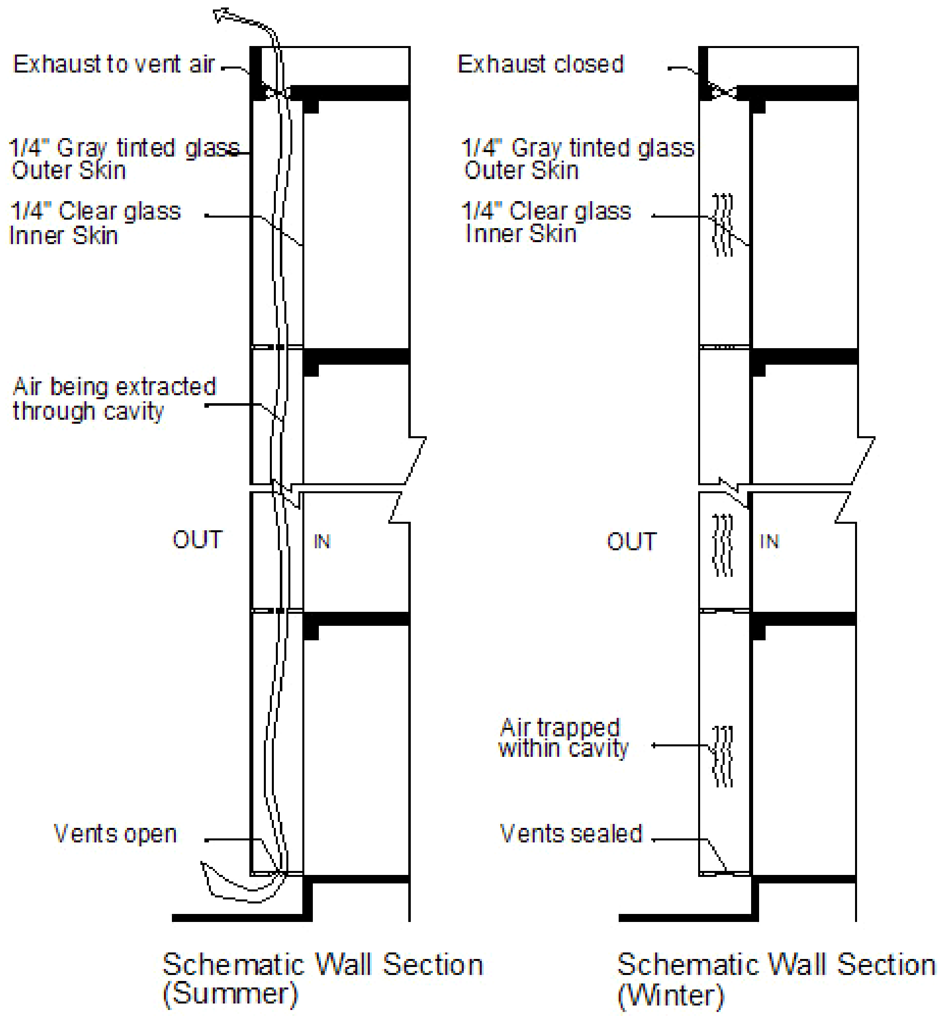


Fig. 17. Schematic Wall Sections of Strategy One for Summer and Winter

3.6.1.2 Input

The proposed double skin strategy is analyzed for its effect on the cooling loads of the building to understand its thermal effect. Also, in order to understand the implication of orientation on the cooling loads, the design strategy is applied sequentially along each orientation of the façade, keeping the remaining three walls same as the base case building. Then finally the strategy is applied to all four orientations to see the difference in the building performance. Thus, the strategy can be broken down into five sub-strategies based on the façade it is applied to as:

1N: Here the proposed skin is applied to only the north façade, keeping the other three facades same as the base case.

1E: The proposed strategy is applied to the east façade only.

1S: The strategy is applied to only the southern façade, and the rest are kept the same as the base case.

1W: The proposed skin is applied to the west façade alone.

1all: The double skin façade is applied to all the four orientations.

The façade to which the strategy is applied is treated like one big window. Therefore, only the window properties of the façade are changed based on the U-factor and SHGC calculation and the wall is given a 100% transparency. Hence, the wall properties of that particular façade need not be changed and are kept the same because the window area (100% of wall area) is deducted from the wall area.

3.6.1.3 U-value and SHGC Calculation

The U-value and SHGC are closest approximations based on the methodology explained in the previous section. Table 1 explains these values for Strategy One. Ener-Win has the option of running calculations separately for summer and winter. This option is used for each double-skin proposed as it functions differently in the two seasons and has different properties.

The basic input of building data and zone properties description remain the same as the base case with most of the values being default values for office buildings. The only parameter changed is that of daylighting. The daylighting switch in Ener-Win is turned on to provide about 40fc of light along 9 feet perimeter zone of the façade.

Table 1
U-value and SHGC Calculation for Strategy One

SNo	Period		Layering	Ufactor	SHGC	Emissivity	Daylight Transmissivity
1	**SUMMER**	Out	1/4 " gray tint (al fixed)	1.13	0.54	0.84	0.41
		In	1/4"clear (al operable)	1.13	0.71	0.84	0.75
	TOTAL			**1.243**	**0.3834**	**0.84**	**0.3075**
	WINTER	Out	1/4 " gray tint (al fixed)		0.54	0.84	0.41
		In	1/4"clear (al operable)		0.71	0.84	0.75
	TOTAL			**0.59**	**0.3834**	**0.84**	**0.3075**

3.6.2 Strategy Two

3.6.2.1 Description

The second proposed double skin strategy consists of an outer layer of¼' gray tint (al fixed) and an inner layer of double-glazing with½'air space separated by an air cavity of 2 feet (Fig. 18). In summer, the façade is vented open from the bottom to facilitate removal of heat trapped within the glass skins. In winter, the façade is sealed to allow heating the space and keeping the inner pane at a comfortable temperature (Fig. 19).

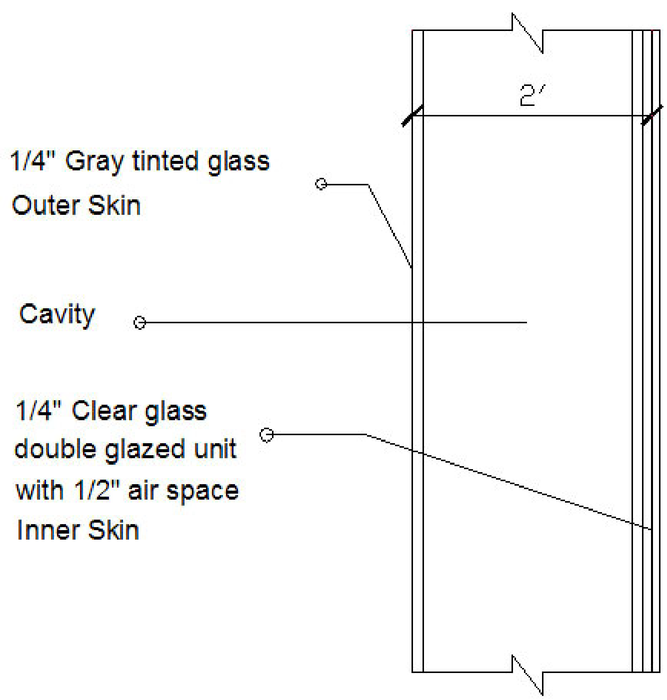


Fig.18. Detail of Wall Section for Strategy Two

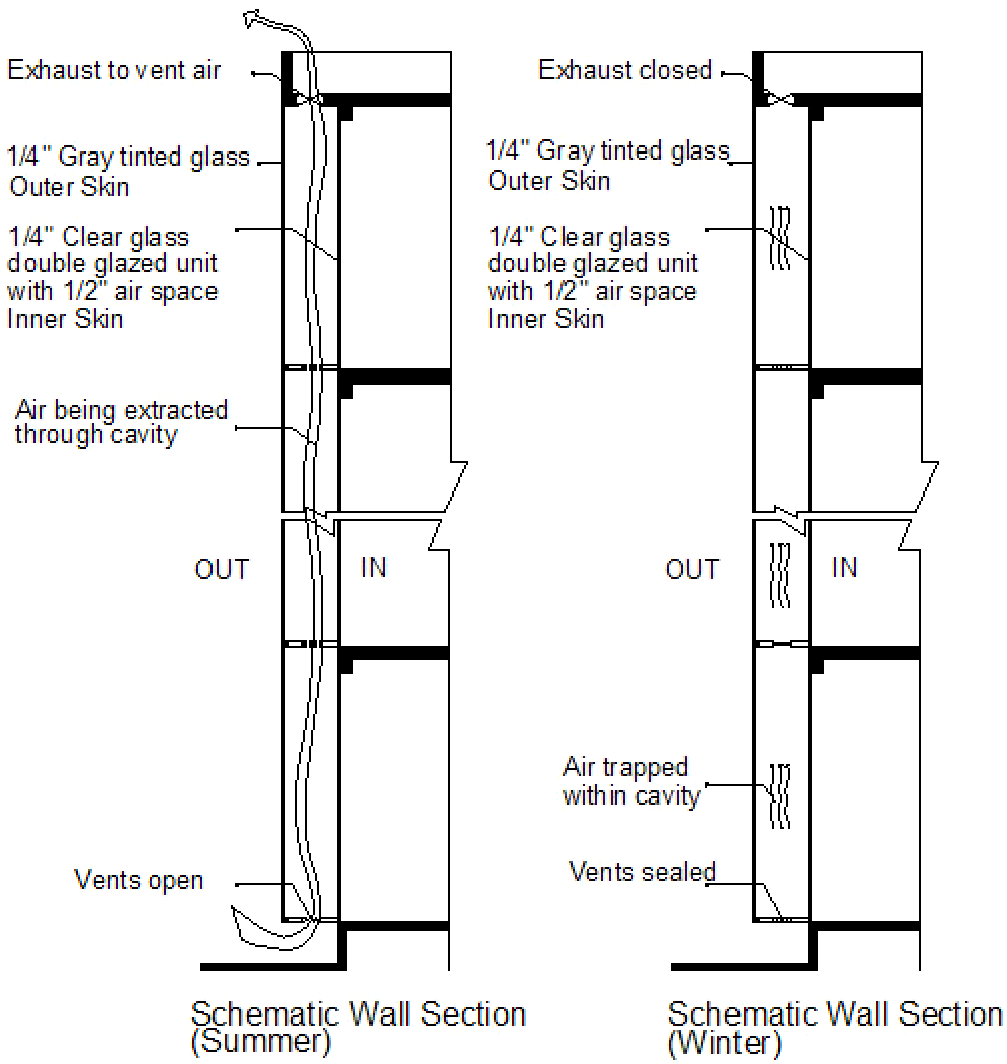


Fig.19. Schematic Wall Sections for Strategy Two for Summer and Winter

3.6.2.2 Input

As in the case of the first strategy, the second strategy is also applied in a similar fashion sequentially to generate different alternatives:

4N: Here the proposed skin is applied to only the north façade, keeping the other three facades same as the base case.

4E: The proposed strategy is applied to the east façade only.

4S: The strategy is applied to only the southern façade, and the rest are kept the same as the base case.

4W: The proposed skin is applied to the west façade alone.

4all: The double skin façade is applied to all the four orientations.

The procedure for simulation is same as the first strategy. All input are same as the first strategy except for the variation in U-value and SHGC due to change in layering of the façade.

3.6.2.3 U-value and SHGC Calculation

The following Table 2 shows the U-factor and SHGC that were calculated for this strategy based on the methodology explained in the previous section.

Table 2
U-value and SHGC Calculation for Strategy Two

S.No	Season	Façade	Description	U-factor	SHGC	Emissivity	Daylight transmissivity
4	**SUMMER**	Out	1/4 " gray tint (al fixed)	1.13	0.54	0.84	0.41
		In	double-glazing 1/2"air space	0.64	0.61	0.84	0.66
			TOTAL	**0.704**	**0.3294**	**0.84**	**0.2706**
	WINTER	Out	1/4 " gray tint (al fixed)		0.54	0.84	0.41
		In	double-glazing 1/2"air space		0.61	0.84	0.66
			TOTAL	**0.57**	**0.3294**	**0.84**	**0.2706**

3.6.3 Strategy Three

3.6.3.1 Description

The third strategy proposed is a brick layered façade with the glazing area functioning like a double skin façade. The wall plan (Fig. 20) and elevation (Fig. 21) explain the same. The basic goal of this façade is to reduce the overall U-value of the façade, thus reducing solar heat gain, which would then reduce cooling loads. The double layered glazing works as a vertical shaft with open vents in summer to remove heat and closed vents in winter to provide for heating. This combination of opaque and transparent layering of the double-layered envelope balances the objectives of heat gain reduction and daylighting.

A preliminary simulation of a brick façade with varying thicknesses of outer and inner layers of the facade was done and it was seen that increasing the thickness of the outer wall from 4½" to 9" caused a reduction in the U-value of the wall section, thereby showing a difference in the energy consumption also. Hence, the final strategy chosen was the one where the outside layer was 9" brick and inside layer was 4½" brick wall. Fig. 22 describes a detail of the wall section.

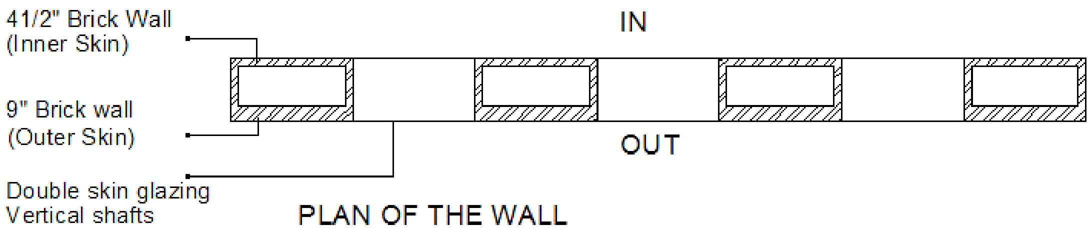


Fig. 20.Facade Wall Plan of Strategy Three

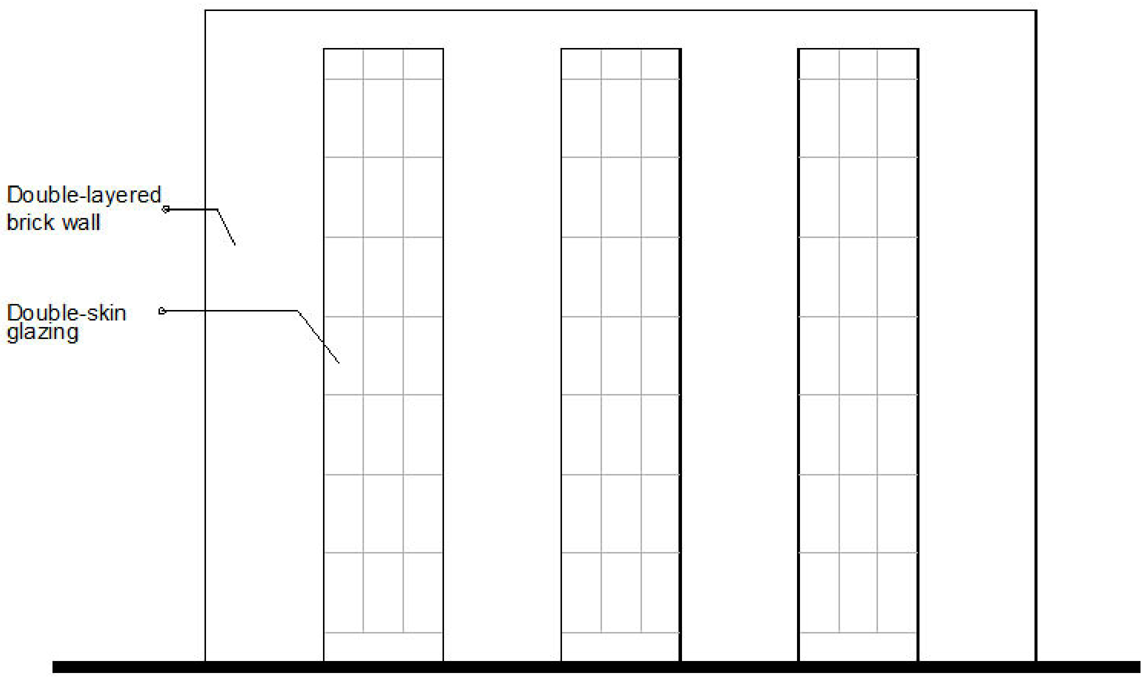


Fig. 21. Schematic Elevation of the Proposed Strategy Three

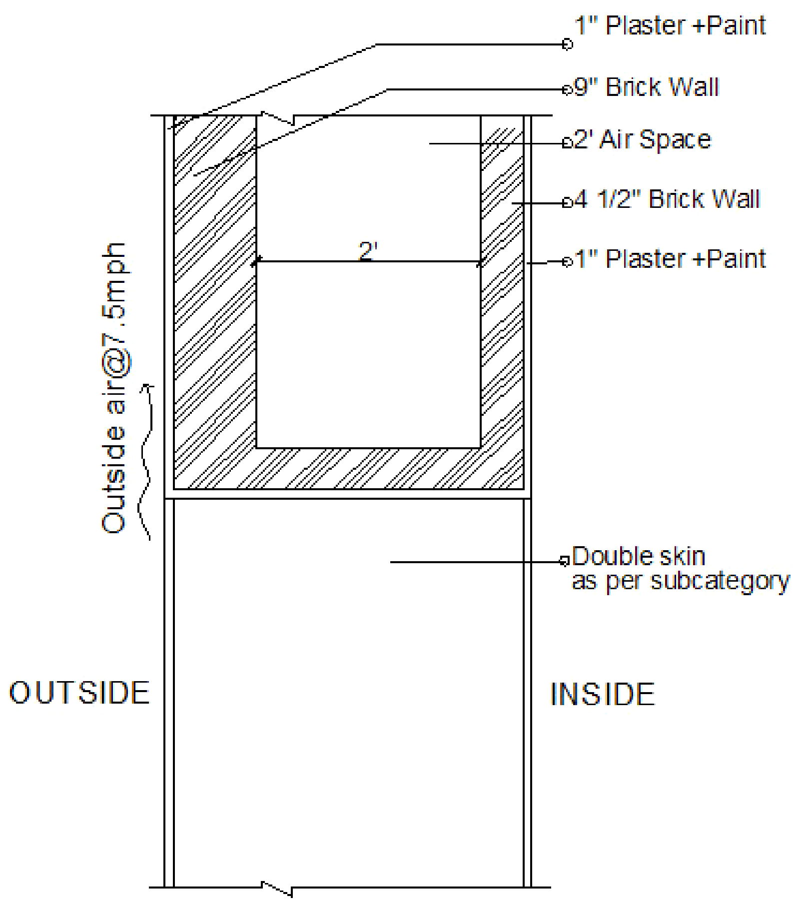
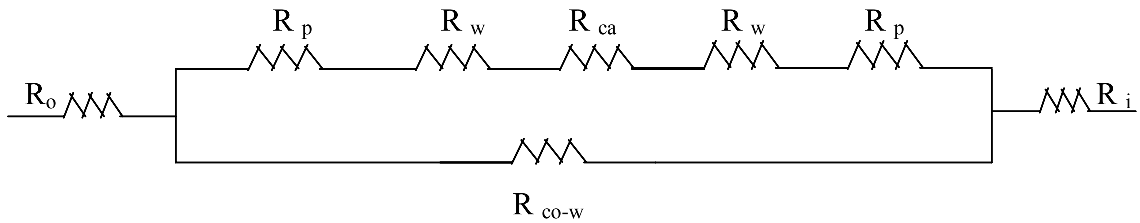


Fig. 22. Detail of Wall Section for Strategy Three

3.6.3.2 Calculation of Resistance for Wall Section of Strategy Three

The overall U-Value of this wall was calculated as an inverse of the sum of the resistances as explained in the Fig. 23 below. The formulae used for calculation have also been further explained. Using the total resistance value, the final U-Value of the wall was obtained as explained in Table 3.



Legend

R_o : Resistance of outside surface R_p : Resistance of plaster and paint R_w : Resistance of wall

R_{ca} : Resistance of cavity $R_{co\text{-}w}$: Resistance of continuous wall R_i : Resistance of inside surface

Fig. 23. Resistance Diagram for Wall Section of Strategy Three

The formulae used for calculation are as follows:

$$R_{total} = R_o + 1/\left(1/R_{ca\text{-}w} + 1/R_{co\text{-}w}\right) + R_i$$

Where, $R_{ca\text{-}w} = R_p + R_w + R_{ca} + R_w + R_p$;

$R_{co\text{-}w} = R_p + R_w + R_p$

Therefore, final U-value = $1/R_{total}$

Table 3
U-value Calculation of Strategy Three Wall Section

Symbols	Material	R_o	$R_{ca\text{-}wall}$	$R_{cont\text{-}wall}$	R_i
R_o	Outside surface(7.5mph)	0.25			
R_p	1"plaster+paint		0.20	0.20	
R_w	9" brick wall		1.80		
R_{ca}	2' air space		0.92		
R_w	41/2" brick wall		0.90		
R_p	1" plaster + paint		0.20	0.20	
$R_{co\text{-}w}$	1'10"wall			5.10	
R_i	Inside surface,still air				0.68
	Totals	0.93	4.02	5.50	0.68
R=	$1/(1/R_{ca\text{-}w)}+(1/R_{co\text{-}w)}$	4.201818			
R_{tot} =	R_o+R+R_i	5.131818			
Uvalue	$1/R_{tot}$	**0.194863**			

3.6.3.3 Input

The U-value of the brick layered façade was calculated and a new wall type was defined with this U-value. This wall type was used to define all the four walls/facades. The glazing area was defined with varying transparencies assigned to façade along each orientation. This glazing was in fact, the double-skin façade that was used in the earlier two strategies. The sub-strategies with the same wall type have variations in their transparencies and layering of the double-skin shaft windows giving rise to the following:

2a: The brick layered façade with double-skin of Strategy One and transparencies of 80%, 50%, 50%, 25% along the north, east, west and south facades respectively.

2b: The brick layered façade with double-skin of Strategy One and transparencies of 70%, 40%, 40%, 25% along the north, east, west and south facades respectively.

2c: The brick layered façade with double-skin of Strategy Two and transparencies of 70%, 40%, 40%, and 25% along the north, east, west and south facades respectively.

3.7 Simulation of Strategies

Each of these strategies were then simulated for both the buildings and output was obtained showing the total cooling energy, cooling loads and energy consumption breakdown. Another set of simulations was done for the first two strategies with shading addition to the double-skin. Because strategy three involved combination of materials with varying transparency, shading was not incorporated for this strategy. A graphical analysis was done from the output data obtained and graphs comparing each strategy with the base case were generated using Microsoft Excel. These comparison graphs led to an easy analysis of the efficiency of each strategy.

3.8 Analyzing Results

The results obtained from the above simulation were then used to derive inferences about the specific factors that influence the efficiency of the double-skin façade. Since each of the strategies had some parameters varying, one could analyze the effect of a particular parameter on the façade. The three main parameters that were found to influence the efficiency of the designed façade were:

a) Layering

b) Transparency and Shading

c) Orientation

3.9 Defining Guidelines

A detailed analysis of these three factors helped in generating a set of design goals and design guidelines for appropriate design of a double skin façade in these two situations specifically and in the Indian climatic conditions in general.

CHAPTER IV

DATA ANALYSIS

Following the methodology explained in the previous chapter, this chapter describes the actual data obtained and the physical simulations done to obtain the desired results.

4.1 Case Study One

4.1.1 Building Description

Mahavir Commercial Complex, Himayat Nagar, Hyderabad (Hyd.), India

The building analyzed was a four-story commercial complex in Hyderabad with shop space on the first floor and offices on other floors. The building was constructed in 2001 and has been successfully occupied since then.

4.1.2 Structure

The building is an RCC frame structure with brick walls and tinted glazing for windows and curtain wall on the north side. Fig. 24 shows a rendered view of the building and Fig. 25 gives a typical floor plan. The detailed floor plans at all levels, sections and elevations have been presented in Appendix B.

Fig. 24.View of Mahavir Commercial Complex, Hyderabad (Hyd.)

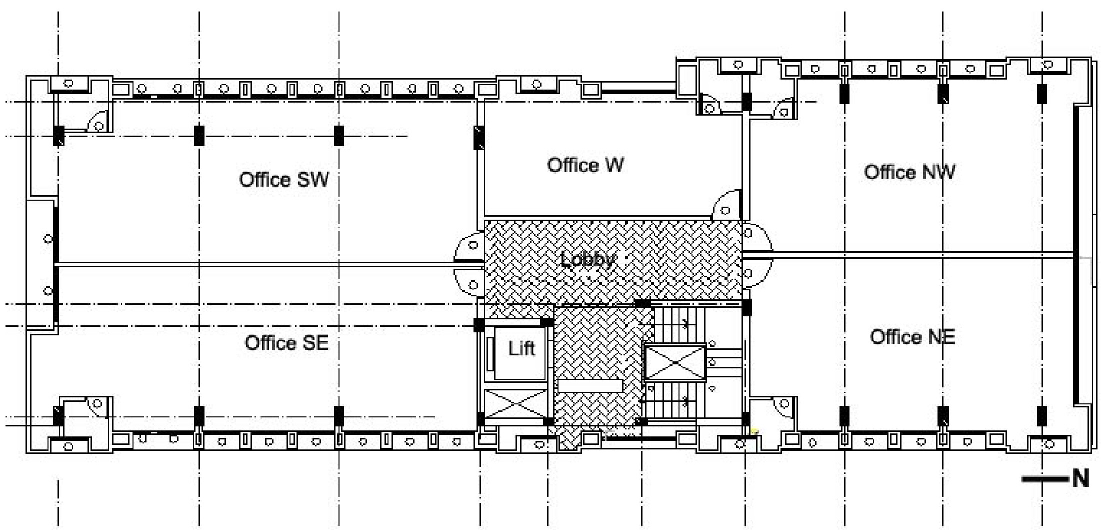


Fig. 25. First Floor Plan of Mahavir Commercial Complex
Note: Typical plan on all floors except the location, type and number of windows on each façade varies

4.1.3 Weather Data

Ener-Win uses hourly weather data with accurate details about temperature, humidity and radiation fluctuations for all days in the year. It is difficult to present that data in this work. However, for a broad idea it presents a screen of data (Fig. 26) that gives monthly average and maximum dry bulb temperatures with their deviations and also dew-point average, solar radiation and wind speed. From the hourly weather report generated by Ener-Win in an excel spreadsheet format, a graph (Fig. 27) was created describing the average daily dry bulb, average daily wet bulb and average daily dew point temperatures for the whole year. This gives a better idea about the climate of Hyderabad. More graphs have been included in Appendix D.

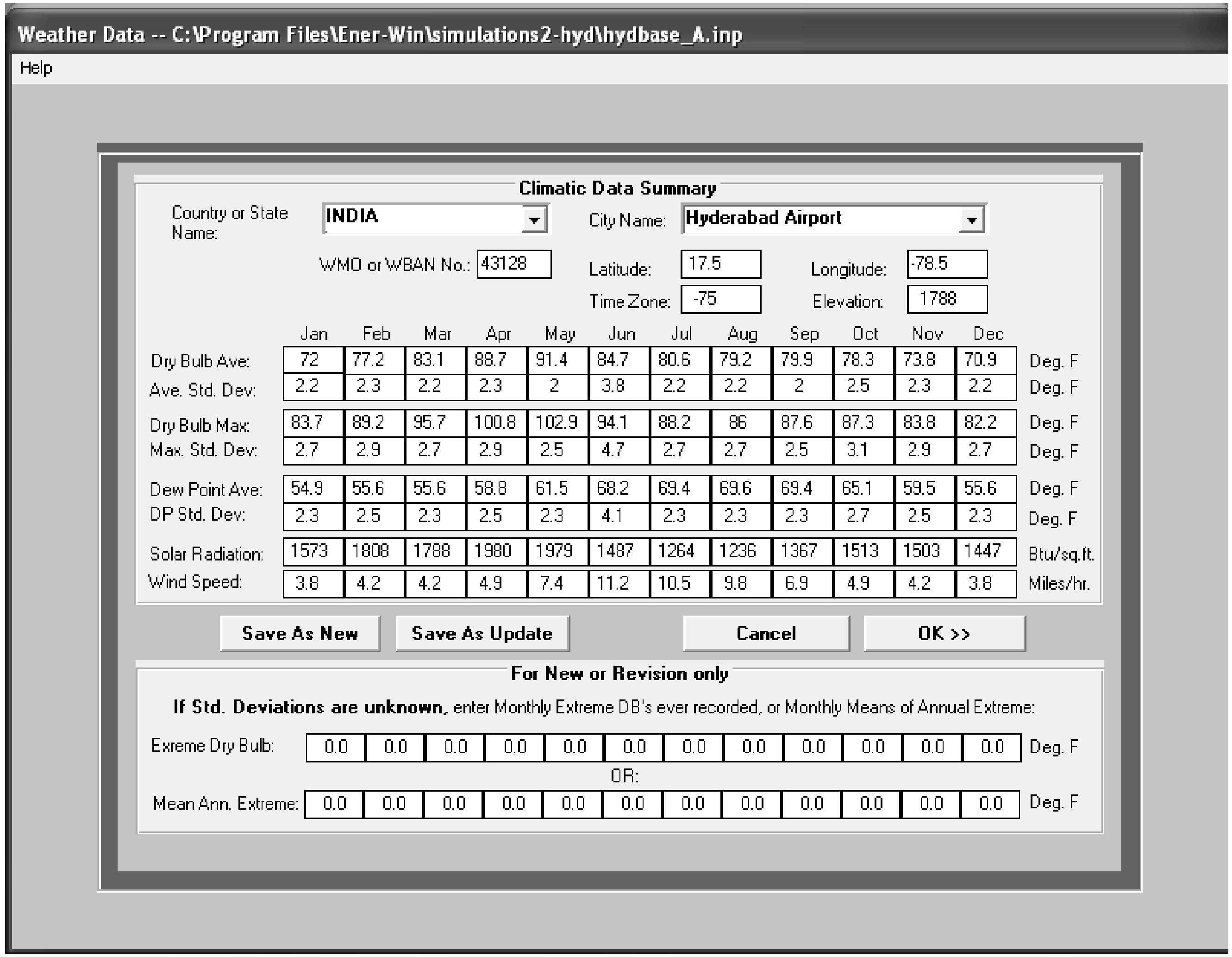


Fig. 26. Weather Data Screen as Obtained from Ener-Win for Hyderabad

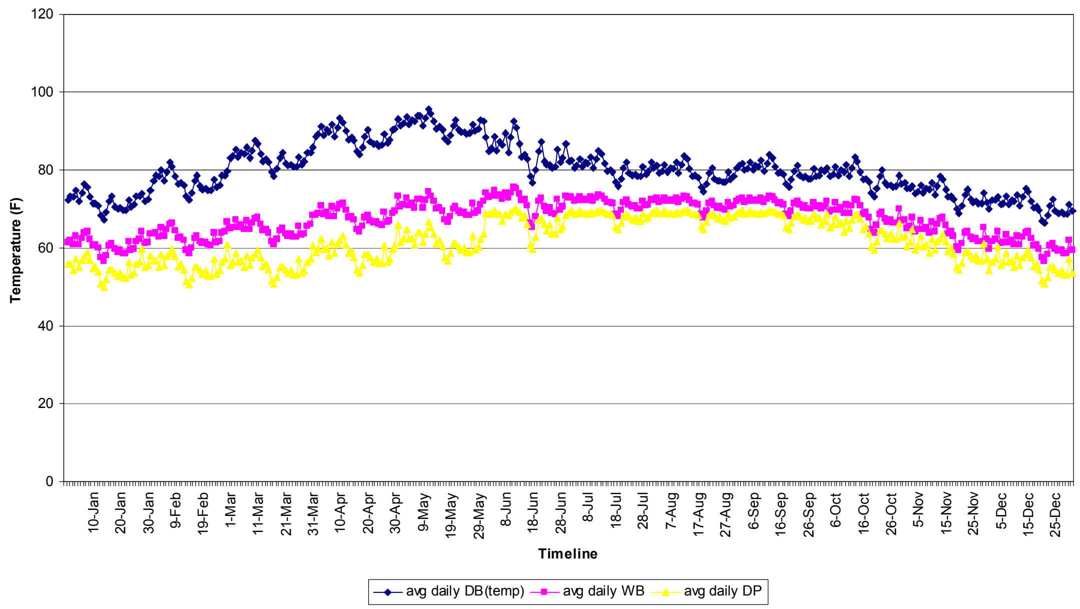


Fig. 27. Graph Showing the Average Daily Temperatures for Hyderabad

4.1.4 Zone Description

The building was divided into various thermal zones based on their orientation and nature of occupancy. The zones were Offices (divided into NW, NE, SE, SW, W based on their location with respect to direction), Staircases, Toilets, Corridors, Elevator and Electrical. Fig. 28 shows the building sketch through which one can define the various thermal zones in Ener-Win. The grid defines the units for near-accurate drawing of the plan and each of the zones is assigned a different color as explained in Table 4. The sketch is defined for each different floor. Number of floors with similar zone description was input to avoid repetition of drawing. Ener-Win calculates the wall area automatically based on this sketch. Window areas were manually calculated for the base case and were input as a ratio of wall area for the strategies.

Table 4
Color Code of Each Zone as Described in the Building Sketch in Ener-Win for Hyderabad

SNo	Zone Name	Color
1	Electrical	Black
2	Offices NE	Blue
3	Offices SE	Green
4	Offices SW	Sea Green
5	Offices W	Maroon
6	Offices NW	Purple
7	Staircase	Olive green
8	Corridor	Grey
9	Toilets	Cyan
10	Elevator	Red

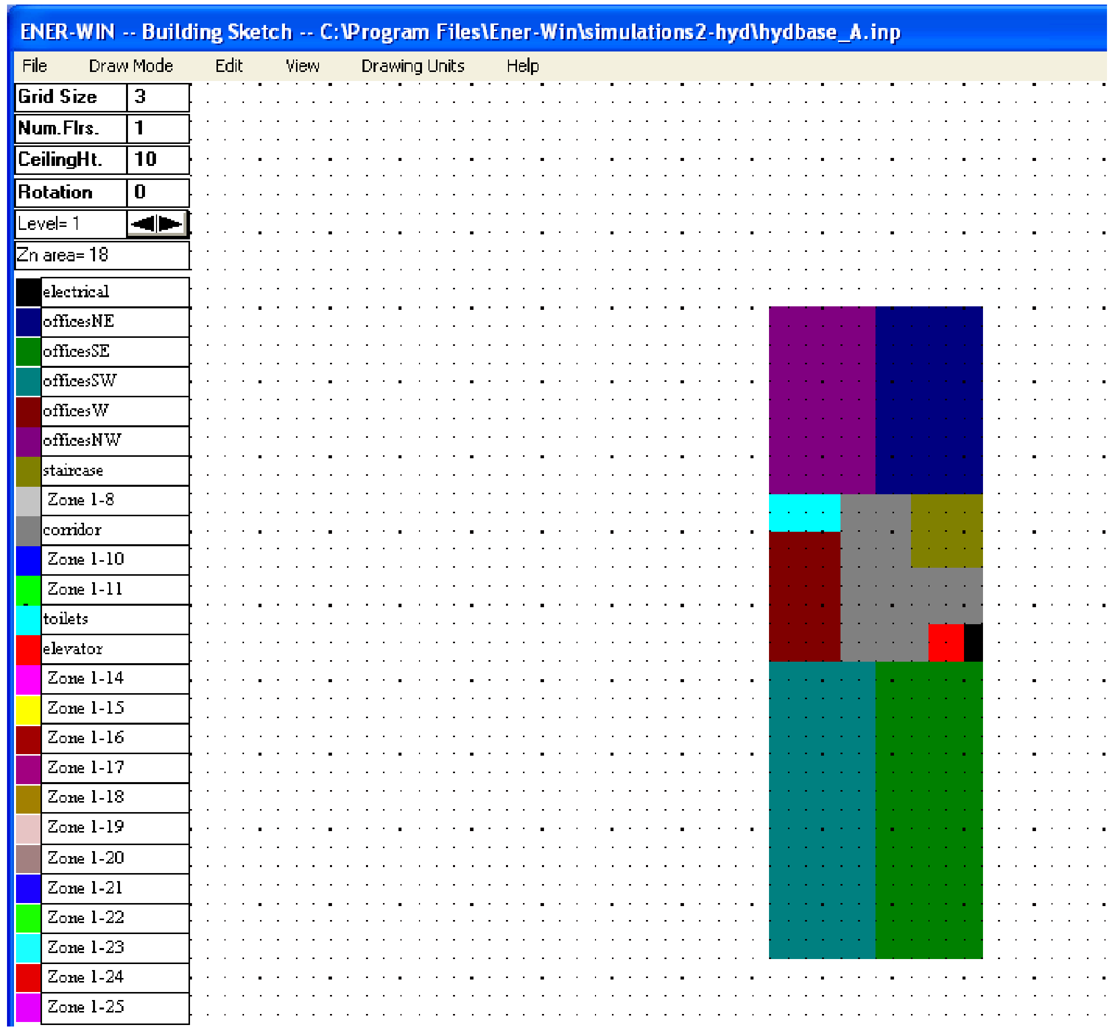


Fig. 28. Screen Showing the Building Sketch Drawn in Ener-Win

4.1.5 Base Case Analysis

4.1.5.1 Typical Wall Section for East and West Facades (Wall A)

The typical wall section (Fig. 29) for the eastern and western facades of the building constitutes of two four and half inch brick walls faced with plaster and paint separated by a gap of approximately one foot.

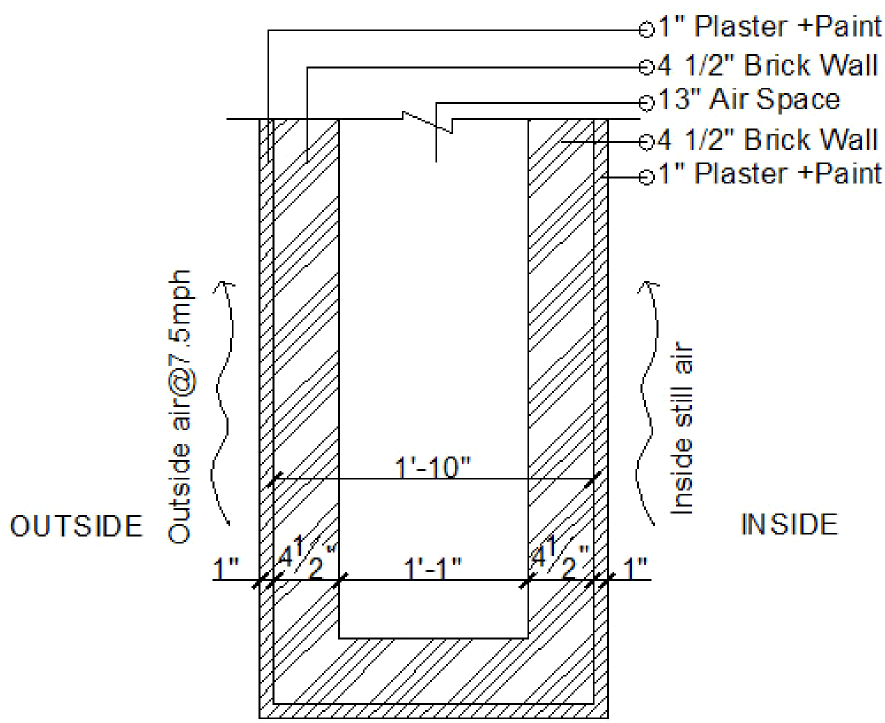
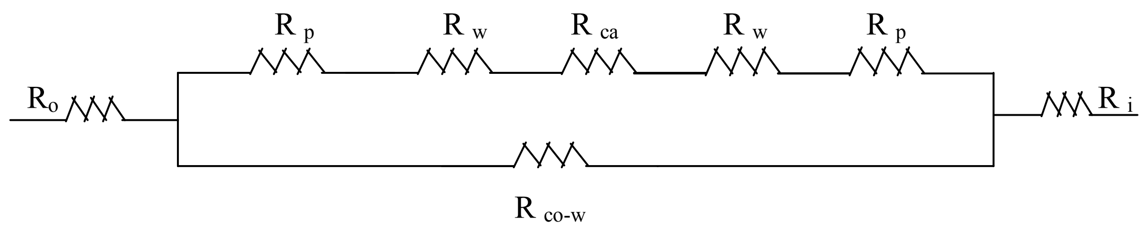


Fig.29. Typical Wall Section of East and West Facades (Wall A)

4.1.5.2 Calculation of Resistance for Wall A

The overall U-Value of this wall was calculated as an inverse of the sum of the resistances as explained in Fig. 30. The formulae used for calculation have also been further explained. Using the total resistance value, the final U-Value of the wall was obtained.



Legend

R_o : Resistance of outside surface R_p : Resistance of plaster and paint R_w : Resistance of wall
R_{ca} : Resistance of cavity $R_{co\text{-}w}$: Resistance of continuous wall R_i : Resistance of inside surface

Fig.30. Resistance Diagram for Wall Section A

The formulae used for calculation are as follows:

$R_{total} = R_o + 1/ (1/R_{ca\text{-}w}+1/R_{co\text{-}w}) + R_i$

Where, $R_{ca\text{-}w} = R_p + R_w + R_{ca} + R_w + R_p$;

$R_{co\text{-}w} = R_p + R_w + R_p$

Therefore, final U-Value = $1/R_{total}$

4.1.5.3 U-Value Calculation

The U-Value of the wall A was calculated as per the expression above and the value thus obtained of 0.234 was used as input for the simulation. Table 5 shows the exact values of each resistance obtained from standard tables obtained from 2001 ASHRAE fundamentals handbook.

Table 5
U-value Calculation for Hyderabad Base Case: Wall A

Symbols	Material	R_o	$R_{ca\text{-}wall}$	$R_{cont\text{-}wall}$	R_i
R_o	Outside surface(7.5mph)	0.25			
R_p	1"plaster+paint		0.20	0.20	
R_w	41/2" brick wall		0.90		
R_{ca}	13" air space		0.92		
R_w	41/2" brick wall		0.90		
R_p	1" plaster + paint		0.20	0.20	
$R_{co\text{-}w}$	1'10"wall			4.40	
R_i	Inside surface,still air				0.68
	Totals	0.25	3.12	4.80	0.68
		$R_{o=}$	**0.25**	**$1/R_{ca\text{-}w=}$**	**0.320513**
		$R_{i=}$	**0.68**	**$1/R_{co\text{-}w=}$**	**0.208333**
		R=	**3.33**	**1/(1/Rca-w+1/Rco-w)**	
$R_{tot\ =}$	**R_o+R+R_i**	4.258333			
Uvalue =	**$1/R_{tot}$**	**0.234834**			

4.1.5.4 Typical Wall Section of North and South Facades (Wall B)

The north façade has a curtain glazing for most of the floors with a four and a half inch brick wall and the southern façade is a single layer (4½'brick) wall with windows (Fig. 31). For convenience these facades have been named as Wall B.

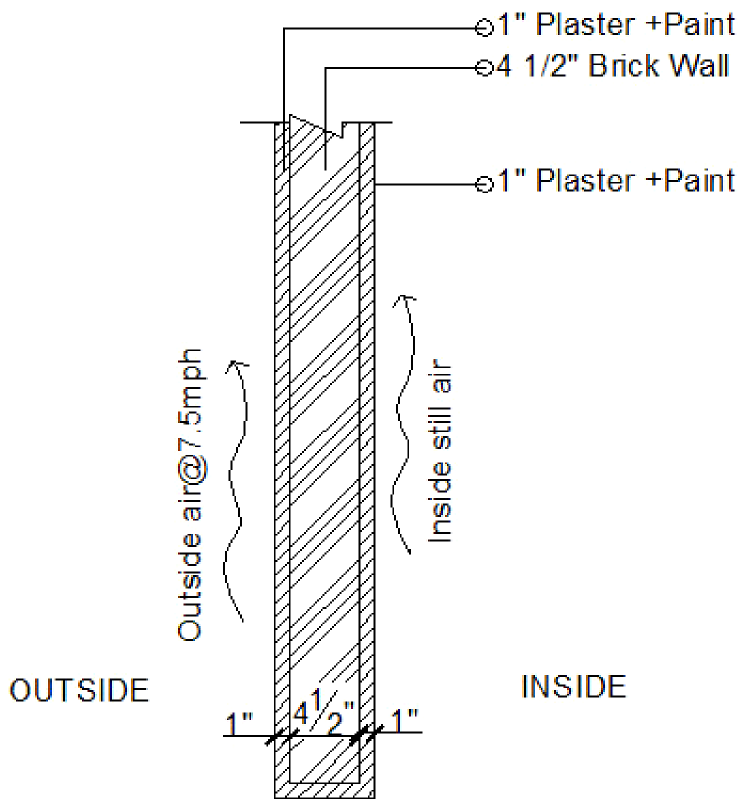
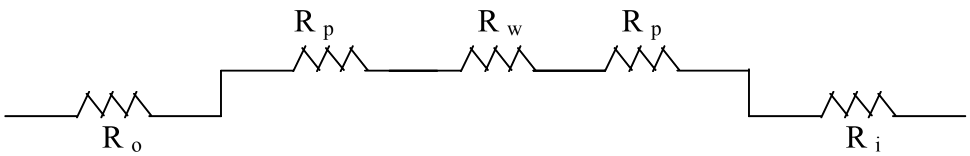


Fig. 31. Typical Wall Section of Wall B

4.1.5.5 Calculation of Resistance for Wall B

The resistance diagram across Wall B (Fig. 32) is shown below. It is essentially a simple sum of all the resistances of materials across the section of the wall.



Legend
R_o : Resistance of outside surface
R_p : Resistance of plaster and paint
R_w : Resistance of wall
R_i : Resistance of inside surface

Fig.32. Resistance Diagram for Wall Section B

The formulae for calculation of resistance and U-value across the wall section are:

$R_{total} = R_o + R_{wall} + R_i$

where $R_{wall} = R_p + R_w + R_p$

U-value= $1/R_{total}$

4.1.5.6 U-Value Calculation

The value of the resistances and the final U-value calculation is explained in Table 6.

Table 6
U-value Calculation for Hyderabad Base Case: Wall B

Symbols	Material	R_o	R_{wall}	R_i
R_o	Outside surface(7.5mph)	0.25		
R_p	1"plaster+paint		0.20	
R_w	41/2" brick wall		0.90	
Rp	1" plaster + paint		0.20	
R_i	Inside surface,still air			0.68
	Totals	0.25	1.30	0.68
R_{tot} =	**$R_o + R_{wall} + R_i$**	2.23		
Uvalue =	**1/ R_{tot}**	**0.44843**		

4.1.5.7 Zone Properties

i) Walls

The wall types are described by the U-values calculated in the previous section for all the four facades. Wall area, orientation and surface exposure are calculated by the program.

ii) Windows

Window type is identified to be 1/4" gray tint plate glass which was used in the building. The glass area was manually calculated and entered based on information from building drawings.

iii) Other Parameters

The other parameters are defaults and only the window sill and window height are changed according to the drawing data.

4.1.5.8 Output

Based on the above, the following output (Figs. 33-36) was obtained which shows the total cooling energy, peak cooling loads, annual cooling loads and breakdown of annual energy consumption.

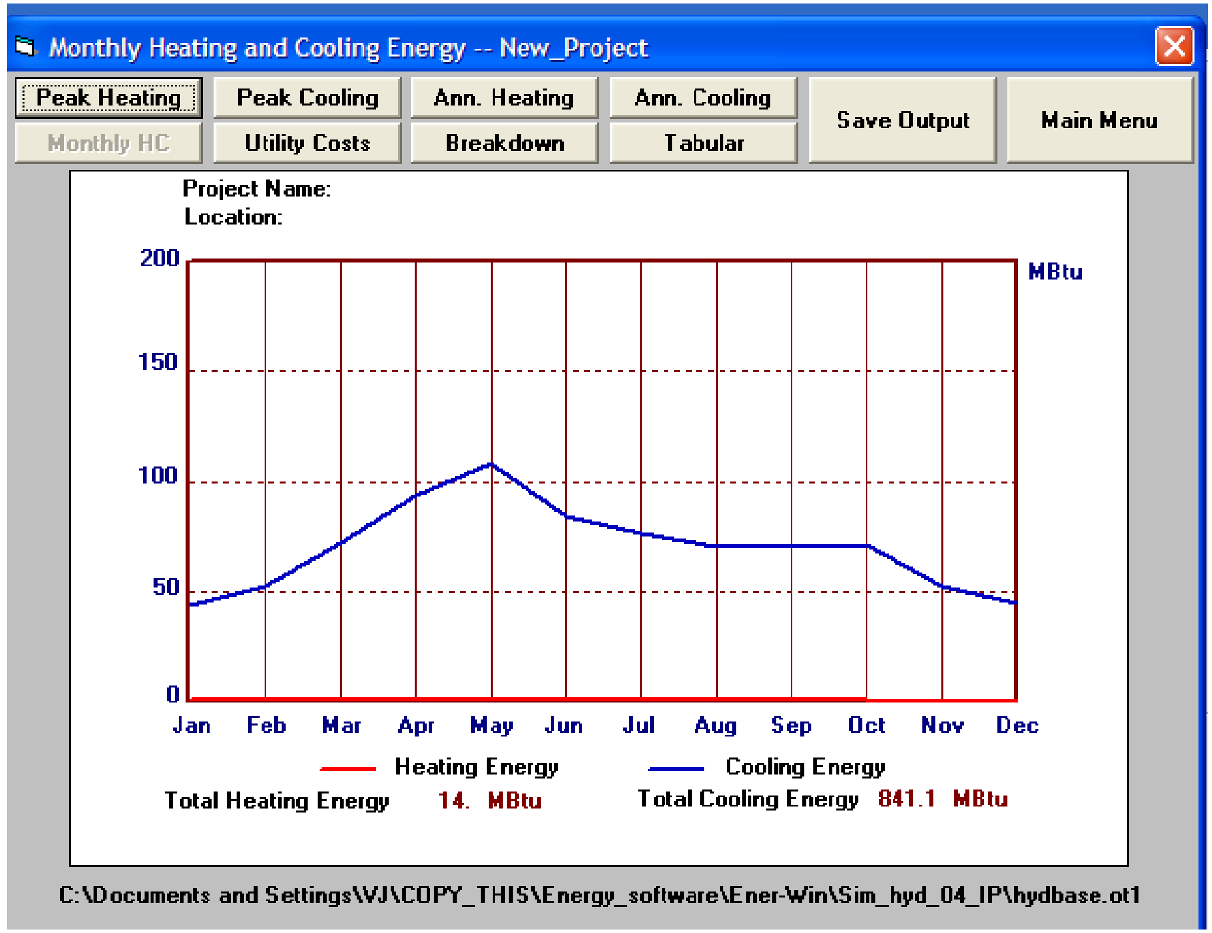


Fig. 33. Screen Capture from Ener-Win Showing the Monthly Cooling Energy for the Base Case: Hyd

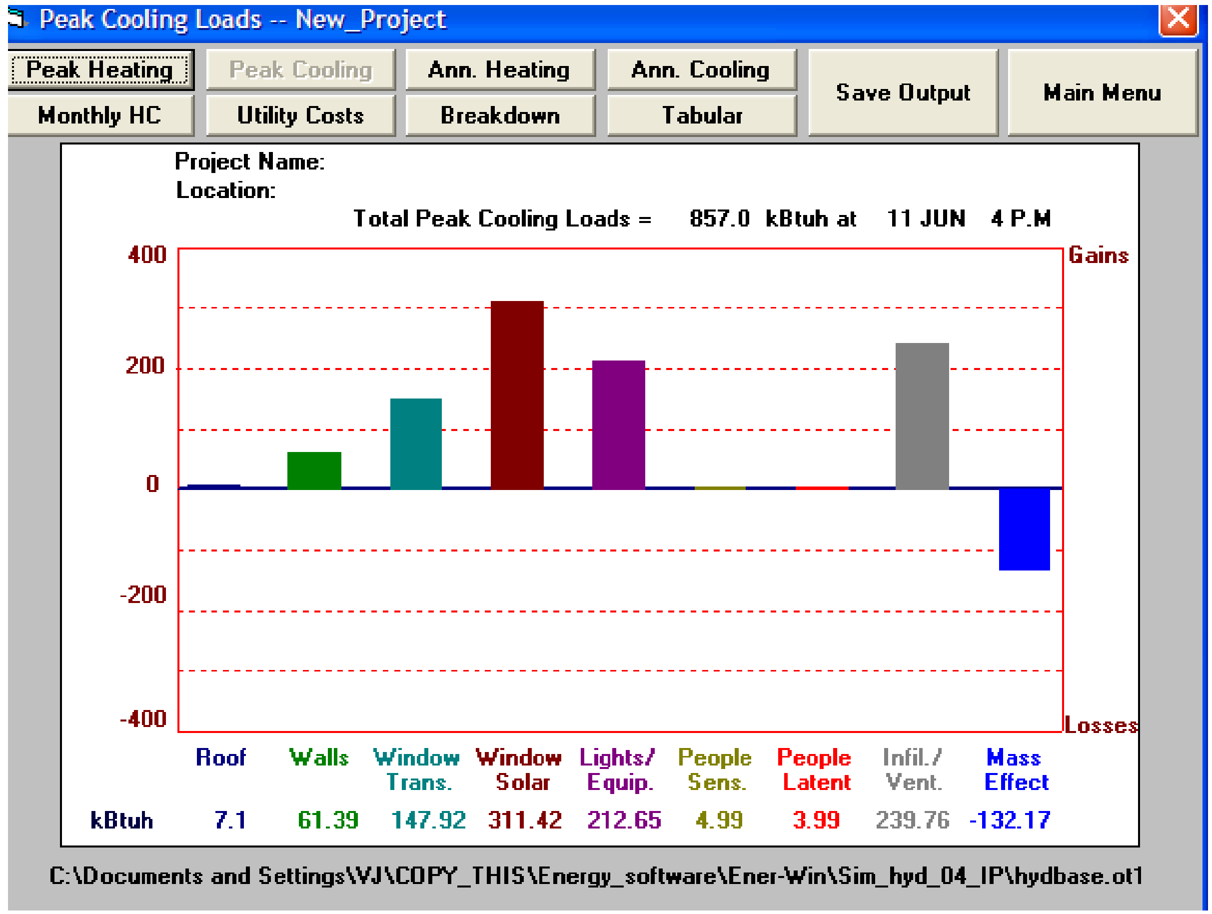


Fig. 34. Screen Capture from Ener-Win Showing the Peak Cooling Loads for the Base Case: Hyd

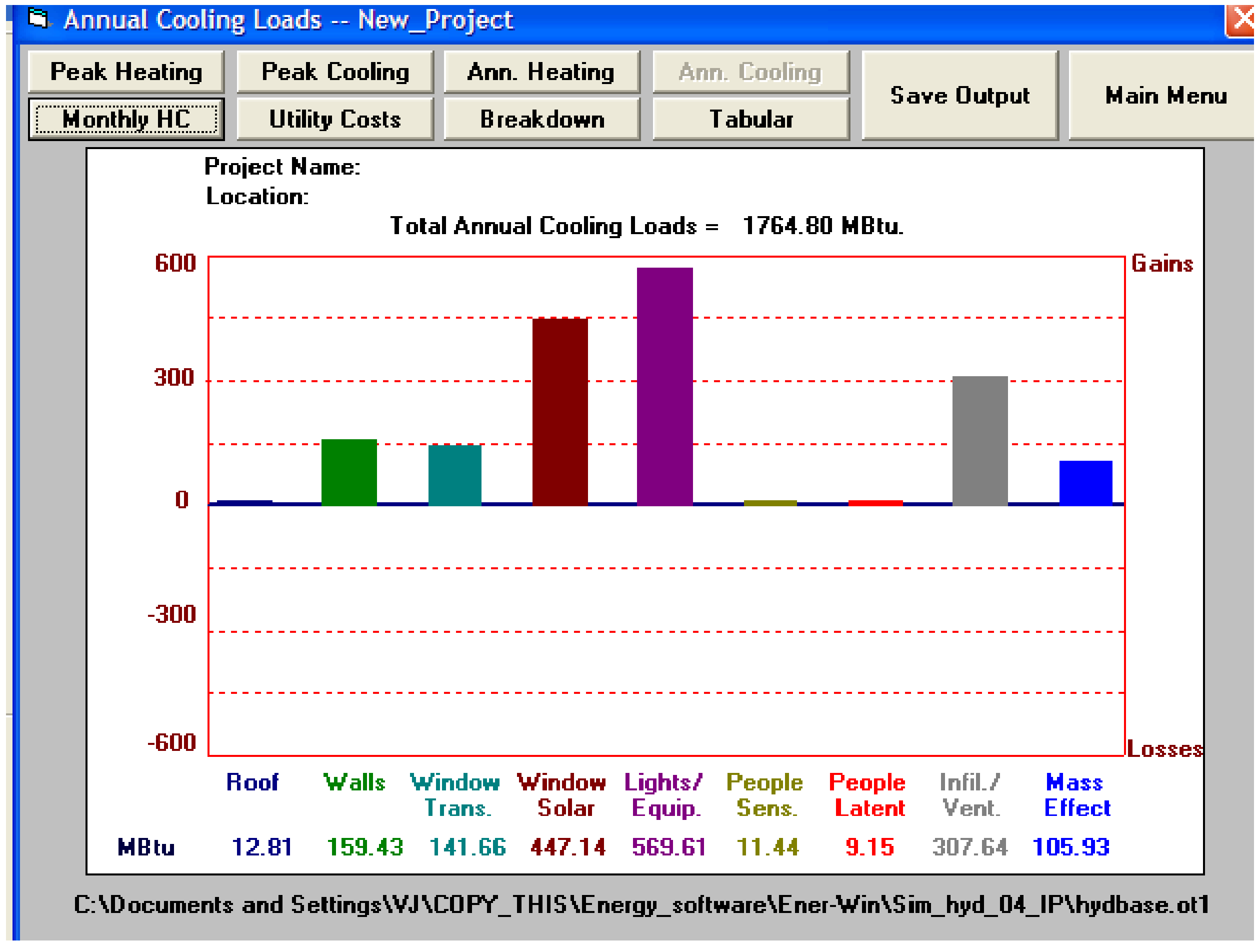


Fig. 35. Screen Capture from Ener-Win Showing the Annual Cooling Loads for the Base Case: Hyd

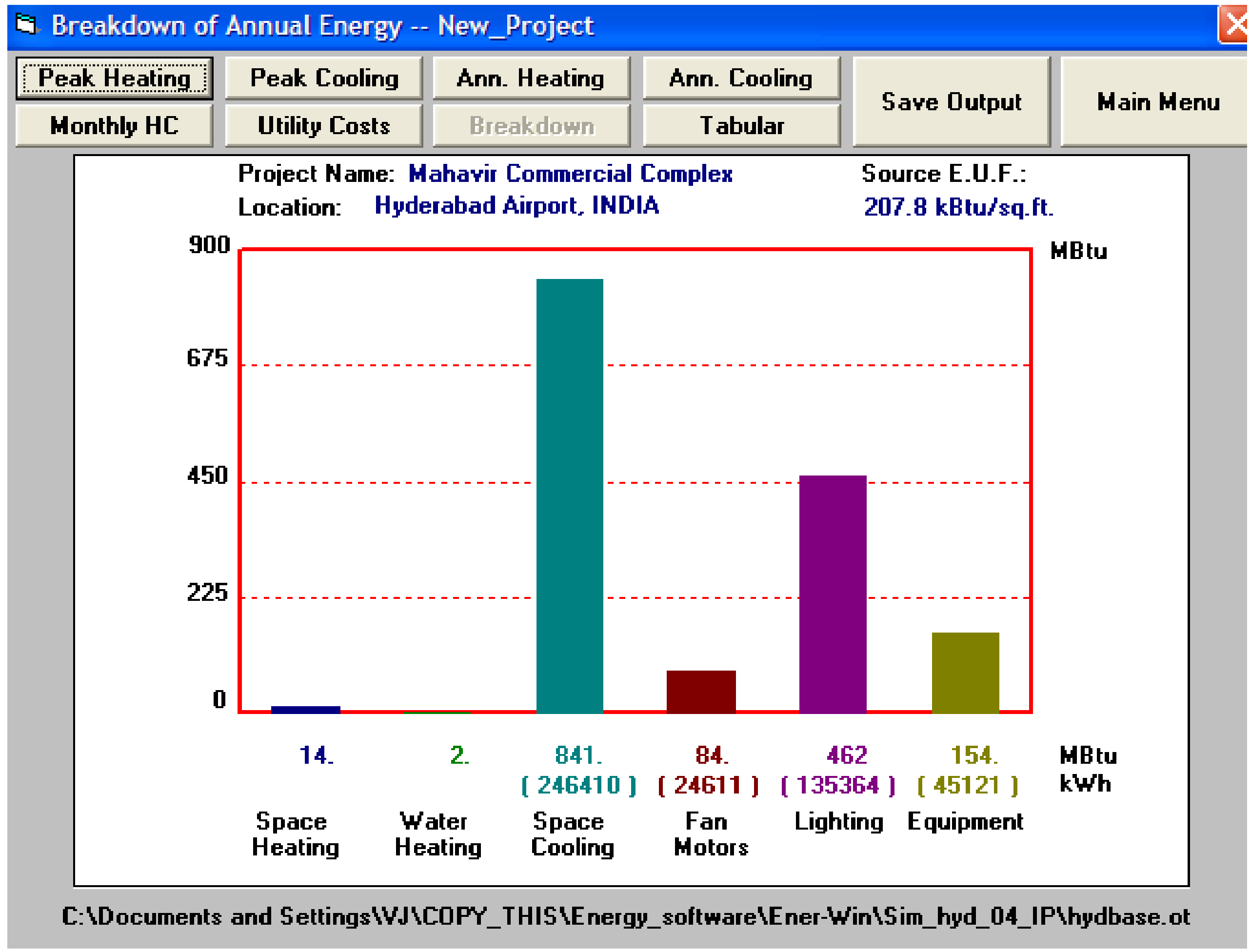


Fig. 36. Screen Capture from Ener-Win Showing the Breakdown of Energy Consumption for Base Case: Hyd

4.1.5.9 Summary of Output for Base Case

From the graphical output, it can be seen that the total cooling energy used by the building in existing conditions is 841.1 Mbtu. The maximum amount of energy (841Mbtu) is being used for space cooling and next for lighting (462 Mbtu).The total peak cooling load is about 857 Mbtu and annual peak cooling is about 1765 Mbtu. Both show that maximum heat gain is through window transmission and solar radiation, followed by the heat gain by walls.

This shows the need to reduce heat gain through these sources, which are actually the constituents of the building envelope, more specifically the façade. Therefore, changing the properties of the façade may prove to be beneficial in cutting down cooling loads.

4.1.6 Analysis of Strategy One

The proposed façade , as described in chapter three, consists of an outer layer of¼' gray tint glass (al. fixed) and an inner layer of¼' clear (al. operable) glass separated by an air cavity of 2 feet. This first strategy was analyzed based on the input described in the methodology and Table 7 shows the basic output obtained. Detailed input and output tables are provided in Appendix A.

Table 7
Output from Analysis of Strategy One: Hyderabad

	Total Cooling Energy(Mbtu)	Total peak cooling (KBtuh)	Total annual cooling (Mbtu)	Lighting (Mbtu)
0	841.1	857	1764.8	462
1N	788.5	826.6	1644.58	284
1E	958.8	945	1993.08	263
1S	873.9	866.6	1824.29	285
1W	1002.5	1043.5	2048.56	268
1all	1373.8	1350.9	2823.29	262

The following graphs (Figs. 37-40) give a graphical representation of the output obtained as a comparison between the variations of Strategy One and the Base Case. 0 represents the Base Case and 1N, 1E, 1S, 1W and 1all describe the strategy as it is applied to the north, east, west, south or all facades respectively.

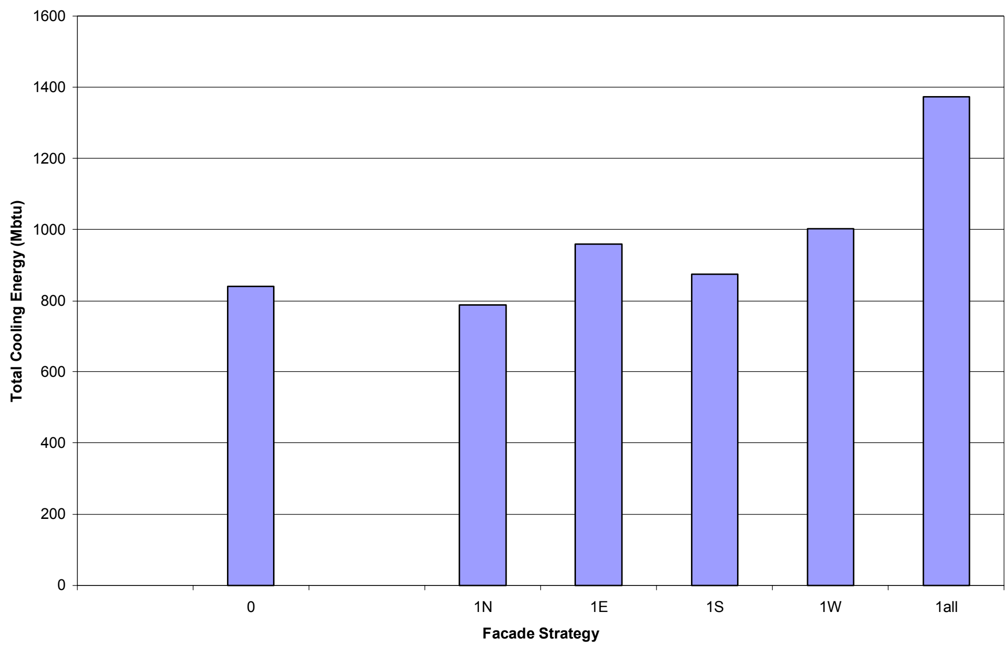


Fig. 37. Total Cooling Energy Comparison of Strategy One Subcategories with Base Case for Hyd.

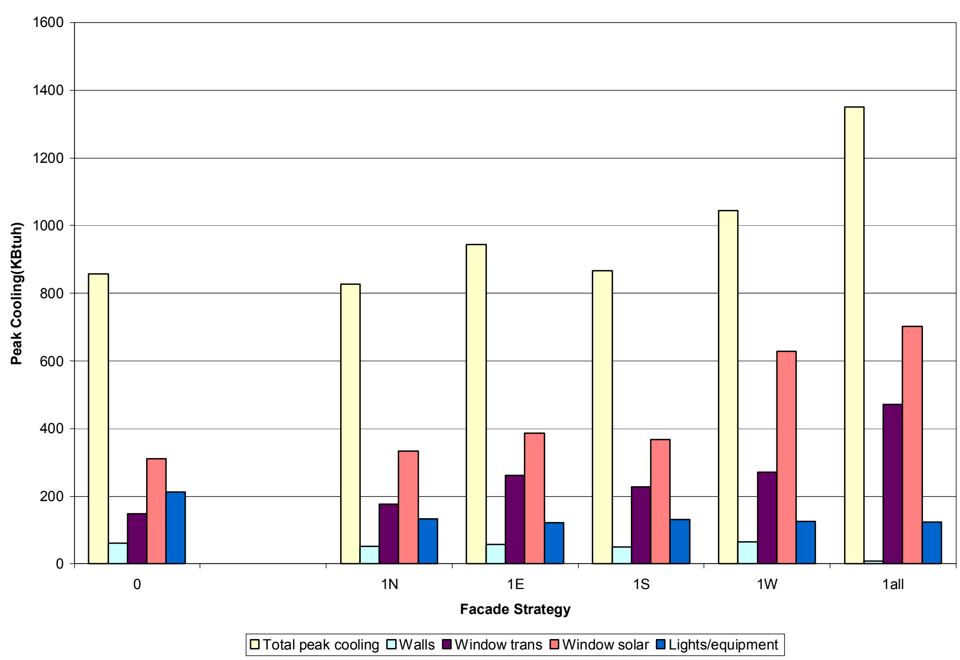


Fig. 38. Peak Cooling Load Comparison of Strategy One Subcategories with Base Case for Hyd.

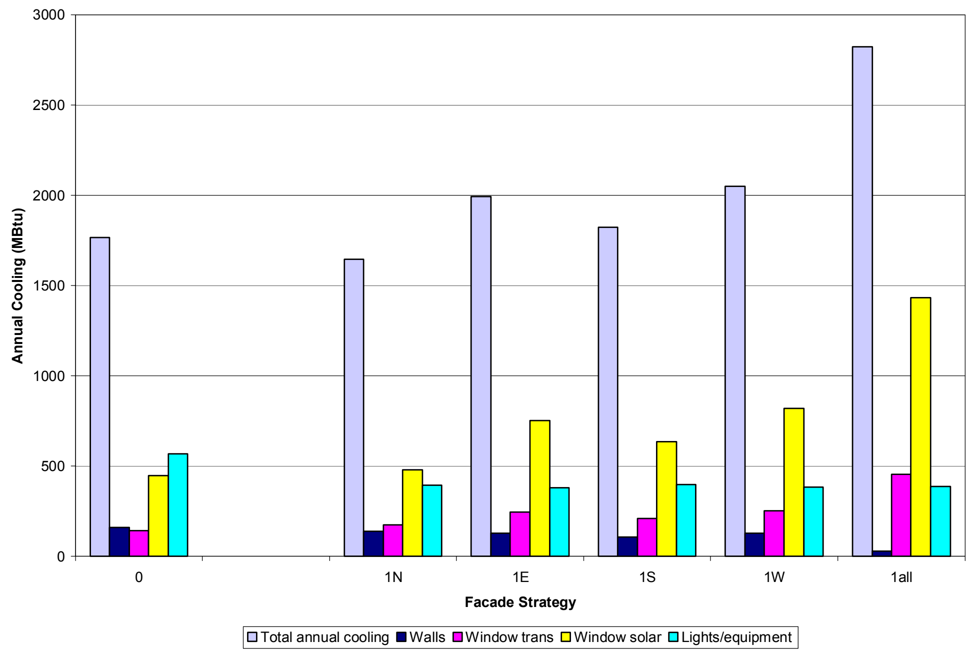


Fig. 39. Annual Cooling Load Comparison of Strategy One Subcategories with Base Case for Hyd.

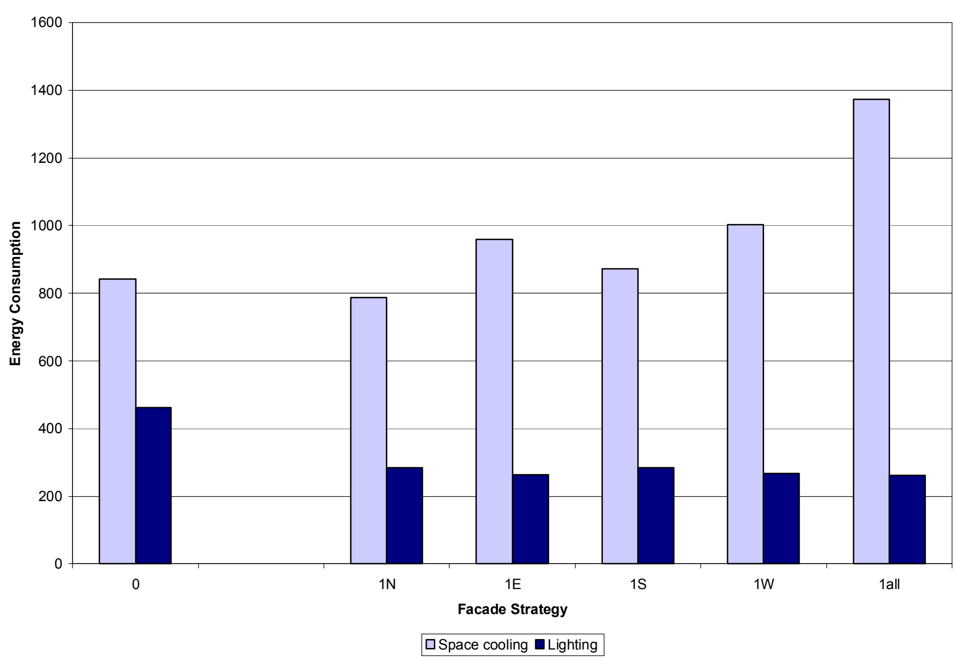


Fig. 40. Breakdown of Energy Consumption of Strategy One and Base Case for Hyd.

4.1.6.1 Effect of Shading

As explained in the methodology, each of the strategy was then simulated by incorporating shading along the façade where the double skin was used. This generated five new subcategories to strategy one:

1N_S: The northern double-skin (1N) is provided with shading of T.1 (overhang).

1E_S: The eastern double-skin has shading values defined by the right and left fins, R .2 and L .2.

1S_S: The southern façade has shading values defined by the overhang and the vertical fins.

1W_S: The western double-skin has vertical fins with shading value R .2 and L .2.

1all_S: The strategy where all the four sides have double skin is given shading values.

The graphs (Figs. 41-44) explain the output obtained by running the simulations with the shading option. Table 8 gives the numerical value of each of the cooling energy consumption.

Table 8
Output for Strategy One with Shading for Hyderabad

	Total Cooling Energy(Mbtu)	Total peak cooling (Kbtuh)	Total annual cooling (Mbtu)	Lighting (Mbtu)
0	841.1	857	1764.8	462
1N_S	771.4	813.5	1609.54	285
1E_S	877.2	903.5	1815.89	270
1S_S	812.1	833	1694.34	280
1W_S	920	998.9	1874.27	273
1all_S	1131.2	1225.6	2302.92	277

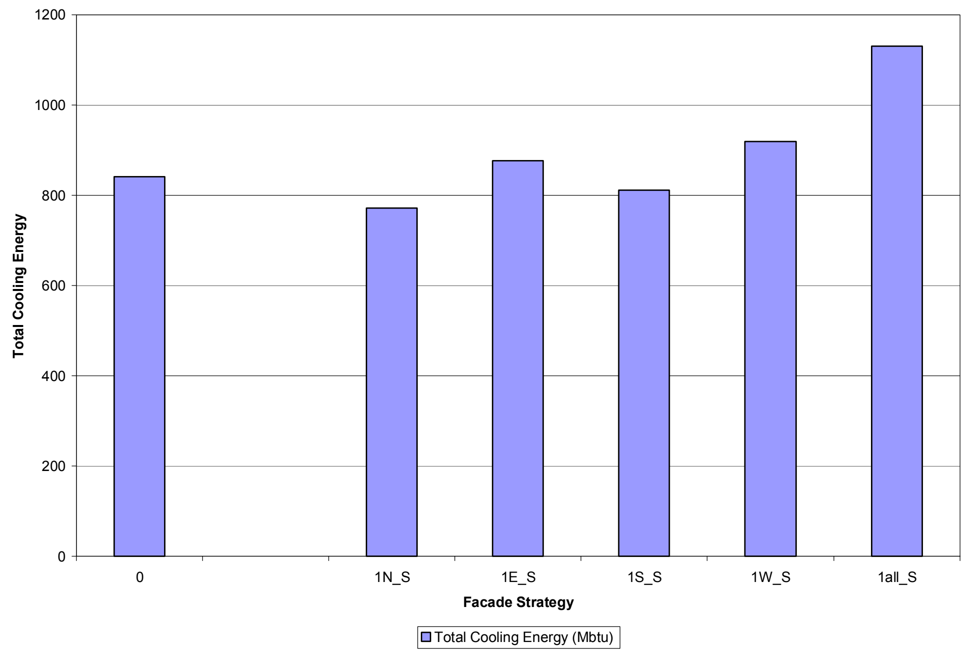


Fig. 41. Total Cooling Energy Comparison of Strategy One (with Shading) and Base Case for Hyd.

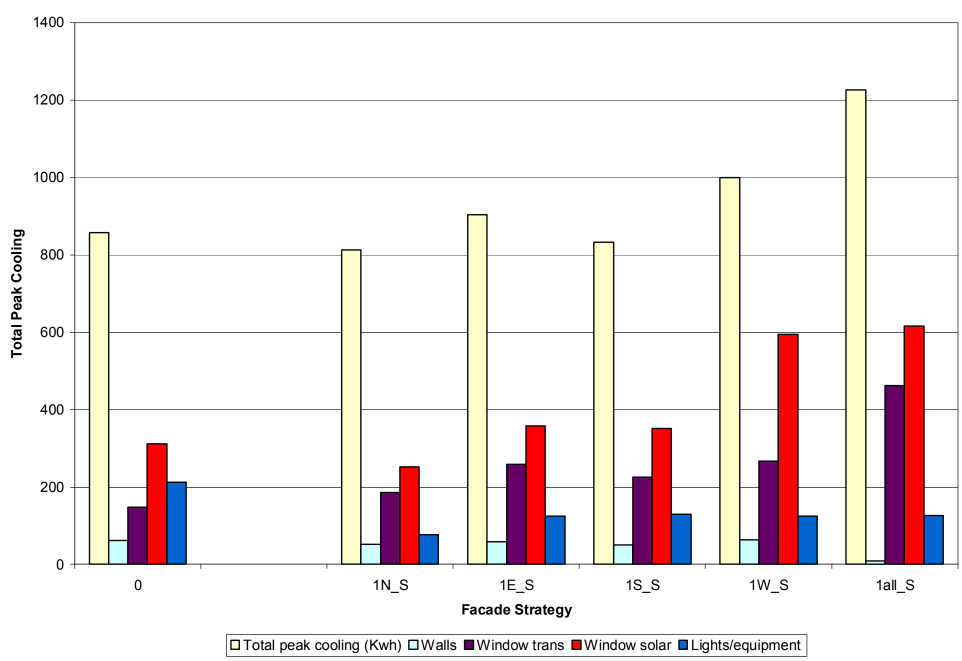


Fig. 42. Peak Cooling Load Comparison of Strategy One (with Shading) and Base Case for Hyd.

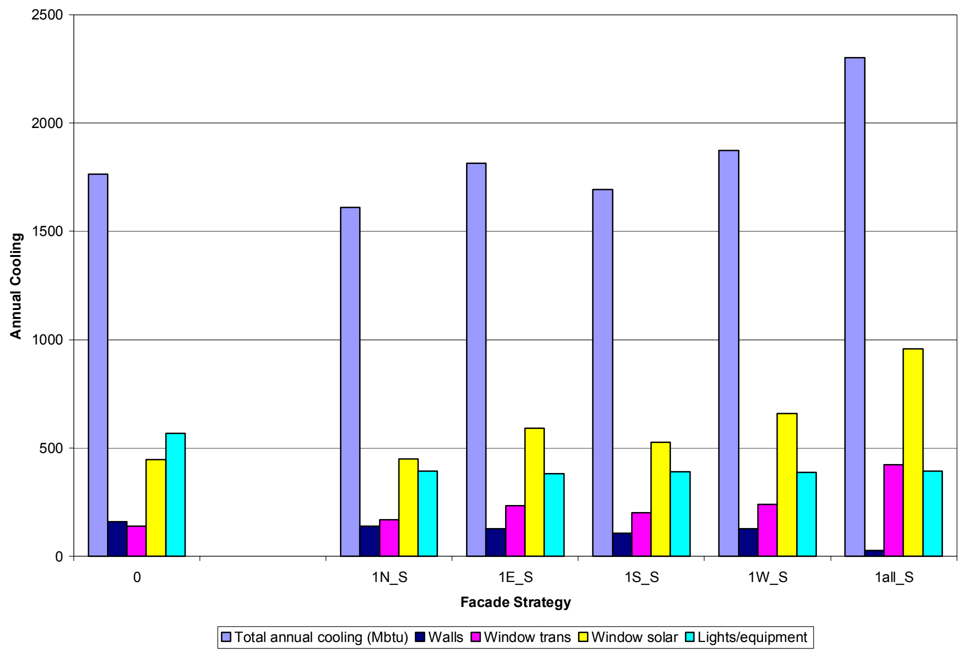


Fig. 43. Annual Cooling Load Comparison of Strategy One (with Shading) and Base Case for Hyd.

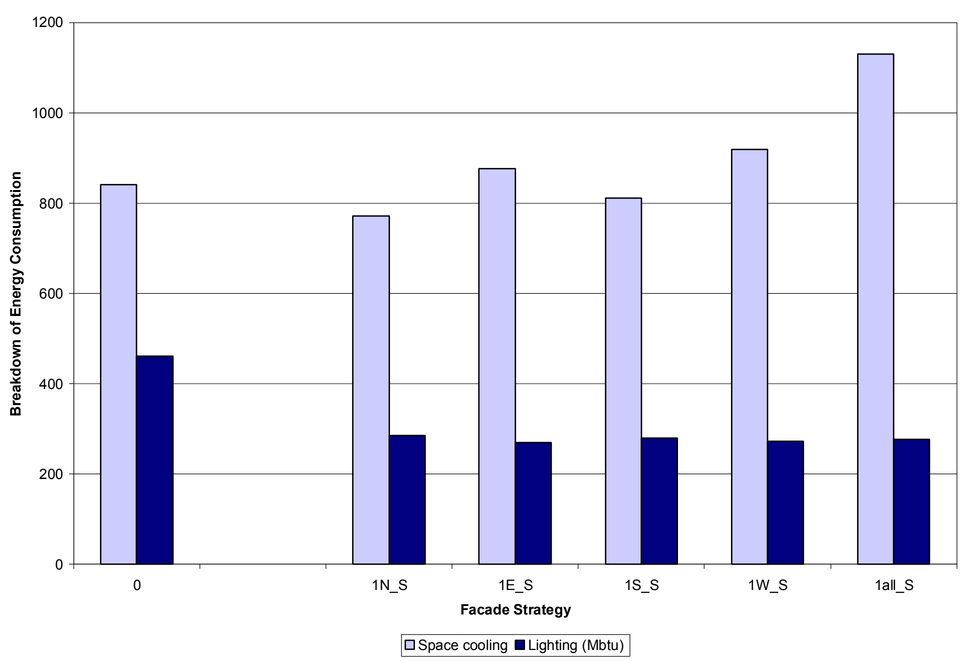


Fig. 44. Breakdown of Energy Consumption of Strategy One (with Shading) and Base Case for Hyd.

4.1.6.2 Summary of Output for Strategy One

a) In the first set of simulations, the total cooling energy is the least for the strategy 1N, which has the three facades same as the base case and the north façade with the double skin strategy and the maximum cooling energy is consumed by the strategy with all four facades with double skins. The difference between the cooling energy for 1N and the base case is not very large and is approximately 8% less than the base case. On the other hand the cooling energy consumed by the strategy with all four facades having double skins is 60% larger than the cooling energy of the base case. After introducing shading, the cooling energy of strategy 1N_S is about 2% less than 1N. Therefore the Strategy One used on the northern façade along with shading would lead to a total reduction of cooling energy of about 10% from the base case.

b) The peak cooling load also follows the same pattern as the total cooling energy being the least for 1N (3% less than base case) and maximum for 1all (55% more than base case). This is further reduced by introduction of shading and the total reduction in peak cooling load from the base case to strategy 1N_S is about 6%. The breakup of energy consumption, shows that the lighting load is reduced notably to almost 40% of the base case. This can be attributed to the daylighting option. The heat gain through walls varies according to the strategy, being the least for 1all and highest for 1N; both of these values are less than the base case.

c) The annual cooling loads also follow a similar trend as the peak cooling. It is the least for 1N_S (less than the base case by 8%) and highest for 1all (60% more than base case).

d) The Ener-Win output for breakdown for energy consumption shows different consumers of the cooling energy. However, the two notable places where energy is used are for space cooling and lighting. Hence, the breakdown of these two is shown. It can be seen that energy for space cooling is least for 1N and most for 1all. The other strategies with single façade on different orientations are almost comparable to the base case, while with more number of glazed facades, the space cooling energy increases. Energy used for lighting is considerably reduced by almost 50% from the base case in all the strategies. Hence, it shows that daylighting is a good design option to reduce loads due to lighting.

4.1.7 Analysis of Strategy Two

Strategy Two was analyzed based on the input described in Chapter Three and Table 9 shows the basic output obtained. Figs. 45-48 give a graphical representation of comparison of cooling energy, peak and annual cooling loads and breakdown of energy consumption between the various strategies.

Table 9
Output Obtained from Analysis of Strategy Two for Hyderabad

	Total Cooling Energy(Mbtu)	Total peak cooling (KBtuh)	Total annual cooling (Mbtu)	Lighting (Mbtu)
0	841.1	857	1764.8	462
4N	753.7	783.7	1566.77	269
4E	883.8	858.7	1846.09	267
4S	829.3	823.5	1735.44	266
4W	914.5	929.6	1884.9	270
4all	1145.9	1075.4	2381.88	266

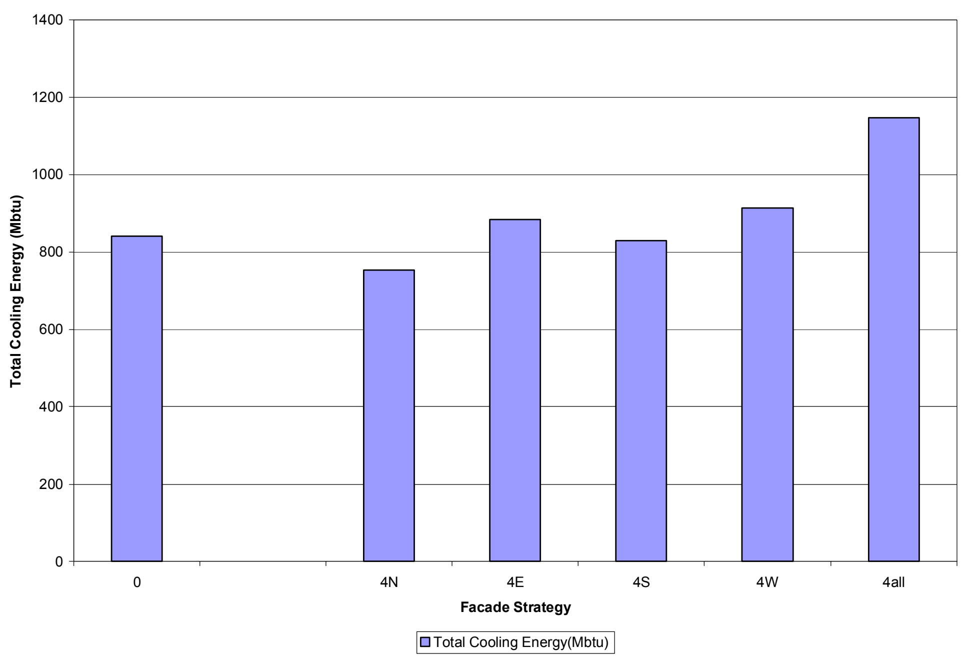


Fig. 45. Total Cooling Energy Comparison of Subcategories of Strategy Two and Base Case for Hyd.

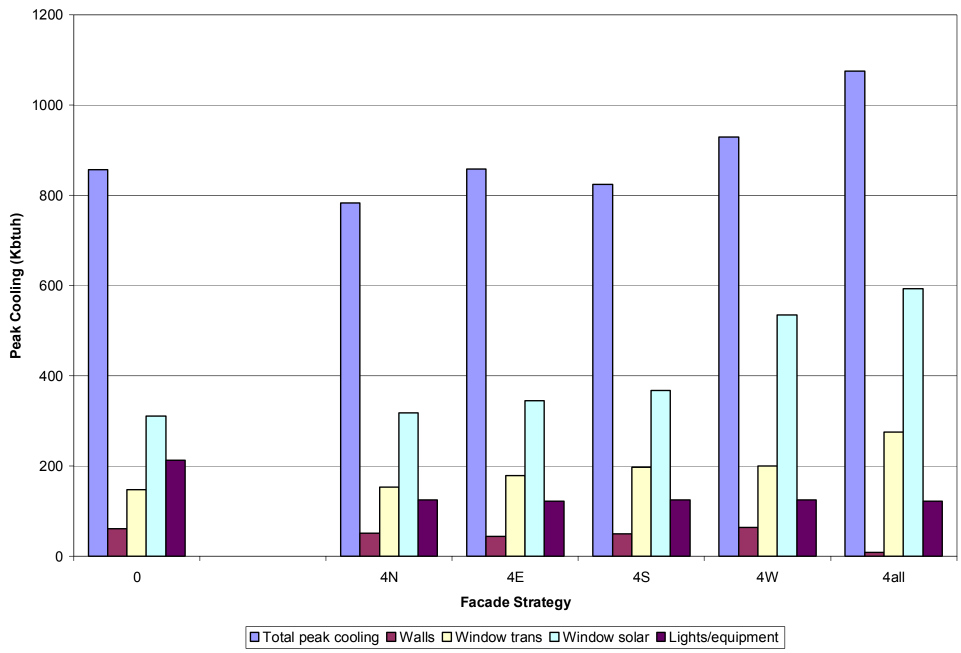


Fig. 46. Peak Cooling Load Comparison of Subcategories of Strategy Two and Base Case for Hyd.

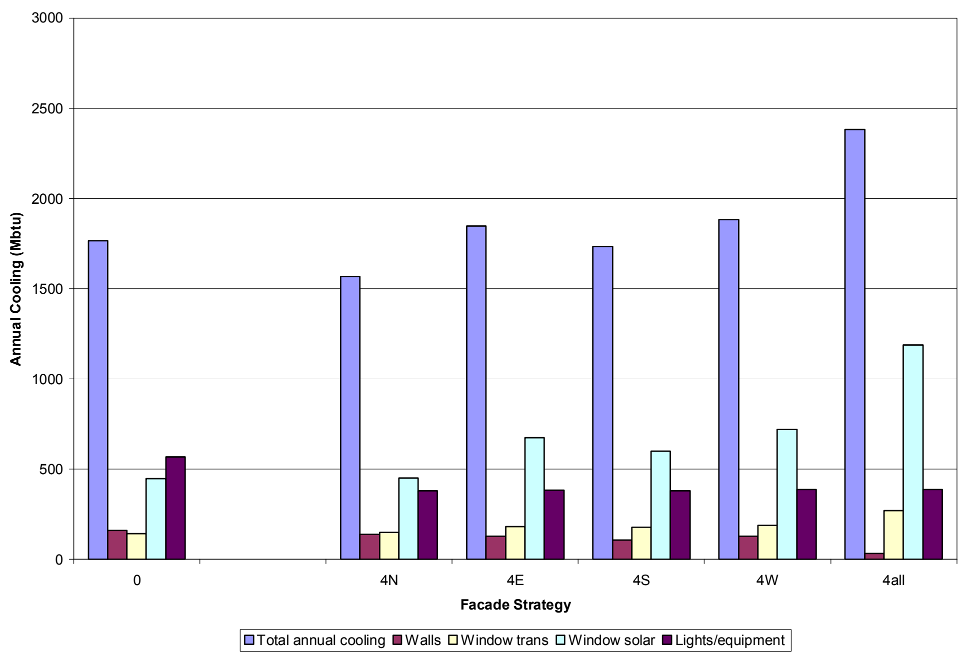


Fig. 47. Annual Cooling Load Comparison of Subcategories of Strategy Two and Base Case for Hyd.

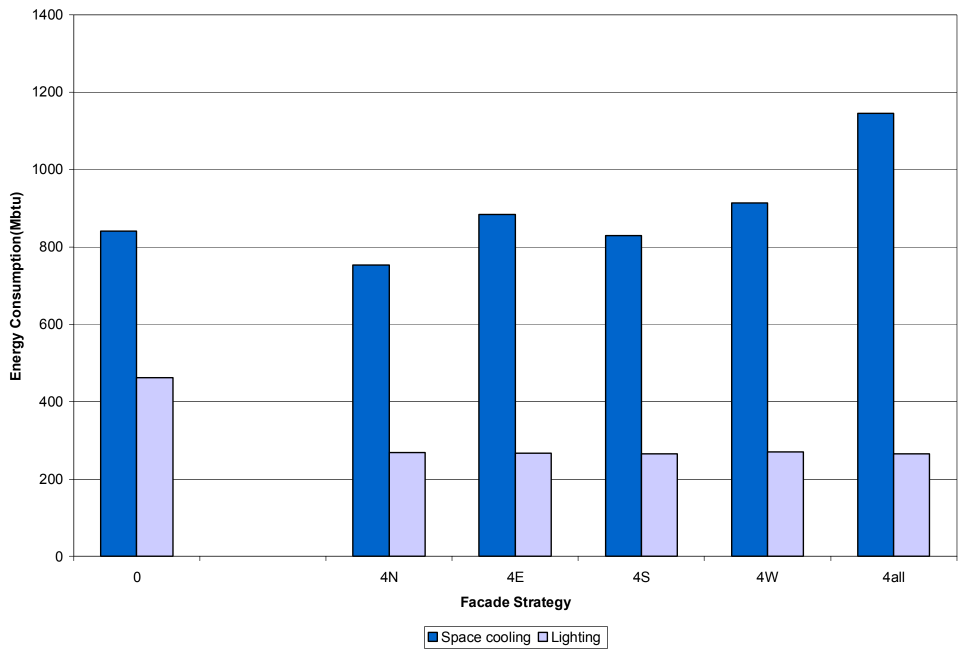


Fig. 48. Comparison of Breakdown of Energy Consumption of Strategy Two and Base Case for Hyd.

4.1.7.1 Effect of Shading

Each of the strategy was simulated by incorporating shading along the façade where the double skin was used. This generated five new subcategories to Strategy Two:

4N_S: The northern double-skin (4N) is provided with shading of T.1 (overhang).

4E_S: The eastern double-skin has shading values defined by the right and left fins, R .2 and L .2.

4S_S: The southern façade has shading values defined by the overhang and the vertical fins.

4W_S: The western double-skin has vertical fins with shading value R .2 and L .2.

4all_S: The strategy where all the four sides have double skin is given shading values.

The graphs (Figs. 49-52) explain the output obtained by running the simulations with the shading option. Table 10 gives the numerical description of the output.

Table 10
Output Obtained from Analysis of Strategy Two with Shading for Hyderabad

	Total Cooling Energy(Mbtu)	Total peak cooling (Kbtuh)	Total annual cooling (Mbtu)	Lighting (Mbtu)
0	841.1	857	1764.8	462
4N_S	739.9	773.3	1548.14	270
4E_S	817.1	823.9	1700.69	274
4S_S	780.7	797.9	1633.54	268
4W_S	845.4	893.6	1739.01	276
4all_S	947.3	972.6	1953.97	281

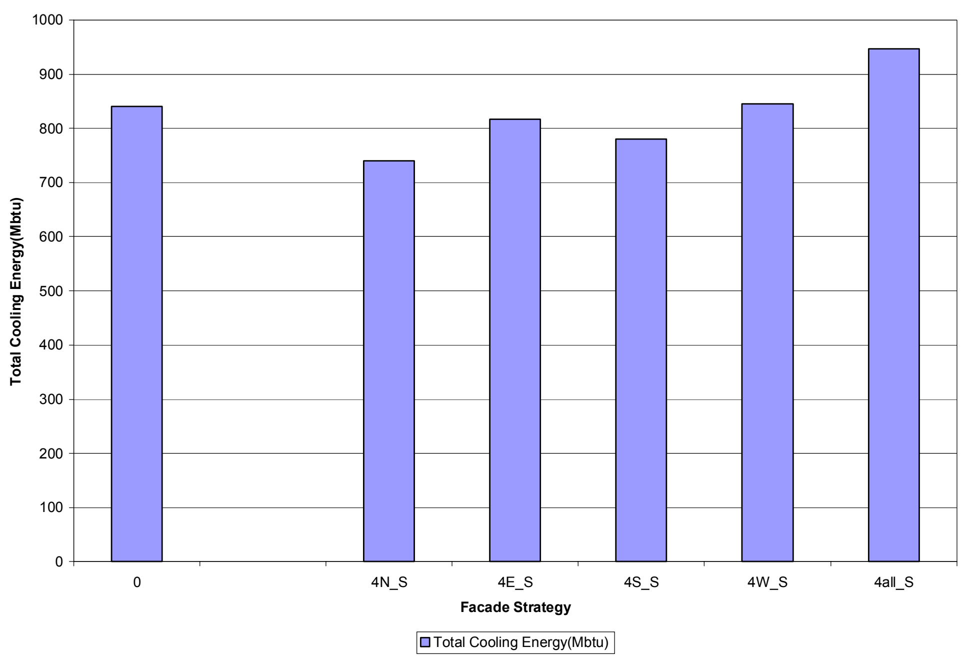


Fig. 49. Total Cooling Energy Comparison of Strategy Two with Shading and Base Case for Hyd.

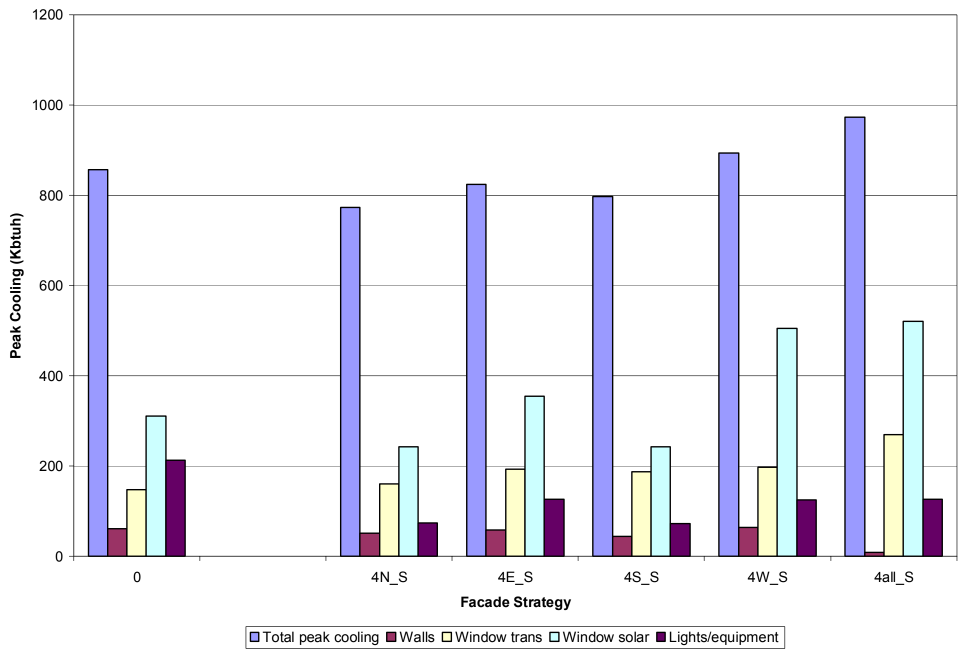


Fig. 50. Peak Cooling Load Comparison of Strategy Two with Shading and Base Case for Hyd.

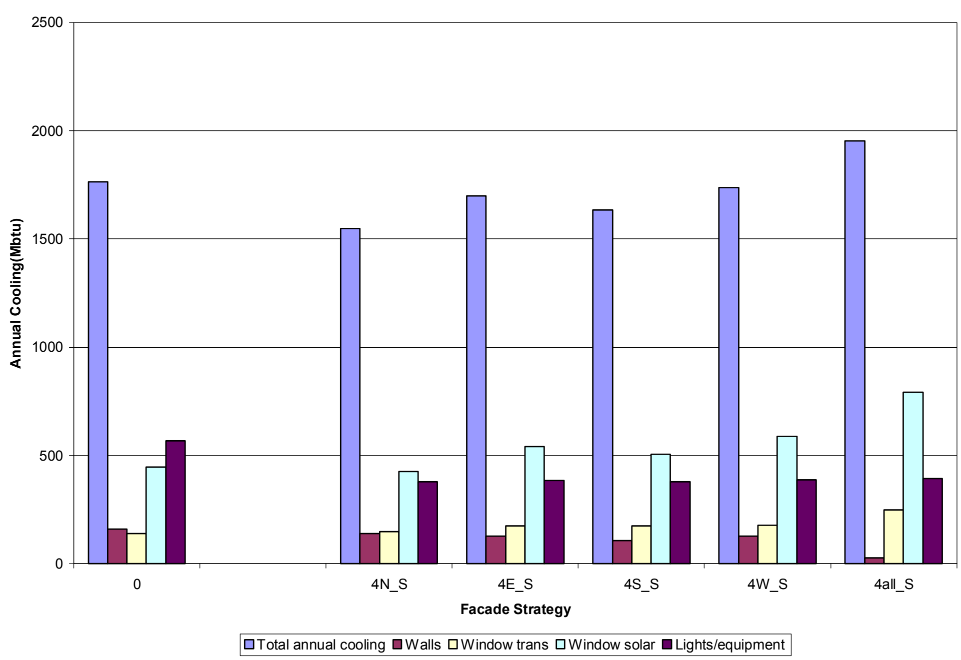


Fig. 51. Annual Cooling Energy Comparison of Strategy Two with Shading and Base Case for Hyd.

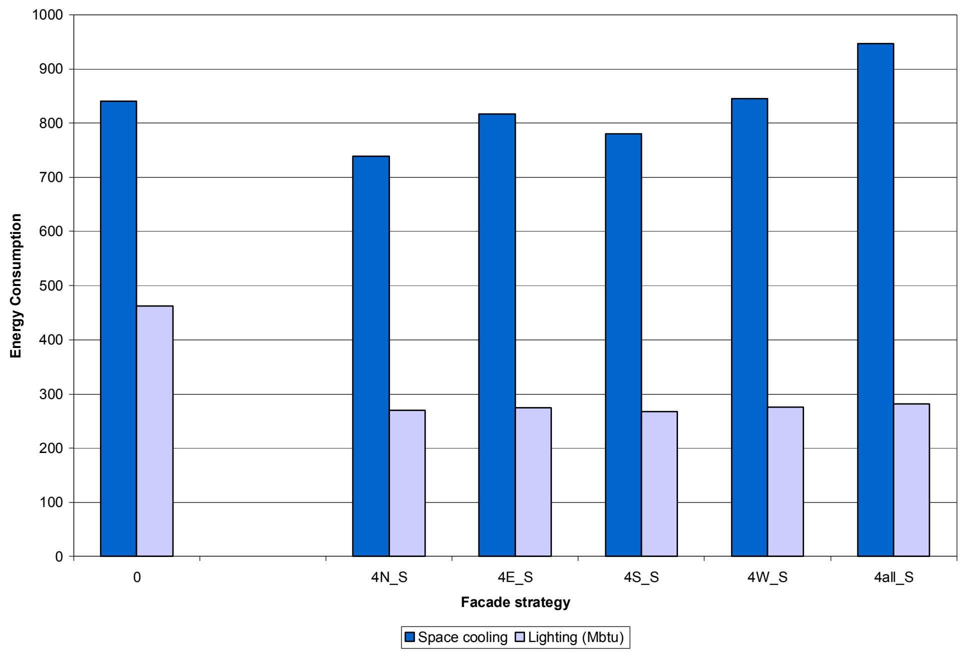


Fig. 52. Breakdown of Energy Consumption of Strategy Two with Shading and Base Case for Hyd.

4.1.7.2 Summary of Output for Strategy Two

a) The total cooling energy for the strategy 4N, which has the three facades same as the base case and the north façade with the double skin strategy is less than the base case by about 11%. The maximum cooling energy is consumed by the strategy with all four facades with double skins which is about 8% larger than the cooling energy of the base case. Upon adding shading to 4N the cooling energy is further reduced by about 1-2%.

b) The peak cooling load also follows the same pattern as the total cooling energy with being the least for 4N_S (9% less than base case) and maximum for 4all (25% more than base case).The load due to lighting is reduced to almost 40-60% of the base case. This can be attributed to the daylighting option. The heat gain through walls varies according to the strategy, being the least for 4all and highest for 4N, both of these values are less than the base case. The heat gain through windows (trans. and solar) increases with increase in the number of facades which have 100% transparency and these values are higher than the base case.

c) It can be seen that energy for space cooling is least for 4N_S and most for 4all.The other strategies with single façade on different orientations are almost comparable to the base case, while with more number of glazed facades, the space cooling energy increases. Energy used for lighting is considerably reduced by almost 50% from the base case in all the strategies.

4.1.8 Analysis of Strategy Three

Strategy Three was analyzed based on the input described in Chapter Three and the following Table 11 shows the basic output obtained. A graphical comparison can be seen in Figs 53-56.

Table 11
Output Obtained from Analysis of Strategy Three for Hyderabad

	Total Cooling Energy(Mbtu)	Total peak cooling (Kbtuh)	Total annual cooling (Mbtu)	Lighting (Mbtu)
0	841.1	857	1764.8	462
2a	715.3	790	1521.75	302
2b	665.6	733.4	1432.41	317
2c	603.6	648.6	1322.52	328

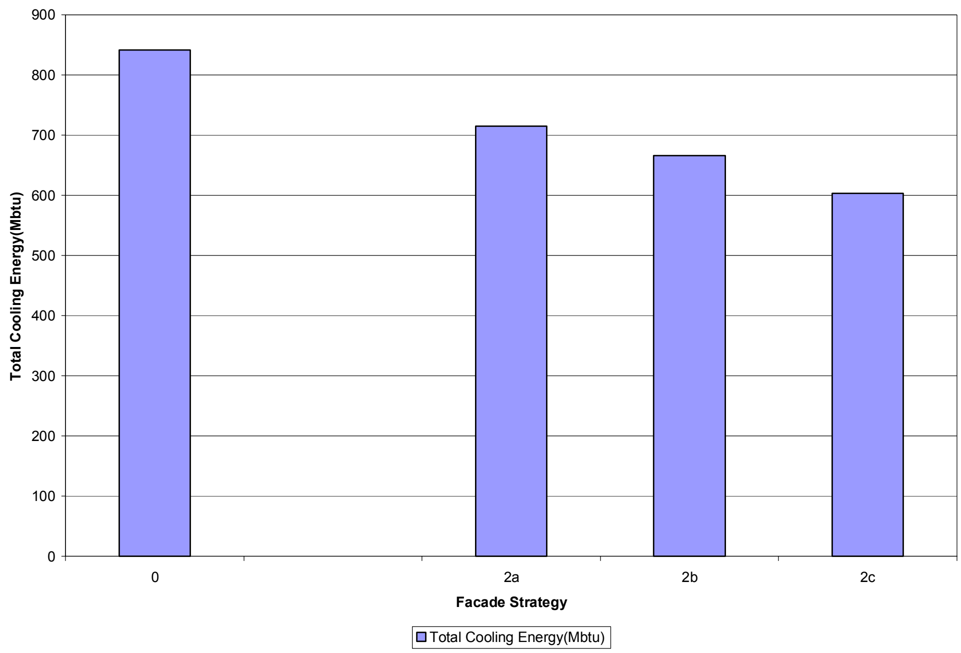


Fig. 53. Total Cooling Energy Comparison of Strategy Three Subcategories and Base Case for Hyd.

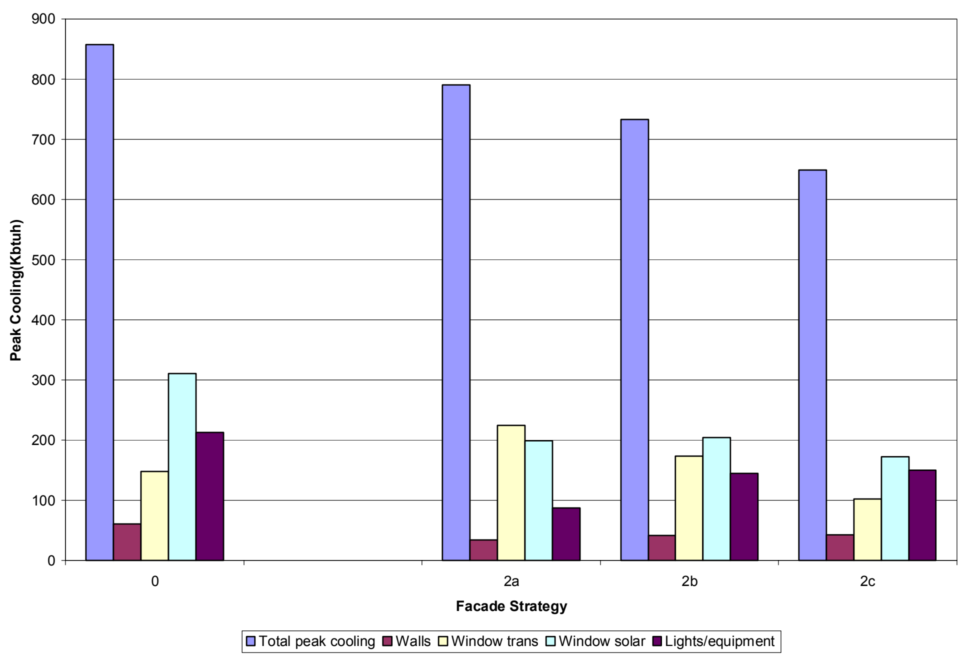


Fig. 54. Peak Cooling Load Comparison of Strategy Three Subcategories and Base Case for Hyd.

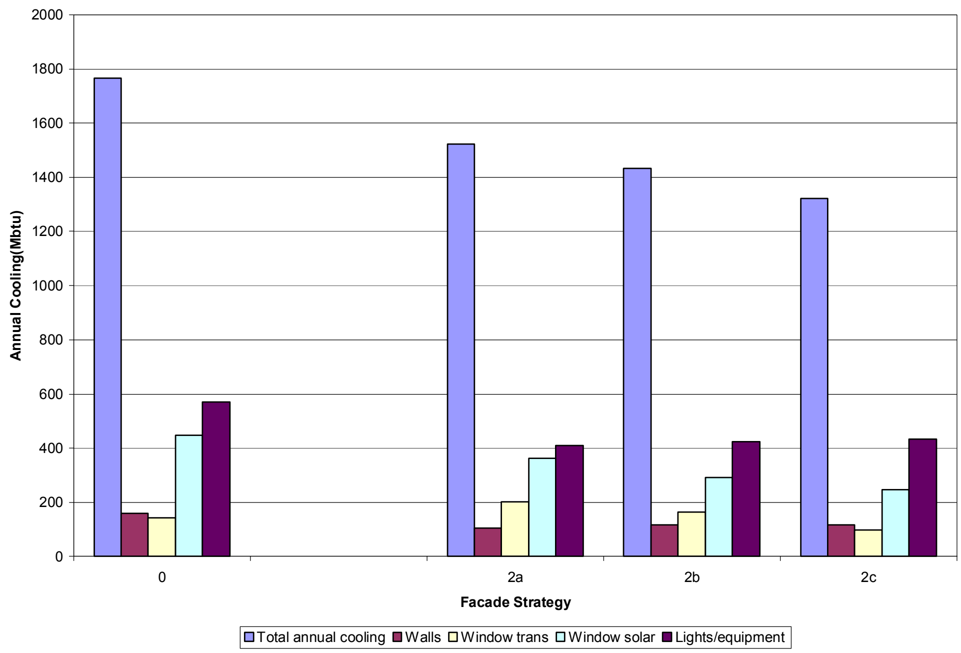


Fig. 55. Annual Cooling Load Comparison of Strategy Three Subcategories and Base Case for Hyd.

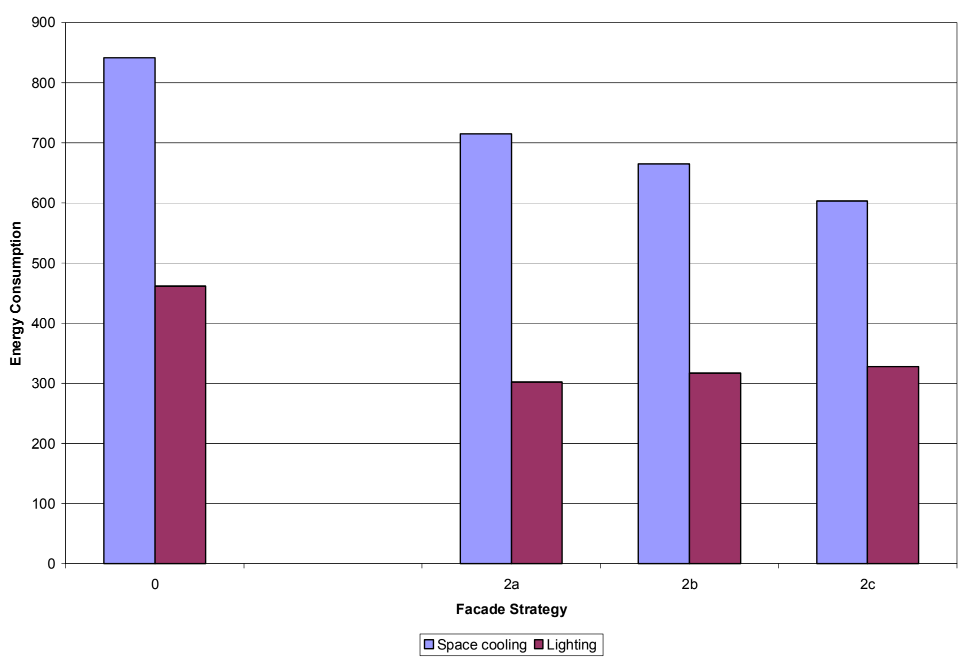


Fig. 56**.** Breakdown of Energy Consumption of Strategy Three Subcategories and Base Case for Hyd.

4.1.8.1Summary of Output for Strategy Three

a) The total cooling energy for the option 2c is about 27% less than the base case, while the cooling energy for options 2a and 2b are about 13% and 19% less than the base case.

b) The peak cooling and annual cooling loads for this strategy are also much less than that of the base case. While 2c option shows the most reduction of about 24% in peak and annual cooling loads than the base case, 2a and 2b show a reduction of 7% and 13% respectively.

c) The annual breakdown of energy consumption shows the energy required for lighting is about 30 % less. The options 2a and 2b also show reductions of 13% and 19% in space cooling and 34% and 31% in lighting respectively.

4.2 Case Study Two

4.2.1 Building Description

Birla Corporate Office Building in New Delhi (Del.), India.

The existing building is a 10 storey RCC framed structure with 5” concrete walls and glass infill. The building is externally clad with stone. Following are the basic ground floor plan (Fig. 58) and rendered view (Fig. 57) of the building. See detailed building plans in Appendix B.

Fig.57. Rendered View of Birla Corporate Office, New Delhi (Del.)

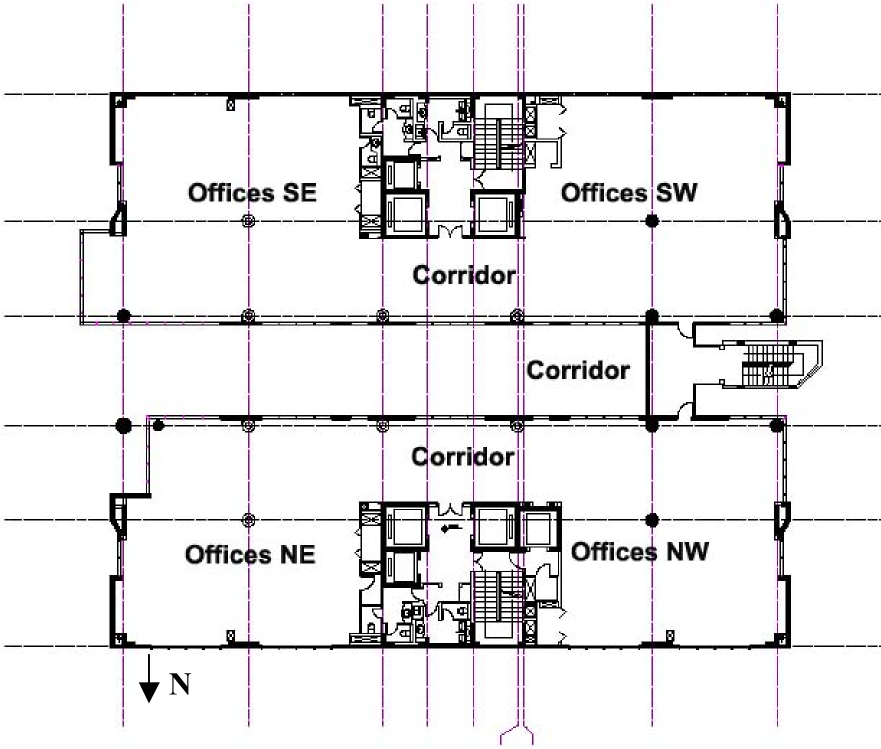


Fig. 58. Typical Plan of the Building in Delhi
Detailed plan of each level has been attached in the appendix.

4.2.2 Weather Data

The following screen capture (Fig. 59) shows the weather screen generated by Ener-Win. As explained in the case of the first building, this is basic weather data and a graph showing the annual daily temperatures has been plotted in Fig. 60. Further details are presented in Appendix D.

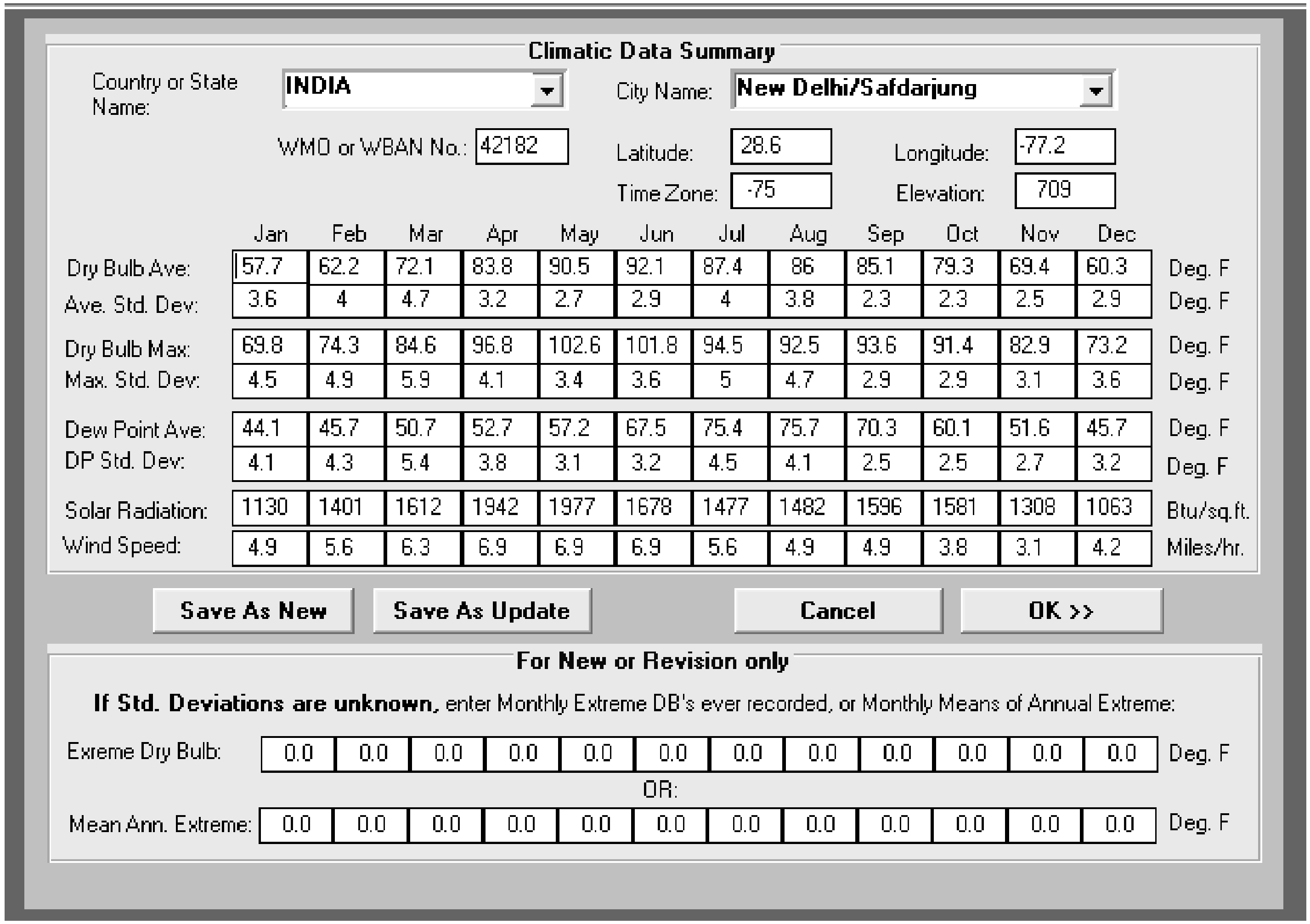


Fig. 59. Weather Data Screen as Obtained from Ener-Win for the City of New Delhi

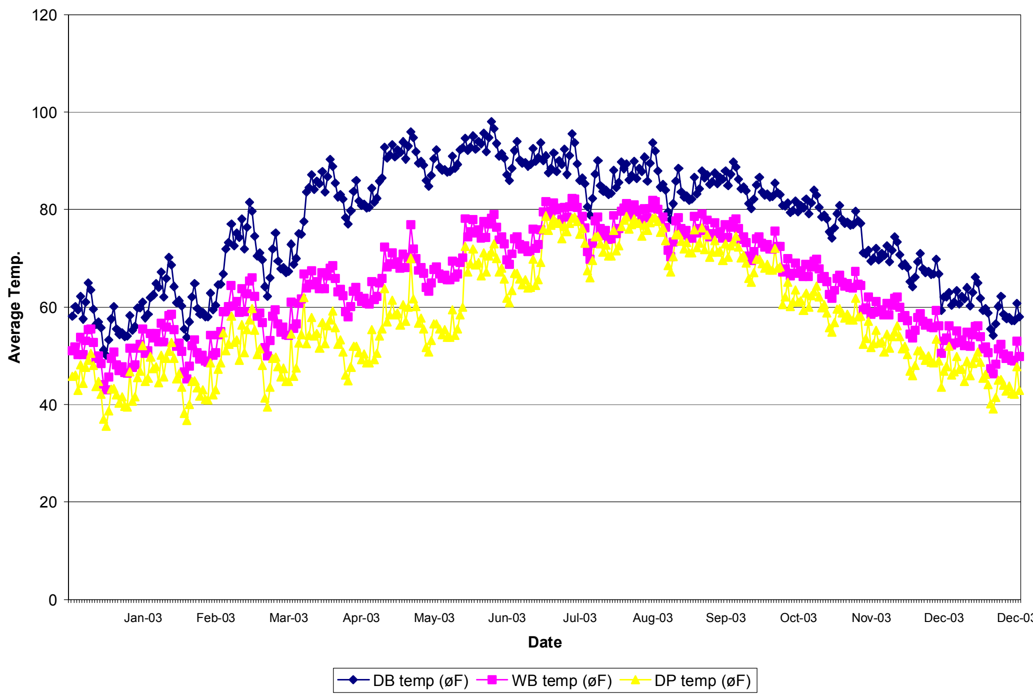


Fig. 60. Average Daily Wet Bulb, Dry Bulb and Dew Point Temperatures for the City of Delhi

4.2.3 Zone Description

The building has been divided into four major thermal zones based on the orientations, as offices on north-east, north-west, south-east, south-west. The other zones are those of the corridor, staircase, toilets and electrical areas. Table 12 describes the color for each thermal zone described in the Ener-Win building sketch. Fig. 61 describes the building sketch as a screen-capture from Ener-Win.

Table 12
Zone Color Legend for the Building Sketch Drawn in Ener-Win for Delhi

Sno	Zone Name	Color
1	Electrical	Black
2	Offices NE	Purple
3	Offices SE	Green
4	Offices SW	Sea Green
5	Offices NW	Blue
6	Staircase	Olive green
7	Corridor	Grey
8	Toilets	Cyan
9	Elevator	Red

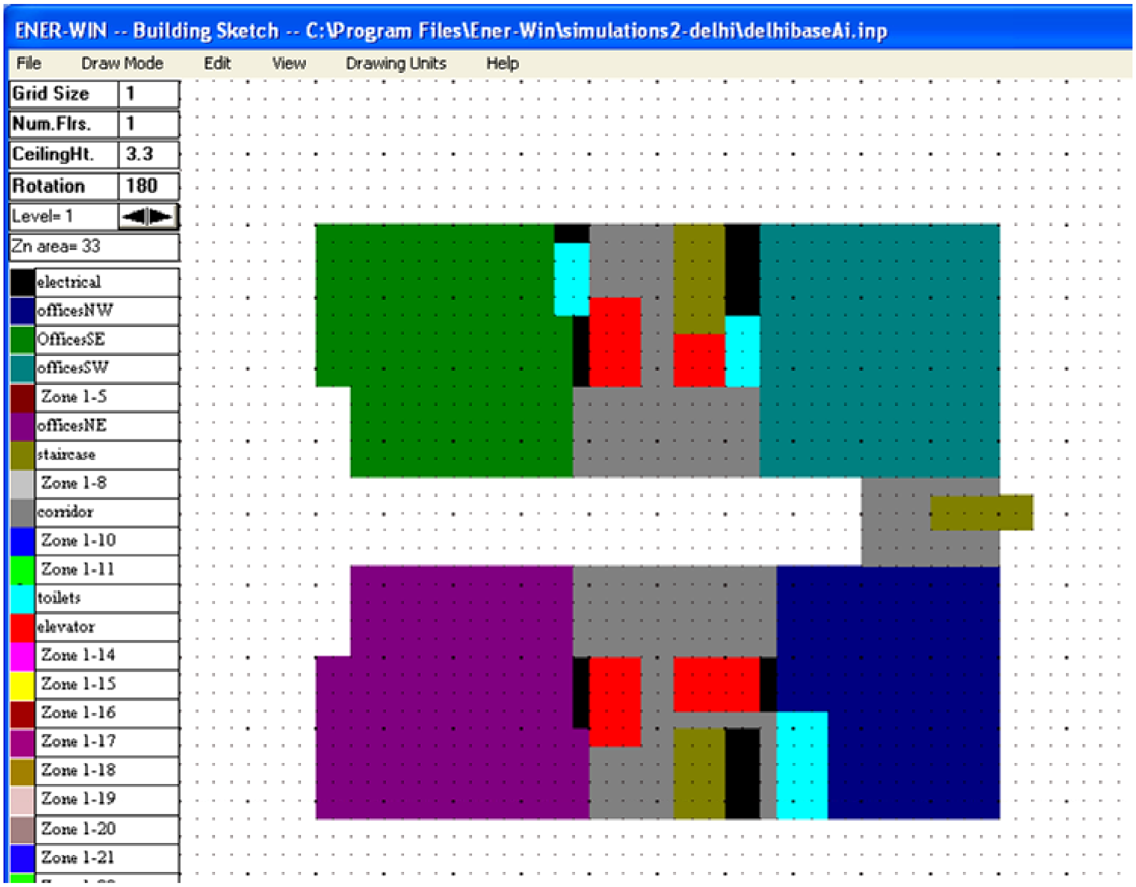


Fig. 61. Screen Capture from Ener-Win Describing the Building Zones for Delhi

4.2.4 Analysis of Base Case

4.2.4.1 Typical Wall Section

The typical wall section of the building comprises of a 5" RCC wall which is plastered on the inside and has stone cladding on the outside. Fig. 62. shows the wall section detail.

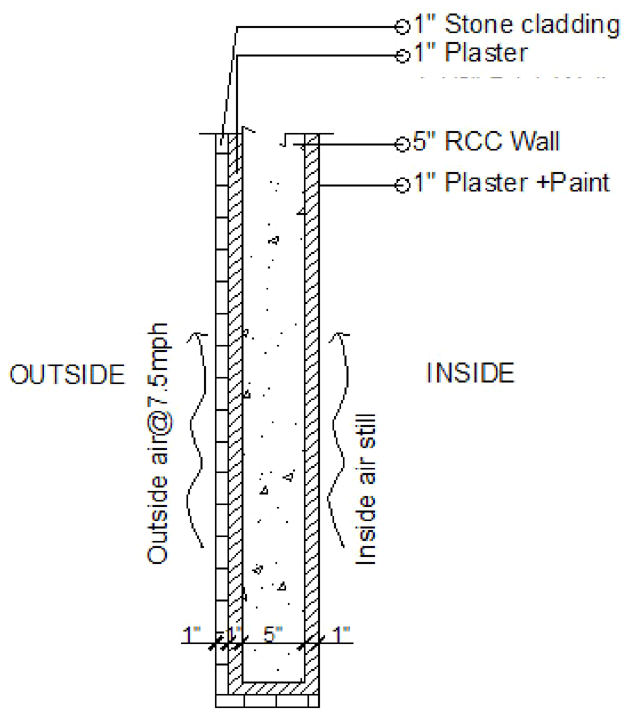
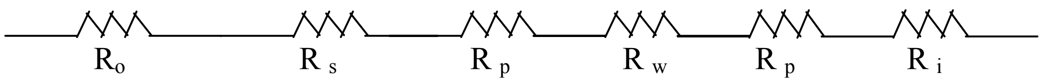


Fig.62. Typical Wall Section for the Building in Delhi

4.2.4.2 Calculation of Resistance

The overall resistance of the wall was calculated as a sum of the resistances of materials across the wall section as explained in Fig. 63.



Legend

R_o : Resistance of outside surface

R_w : Resistance of wall

R_p : Resistance of plaster and paint

R_i : Resistance of inside surface

Fig.63. Resistance Diagram for Typical Wall Section for the Building in Delhi

The formulae for calculation are

Total R value = $R_o + R_s + R_p + R_w + R_p + R_i$

U-value= $1/R_{tot}$

4.2.4.3 U-Value Calculation

The following Table 13 shows the calculation of the U-value. The R-values for each component are standards taken from 2001 Ashrae Fundamentals Handbook. This U-value was used to create a new wall type and that was used in the simulation runs

Table 13
U-value Calculation for Typical Wall Section of the Base Case

Delhi Base Case		
Symbol	**Component**	**R-value**
Ro	Outside surface(7.5mph)	0.25
Rs	1" stone cladding	0.08
Rp	1"plaster	0.20
Rw	5" RCC wall	0.55
Rp	1"plaster	0.20
Ri	Inside surface,still air	0.68
	Total	**1.96**
	U-value	**0.51**

4.2.4.4 Zone Properties Description

i) Walls

The façade walls were defined using the U-value calculated in the previous section. Wall area, orientation and surface exposure are calculated by the program.

ii) Windows

Window type is identified to be 1"double plate gray tinted glass which was used in the building. The glass area was manually calculated and entered based on information from building drawings.

iii) Other Parameters

The other parameters are defaults and only the window sill and window height are changed according to the drawing data.

4.2.4.5 Output

Based on the above input, the following output was obtained which shows the total cooling energy, peak cooling loads, annual cooling loads and breakdown of annual energy consumption. Figs. 64-67 show the screen captures from Ener-Win of the graphical output obtained.

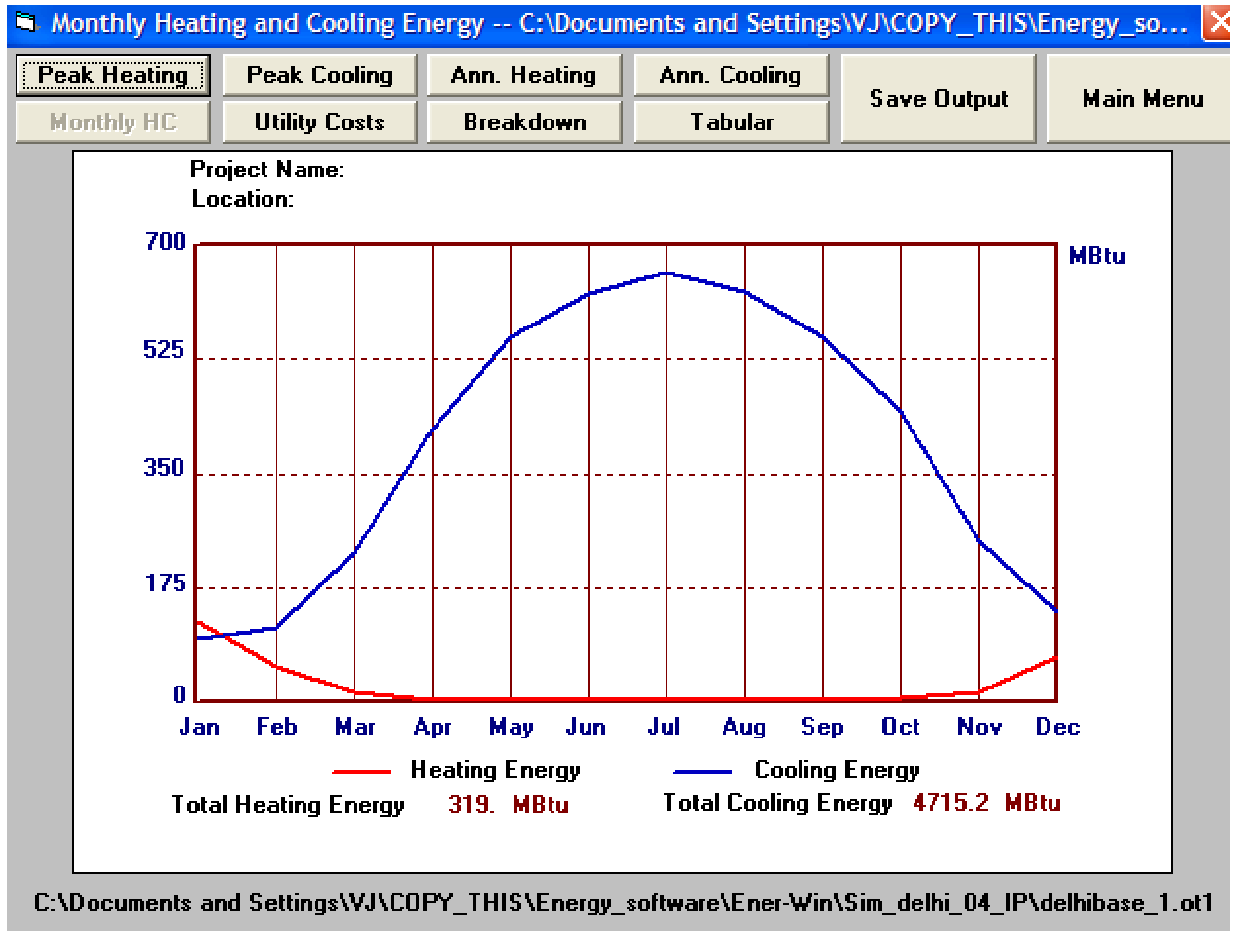


Fig. 64. Screen Capture from Ener-Win Showing Monthly Cooling Energy (Mbtu) for the Base Case:

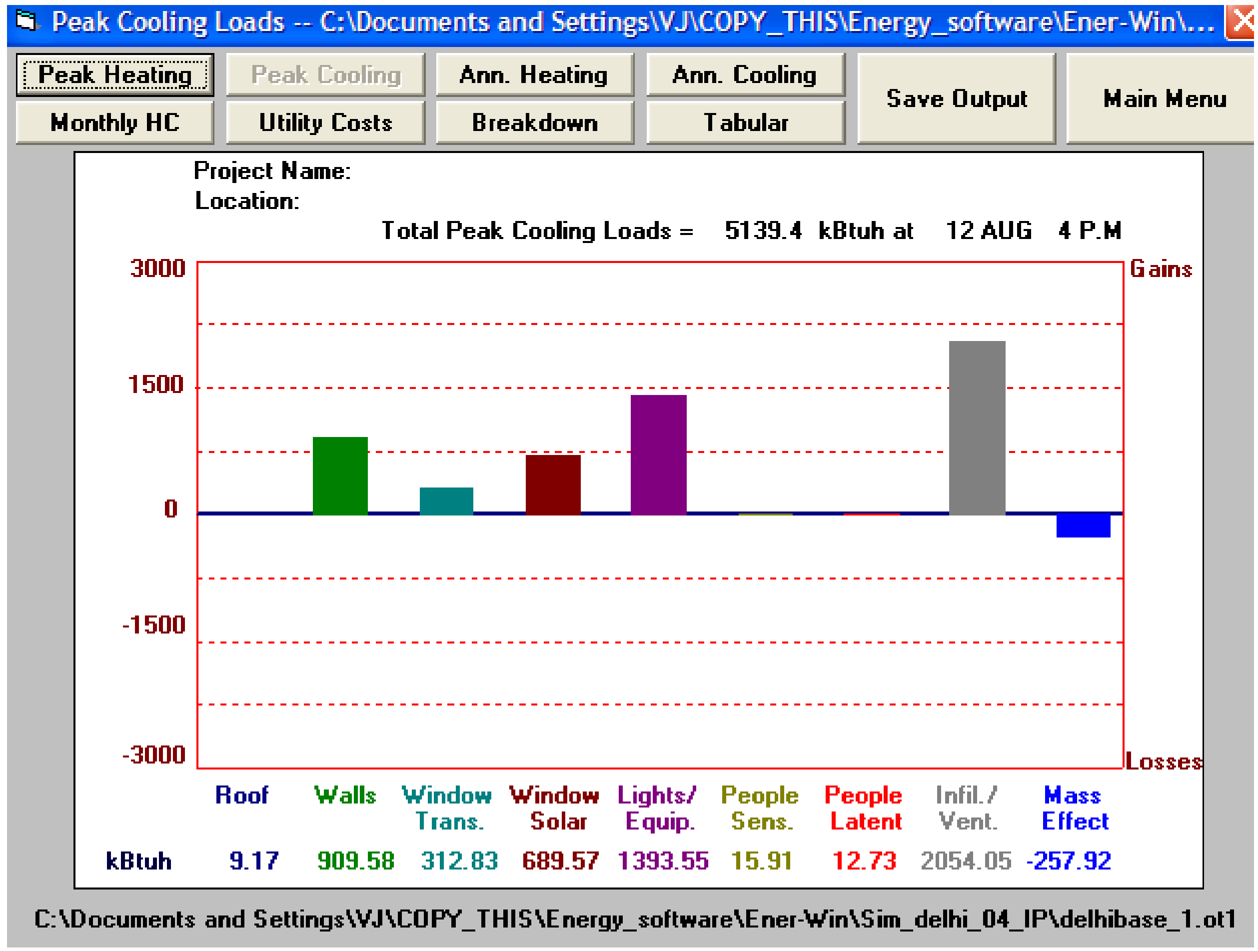


Fig. 65. Peak Cooling Load Output for the Base Case: Delhi

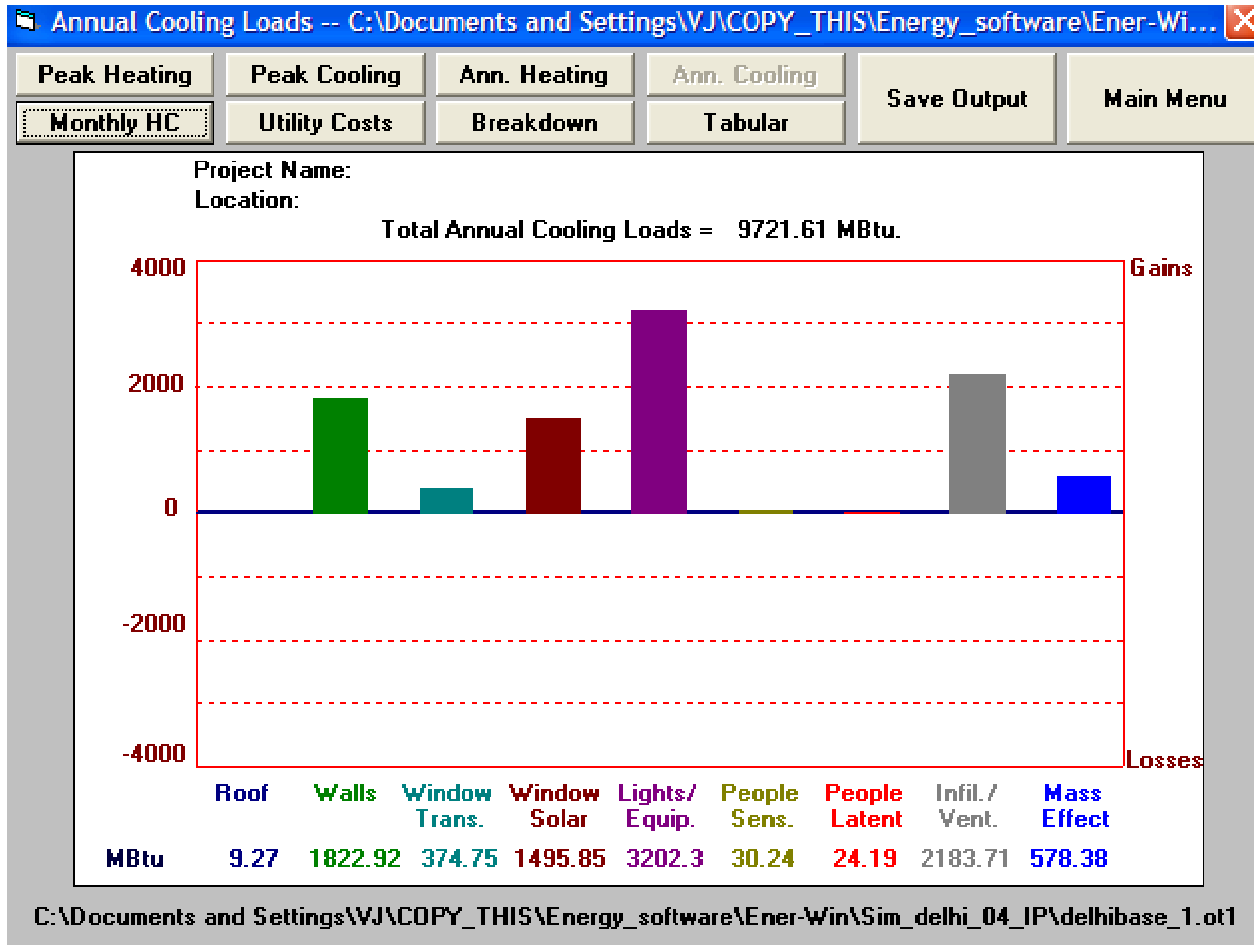


Fig. 66. Annual Cooling Load Output Generated by Ener-Win for the Base Case: Delhi

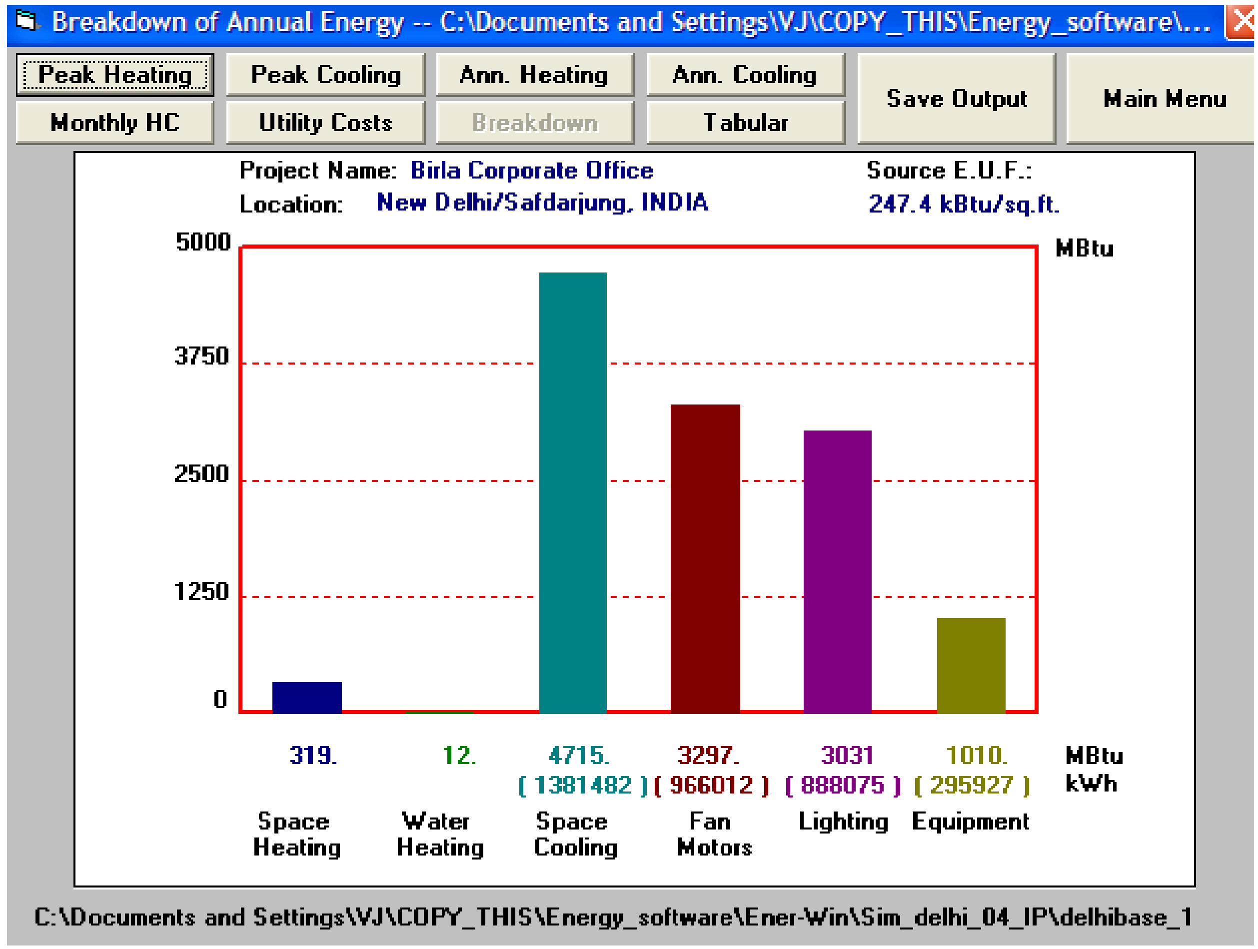


Fig. 67. Output Obtained from Ener-Win Showing the Annual Breakdown of Energy Consumption for Base Case: Delhi

4.2.4.6 Summary of Output of Base Case

From the graphical output, it can be seen that the total cooling energy used by the building in existing conditions is 4715 Mbtu. The maximum amount of energy (4715 Mbtu) is being used for space cooling and next for lighting (3031 Mbtu).The total peak cooling load is about 5139 Kbtuh and annual peak cooling is about 9721 Mbtu.

Both show that maximum heat gain is through window transmission and solar radiation, followed by the heat gain by walls. This shows the need to reduce heat gain through these sources, similar to the building studied in Hyderabad.

4.2.5 Analysis of Strategy One

Strategy One was analyzed as explained in the methodology according to the orientation of the façade. Each of these was then analyzed with the shading option also. Table 14 gives basic information of the output obtained. Graphs explaining the performance of each strategy in comparison with each other are shown in Figs. 68-71.

Table 14
Output for Analysis of Strategy One for Delhi

	Total Cooling Energy(Mbtu)	Total peak cooling (Kbtuh)	Total annual cooling(Mbtu)	Lighting (Mbtu)
0	4715.2	5139.4	9721.61	3031
1N	4620.5	5179.8	9496.38	2136
1E	4630.1	5098.1	9547.33	2168
1S	4786	5166.9	9877.4	2114
1W	4692	5239.1	9604.9	2179
1all	5707.6	6360.6	11648.74	2073

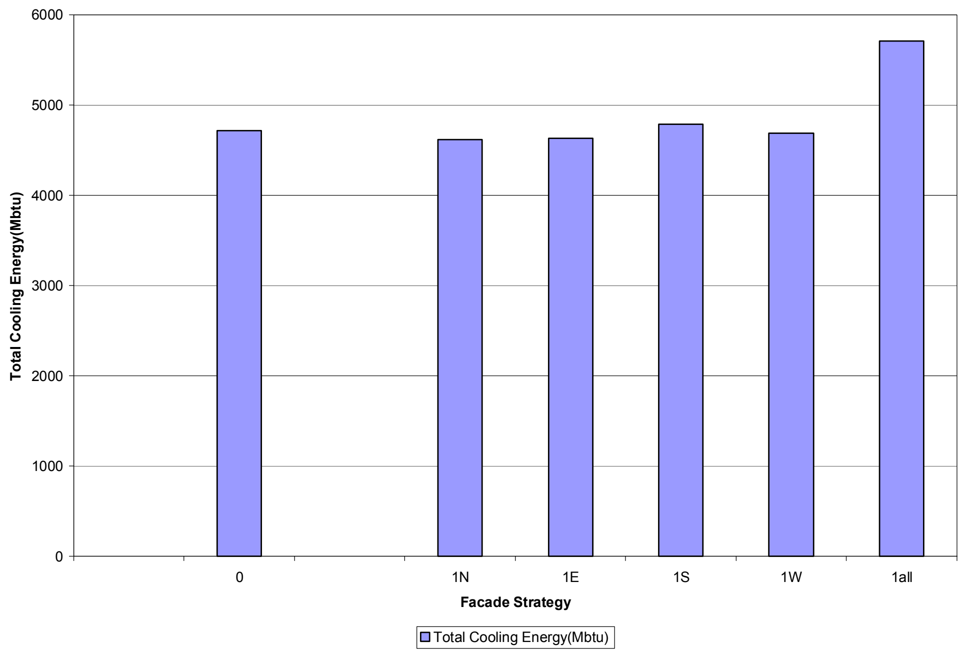


Fig. 68. Total Cooling Energy Comparison of Strategy One Subcategories with Base Case for Delhi

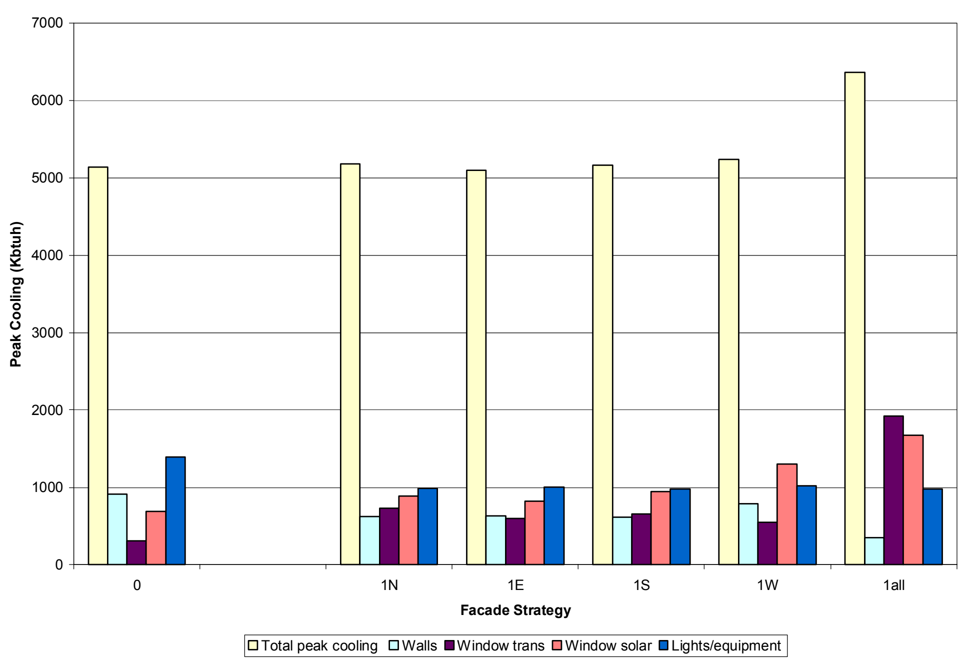


Fig. 69 Peak Cooling Load Comparison of Strategy One Subcategories with Base Case for Delhi

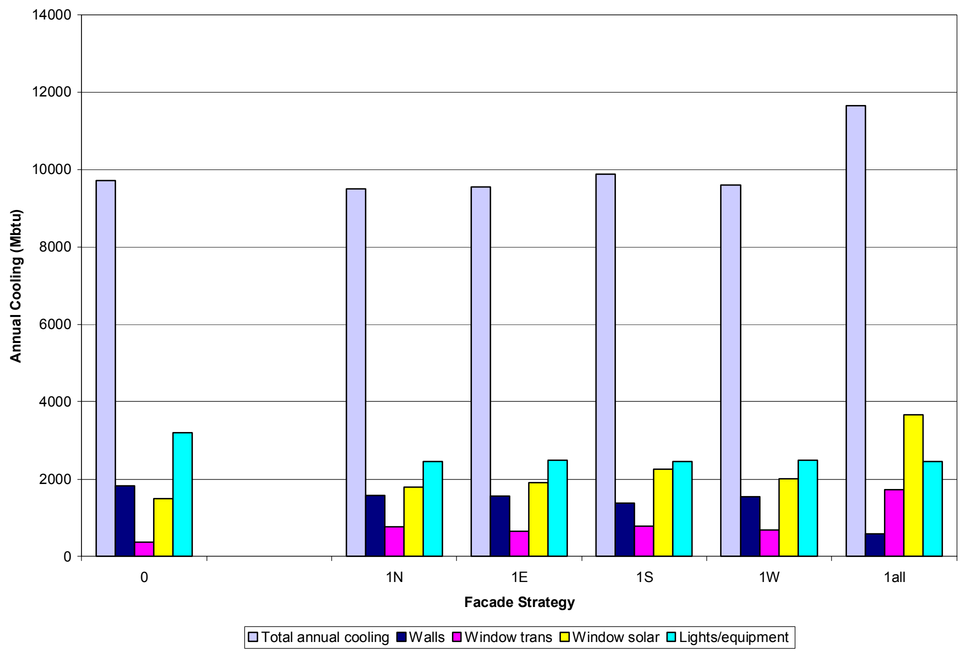


Fig. 70. Annual Cooling Load Comparison of Strategy One Subcategories with Base Case for Delhi

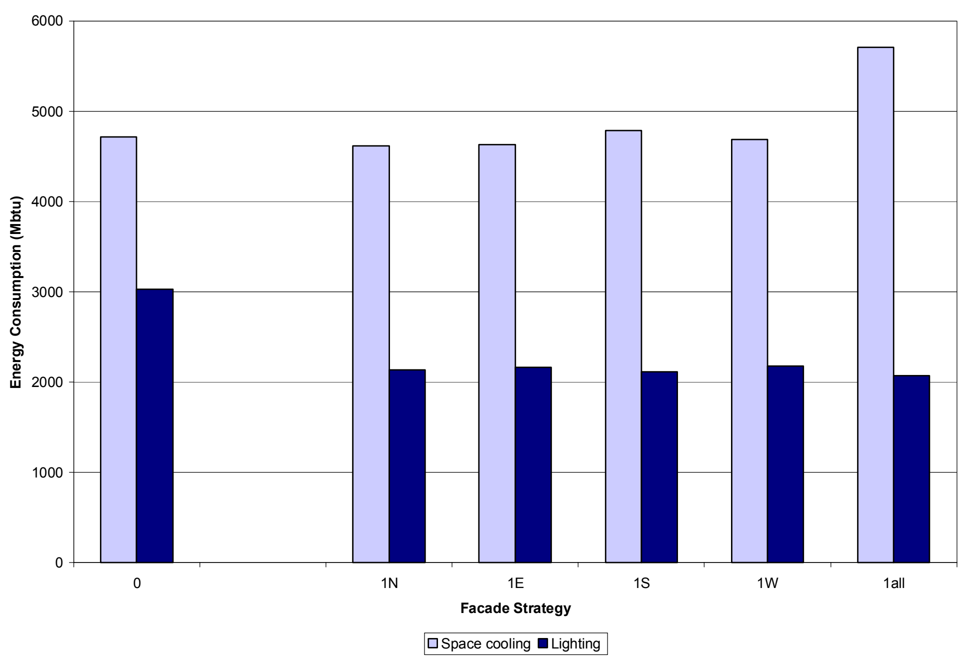


Fig. 71. Annual Breakdown of Energy Consumption for Strategy One and Base Case for Delhi

4.2.5.1 Effect of Shading

The shading values were added to the input and the above mentioned strategies were simulated to analyze the effect of shading on the energy performance. Table 15 gives the exact values of the output and Figs. 72-75 give a graphical representation of the output.

Table 15
Output for Analysis of Strategy One with Shading for Delhi

	Total Cooling Energy(Mbtu)	Total peak cooling (Kbtuh)	Total annual cooling(Mbtu)	Lighting (Mbtu)
0	4715.2	5139.4	9721.61	3031
1N_S	4516.9	5095.4	9290.62	2142
1E_S	4503.4	5022.3	9288.2	2175
1S_S	4464.2	4969.6	9210.07	2119
1W_S	4534.5	5148.2	9284.74	2190
1all_S	4975.6	5969	10154.21	2086

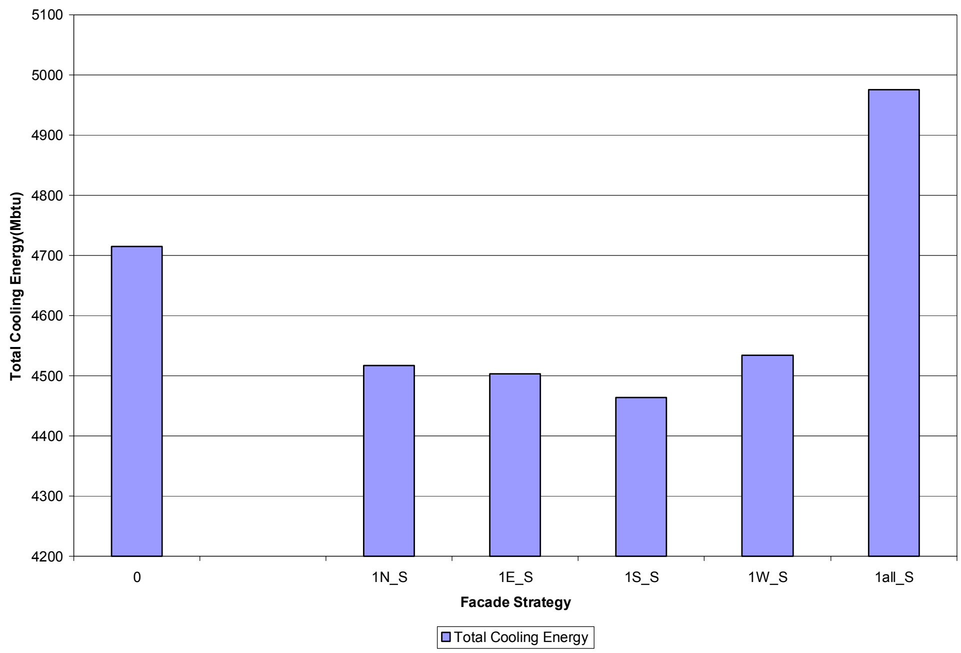


Fig. 72. Total Cooling Energy Comparison of Strategy One with Shading and Base Case for Delhi

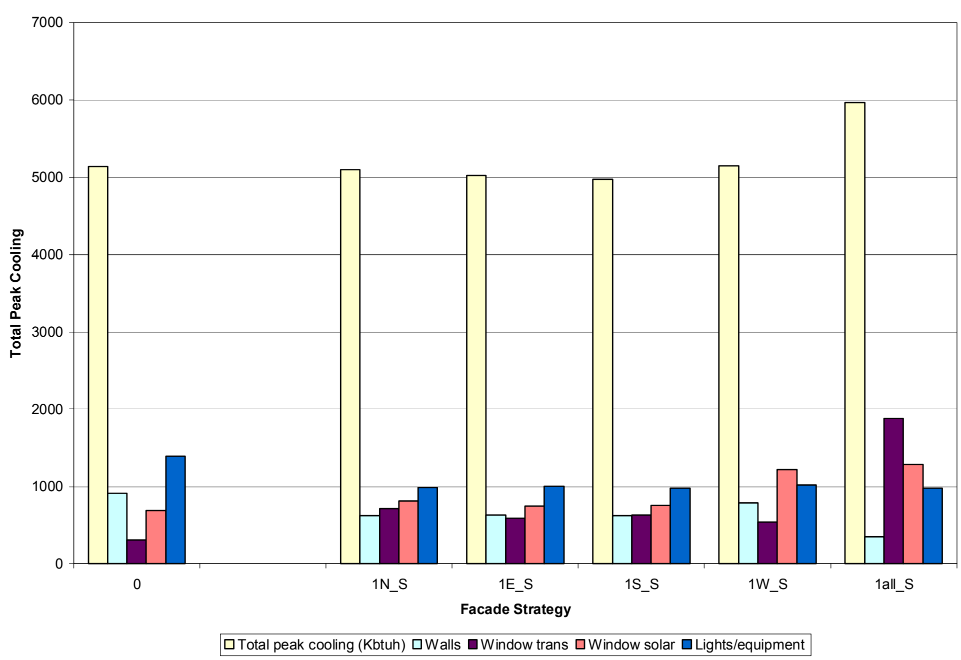


Fig. 73. Peak Cooling Load Comparison of Strategy One with Shading and Base Case for Delhi

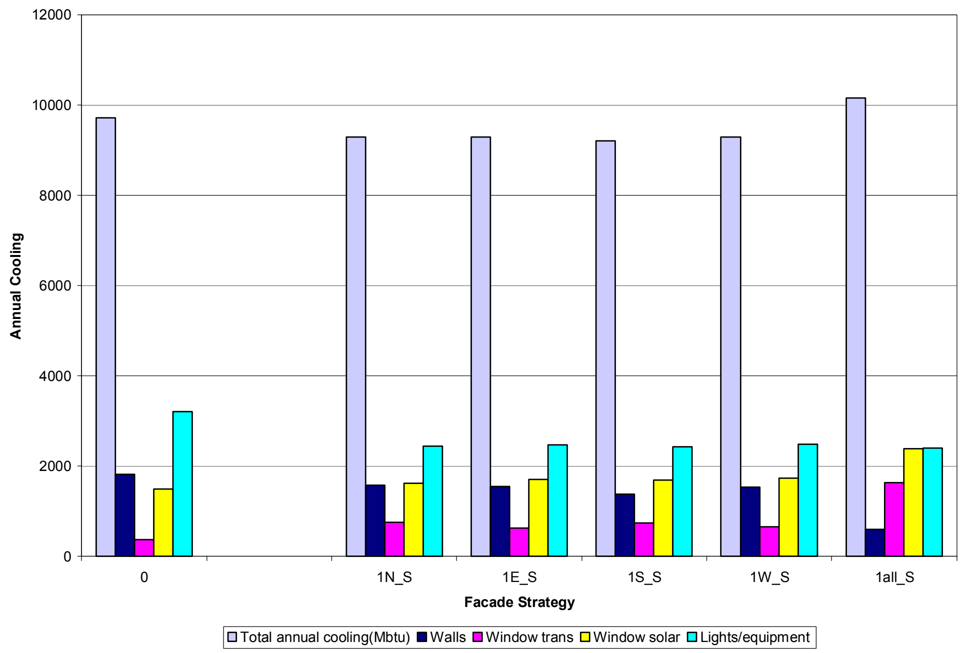


Fig. 74. Annual Cooling Load Comparison of Strategy One with Shading and Base Case for Delhi

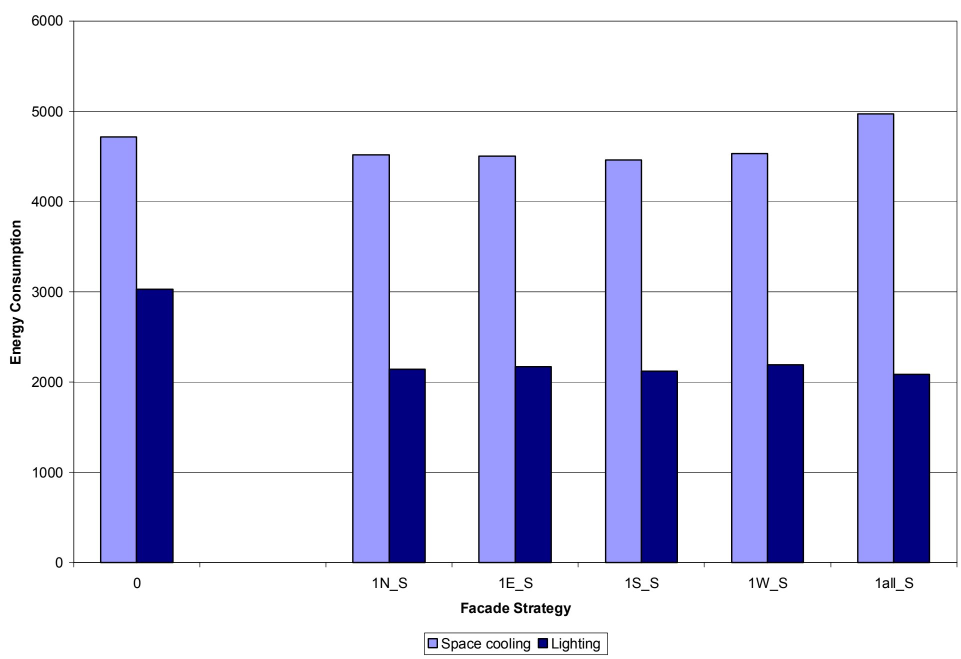


Fig. 75. Breakdown of Energy Consumption of Strategy One with Shading and Base Case for Delhi

4.2.5.2 Summary of Output for Strategy One

a) The total cooling energy is the least for the strategy 1N_S, which has three facades same as the base case and the north façade with the double skin strategy and includes shading. The maximum cooling energy is consumed by the strategy with all four facades with double skins. The cooling energy for 1N is approximately 3% less than the base case and 1N_S is about 4% less than the base case. On the other hand the cooling energy consumed by the strategy with all four facades having double skins is 21% larger than the cooling energy of the base case.

b) The peak cooling load is least for 1N_S and maximum for 1all. The peak cooling load break-up shows that the load due to lighting is reduced notably to about 25-30% of the base case. The heat gain through walls varies according to the strategy, being the least for 1all and highest for 1N; both of these values are less than the base case. The heat gain through windows (trans. and solar) increases with increase in the number of facades which have 100% transparency and these values are higher than the base case. The annual cooling load also follows a similar trend.

c) It can be seen that energy for space cooling is least for 1N_S and most for 1all. The other strategies with single DSF on different orientations are almost comparable to the base case; with more number of glazed facades the space cooling energy increases. Energy used for lighting is considerably reduced by almost 25% from the base case in all the strategies.

4.2.6 Analysis of Strategy Two

Strategy Two was analyzed in a manner similar to that done for the city of Hyderabad. Table 16 gives the numerical data of the output while Figs. 76-79 present a graphical comparison of the behavior of each strategy.

Table 16
Output for Analysis of Strategy Two for Delhi

	Total Cooling Energy(Mbtu)	Total peak cooling (Kbtuh)	Total annual cooling(Mbtu)	Lighting (Mbtu)
0	4715.2	5139.4	9721.61	3031
4N	4476.6	4976.2	9230.52	2139
4E	4487.3	4949.7	9273.18	2171
4S	4557.5	4964.3	9420.83	2117
4W	4523.2	5061.1	9289.87	2181
4all	5013.3	5535.9	10316.64	2078

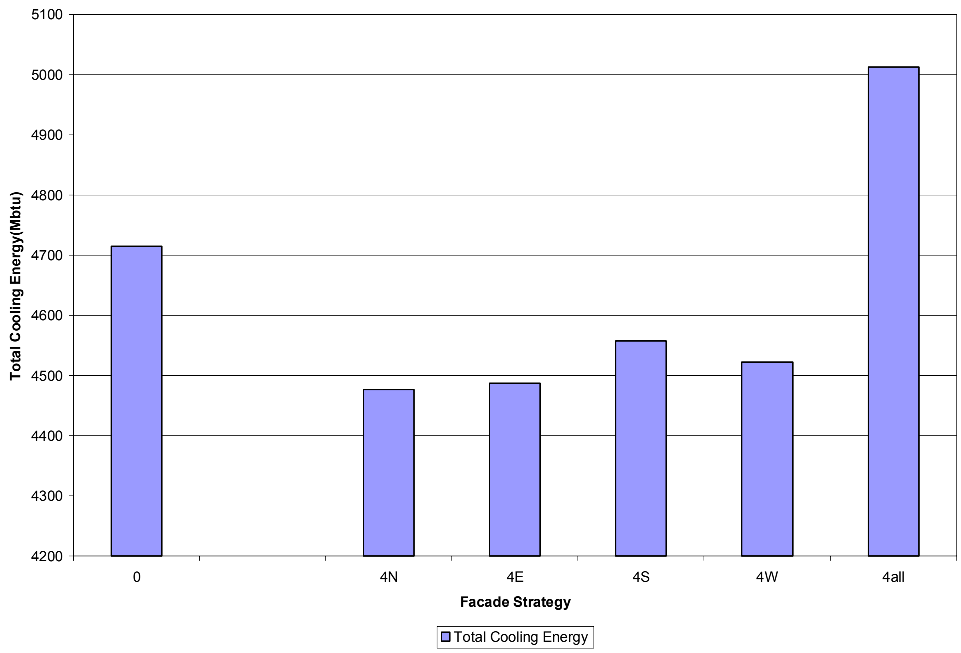


Fig. 76. Total Cooling Energy Comparison of Strategy Two and Base Case for Delhi

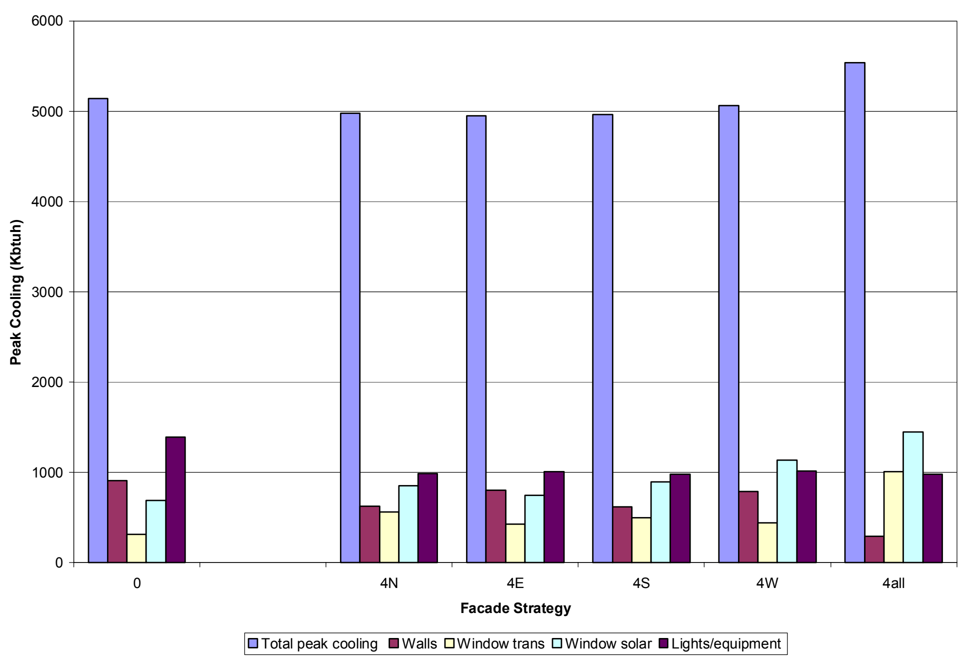


Fig. 77. Peak Cooling Load Comparison of Strategy Two and Base Case for Delhi

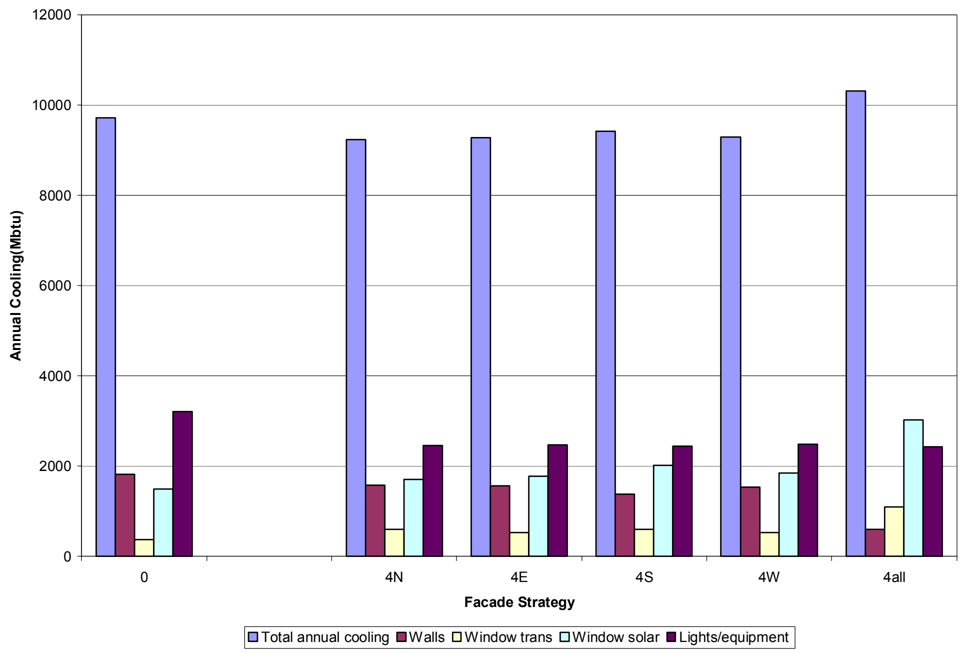


Fig. 78. Annual Cooling Load Comparison of Strategy Two and Base Case for Delhi

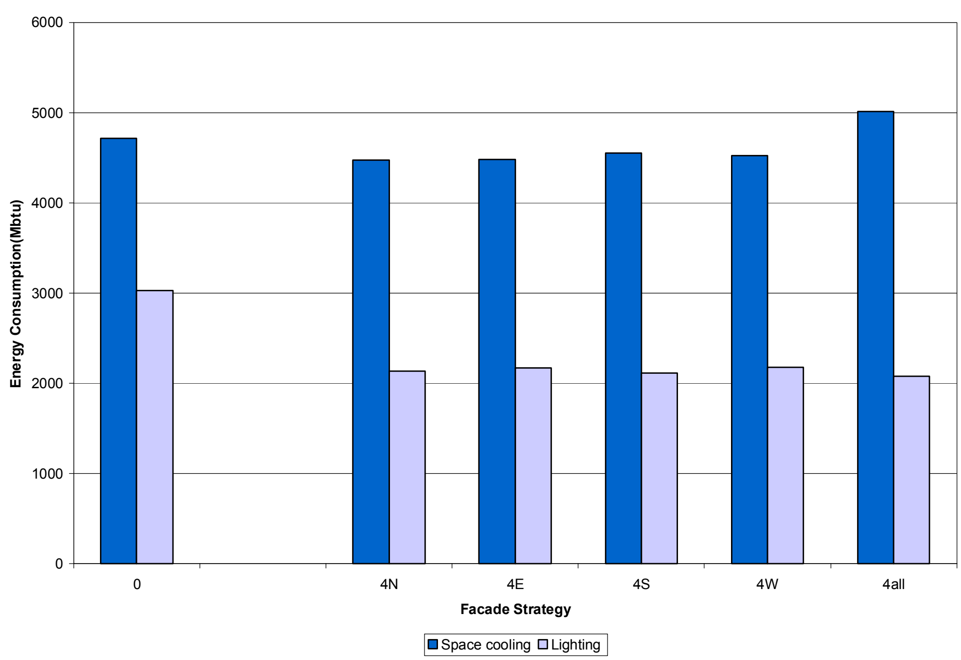


Fig. 79. Annual Breakdown of Energy Consumption for Strategy Two and Base Case for Delhi

4.2.6.1 Effect of Shading

Shading was incorporated along the proposed double-skin strategies and it was seen that the energy performance improved by addition of shading devices. Table 17 presents a numerical output of the data obtained. Figs. 80-83 describe a graphical representation of the output.

Table 17
Output for Analysis of Strategy Two with Shading for Delhi

	Total Cooling Energy(Mbtu)	Total peak cooling (Kbtuh)	Total annual cooling(Mbtu)	Lighting (Mbtu)
0	4715.2	5139.4	9721.61	3031
4N_S	4391.9	4909.5	9062.51	2146
4E_S	4380	4883.4	9054.39	2179
4S_S	4290.4	4808	8870.08	2123
4W_S	4396.3	4988.6	9034.3	2193
4all_S	4410	5186.3	9091.5	2093

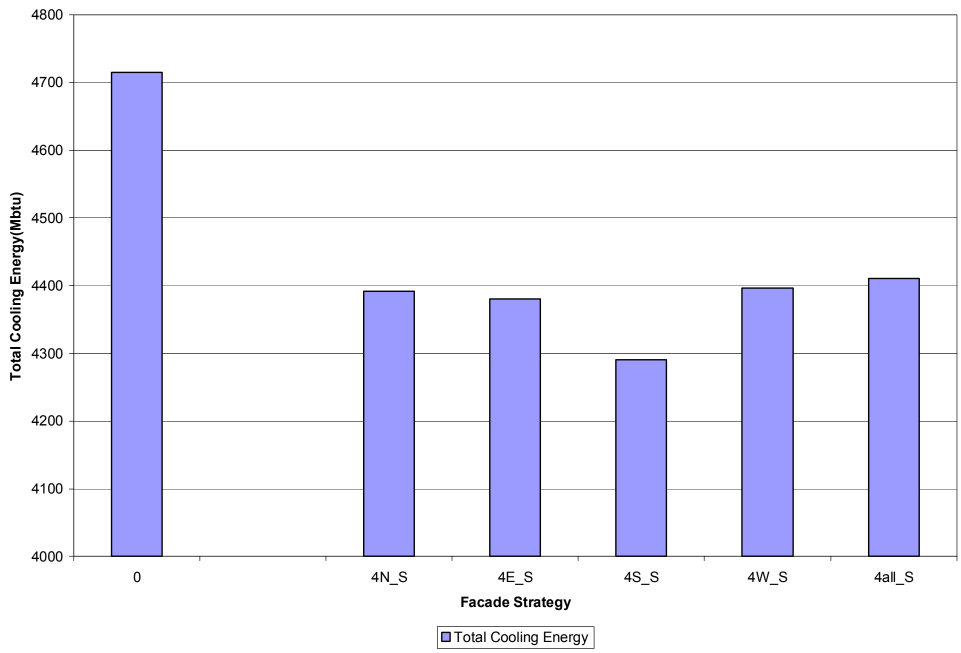


Fig. 80. Total Cooling Energy Comparison of Strategy Two (with Shading) and Base Case for Delhi

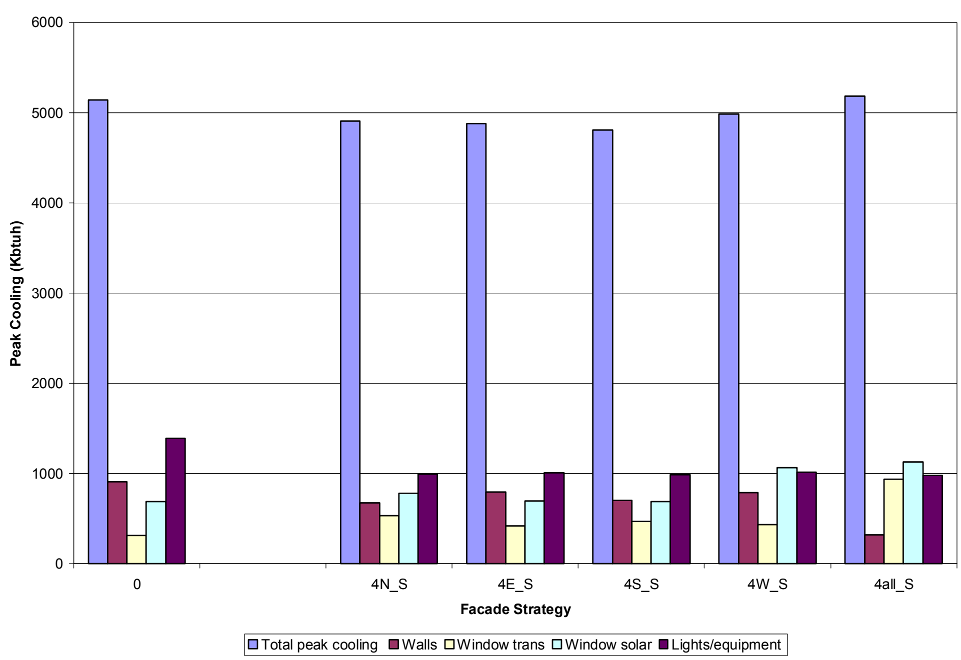


Fig. 81. Peak Cooling Load Comparison of Strategy Two (with Shading) and Base Case for Delhi

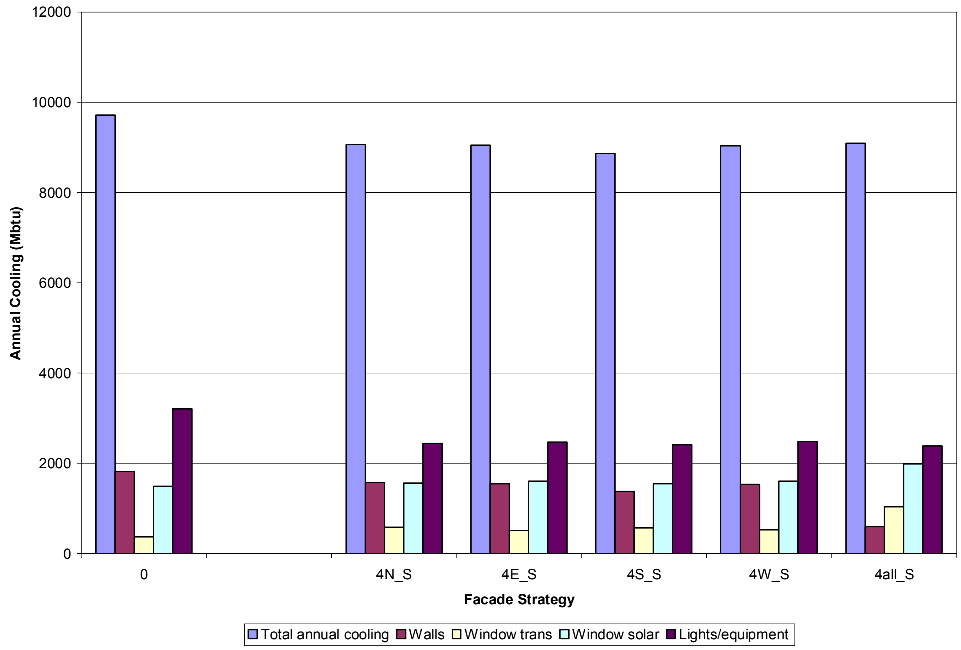


Fig. 82. Annual Cooling Load Comparison of Strategy Two (with Shading) and Base Case for Delhi

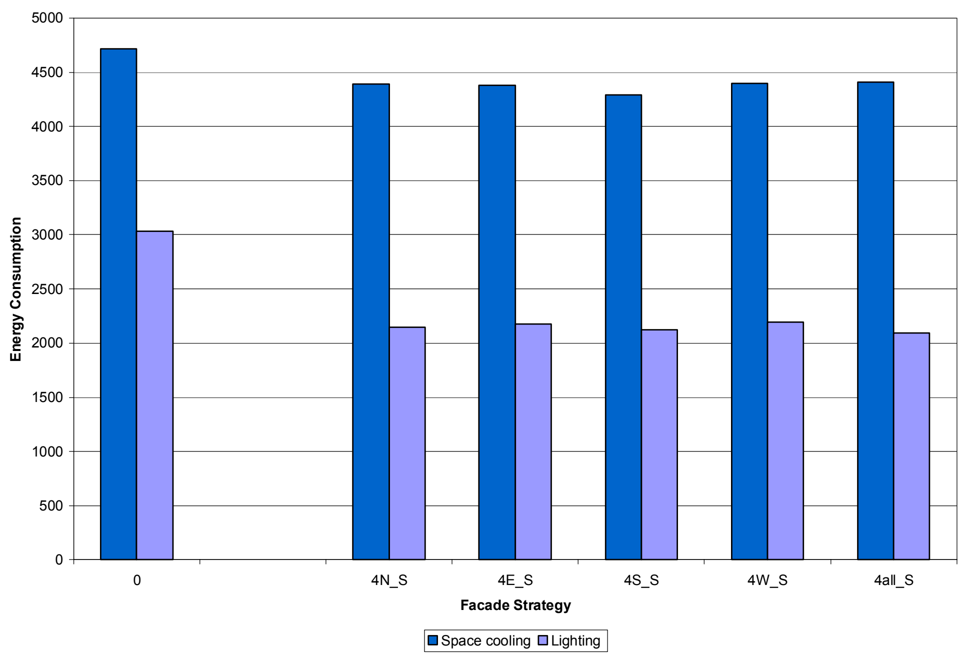


Fig. 83. Breakdown of Energy Consumption of Strategy Two (with Shading) and Base Case for Delhi

4.2.6.2 Summary of Output for Strategy Two

a) The total cooling energy is the least for the strategy 4N_S, which has three facades same as the base case and the north façade with the double skin strategy and includes shading. The maximum cooling energy is consumed by the strategy with all four facades with double skins. The cooling energy for 4N is approximately 4% less than the base case and 4N_S is about 6% less than the base case. On the other hand the cooling energy consumed by the strategy with all four facades having double skins is 6% larger than the cooling energy of the base case.

b) The peak cooling load is least for 4N_S and maximum for 4all. The break-up of peak cooling load show that the load due to lighting is reduced notably to about 25-30% of the base case.

c) It can be seen that energy for space cooling is least for 4N_S and most for 4all. The other strategies with single DSF on different orientations are almost comparable to the base case. Energy used for lighting is considerably reduced by almost 25% from the base case in all the strategies.

4.2.7 Analysis of Strategy Three

Strategy Three was analyzed as explained in the methodology for the Case Study Building Two in Delhi. The following output, presented in Table 18, was obtained. Figs. 84-87 give a graphical description of the output.

Table 18
Output for Analysis of Strategy Three for Delhi

	Total Cooling Energy(Mbtu)	Total peak cooling (Kbtuh)	Total annual cooling (Mbtu)	Lighting (Mbtu)
0	4715.2	5139.4	9721.6	3031
2a	4294.8	5171.3	8863.7	2114
2b	4114.2	4987.5	8520.4	2125
2c	3839.4	4653.5	7999.4	2138

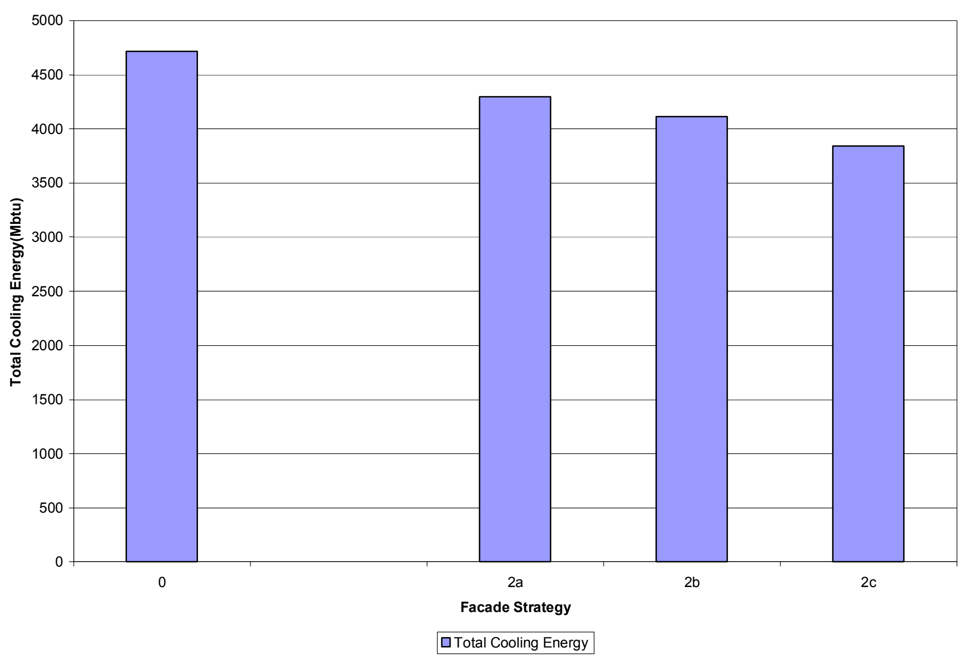


Fig. 84. Total Cooling Energy Comparison of Strategy Three Subcategories and Base Case for Delhi

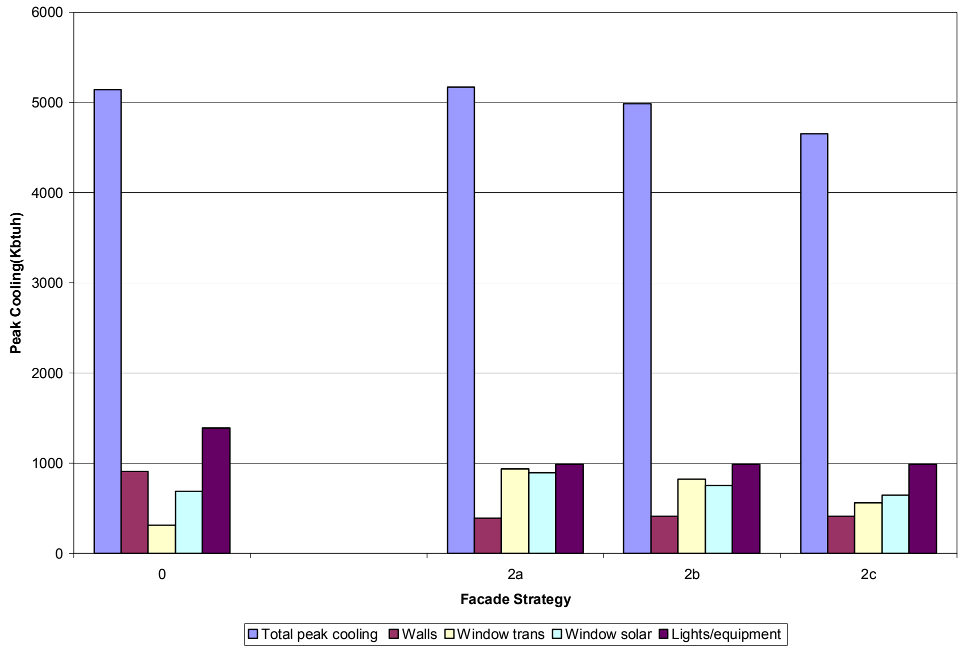


Fig. 85. Peak Cooling Load Comparison of Strategy Three Subcategories and Base Case for Delhi

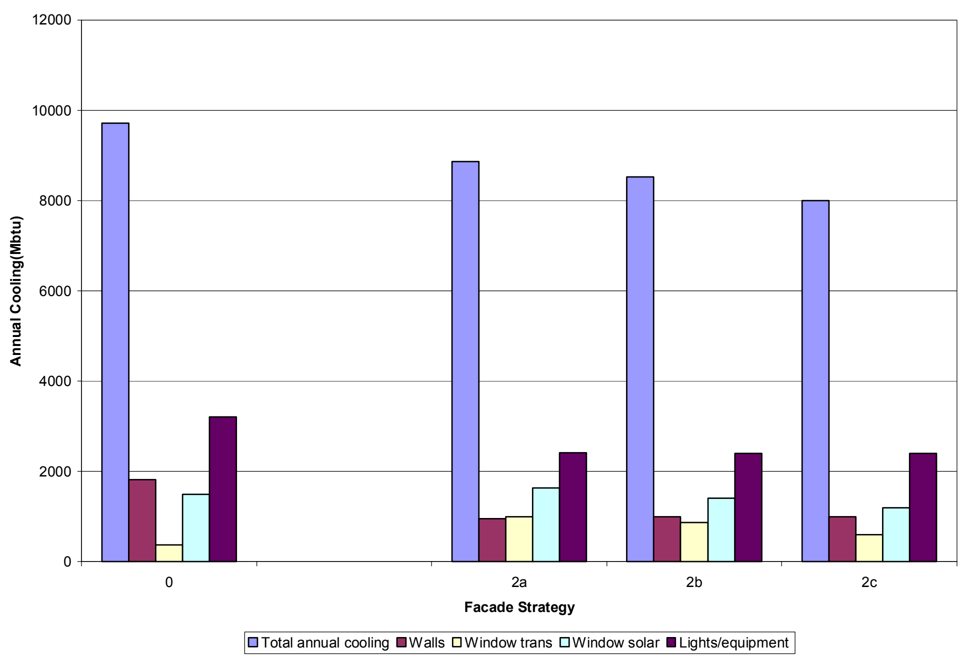


Fig. 86. Annual Cooling Load Comparison of Strategy Three Subcategories and Base Case for Delhi

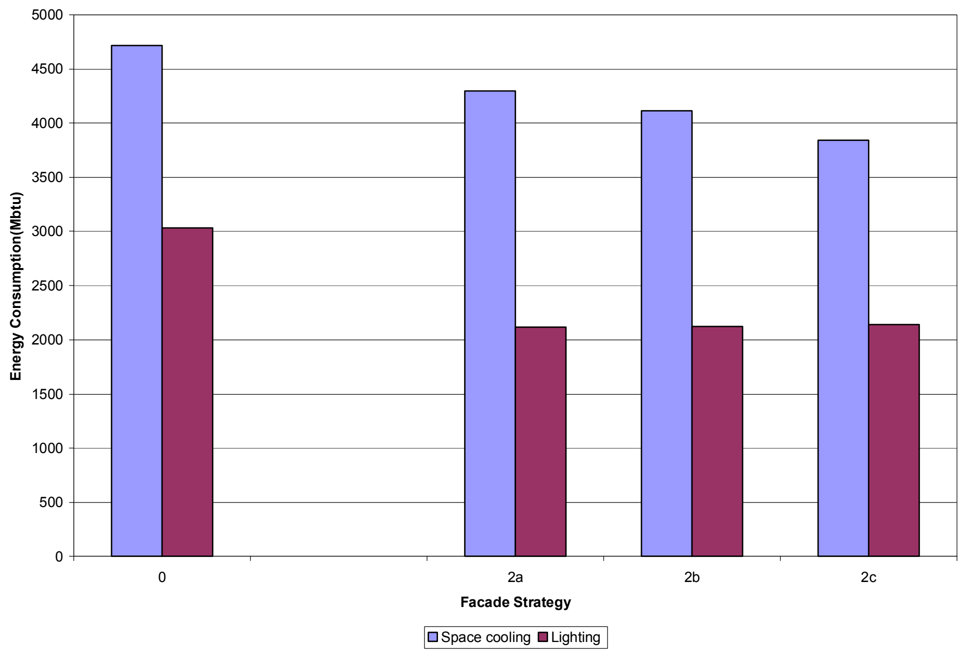


Fig. 87. Comparison of Breakdown of Energy Consumption for Strategy Three and Base Case for Delhi

4.2.7.1 Summary of Output for Strategy Three

a) The total cooling energy is reduced by about 10-20% from the base case with the introduction of this strategy.

b) The peak cooling load shows a reduction that varies from 5-12% between the various subcategories of the strategy and the base case. The option 2c appears most efficient.

c) The annual cooling loads show a more steep reduction in figures, about 15-24% less than the base case.

d) It can be seen that energy for space cooling is least for 2c. Energy used for lighting is considerably reduced by almost 25% from the base case in all the strategies.

CHAPTER V

CONCLUSIONS

The basic purpose of this research was to investigate the performance of double-skin facades in office buildings in the hot climates of Hyderabad and Delhi. After conducting the research as per the methodology and analyzing the results obtained from the simulations, it becomes evident that double skin facades typically defined as ‘a pair of glass skins separated by an air corridor’ are not more energy efficient than the conventional skin in hot climates. Hence, the hypothesis is rejected. The study reveals the need to redefine double-skin facades to include a broader range of materials and other parameters that are representative of the context in which they are being built.

5.1 Inferences from Simulations

5.1.1 Effect of Layering of the Double-Skin Facade

In terms of layering of the façade, it can be clearly seen that adding another layer to the existing façade has an impact on the total cooling energy consumed and the cooling loads. The double skin has an immediate effect on the U-value of the envelope. The material or the nature of the double-skin has to be decided with care because even though the use of two glass layers would decrease the U-value of the envelope, it will also involve a lot of radiation and convective heat transfer through the glass which would get trapped within the cavity.

From the simulations it can be seen that,

i) The first strategy with single glazing both on the outer and inner skin is not very energy efficient as its cooling energy consumption is only slightly less (4-8%) than the existing conventional single skin. Within the various proposed alternatives, the option with the north façade as the glazed double-skin and the other faces same as the base case, seems the only feasible solution. Keeping all four facades as glazed double skins can be clearly regarded as a bad solution as the cooling energy is almost 30% higher than the base case.

ii) The second strategy with inner layer as a double-glazed unit and outer layer as single glazed layer can be seen to be definitely more energy efficient than the first strategy and the base case. However, the difference in cooling energy consumed (4-10%) is again not very large and may not be an entirely viable solution. The energy consumption of the option with all four facades as double-skin is about 8% higher than the base case.

iii) The third strategy which uses a combination of a brick layered façade and double-skin glazed openings shows a notable difference in the cooling energy consumption, making this one of the most energy efficient strategies. The energy efficiency further varies with the type of double-skin glazing and the transparency of each façade. The overall cooling energy is about 13-28% less than the base case.

This also leads to the possibility of using other materials that are locally available or manufactured to reduce transportation and other costs of materials which may otherwise have to be imported from elsewhere.

Therefore, it can be concluded that using a layered façade which is a combination of transparent and opaque materials is a much more energy efficient design strategy than a typical all transparent double-skin and the conventional single skin façade in hot climates. The opaque layering with cavity improves the insulating value of the envelope which reduces solar heat gain and the transparent double-skin vents out the trapped heat and also provides benefits from daylighting.

Fig. 88 describes the order of efficiency (1 being the most efficient) of each type of façade strategy and Table 19 is a tabular expression of the same.

5.1.2 Effect of Transparency of the Facade

It is accepted that variation in transparency of the facades affects the energy loads in buildings. This is because the heat transmitted through glass increases the cooling needs and therefore the energy consumption. Therefore, it is extremely important to design the amount of transparency on each façade especially in relation to the orientation of the façade. The amount of heat gain through glass can be further reduced by using various types of shading devices.

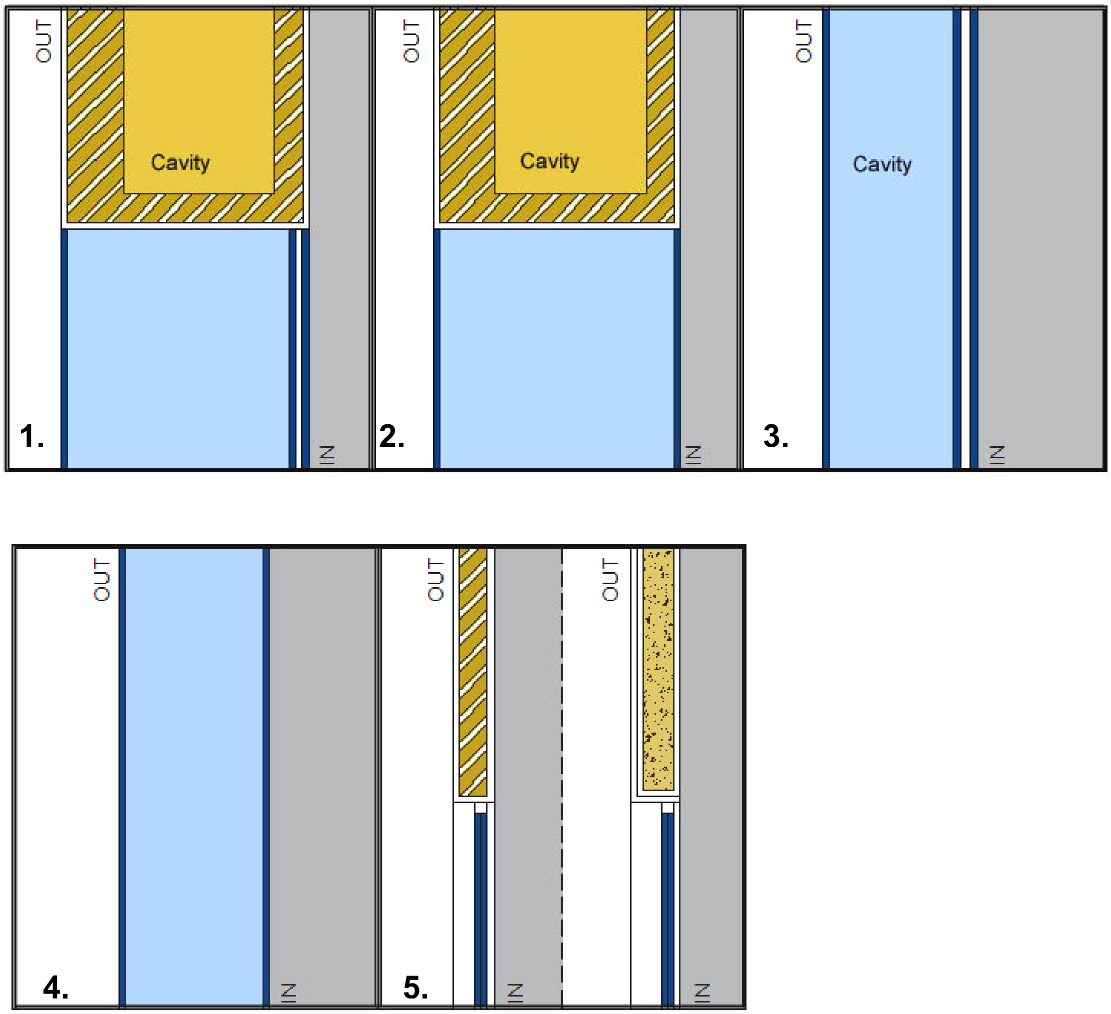


Fig. 88. Efficiency of Each Type of Façade Based on the Layers Constituting the Facade

Table 19
Efficiency of Each Strategy Based upon the Layers of the Facade

Layering	Efficiency
9" Brick Layer+cavity+41/2" Brick with DSF 2	1
9" Brick Layer+cavity+41/2" Brick with DSF 1	2
Double-skin façade(DSF 2)	3
Double-skin façade(DSF 1)	4
Base Case(exisiting building)	5

From the simulations it can be seen that in terms of efficiency, having the least transparency on the southern façade and maximum transparency on the northern façade, with the east and west facades having equal transparency (about half that of the north façade) is a good solution. Fig. 89 gives a diagrammatic representation of the efficiency of each type of strategy in terms of transparency of the façade. Table 20 presents the inference in a numerical format.

Table 20
Efficiency of Each Strategy Based on the Transparency of the Facade

Transparency(%)	**Efficiency**
N=70; S=25; E=40; W=40	1
N=80; S=25; E=50; W=50	2
N=100; S=W=E=existing	3
E=100; N=W=E=existing	4
W=100; N=S=E=existing	5
S=100; N=W=E=existing	6
Base Case	7
N=100; S=100; E=100; W=100	8

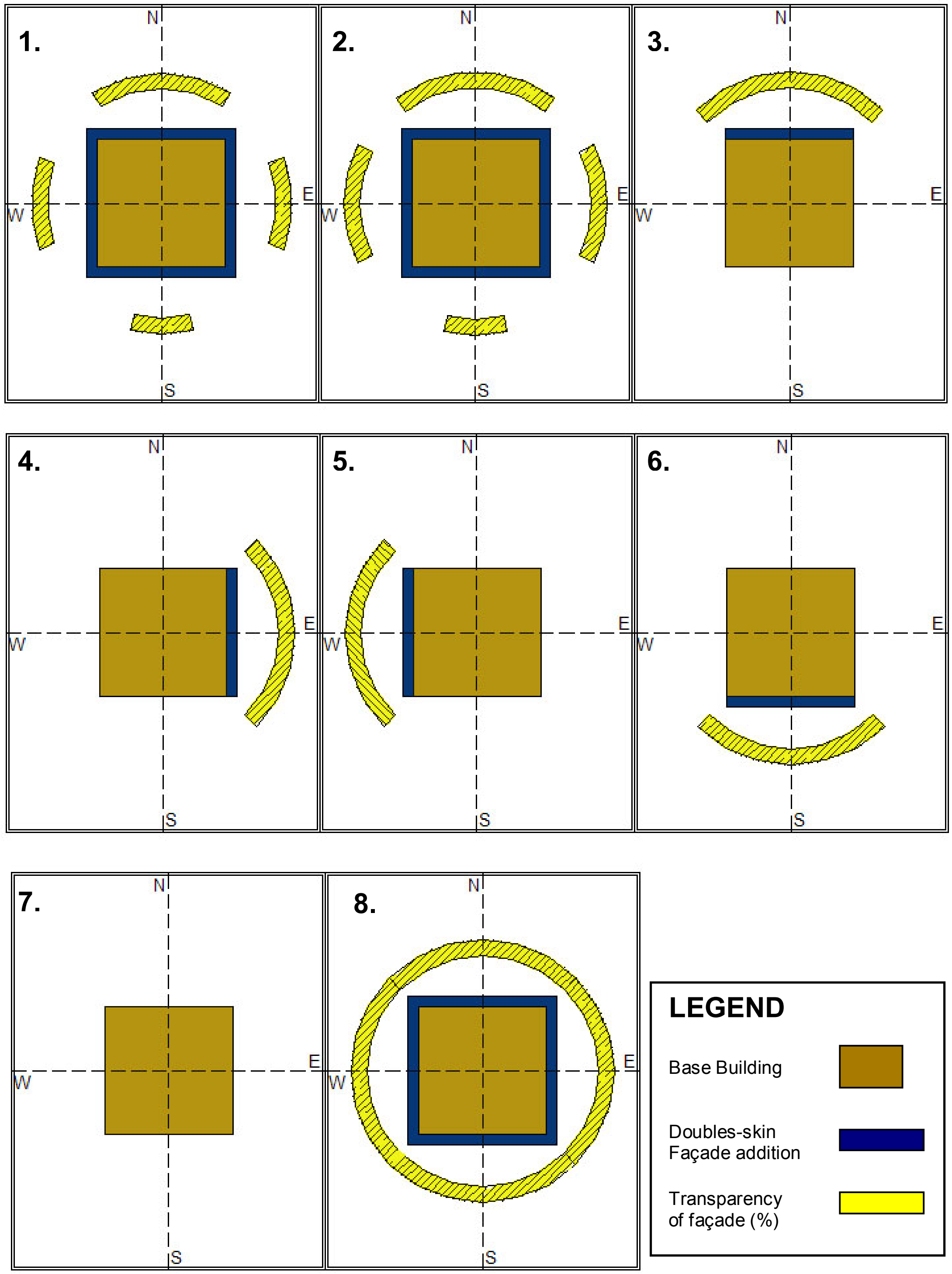


Fig. 89. Effect of Transparency of the Façade as per Orientation, on the Efficiency of the Building

5.1.3 Effect of Orientation

The performance of a building is affected by the type of façade along each orientation of the building. The simulations show how changes along each orientation affect the energy performance. These runs are specifically beneficial if one wants to cut down on the energy costs with minimal damage to the original structure. By knowing the behavior of a façade along each orientation, one can decide on which façade to alter to achieve the maximum benefit.

From the simulations, it can be seen that changing the north façade alone to a double-skin is more efficient than changing the facades on other orientations. This is shown in the Table 21 below. Fig. 90 explains the order of efficiency for each strategy based on the orientation of the double-skin façade.

Table 21
Efficiency of the Building as per Orientation of the Double-Skin

Orientation of double-skin façade	**Efficiency**
North	1
East	2
West	3
South	4
Base Case	5

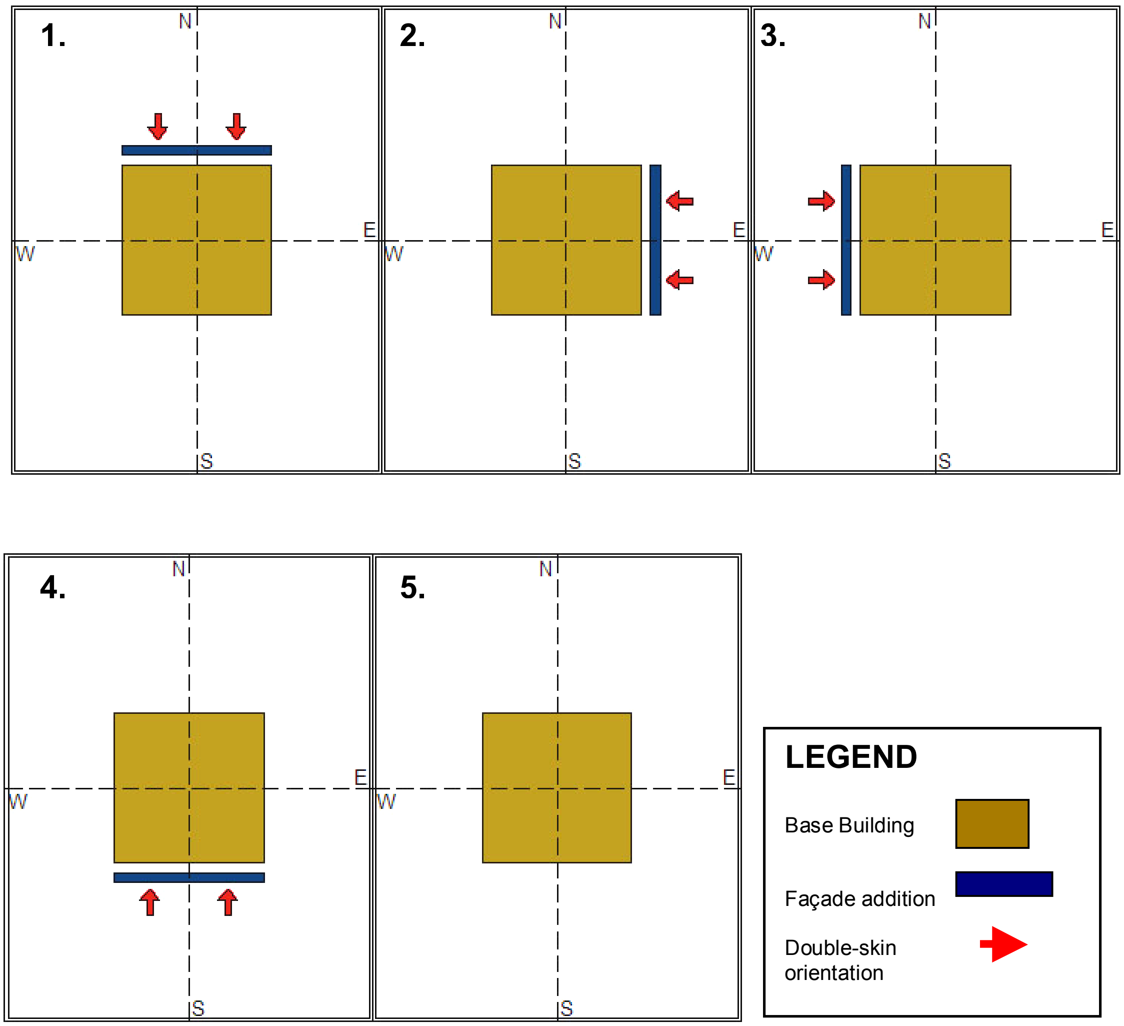


Fig. 90. Effect of Orientation of the Double-Skin on the Efficiency of the Building

5.1.4 Effect of Shading on the Energy Performance of the Buildings

It was seen that there was a reduction of almost 2-5% in the cooling energy consumption with the introduction of shading devices to the double-skin, where it was 100% transparent. The façade on the north with the double skin and horizontal overhangs for shading (1N_S and 4N_S) were more efficient than the same facades with no shading devices. A notable reduction in cooling energy was found in double-skin facades oriented to the south; with shading the cooling energy was reduced by almost 7% which was less than the base case in one case. This could be attributed to the extra shading devices (vertical and overhangs) used for this façade unlike the other orientations.

This study used shading values to study the affect of shading on the performance of double-skin, and found a notable improvement. If the shading devices are appropriately designed with exact values the performance may vary. But as a conclusion, it can be inferred that an appropriately shaded double-skin would lead to a reduction in the energy consumption of the building.

5.2 Effect of Double-Skin Façade on Lighting Loads and Cooling Loads

The breakdown of energy consumption shows a reduction in the energy needed for lighting for the proposed double-skin strategies than the base case. This is because the option for using daylighting was turned on and ample daylight would be available because of the glazed double-skin. However, there is a trade-off between the cooling and lighting loads when comparing the various strategies because in order to reduce cooling loads, one needs to reduce the transparent areas which would then cause the lighting loads to increase as there would be reduced daylighting.

Therefore from the simulations it can be seen that, that the break-up of the peak and annual cooling loads shows that in strategies with more transparency the lighting load is less but the load due to window solar and transmission are more and consequently the cooling loads are also higher. On the other hand, the lighting load is higher for strategies with less transparency but their cooling loads are lesser (Fig. 91).

Since, the amount of energy required for cooling is much higher than the amount of energy for lighting, the strategies showing lesser cooling loads gain predominance over the strategies that show less lighting loads.

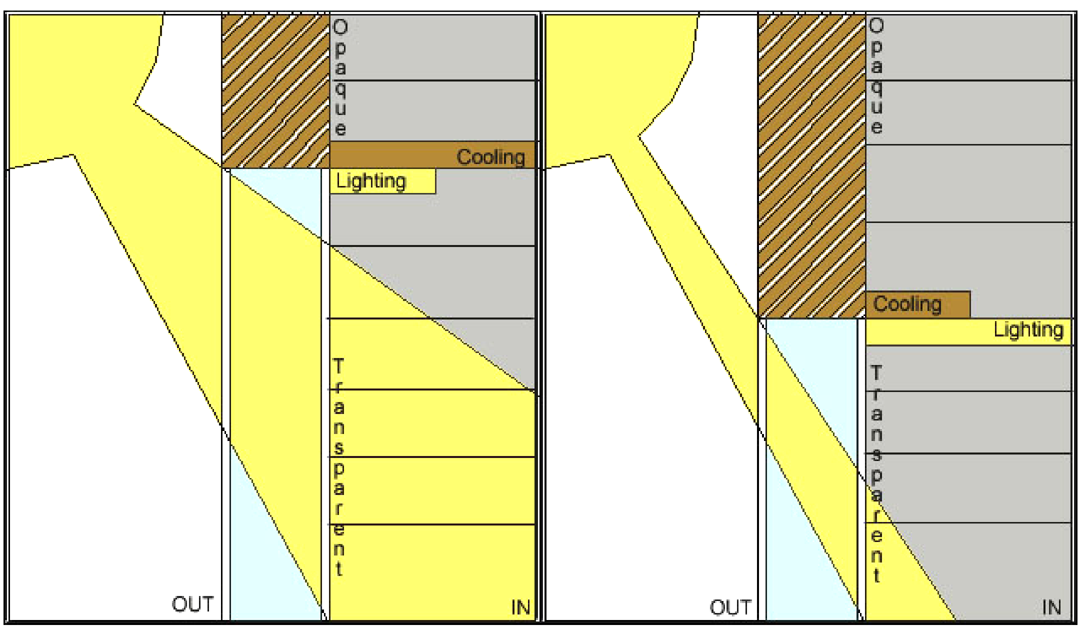


Fig. 91. Variation of Cooling and Lighting Loads Based on Transparency and Opaqueness of Façade. Strategies with lesser cooling load gain predominance over strategies with lesser lighting load, because energy consumed for cooling is much higher than that consumed by lighting.

5.3 Design Guidelines

A number of factors and issues influence the functioning of a double-skin façade. Through this thesis some basic and key issues were identified that influenced the efficiency of the double-skin. There may be a number of other issues which may arise depending on the specific context of the design but were beyond the scope of this investigation.

5.3.1 Goals for Design of Façade

In order to design a façade that is energy efficient and most appropriate for a given context, one first needs to establish a framework of goals that the façade needs to achieve. These goals would then help generate a sequence of design ideas that can be followed to achieve them. These are broad guidelines which may have to be tailored to specific situations. The primary goals of the façade in a hot climate can be identified as:

a) Solar Heat Gain Reduction: Design the façade is such a way that there is minimum solar heat gain through the façade as explained in Fig. 92. Minimize this heat gain by appropriate use of material in the correct proportion according to the orientation of the façade. This would cut down the cooling loads and cooling energy requirement.

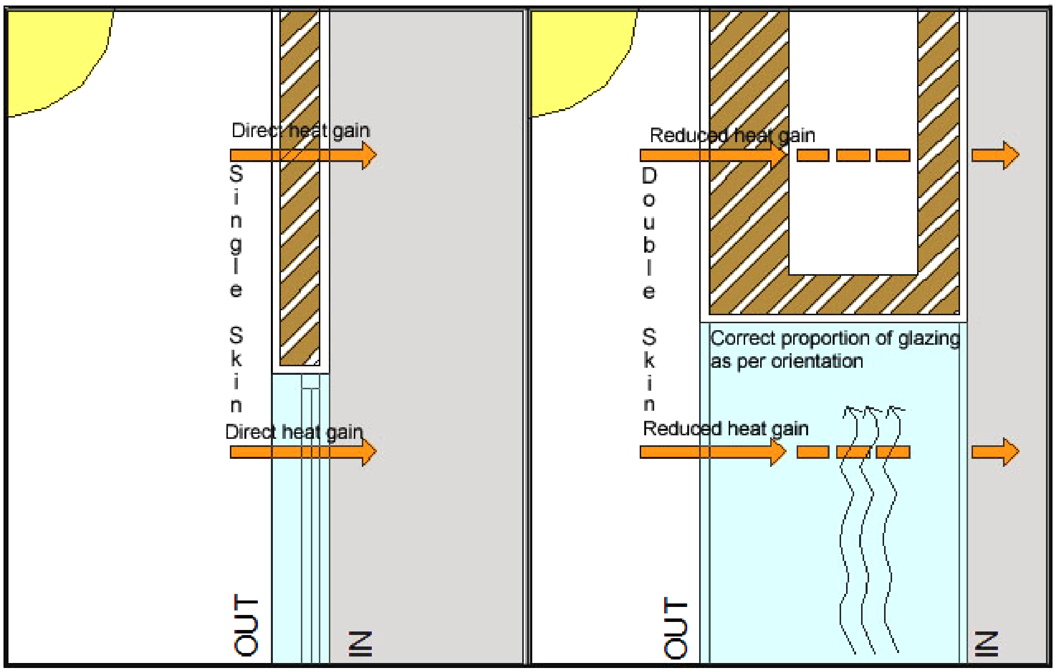


Fig. 92. Goal of the Façade: Solar Heat Gain Reduction
Reduce heat gain by using double layer of a combination of glass and other materials in correct proportion as per the orientation of the facade

b) Daylighting: Design the façade in a way to utilize daylighting, so that lighting loads due to artificial loads can be reduced. Sufficient shading devices need to be incorporated to avoid excessive heat gain and glare. A balance between daylighting and heat-gain needs to be achieved.

c) Ventilation: Design the façade to allow for ventilation for the following conditions as explained in Fig. 93.

    i) During certain periods of time when the outside air temperature is at a comfortable level (as per the standard of the people using the space) and can be allowed inside the space.

ii) During summer time, allow ventilation through the cavity of the glass façade to remove the trapped heat. This thesis tested this option only.

iii) During night time, facilitate ventilation to happen from within the building to the outside to dissipate heat that has been absorbed by the building through the day. This would bring down the building temperatures considerably and reduce the energy needed to cool the space next day morning.

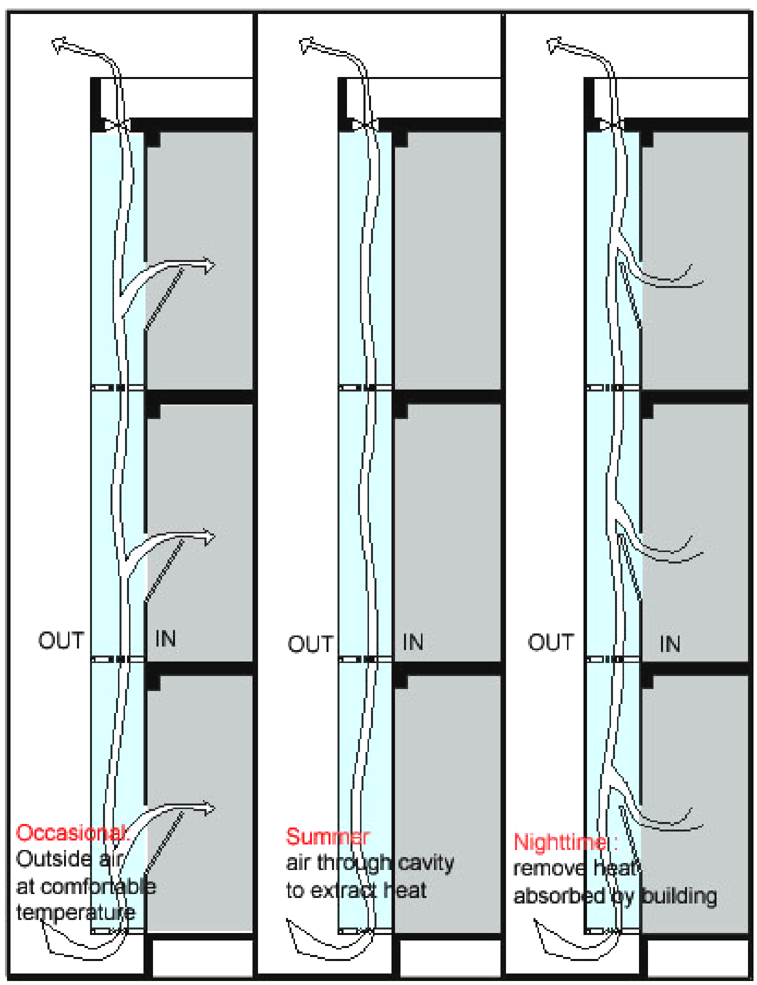


Fig. 93. Goal of the Façade: Provide Ventilation through the Cavity as per Specific Conditions

5.3.2 Design Parameters

The key factors contributing to the above mentioned design goals, which in turn would affect the efficiency of the façade, have been identified to be:

5.3.2.1 Materials

a) Type: In the Indian context of this study, the common construction materials include brick, concrete blocks and stone. Alternate materials are also being used like hollow concrete blocks and bricks made of fly-ash. Use the material with a high resistance (R-value) so that there is minimum heat gain (Fig. 94). But this should not be at the expense of using vast amount of energy to acquire these materials.

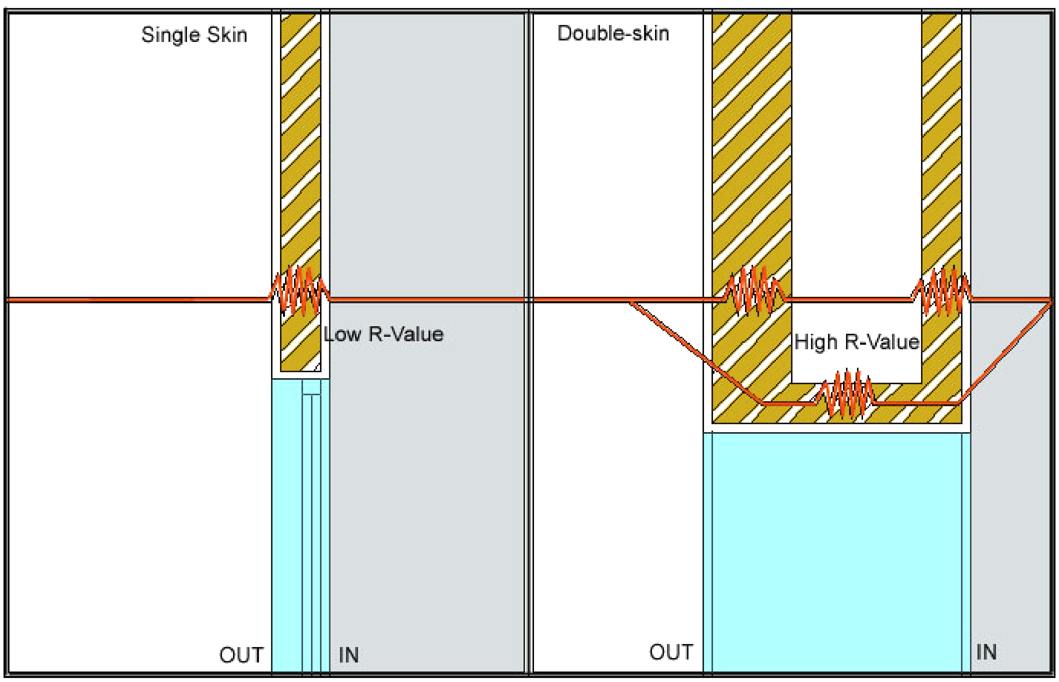


Fig. 94. Design Guideline: Comparison of Resistance of Single and Double-Skin.
Use materials with high R-value in two layers to increase overall resistance of the wall section, bringing down the U-Value.

b) Glazing Material: In terms of glazing, more than the type of glass that is used in the façade, it is crucial to determine how much of it is used, along which façade it is used and whether it is appropriately shaded. This is because using the locally manufactured glass in two layers (double-skin) for the glazed areas in a façade (Fig. 95) may be more cost effective than using a highly advanced glazing technology that may have to be imported.

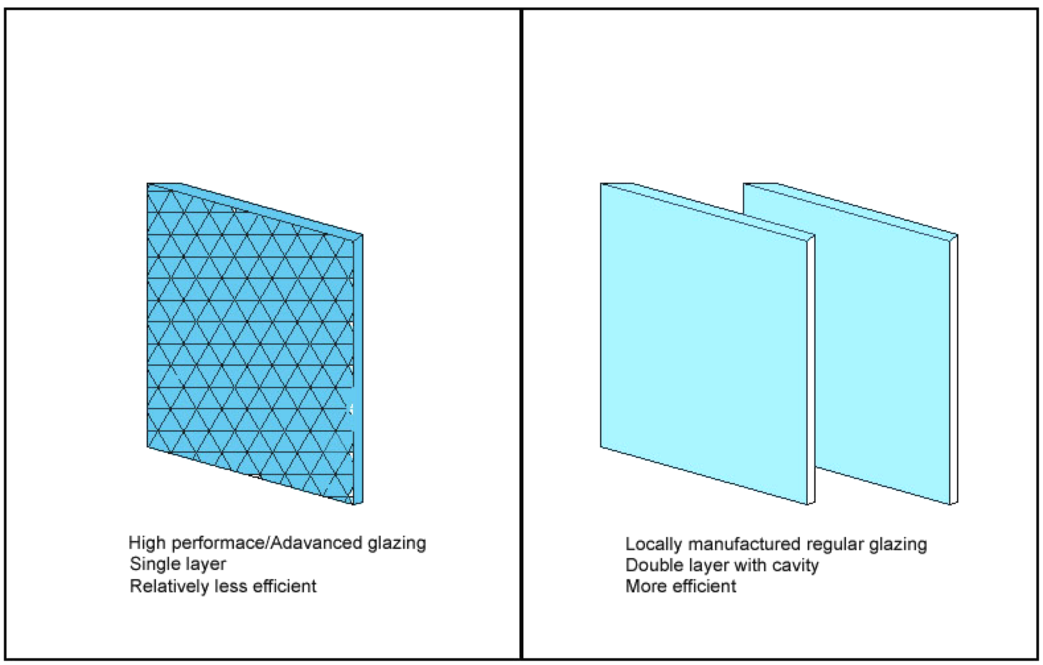


Fig. 95. Design Guideline: Choose Glazing Material Carefully
Using glazing in appropriate proportion and orientation in two layers than using highly advanced glazing that may have to be imported in single layer

5.3.2.2 Physical Design

a) Nature of Layers: The two layers should not be completely transparent on any of the facades except the one oriented to north, if desired (Fig. 96). This should also be avoided if possible unless aesthetics or any other reason gains priority to have a completely transparent façade. Both the opaque layers may be of the same thickness or for better insulating effect, the outer layer can be thicker than the inner layer (as in the case of Strategy Three).

b) Dimensions: The width of the cavity between the two layers may be decided based on available space and also space required for maintenance of the cavity (Fig. 96). This is because the U-value of the air space is almost constant after 8" of thickness. Hence, the width of the cavity is flexible as long as it facilitates ventilation of trapped air. Some case studies had shown the cavity to include plants and vegetation to cool the air in the cavity. A quantitative analysis of how much insulating effect these plants would have is difficult to simulate.

c) Nature of the Cavity: The cavity space between the two layers of glazing can be continuous for low-rise structures (Fig. 97). It can be partitioned horizontally at each floor level to allow easy movement of air within each floor for taller buildings.

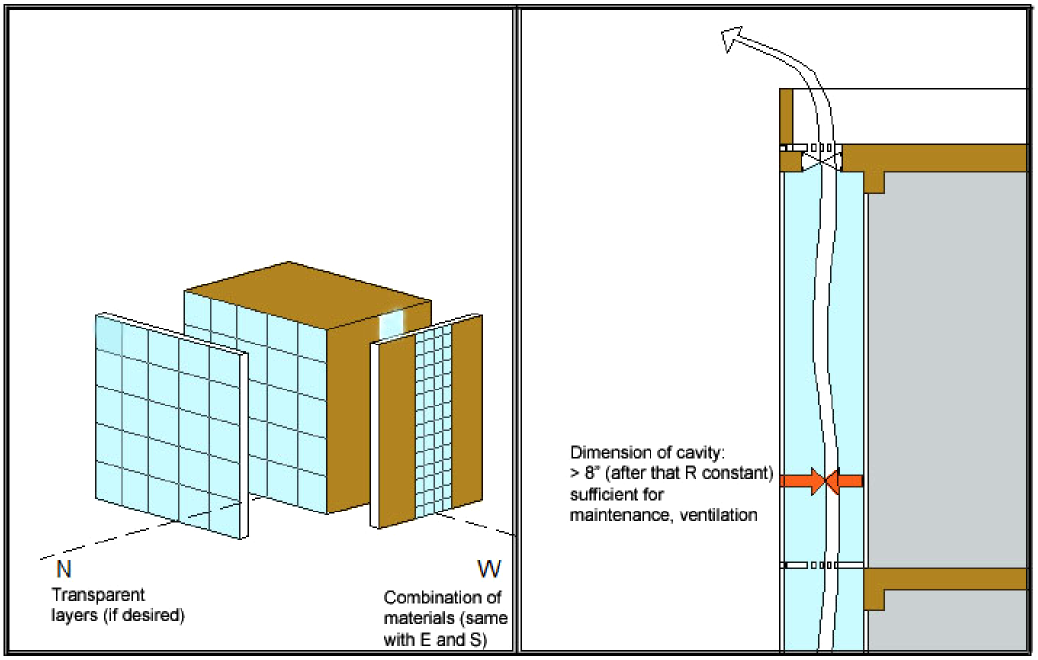


Fig. 96. Design Guideline: Never 100% Transparency, If at All with Shading Devices
Dimension of cavity should be sufficient for maintenance and ventilation

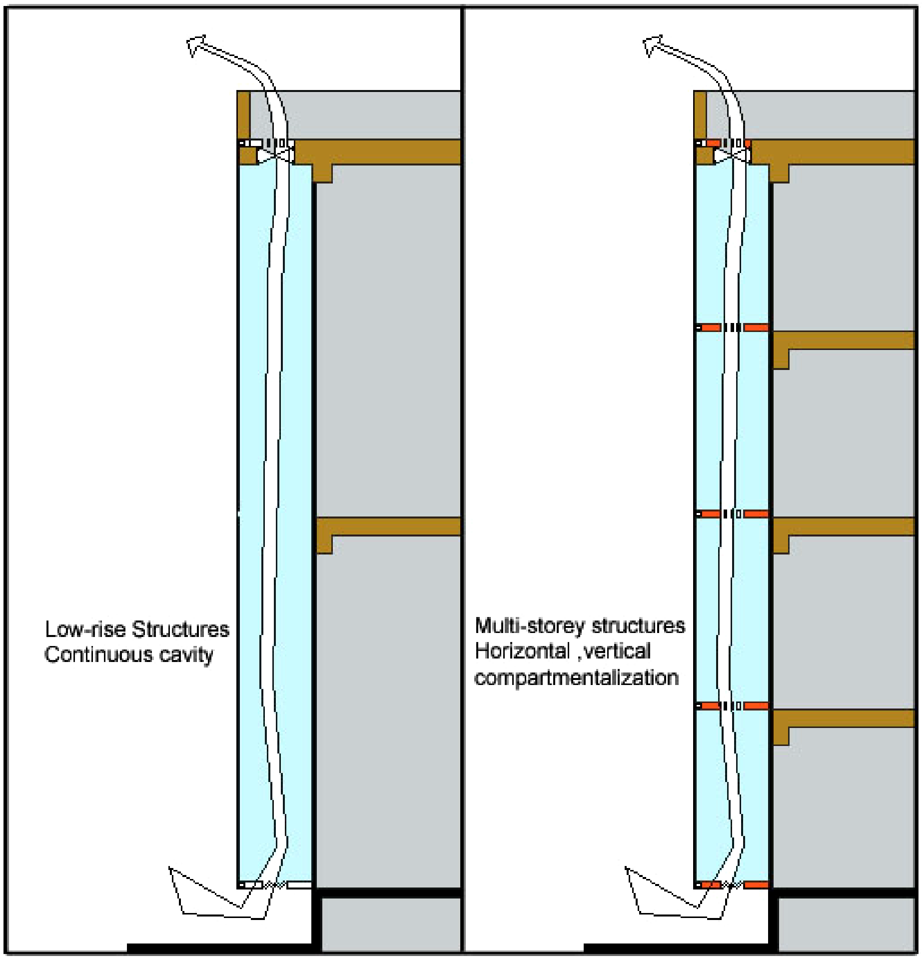


Fig. 97. Design Guideline: Compartmentalization of Façade Based on Low or High-Rise Structures

d) U-value: The overall U-value of the façade should be reduced as much as possible for maximum benefit. From the simulations, it was seen that a U-value of 0.19 Btu/h ft^2 F was more efficient than the existing base case façade's U-value of 0.3-0.68 Btu/h ft^2 F. The U-factor of the glazed double-skin varies between 0.5 -1.2 Btu/h ft^2 F, which may get further reduced depending on the type of glass used and shading devices within the cavity (Fig. 98). Therefore, design the facade to keep the U-value as low as possible of both the opaque and the glazed portion of the façade.

e) SHGC: The solar heat gain coefficient of the glazed double skin is based on the type of glass used on both the inside and the outside as it is the product of the two layers. The lesser the solar heat gain coefficient, the more efficient the façade. Thus, the choice of glazing should be made based on this solar heat gain coefficient.

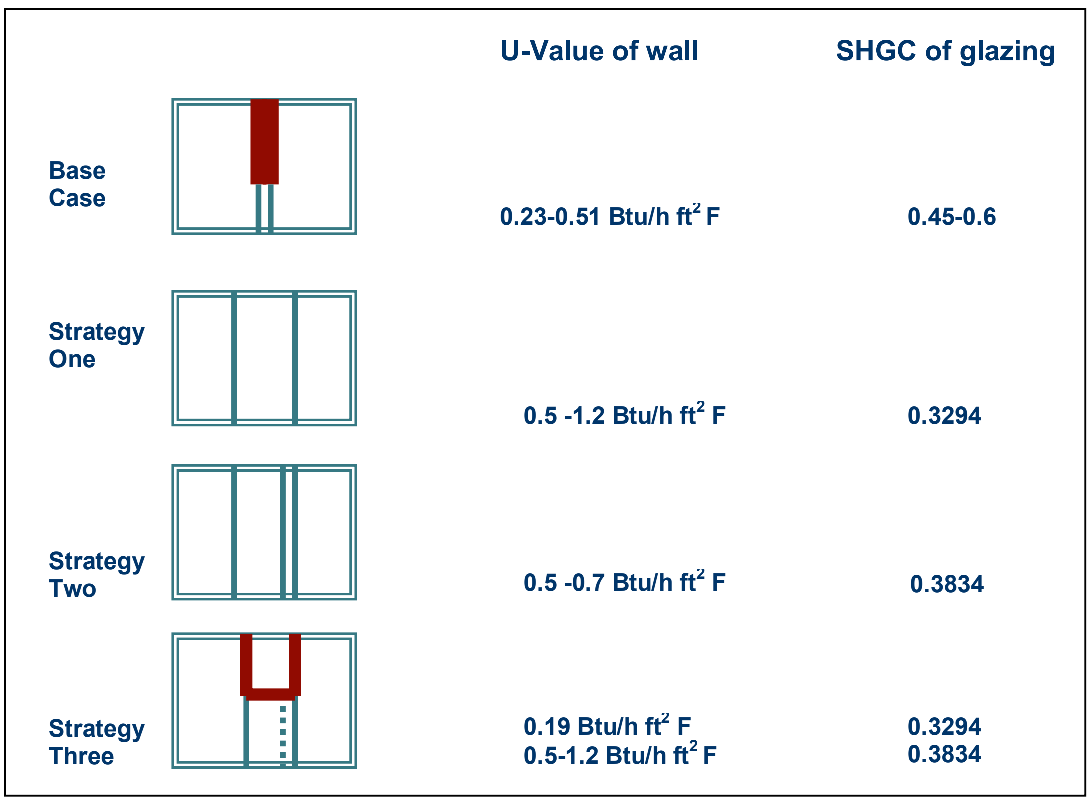


Fig. 98. Comparison of U-Values and SHGC of the Different Strategies

f) Transparency and Shading: Design façade in such a way that maximum transparency is on the north façade and minimum transparency is on the south side. The east and west façade can have about half the transparency on the north side. One needs to provide some horizontal shading devices on the north and south side and vertical shading devices on the east and west facades to block off direct sun and excessive glare. Fig. 99 gives a schematic diagram of the same.

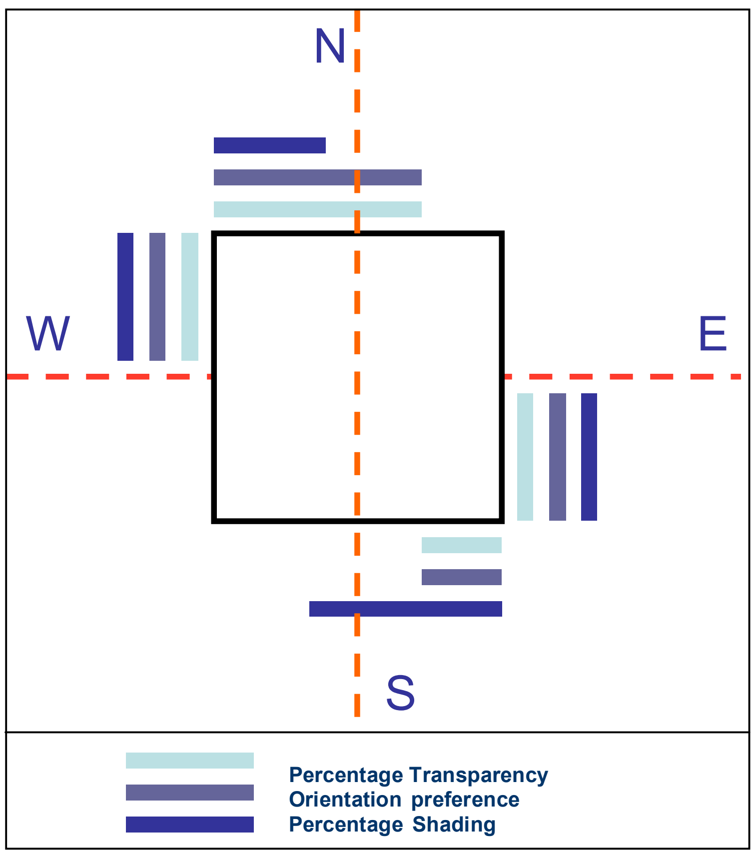


Fig. 99. Design Guideline for Transparency, Orientation and Shading of the Double-Skin Facade

g) Orientation: The performance of the building can be notably altered by treating a specific façade of the building (Fig. 99). The following can serve as a guideline:

   i) North façade: The north façade can have maximum transparency and making it an all glass double-skin façade is more efficient than having a single skin on that particular façade. Though, the difference does not seem very large but with the use of additional shading devices, the solar heat gain can be further reduced. Hence, the northern façade is the most preferred orientation for a double skin.

   ii) South façade: It is not a preferred orientation for a glazed double skin. The south façade should be designed with minimum transparency and should be essentially an opaque layered wall. This would increase the thermal mass of the building and the air gap between the layers will have an insulating effect on the building. The overall heat gain and direct sun through the south side should be reduced.

   iii) East: The east façade also cannot be a completely transparent double skin facade because of the intense direct sunlight which it receives especially during the morning hours. It can consist of alternate shafts of opaque and transparent double-skins, with the percentage of glazing being about 40-50% of the wall area. This glazing also needs to incorporate some shading devices to cut off the direct sunlight from entering the spaces.

   iv) West: The west façade cannot be a completely transparent double skin facade because of the intense direct sunlight which it receives especially during afternoon and evening. It can be designed similar to the east façade with alternate shafts of opaque and transparent double-skins. However, the orientation of the shading devices would be exactly opposite to those on the east façade.

5.4 Summary

The evaluation of the double-skin façade for office buildings in hot climates (represented by the two Indian cities New Delhi and Hyderabad), showed that a typical façade defined as 'a pair of glass skins separated by an air corridor' is not an entirely energy efficient strategy. However, it proves to be an energy efficient strategy when used in combination with other opaque materials, in the right proportion and along the appropriate orientation as displayed by the design Strategy Three.

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APPENDIX A

INPUT AND OUTPUT TABLES FOR SIMULATIONS

Table A- 1
Input Values Used in Ener-Win Simulation for Strategy One for Hyderabad

File name	Facades	wall name	Wall id	U-value	Window des.	Win id	Transparency	Shading	Daylighting
hydbase_A	N	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		n
	E	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	W	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	S	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		
hydalt_1N.inp	N	HYD-dsfcurtain	S	1.243	dsf-curtain	9	100%		y
			W	0.59	dsf-curtain	10	100%		
	E	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	W	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	S	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		
hydalt_1E.inp	N	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		y
	E	HYD-dsfcurtain	S	1.243	dsf-curtain	9	100%		
			W	0.59	dsf-curtain	10	100%		
	W	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	S	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		
hydalt_1S.inp	N	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		y
	E	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	W	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	S	HYD-dsfcurtain	S	1.243	dsf-curtain	9	100%		
			W	0.59	dsf-curtain	10	100%		
hydalt_1W.inp	N	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		y
	E	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	W	HYD-dsfcurtain	S	1.243	dsf-curtain	9	100%		
			W	0.59	dsf-curtain	10	100%		
	S	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		
hydalt_1all.inp	N	HYD-dsfcurtain	S	1.243	dsf-curtain	9	100%		y
			W	0.59	dsf-curtain	10	100%		
	E	HYD-dsfcurtain	S	1.243	dsf-curtain	9	100%		
			W	0.59	dsf-curtain	10	100%		
	W	HYD-dsfcurtain	S	1.243	dsf-curtain	9	100%		
			W	0.59	dsf-curtain	10	100%		
	S	HYD-dsfcurtain	S	1.243	dsf-curtain	9	100%		
			W	0.59	dsf-curtain	10	100%		
hydalt_1N_S.inp	N	HYD-dsfcurtain	S	1.243	dsf-curtain	9	100%	N0.N0.T.1	y
			W	0.59	dsf-curtain	10	100%	N0.N0.T.1	
	E	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	W	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	S	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		
hydalt_1E_S.inp	N	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		y
	E	HYD-dsfcurtain	S	1.243	dsf-curtain	9	100%	R.2 L.2 N0.	
			W	0.59	dsf-curtain	10	100%	R.2 L.2 N0.	
	W	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	S	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		
hydalt_1S_S.inp	N	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		y
	E	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	W	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	S	HYD-dsfcurtain	S	1.243	dsf-curtain	9	100%	R.2 L.2 T.1	
			W	0.59	dsf-curtain	10	100%	R.2 L.2 T.1	
hydalt_1W_S.inp	N	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		y
	E	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	W	HYD-dsfcurtain	S	1.243	dsf-curtain	9	100%	R.2 L.2 N0.	
			W	0.59	dsf-curtain	10	100%	R.2 L.2 N0.	
	S	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		
hydalt_1all_S.inp	N	HYD-dsfcurtain	S	1.243	dsf-curtain	9	100%	N0.N0.T.1	y
			W	0.59	dsf-curtain	10	100%	N0.N0.T.1	
	E	HYD-dsfcurtain	S	1.243	dsf-curtain	9	100%	R.2 L.2 N0.	
			W	0.59	dsf-curtain	10	100%	R.2 L.2 N0.	
	W	HYD-dsfcurtain	S	1.243	dsf-curtain	9	100%	R.2 L.2 N0.	
			W	0.59	dsf-curtain	10	100%	R.2 L.2 N0.	
	S	HYD-dsfcurtain	S	1.243	dsf-curtain	9	100%	R.2 L.2 T.1	
			W	0.59	dsf-curtain	10	100%	R.2 L.2 T.1	

Table A- 2
Input Values for Ener-win Simulation for Strategy Two for Hyderabad

File name	Facades	Wall name	Wall id	U-value	Window des.	Win id	Transparency	Shading	Daylighting
hydbase_A	N	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		n
	E	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	W	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	S	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		
hydalt_4N.inp	N	HYD-dsfcurtain	S	0.704	dsf-curtain	17	100%		y
			W	0.57	dsf-curtain	18	100%		
	E	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	W	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	S	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		
hydalt_4E.inp	N	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		y
	E	HYD-dsfcurtain	S	0.704	dsf-curtain	17	100%		
			W	0.57	dsf-curtain	18	100%		
	W	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	S	HYDBASE-B	6	0.45	1/4"gray tint plate	3	as/existing		
hydalt_4S.inp	N	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		y
	E	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	W	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	S	HYD-dsfcurtain	S	0.704	dsf-curtain	17	100%		
			W	0.57	dsf-curtain	18	100%		
hydalt_4W.inp	N	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		y
	E	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	W	HYD-dsfcurtain	S	0.704	dsf-curtain	17	100%		
			W	0.57	dsf-curtain	18	100%		
	S	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		
hydalt_4all.inp	N	HYD-dsfcurtain	S	0.704	dsf-curtain	17	100%		y
			W	0.57	dsf-curtain	18	100%		
	E	HYD-dsfcurtain	S	0.704	dsf-curtain	17	100%		
			W	0.57	dsf-curtain	18	100%		
	W	HYD-dsfcurtain	S	0.704	dsf-curtain	17	100%		
			W	0.57	dsf-curtain	18	100%		
	S	HYD-dsfcurtain	S	0.704	dsf-curtain	17	100%		
			W	0.57	dsf-curtain	18	100%		
hydalt_4N_S.in	N	HYD-dsfcurtain	S	0.704	dsf-curtain	17	100%	N0.N0.T.1	y
			W	0.57	dsf-curtain	18	100%	N0.N0.T.1	
	E	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	W	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	S	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		
hydalt_4E_S.in	N	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		y
	E	HYD-dsfcurtain	S	0.704	dsf-curtain	17	100%	R.2 L.2 N0.	
			W	0.57	dsf-curtain	18	100%	R.2 L.2 N0.	
	W	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	S	HYDBASE-B	6	0.45	1/4"gray tint plate	3	as/existing		
hydalt_4S_S.in	N	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		y
	E	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	W	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	S	HYD-dsfcurtain	S	0.704	dsf-curtain	17	100%	R.2 L.2 T.1	
			W	0.57	dsf-curtain	18	100%	R.2 L.2 T.1	
hydalt_4W_S.in	N	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		y
	E	HYDBASE-A	6	0.23	1/4"gray tint plate	3	as/existing		
	W	HYD-dsfcurtain	S	0.704	dsf-curtain	17	100%	R.2 L.2 N0.	
			W	0.57	dsf-curtain	18	100%	R.2 L.2 N0.	
	S	HYDBASE-B	10	0.45	1/4"gray tint plate	3	as/existing		
hydalt_4all_S.in	N	HYD-dsfcurtain	S	0.704	dsf-curtain	17	100%	N0.N0.T.1	y
			W	0.57	dsf-curtain	18	100%	N0.N0.T.1	
	E	HYD-dsfcurtain	S	0.704	dsf-curtain	17	100%	R.2 L.2 N0.	
			W	0.57	dsf-curtain	18	100%	R.2 L.2 N0.	
	W	HYD-dsfcurtain	S	0.704	dsf-curtain	17	100%	R.2 L.2 N0.	
			W	0.57	dsf-curtain	18	100%	R.2 L.2 N0.	
	S	HYD-dsfcurtain	S	0.704	dsf-curtain	17	100%	R.2 L.2 T.1	
			W	0.57	dsf-curtain	18	100%	R.2 L.2 T.1	

Table A- 3
Input Values for Ener-Win Simulation for Strategy Three for Hyderabad

File name	Facades	Wall name	Wall id	U-value	Window design	Window desc.	Win id	Transparency	Daylighting
hydalt2_a.inp	N	HYD-cavitybk	22	0.19	dsf-alt 1	alt1-summer	9	80	y
						alt1-winter	10		
	E	HYD-cavitybk	22	0.19	dsf-alt 1	alt1-summer	9	50	
						alt1-winter	10		
	W	HYD-cavitybk	22	0.19	dsf-alt 1	alt1-summer	9	50	
						alt1-winter	10		
	S	HYD-cavitybk	22	0.19	dsf-alt 1	alt1-summer	9	25	
						alt1-winter	10		
hydalt2_b.inp	N	HYD-cavitybk	22	0.19	dsf-alt 1	alt1-summer	9	70	y
						alt1-winter	10		
	E	HYD-cavitybk	22	0.19	dsf-alt 1	alt1-summer	9	40	
						alt1-winter	10		
	W	HYD-cavitybk	22	0.19	dsf-alt 1	alt1-summer	9	40	
						alt1-winter	10		
	S	HYD-cavitybk	22	0.19	dsf-alt 1	alt1-summer	9	25	
						alt1-winter	10		
hydalt2_c.inp	N	HYD-cavitybk	22	0.19	dsf-alt 2	alt4-summer	17	80	y
						alt4-winter	18		
	E	HYD-cavitybk	22	0.19	dsf-alt 2	alt4-summer	17	50	
						alt4-winter	18		
	W	HYD-cavitybk	22	0.19	dsf-alt 2	alt4-summer	17	50	
						alt4-winter	18		
	S	HYD-cavitybk	22	0.19	dsf-alt 2	alt4-summer	17	25	
						alt4-winter	18		

Table A- 4
Output Values Obtained after Ener-Win Simulation for all the Strategies

		PEAK COOLING LOADS (KWH)					ANNUAL COOLING LOADS (MBTU)					BREAKDOWN OF ENERGY CONSUMPTION (MBTU)	
	Total Cooling Energy (Mbtu)	Total peak cooling (Kwh)	Walls	Window trans	Window solar	Lights/equipment	Total annual cooling (Mbtu)	Walls	Window trans	Window solar	Lights/equipment	Space cooling	Lighting (Mbtu)
0	841.1	857	61.39	147.92	311.42	212.65	1764.8	159.43	141.66	447.14	569.61	841	462
1N	788.5	826.6	51.93	177.03	334.42	132.26	1644.58	140.94	173.93	479.31	395.36	788	284
1E	958.8	945	58.5	262.04	386.44	121.33	1993.08	129.14	246.07	751.51	379.35	958	263
1S	873.9	866.6	49.38	228.21	367.81	131.89	1824.29	106.46	209.5	636.98	399.57	873	285
1W	1002.5	1043.5	64.35	270.78	627.83	125.02	2048.56	128.44	254.04	818.25	385.02	1002	268
1all	1373.8	1350.9	8.9	471.29	702.15	122.57	2823.29	30.58	456.21	1434.38	387.96	1373	262
4N	753.7	783.7	50.92	154.16	318.14	125.48	1566.77	138.71	150.78	452.7	379.37	753	269
4E	883.8	858.7	44.98	179.06	344.55	122.72	1846.09	128.73	182.78	674.06	382.58	883	267
4S	829.3	823.5	50.08	196.94	367.67	125.64	1735.44	106.67	179.67	598.84	379.31	829	266
4W	914.5	929.6	63.83	199.91	535.13	125.13	1884.9	127.99	187.38	722.93	385.9	914	270
4all	1145.9	1075.4	9.4	275.99	593.68	122.96	2381.88	31.45	271.11	1188.22	388.4	1145	266
2a	715.3	790	34.79	225.1	198.82	87.21	1521.75	105.7	202.15	361.35	410.61	715	302
2b	665.6	733.4	42.34	173.87	204.03	145.19	1432.41	117.29	163.66	292.65	424.49	665	317
2c	603.6	648.6	42.84	101.94	172.81	150.24	1322.52	115.83	97.26	245.81	433.26	603	328
1N_S	771.4	813.5	52.21	185.58	251.81	77.02	1609.54	140.5	170.99	448.94	395.35	771	285
1E_S	877.2	903.5	57.48	259.3	357.28	124.61	1815.89	127.5	234.65	591.76	382.34	877	270
1S_S	812.1	833	50.07	225.5	351.95	129.94	1694.34	106.59	201.07	526.41	391.48	812	280
1W_S	920	998.9	63.92	266.96	593.81	125.02	1874.27	127.63	241.34	660.94	387.9	920	273
1all_S	1131.2	1225.6	9.58	461.35	615.66	126.14	2302.92	28.33	422.22	959.31	393.46	1131	277
4N_S	739.9	773.3	52	160.54	243.2	74.17	1548.14	138.65	149.06	427.1	379.37	739	270
4E_S	817.1	823.9	58.52	194.04	355.42	127.38	1700.69	127.4	175.77	541.16	385.94	817	274
4S_S	780.7	797.9	43.99	186.86	243.39	72.27	1633.54	106.18	174.79	507.01	378.21	780	268
4W_S	845.4	893.6	64.4	197.63	505.97	125.32	1739.01	126.65	179.4	587.92	389.07	845	276
4all_S	947.3	972.6	9.47	270.15	520.42	127.08	1953.97	29.03	250.05	792.3	395.08	947	281

Table A- 5
Input Values for Ener-Win Simulation for Strategy One for Delhi

File name	Facades	Wall name	Wall id	U-value	Window des.	Win id	Transparency	Shading	Daylighting
delhibase_1.inp	N	delhibase	23	0.51	1"double plate gray	5	as/existing		n
	E	delhibase	23	0.51	1"double plate gray	5	as/existing		
	W	delhibase	23	0.51	1"double plate gray	5	as/existing		
	S	delhibase	23	0.51	1"double plate gray	5	as/existing		
delhialt_1N.inp	N	HYD-dsfcurtain	S	1.243	dsf-curtain	9	100%		y
			W	0.59	dsf-curtain	10	100%		
	E	delhibase	23	0.51	1"double plate gray	3	as/existing		
	W	delhibase	23	0.51	1"double plate gray	3	as/existing		
	S	delhibase	23	0.51	1"double plate gray	3	as/existing		
delhialt_1E.inp	N	delhibase	23	0.51	1"double plate gray	3	as/existing		y
	E	dsfcurtain	S	1.243	dsf-curtain	9	100%		
			W	0.59	dsf-curtain	10	100%		
	W	delhibase	23	0.51	1"double plate gray	3	as/existing		
	S	delhibase	23	0.51	1"double plate gray	3	as/existing		
delhialt_1S.inp	N	delhibase	23	0.51	1"double plate gray	3	as/existing		y
	E	delhibase	23	0.51	1"double plate gray	3	as/existing		
	W	delhibase	23	0.51	1"double plate gray	3	as/existing		
	S	dsfcurtain	S	1.243	dsf-curtain	9	100%		
			W	0.59	dsf-curtain	10	100%		
delhialt_1W.inp	N	delhibase	23	0.51	1"double plate gray	3	as/existing		y
	E	delhibase	23	0.51	1"double plate gray	3	as/existing		
	W	dsfcurtain	S	1.243	dsf-curtain	9	100%		
			W	0.59	dsf-curtain	10	100%		
	S	delhibase	23	0.51	1"double plate gray	3	as/existing		
delhialt_1all.inp	N	dsfcurtain	S	1.243	dsf-curtain	9	100%		y
			W	0.59	dsf-curtain	10	100%		
	E	dsfcurtain	S	1.243	dsf-curtain	9	100%		
			W	0.59	dsf-curtain	10	100%		
	W	dsfcurtain	S	1.243	dsf-curtain	9	100%		
			W	0.59	dsf-curtain	10	100%		
	S	dsfcurtain	S	1.243	dsf-curtain	9	100%		
			W	0.59	dsf-curtain	10	100%		
delhialt_1N_S.inp	N	HYD-dsfcurtain	S	1.243	dsf-curtain	9	100%	N0.N0.T.1	y
			W	0.59	dsf-curtain	10	100%	N0.N0.T.1	
	E	delhibase	23	0.51	1"double plate gray	3	as/existing		
	W	delhibase	23	0.51	1"double plate gray	3	as/existing		
	S	delhibase	23	0.51	1"double plate gray	3	as/existing		
delhialt_1E_S.inp	N	delhibase	23	0.51	1"double plate gray	3	as/existing		y
	E	dsfcurtain	S	1.243	dsf-curtain	9	100%	R.2 L.2 N0.	
			W	0.59	dsf-curtain	10	100%	R.2 L.2 N0.	
	W	delhibase	23	0.51	1"double plate gray	3	as/existing		
	S	delhibase	23	0.51	1"double plate gray	3	as/existing		
delhialt_1S_S.inp	N	delhibase	23	0.51	1"double plate gray	3	as/existing		y
	E	delhibase	23	0.51	1"double plate gray	3	as/existing		
	W	delhibase	23	0.51	1"double plate gray	3	as/existing		
	S	dsfcurtain	S	1.243	dsf-curtain	9	100%	R.2 L.2 T.1	
			W	0.59	dsf-curtain	10	100%	R.2 L.2 T.1	
delhialt_1W_S.inp	N	delhibase	23	0.51	1"double plate gray	3	as/existing		y
	E	delhibase	23	0.51	1"double plate gray	3	as/existing		
	W	dsfcurtain	S	1.243	dsf-curtain	9	100%	R.2 L.2 N0.	
			W	0.59	dsf-curtain	10	100%	R.2 L.2 N0.	
	S	delhibase	23	0.51	1"double plate gray	3	as/existing		
delhialt_1all_S.inp	N	dsfcurtain	S	1.243	dsf-curtain	9	100%	N0.N0.T.1	y
			W	0.59	dsf-curtain	10	100%	N0.N0.T.1	
	E	dsfcurtain	S	1.243	dsf-curtain	9	100%	R.2 L.2 N0.	
			W	0.59	dsf-curtain	10	100%	R.2 L.2 N0.	
	W	dsfcurtain	S	1.243	dsf-curtain	9	100%	R.2 L.2 N0.	
			W	0.59	dsf-curtain	10	100%	R.2 L.2 N0.	
	S	dsfcurtain	S	1.243	dsf-curtain	9	100%	R.2 L.2 T.1	
			W	0.59	dsf-curtain	10	100%	R.2 L.2 T.1	

Table A- 6
Input Values for Ener-Win Simulation for Strategy Two for Delhi

File name	Facades	Wall name	Wall id	U-value	Window des.	Win id	Transparency	Shading	Daylighting
delhialt_4N.inp	N	HYD-dsfcurtain	S	0.704	dsf-curtain	17	100%		y
			W	0.57	dsf-curtain	18	100%		
	E	delhibase	23	0.51	1"double plate gray	5	as/existing		
	W	delhibase	23	0.51	1"double plate gray	5	as/existing		
	S	delhibase	23	0.51	1"double plate gray	5	as/existing		
delhialt_4E.inp	N	delhibase	23	0.51	1"double plate gray	5	as/existing		y
	E	dsfcurtain	S	0.704	dsf-curtain	17	100%		
			W	0.57	dsf-curtain	18	100%		
	W	delhibase	23	0.51	1"double plate gray	5	as/existing		
	S	delhibase	23	0.51	1"double plate gray	5	as/existing		
delhialt_4S.inp	N	delhibase	23	0.51	1"double plate gray	5	as/existing		y
	E	delhibase	23	0.51	1"double plate gray	5	as/existing		
	W	delhibase	23	0.51	1"double plate gray	5	as/existing		
	S	dsfcurtain	S	0.704	dsf-curtain	17	100%		
			W	0.57	dsf-curtain	18	100%		
delhialt_4W.inp	N	delhibase	23	0.51	1"double plate gray	5	as/existing		y
	E	delhibase	23	0.51	1"double plate gray	5	as/existing		
	W	dsfcurtain	S	0.704	dsf-curtain	17	100%		
			W	0.57	dsf-curtain	18	100%		
	S	delhibase	23	0.51	1"double plate gray	5	as/existing		
delhialt_4all.inp	N	dsfcurtain	S	0.704	dsf-curtain	17	100%		y
			W	0.57	dsf-curtain	18	100%		
	E	dsfcurtain	S	0.704	dsf-curtain	17	100%		
			W	0.57	dsf-curtain	18	100%		
	W	dsfcurtain	S	0.704	dsf-curtain	17	100%		
			W	0.57	dsf-curtain	18	100%		
	S	dsfcurtain	S	0.704	dsf-curtain	17	100%		
			W	0.57	dsf-curtain	18	100%		
delhialt_4N_S.inp	N	HYD-dsfcurtain	S	0.704	dsf-curtain	17	100%	N0.N0.T.1	y
			W	0.57	dsf-curtain	18	100%	N0.N0.T.1	
	E	delhibase	23	0.51	1"double plate gray	5	as/existing		
	W	delhibase	23	0.51	1"double plate gray	5	as/existing		
	S	delhibase	23	0.51	1"double plate gray	5	as/existing		
delhialt_4E_S.inp	N	delhibase	23	0.51	1"double plate gray	5	as/existing		y
	E	dsfcurtain	S	0.704	dsf-curtain	17	100%	R.2 L.2 N0.	
			W	0.57	dsf-curtain	18	100%	R.2 L.2 N0.	
	W	delhibase	23	0.51	1"double plate gray	5	as/existing		
	S	delhibase	23	0.51	1"double plate gray	5	as/existing		
delhialt_4S_S.inp	N	delhibase	23	0.51	1"double plate gray	5	as/existing		y
	E	delhibase	23	0.51	1"double plate gray	5	as/existing		
	W	delhibase	23	0.51	1"double plate gray	5	as/existing		
	S	dsfcurtain	S	0.704	dsf-curtain	17	100%	R.2 L.2 T.1	
			W	0.57	dsf-curtain	18	100%	R.2 L.2 T.1	
delhialt_4W_S.inp	N	delhibase	23	0.51	1"double plate gray	5	as/existing		y
	E	delhibase	23	0.51	1"double plate gray	5	as/existing		
	W	dsfcurtain	S	0.704	dsf-curtain	17	100%	R.2 L.2 N0.	
			W	0.57	dsf-curtain	18	100%	R.2 L.2 N0.	
	S	delhibase	23	0.51	1"double plate gray	5	as/existing		
delhialt_4all_S.inp	N	dsfcurtain	S	0.704	dsf-curtain	17	100%	N0.N0.T.1	y
			W	0.57	dsf-curtain	18	100%	N0.N0.T.1	
	E	dsfcurtain	S	0.704	dsf-curtain	17	100%	R.2 L.2 N0.	
			W	0.57	dsf-curtain	18	100%	R.2 L.2 N0.	
	W	dsfcurtain	S	0.704	dsf-curtain	17	100%	R.2 L.2 N0.	
			W	0.57	dsf-curtain	18	100%	R.2 L.2 N0.	
	S	dsfcurtain	S	0.704	dsf-curtain	17	100%	R.2 L.2 T.1	
			W	0.57	dsf-curtain	18	100%	R.2 L.2 T.1	

Table A- 7
Input Values for Ener-Win Simulation for Strategy Three for Delhi

File name	Facades	Wall name	Wall id	U-value	Window design	Window desc.	Win id	Transparency	Daylighting
delhi2_a.inp	N	HYD-cavitybk	22	0.19	dsf-alt 1	alt1-summer	9	80	y
						alt1-winter	10		
	E	HYD-cavitybk	22	0.19	dsf-alt 1	alt1-summer	9	50	
						alt1-winter	10		
	W	HYD-cavitybk	22	0.19	dsf-alt 1	alt1-summer	9	50	
						alt1-winter	10		
	S	HYD-cavitybk	22	0.19	dsf-alt 1	alt1-summer	9	25	
						alt1-winter	10		
delhi2_b.inp	N	HYD-cavitybk	22	0.19	dsf-alt 1	alt1-summer	9	70	y
						alt1-winter	10		
	E	HYD-cavitybk	22	0.19	dsf-alt 1	alt1-summer	9	40	
						alt1-winter	10		
	W	HYD-cavitybk	22	0.19	dsf-alt 1	alt1-summer	9	40	
						alt1-winter	10		
	S	HYD-cavitybk	22	0.19	dsf-alt 1	alt1-summer	9	25	
						alt1-winter	10		
delhi2_c.inp	N	HYD-cavitybk	22	0.19	dsf-alt 2	alt4-summer	17	80	y
						alt4-winter	18		
	E	HYD-cavitybk	22	0.19	dsf-alt 2	alt4-summer	17	50	
						alt4-winter	18		
	W	HYD-cavitybk	22	0.19	dsf-alt 2	alt4-summer	17	50	
						alt4-winter	18		
	S	HYD-cavitybk	22	0.19	dsf-alt 2	alt4-summer	17	25	
						alt4-winter	18		

Table A- 8
Output Values Obtained after Ener-Win Simulations for all Three Strategies for Delhi

		PEAK COOLING LOADS (KWH)					ANNUAL COOLING LOADS (MBTU)					BREAKDOWN OF ENERGY CONSUMPTION (MBTU)	
	Total Cooling Energy(Mbtu)	Total peak cooling	Walls	Window trans	Window solar	Lights/equipment	Total annual cooling(	Walls	Window trans	Window solar	Lights/equipment	Space cooling	Lighting
0	4715.2	5139.4	909.58	312.83	689.57	1393.55	9721.61	1822.92	374.75	1495.85	3202.3	4715	3031
1N	4620.5	5179.8	625.13	732.39	889.88	990.09	9496.38	1580.9	770.74	1794.11	2455.23	4620	2136
1E	4630.1	5098.1	633.47	594.41	825.59	1006.58	9547.33	1558.18	646.75	1912.95	2484.11	4630	2168
1S	4786	5166.9	615.95	654.53	944.54	979.97	9877.4	1373.7	779	2252.93	2452.81	4786	2114
1W	4692	5239.1	786.34	552.31	1302.19	1016.4	9604.9	1538.25	679.49	2010.1	2489.87	4692	2179
1all	5707.6	6360.6	347.81	1918.03	1675.01	980.64	11648.7	592.04	1723.9	3655.3	2458.4	5707	2073
4N	4476.6	4976.2	624.58	563.97	851.15	990.09	9230.52	1578.62	598.45	1710.35	2453.76	4476	2139
4E	4487.3	4949.7	802.36	427.81	747.44	1010.22	9273.18	1560.56	527.34	1781.86	2477.67	4487	2171
4S	4557.5	4964.3	617.46	500.1	898.88	979.97	9420.83	1377.75	594.12	2019.11	2443.31	4557	2117
4W	4523.2	5061.1	786.76	439.31	1139.46	1016.4	9289.87	1537.73	536.65	1847.76	2486.98	4523	2181
4all	5013.3	5535.9	291.32	1005.25	1448.04	980.61	10316.6	599.74	1100.61	3027.16	2432.94	5013	2078
2a	4294.8	5171.3	389	936.77	897.8	984.79	8863.71	954.9	992.5	1641.89	2411.66	4294	2114
2b	4114.2	4987.5	411.3	826.54	755.36	984.85	8520.38	1004.97	873.1	1405.34	2408.41	4114	2125
2c	3839.4	4653.5	412.29	563.21	648.08	987.18	7999.43	1002.2	596.73	1191.98	2399.24	3839	2138
1N_S	4516.9	5095.4	623.17	718.44	810.66	990.09	9290.62	1576.64	756.11	1622.83	2450.06	4516	2142
1E_S	4503.4	5022.3	630.94	587.26	751.73	1006.58	9288.2	1552.58	632.29	1707.48	2474.66	4503	2175
1S_S	4464.2	4969.6	618.82	628.41	758.19	979.97	9210.07	1382.18	741.61	1684.96	2427.97	4464	2119
1W_S	4534.5	5148.2	785.35	542.55	1218.24	1016.4	9284.74	1538.03	658.87	1732.38	2486.78	4534	2190
1all_S	4975.6	5969	348.64	1879.63	1283.83	980.64	10154.2	601.71	1639	2384.79	2401.68	4975	2086
4N_S	4391.9	4909.5	675.46	535.58	786.25	993.45	9062.51	1575.93	589.27	1566	2450.36	4391	2146
4E_S	4380	4883.4	799.48	424.36	698.54	1010.22	9054.39	1556.58	517.8	1603.65	2472.2	4380	2179
4S_S	4290.4	4808	703.02	471.69	692.4	988.97	8870.08	1382.02	571.36	1549.69	2418.98	4290	2123
4W_S	4396.3	4988.6	788.1	433.43	1068.22	1016.4	9034.3	1542.46	524.06	1615.44	2483.28	4396	2193
4all_S	4410	5186.3	320.34	941.75	1131.37	981.61	9091.5	604.46	1047.88	1985.4	2379.71	4410	2093

APPENDIX B

DRAWINGS OF BUILDINGS

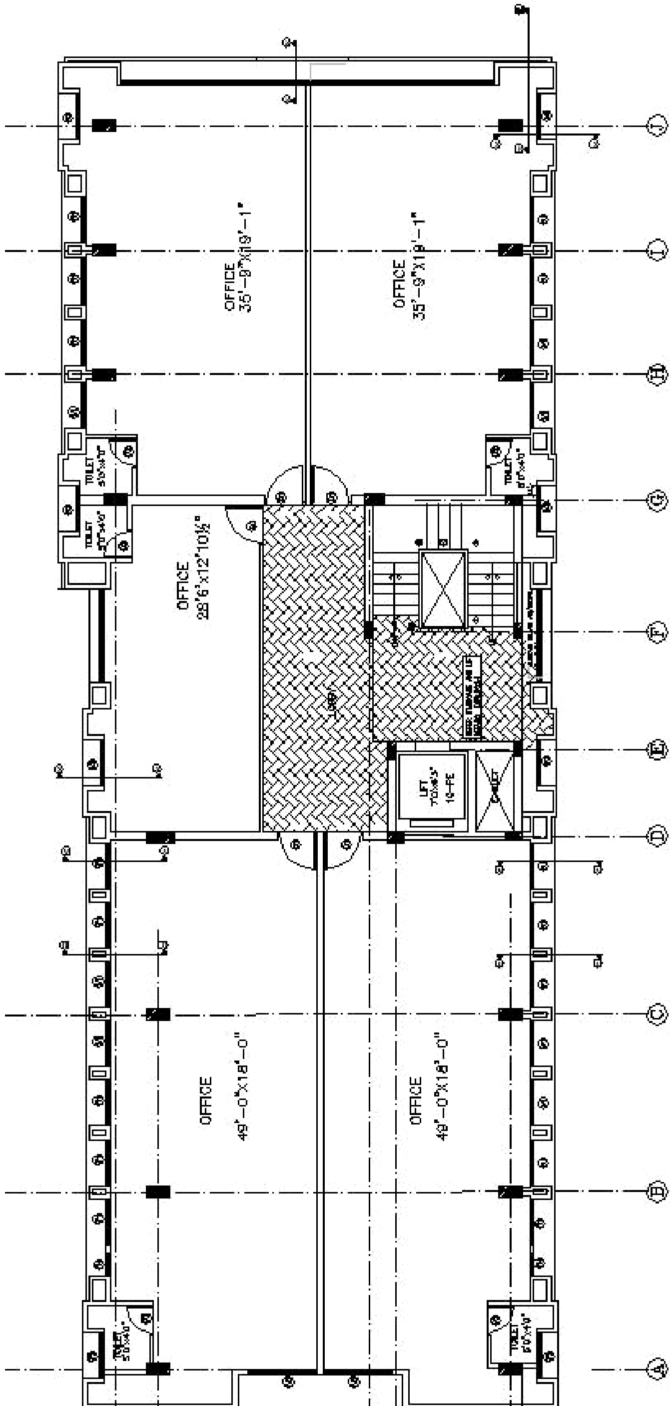

Fig. B-1 Mahavir Commercial Complex, Hyderabad: First Floor Plan

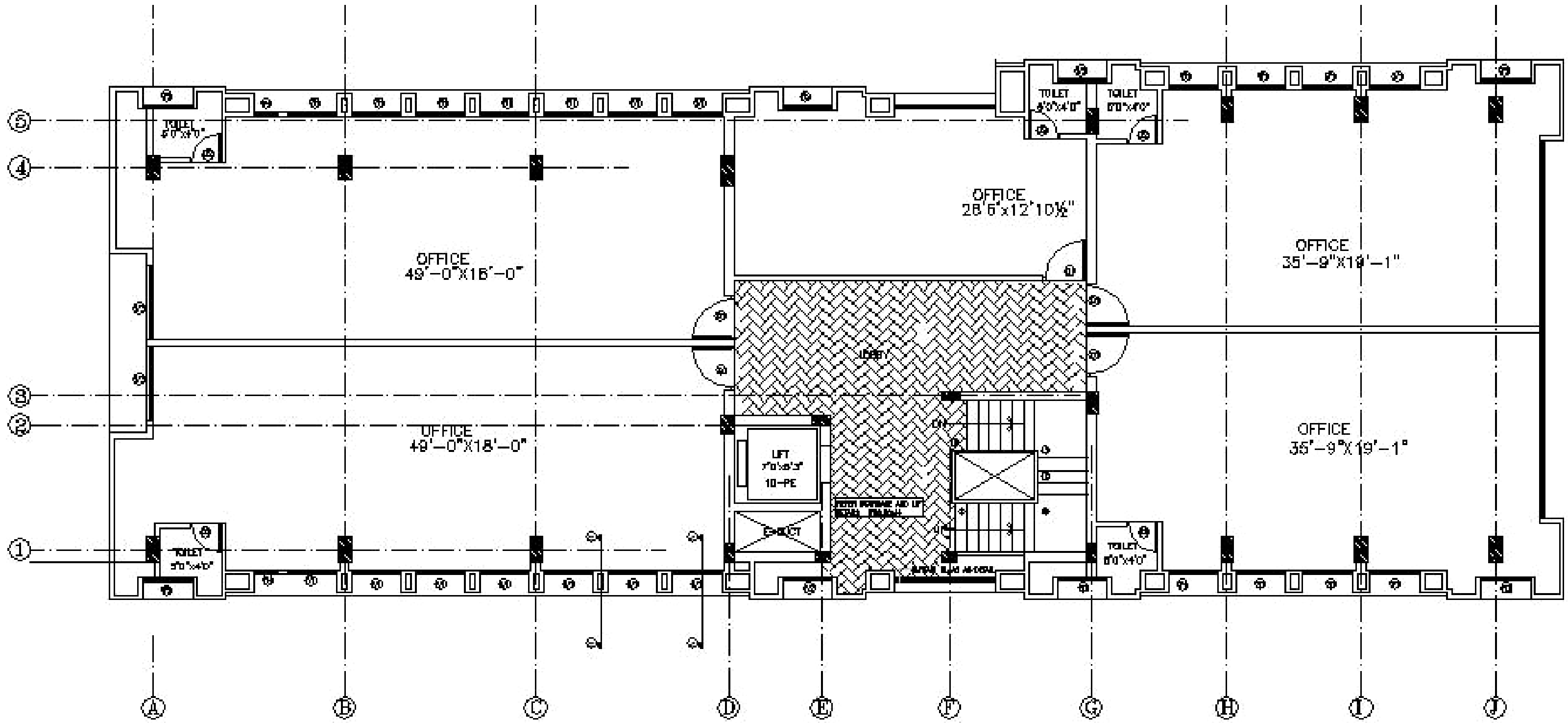

Fig. B-2 Mahavir Commercial Complex, Hyderabad: Second Floor Plan

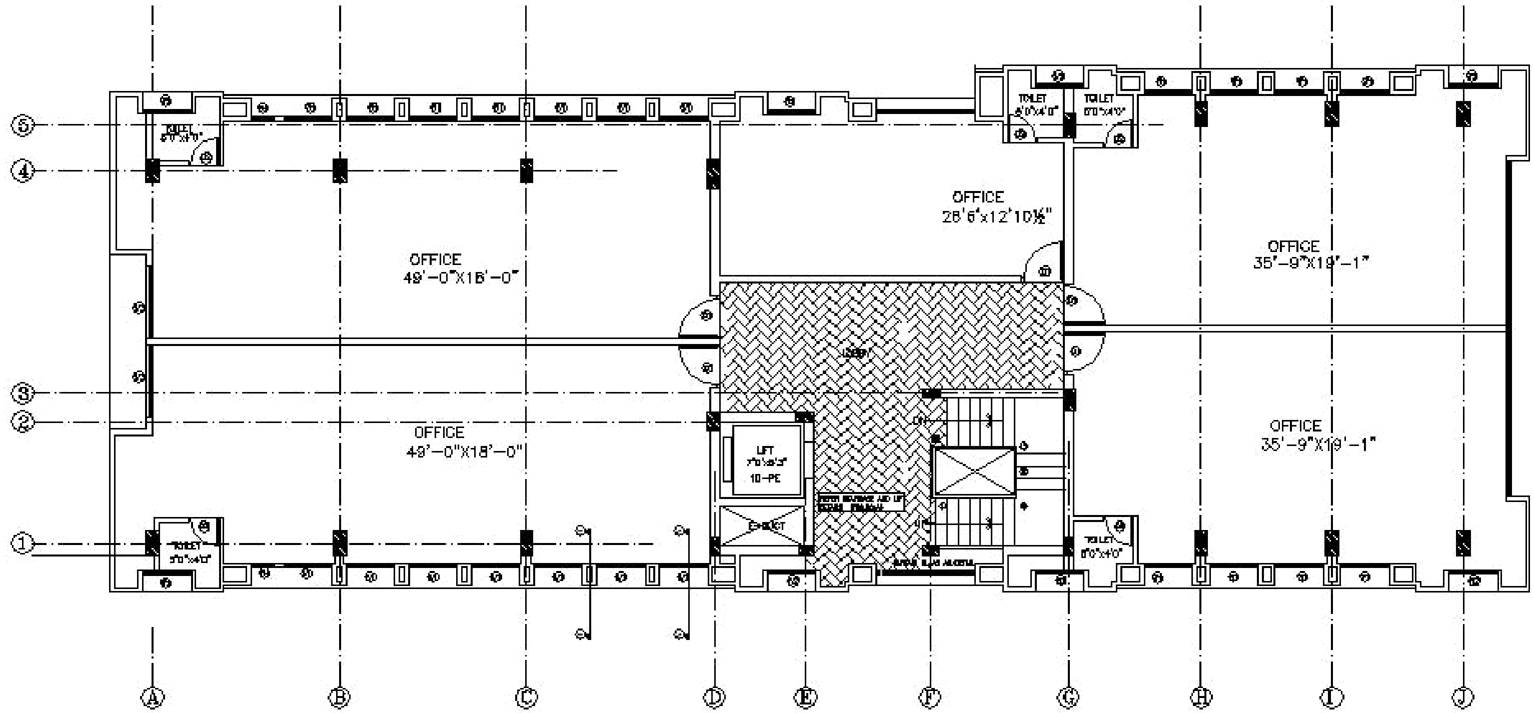

Fig. B-3 Mahavir Commercial Complex, Hyderabad: Third Floor Plan

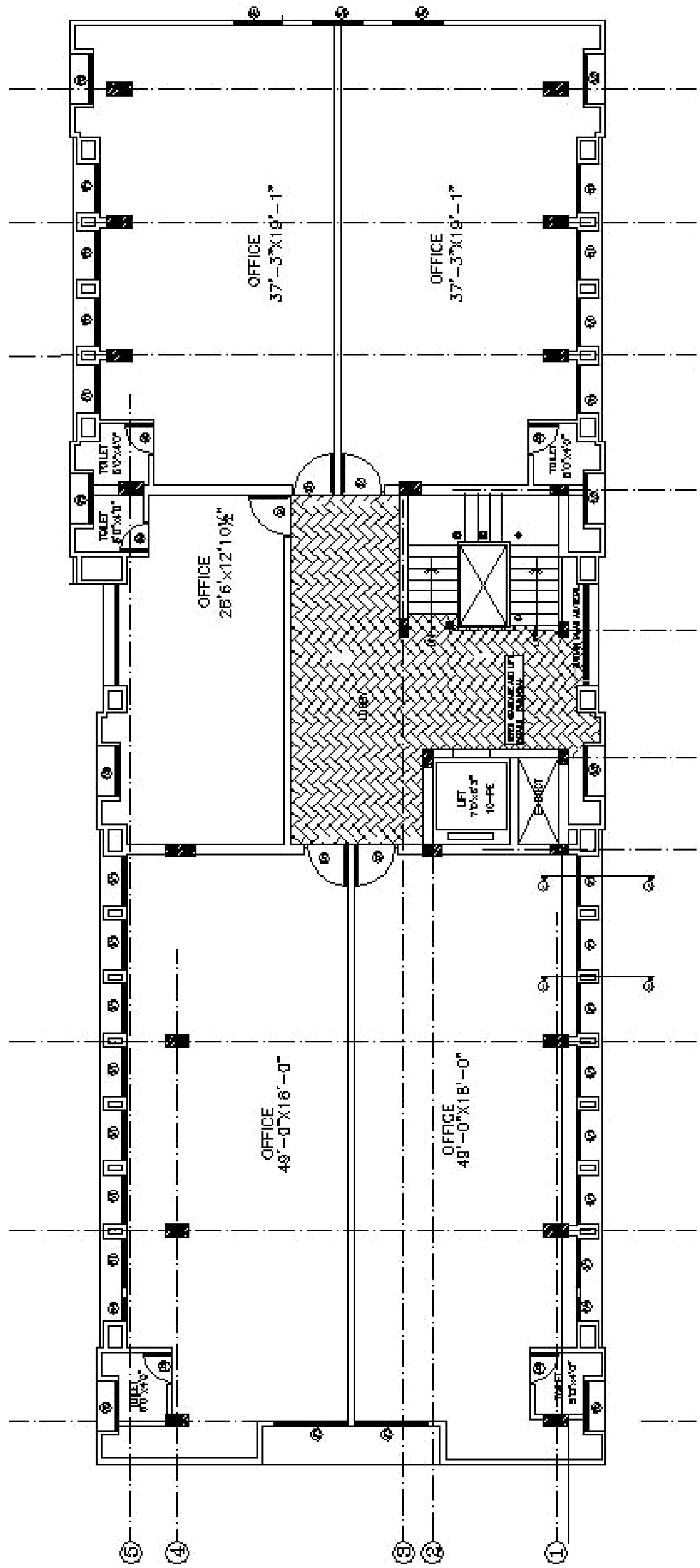

Fig. B-4 Mahavir Commercial Complex, Hyderabad: Fourth Floor Plan

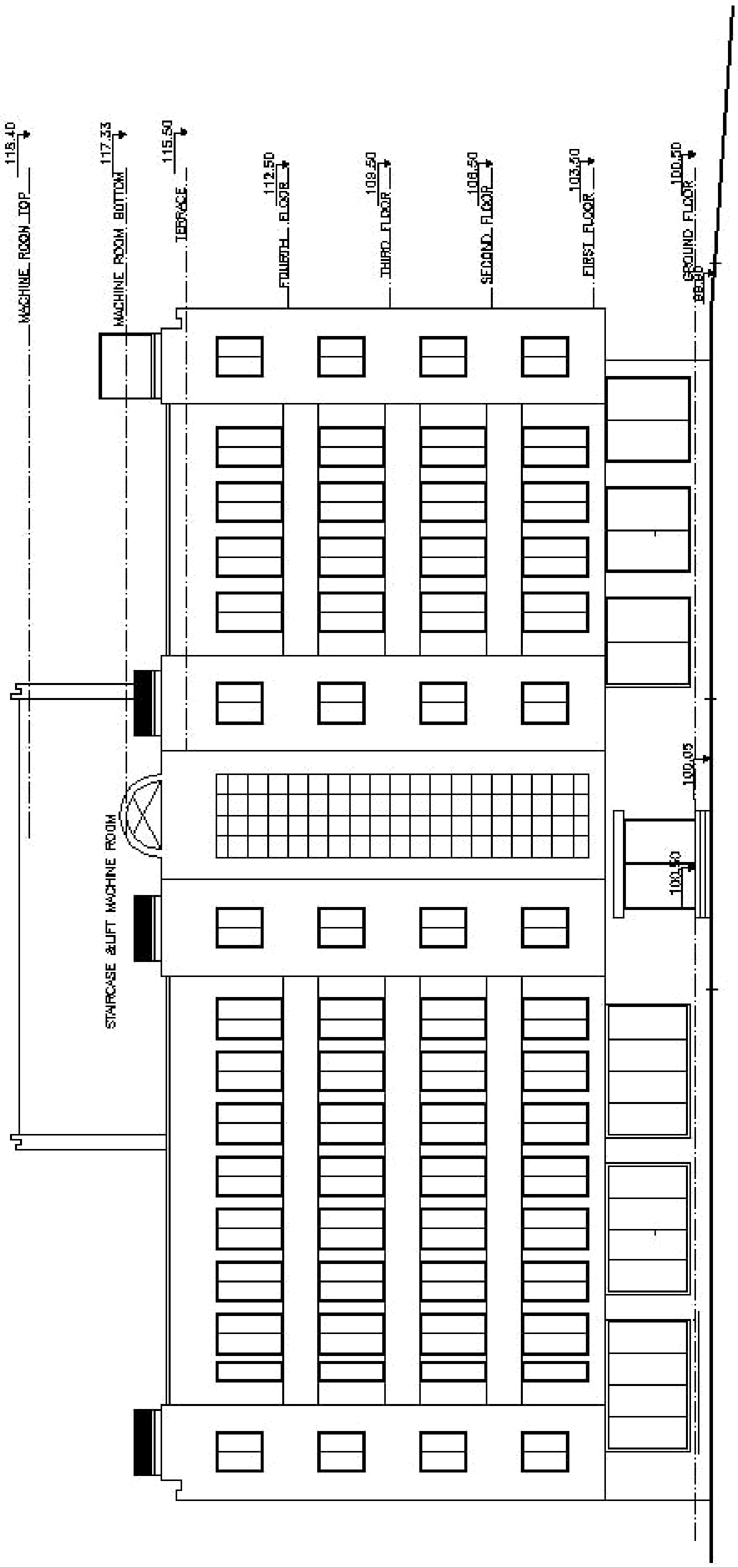

Fig. B-5 Mahavir Commercial Complex, Hyderabad: East-side Elevation

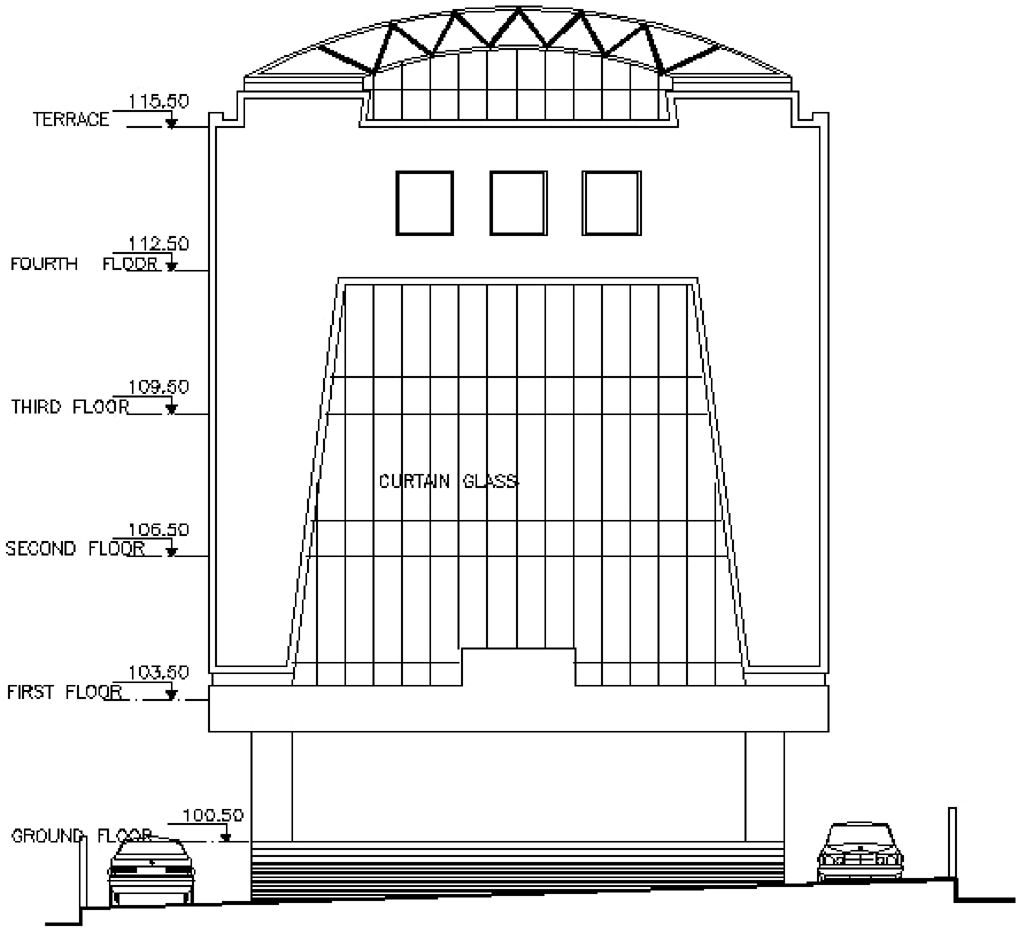

Fig. B- 6 Mahavir Commercial Complex: North side Elevation

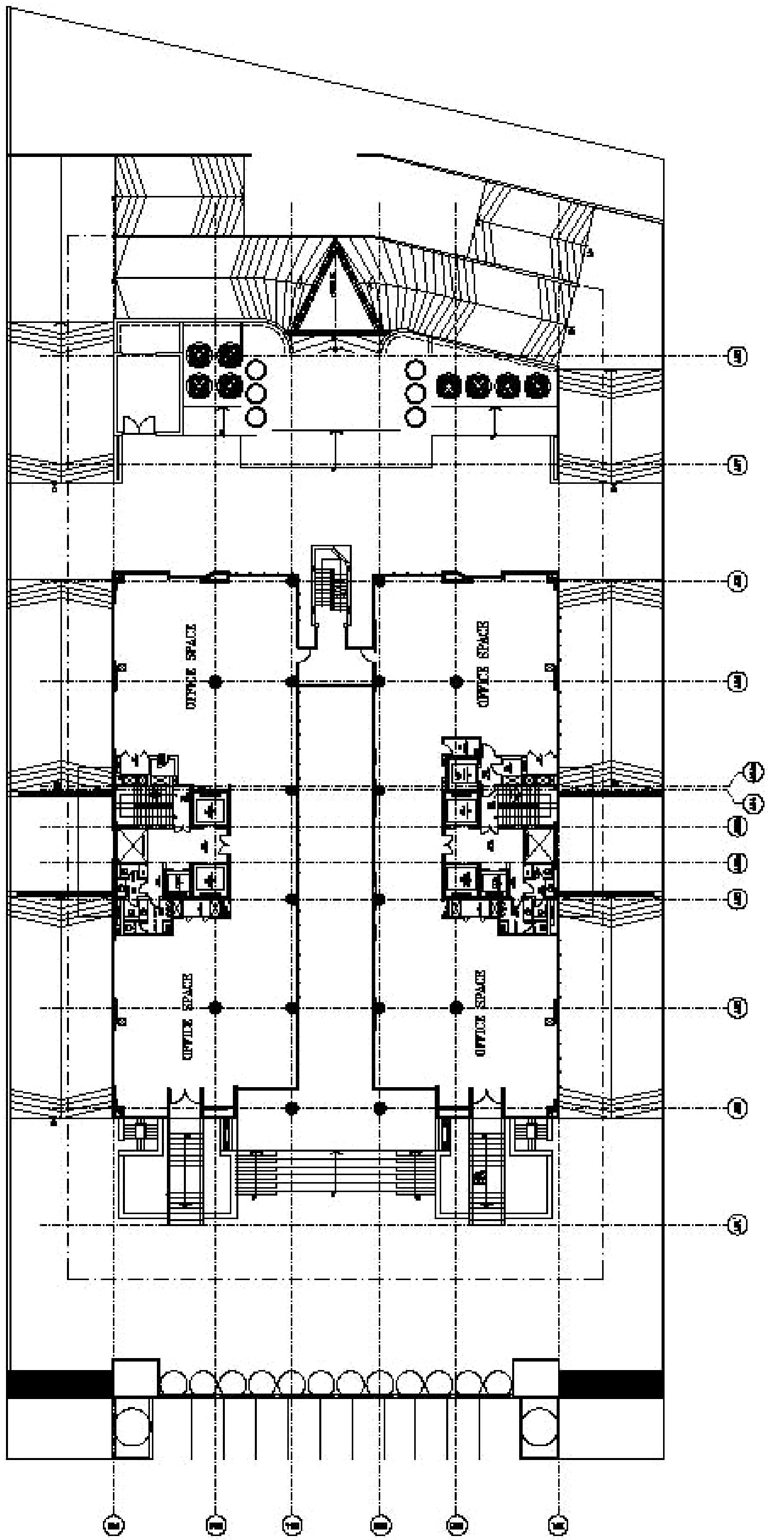

Fig. B -7 Birla Corporate Office, New Delhi: Lower Ground Floor Plan

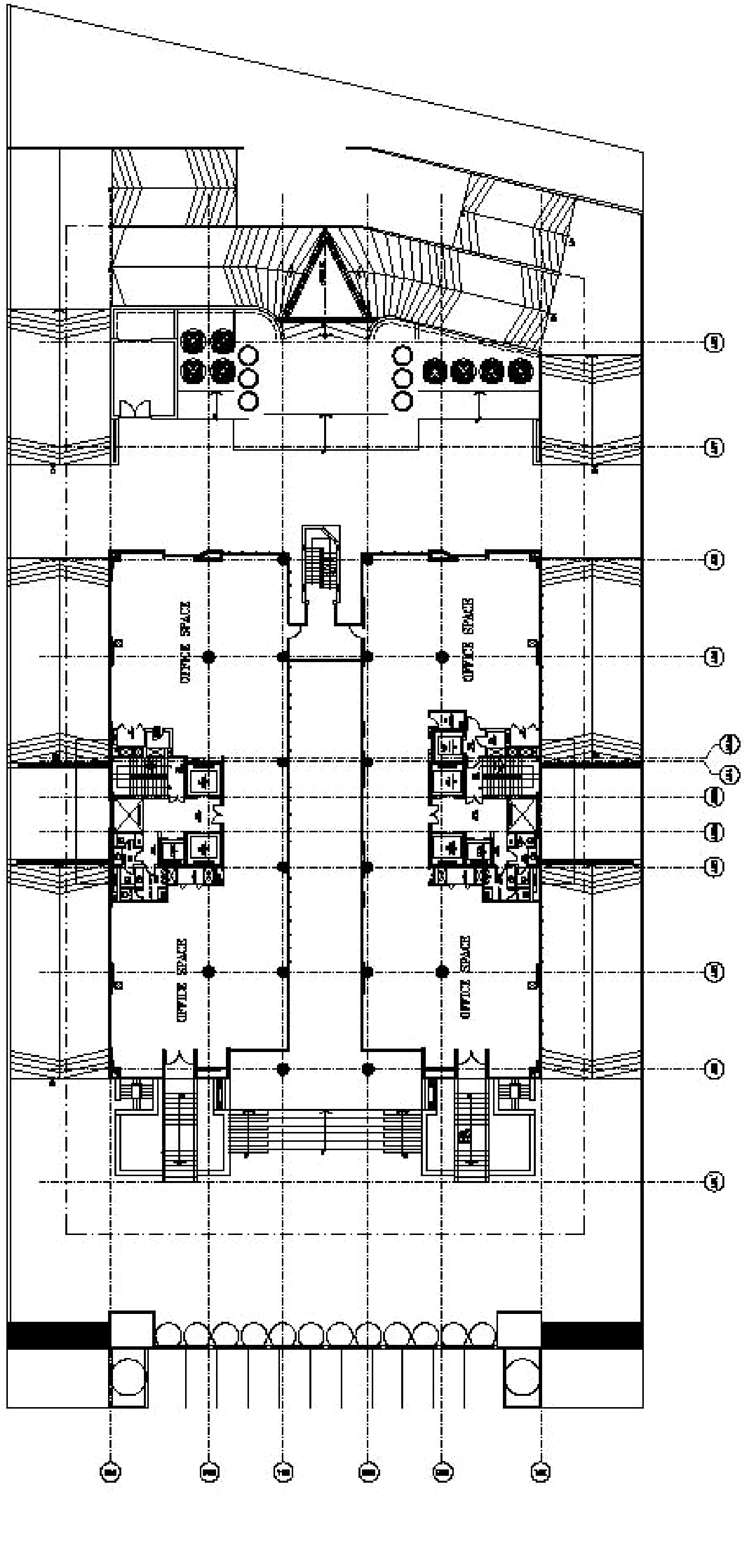

Fig. B -8 Birla Corporate Office, New Delhi: Upper Ground Floor Plan

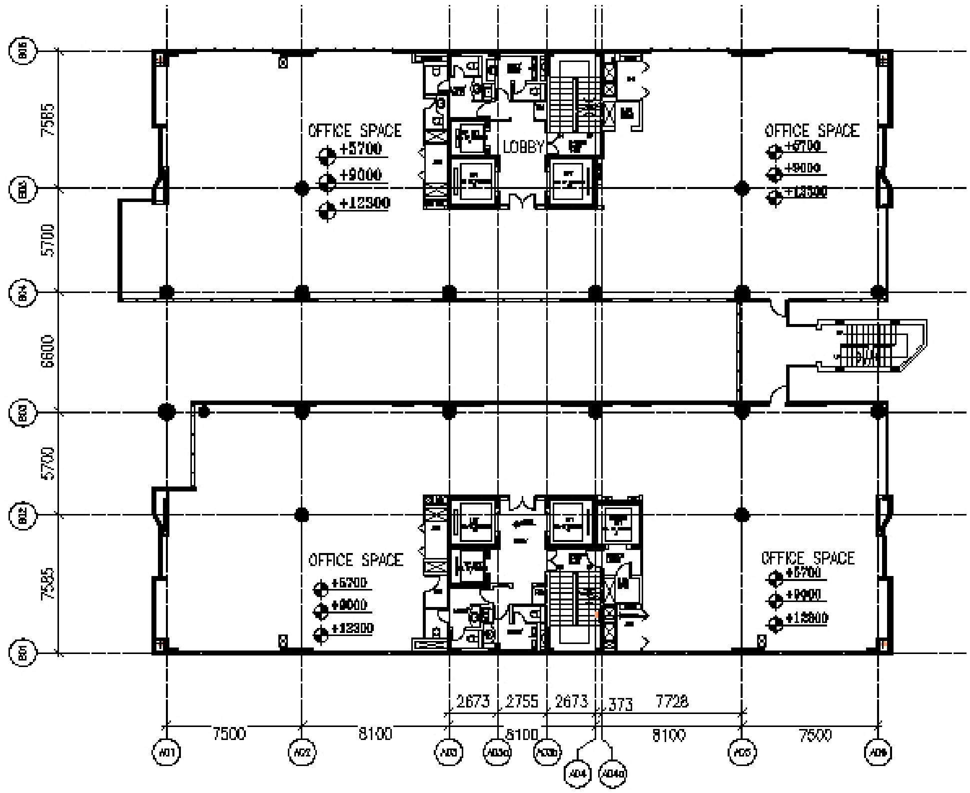

Fig. B- 9 Birla Corporate Office, New Delhi: First, Second, Third Floor Plans

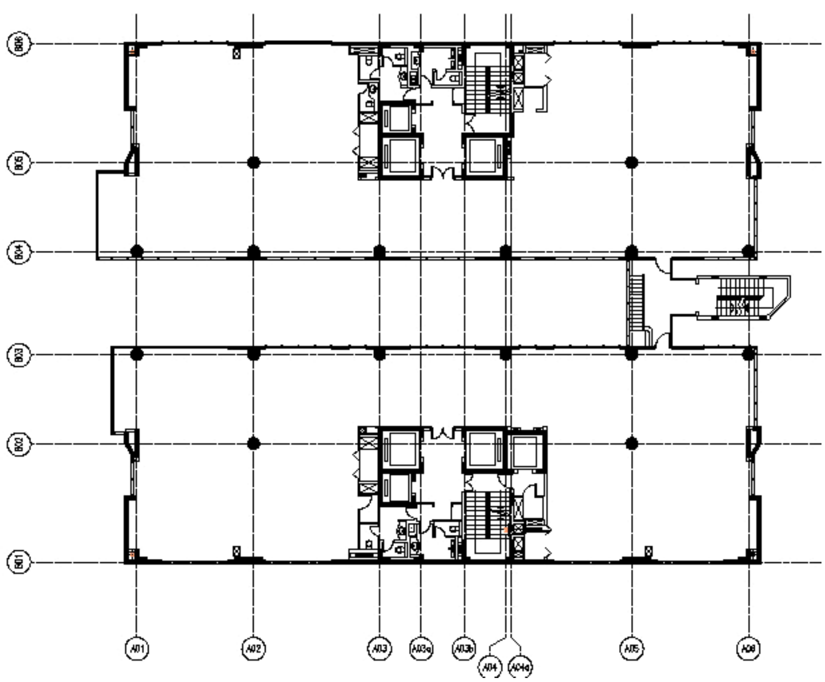

Fig. B- 10 Birla Corporate Office, New Delhi: Fourth Floor Plan

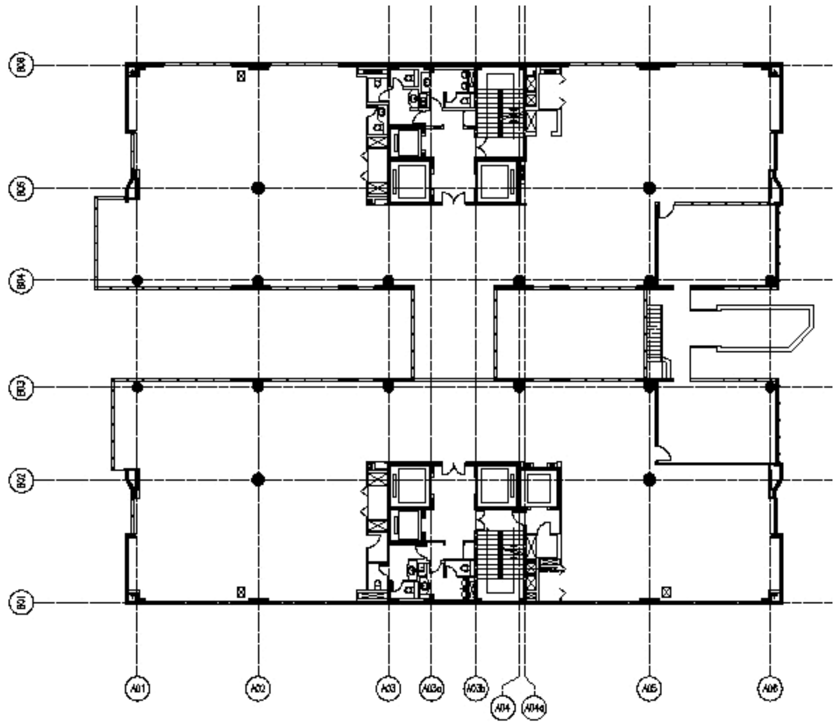

Fig. B- 11 Birla Corporate Office, New Delhi: Fifth Floor Plan

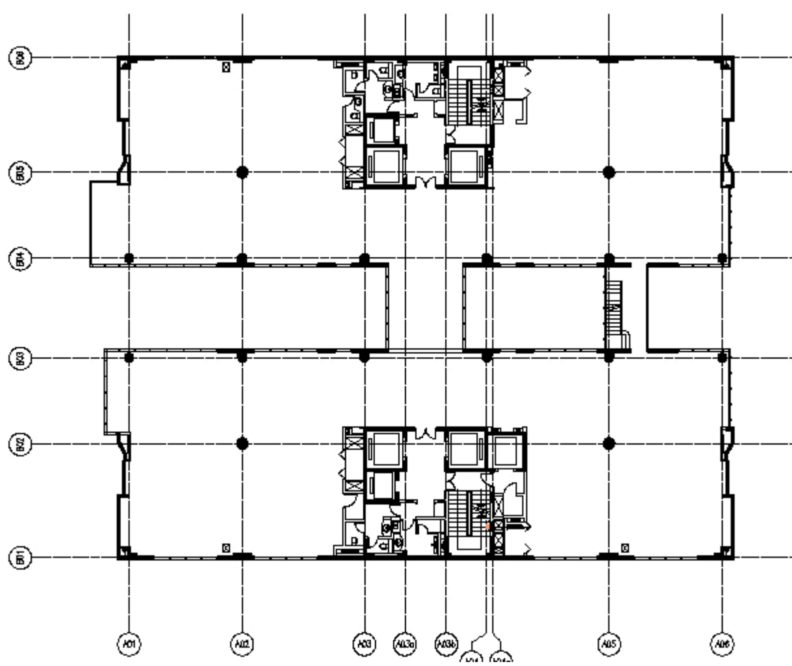

Fig. B- 12 Birla Corporate Office, New Delhi: Sixth & Eighth Floor Plan

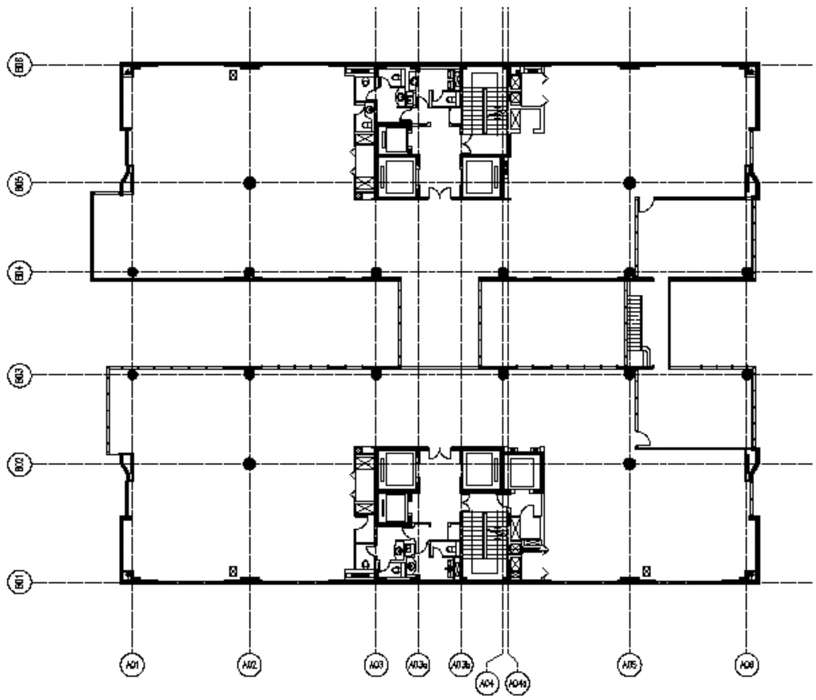

Fig. B- 13 Birla Corporate Office, New Delhi: Seventh Floor Plan

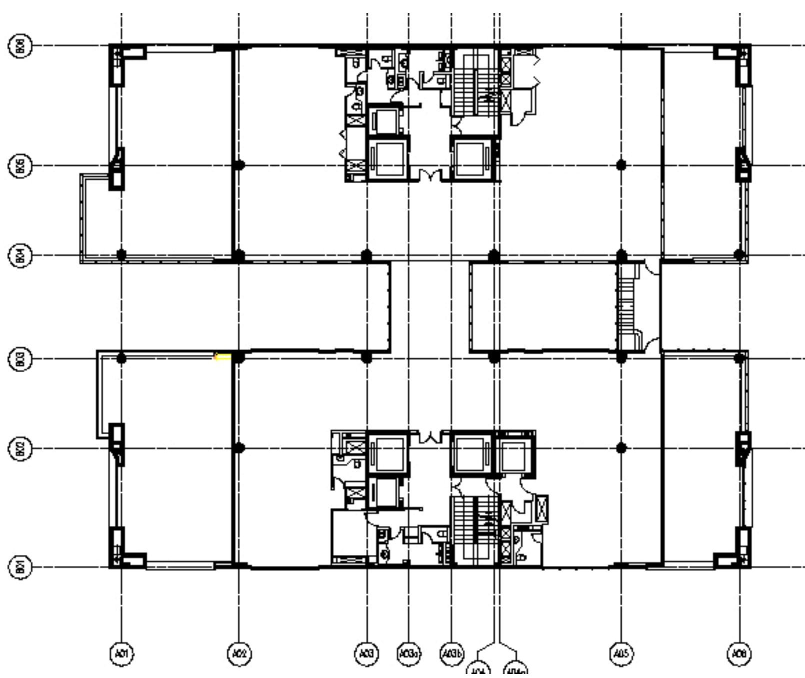

Fig. B- 14 Birla Corporate Office, New Delhi: Ninth Floor Plan

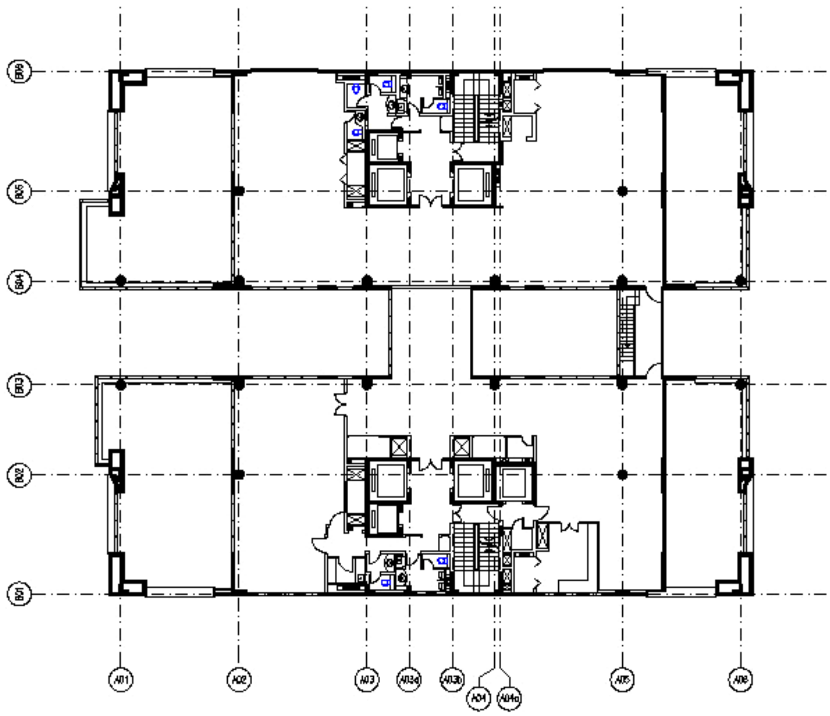

Fig. B- 15 Birla Corporate Office, New Delhi: Tenth Floor Plan

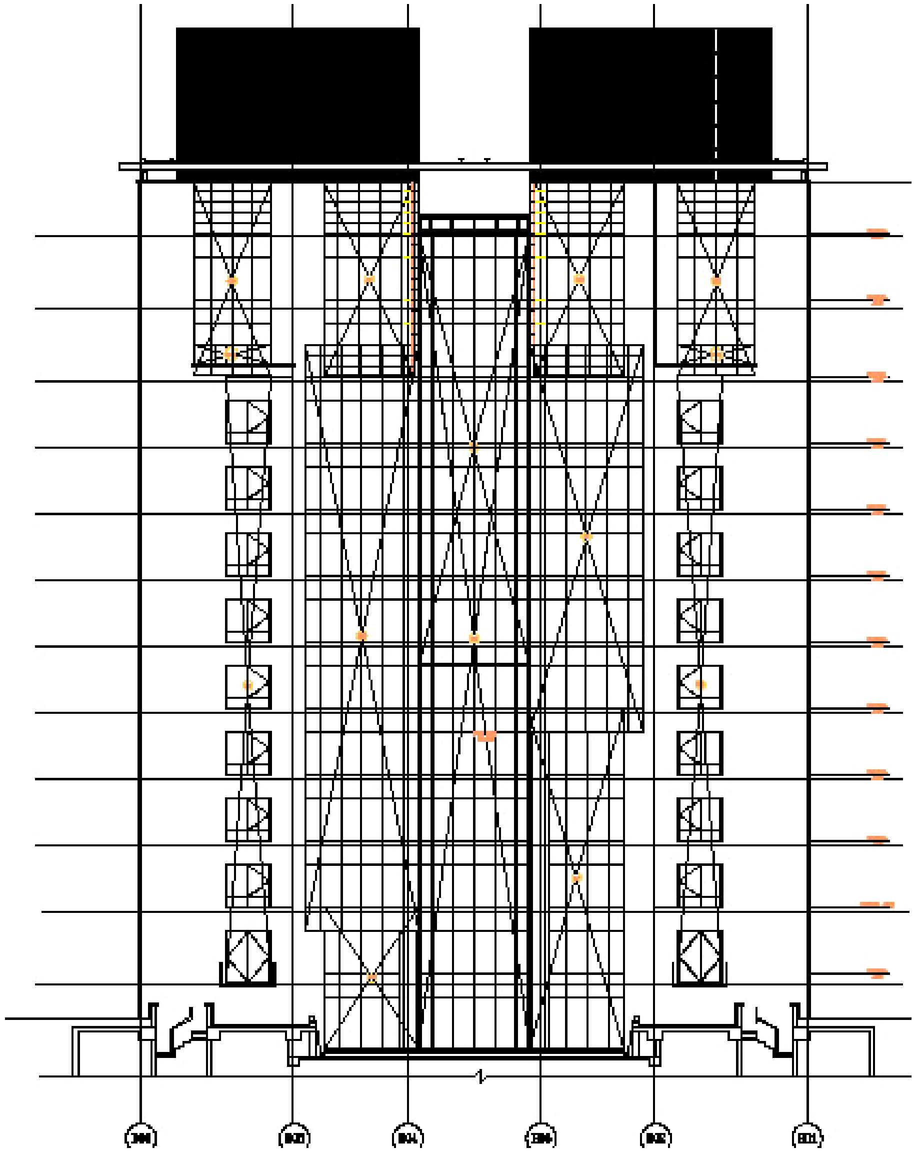

Fig. B- 16 Birla Corporate Office, New Delhi: Front (East Elevation)

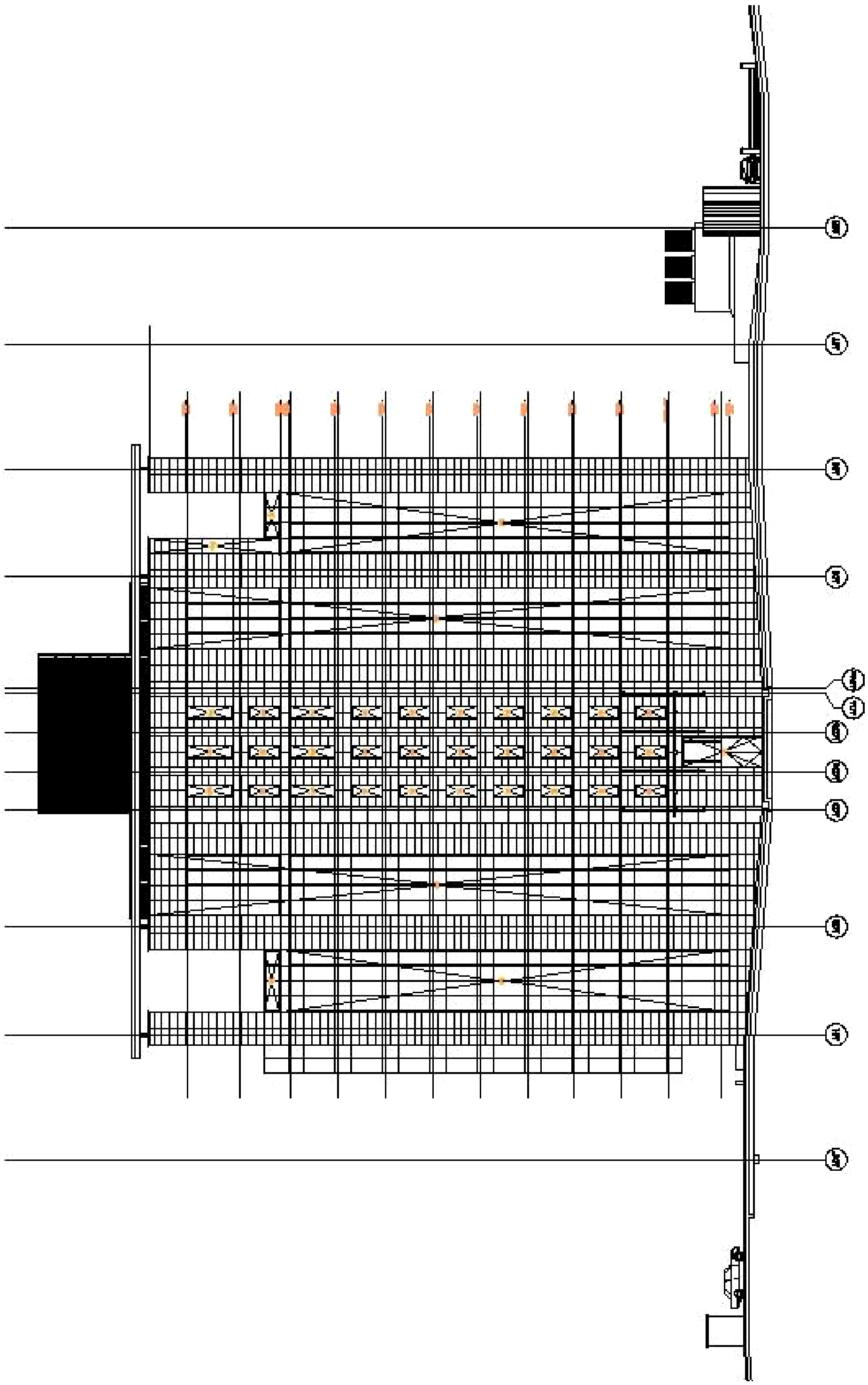

Fig. B -17 Birla Corporate Office, New Delhi: Side (North) Elevation

APPENDIX C

SUNPATH DIAGRAMS

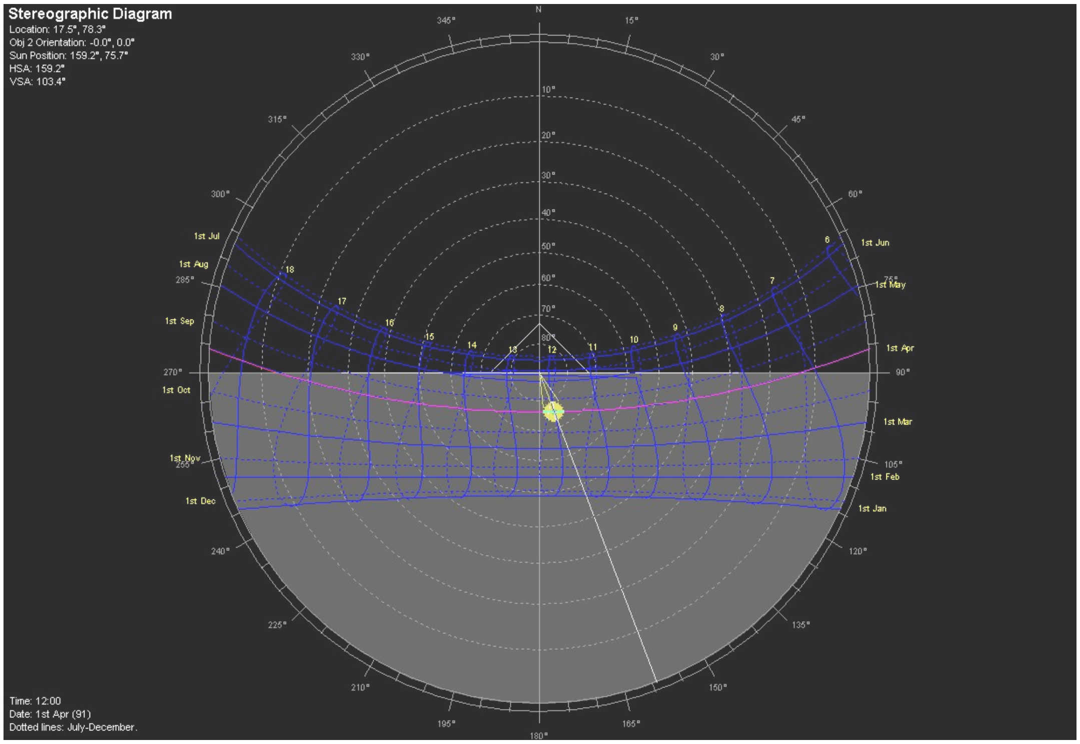

Fig. C-1 Sunpath Analysis for Façade Oriented to North: Hyderabad (17.5 N), India

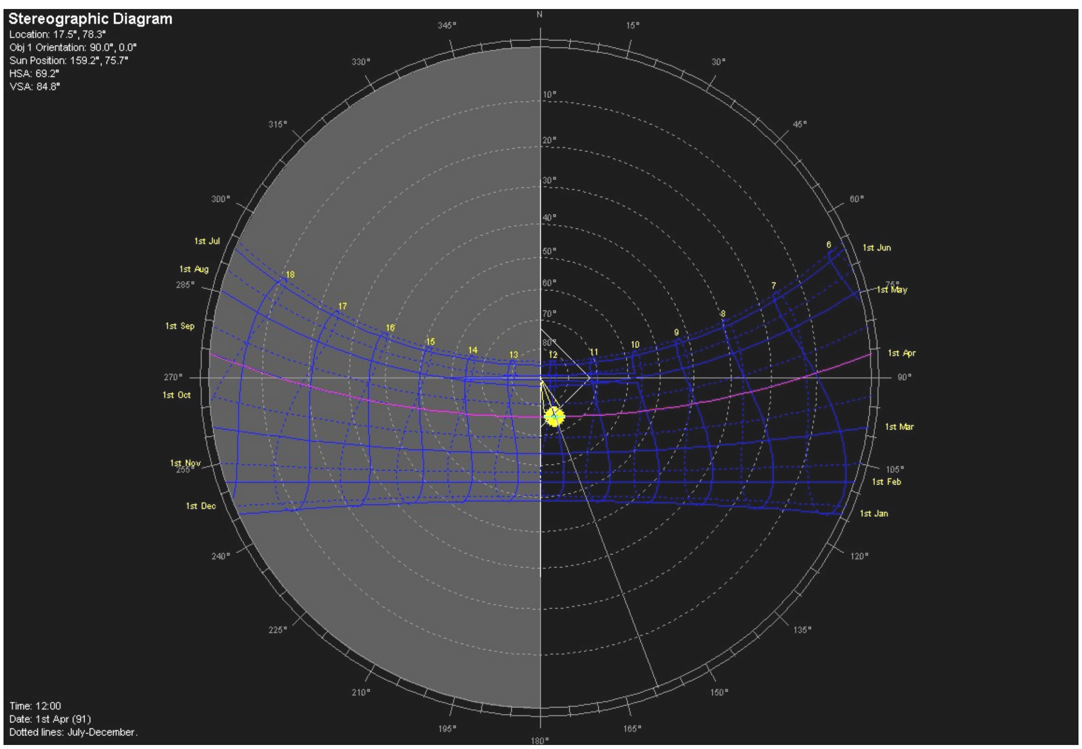

Fig. C-2 Sunpath Analysis for Façade Oriented to East: Hyderabad (17.5 N), India

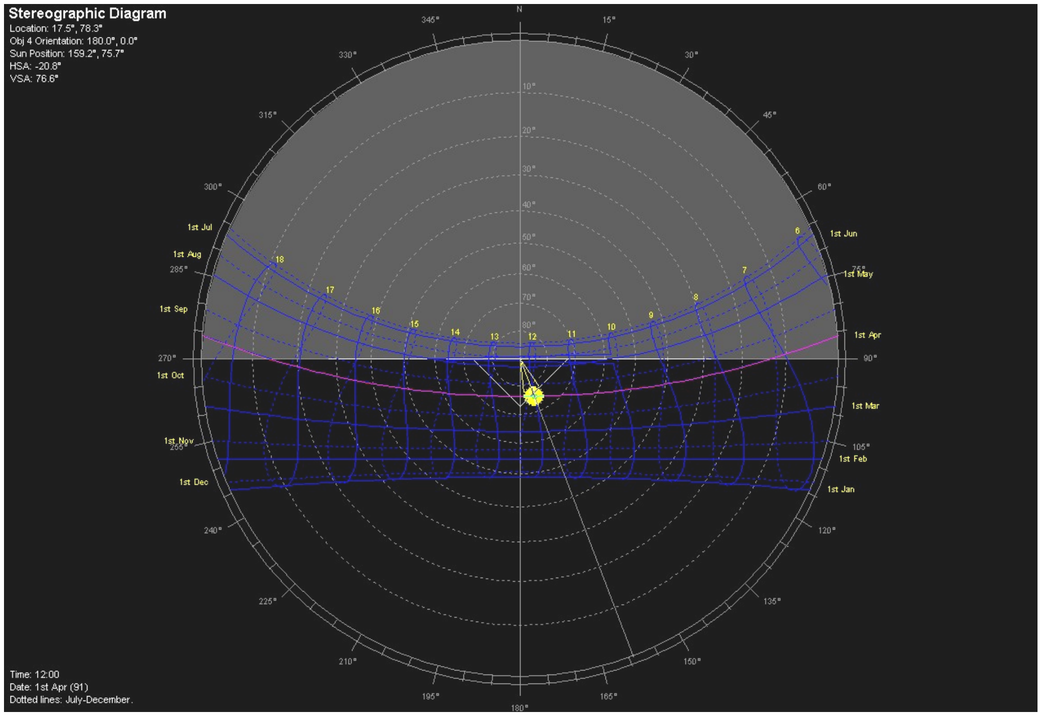

Fig. C-3 Sunpath Analysis for Façade Oriented to South: Hyderabad (17.5 N), India

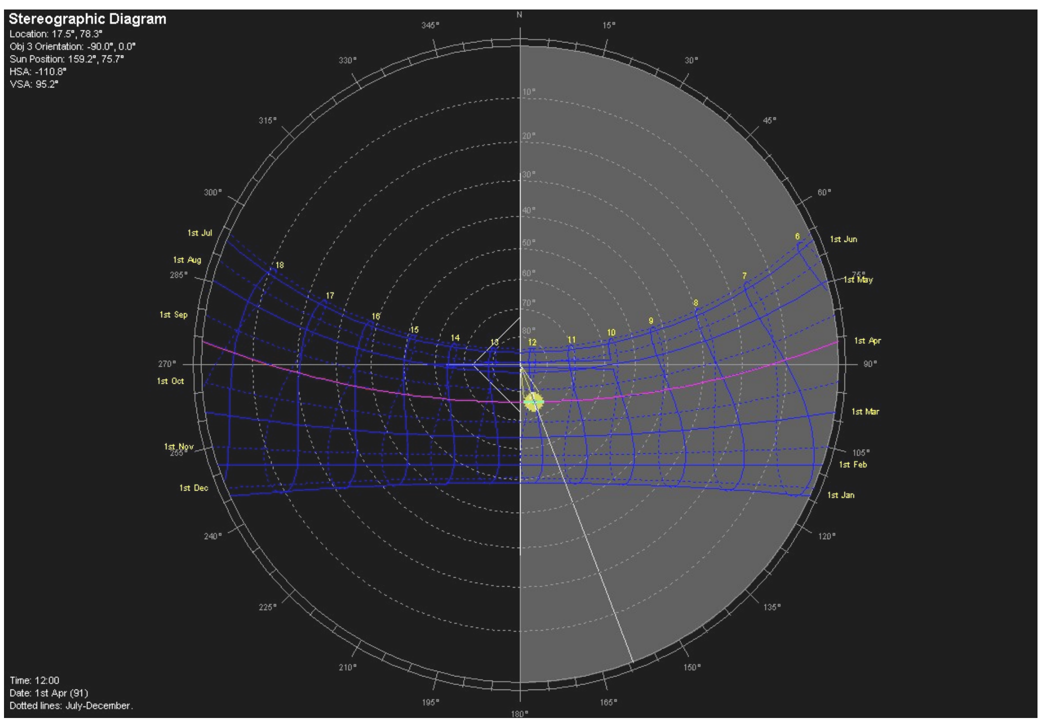

Fig. C-4 Sunpath Analysis for Façade Oriented to West: Hyderabad (17.5 N), India

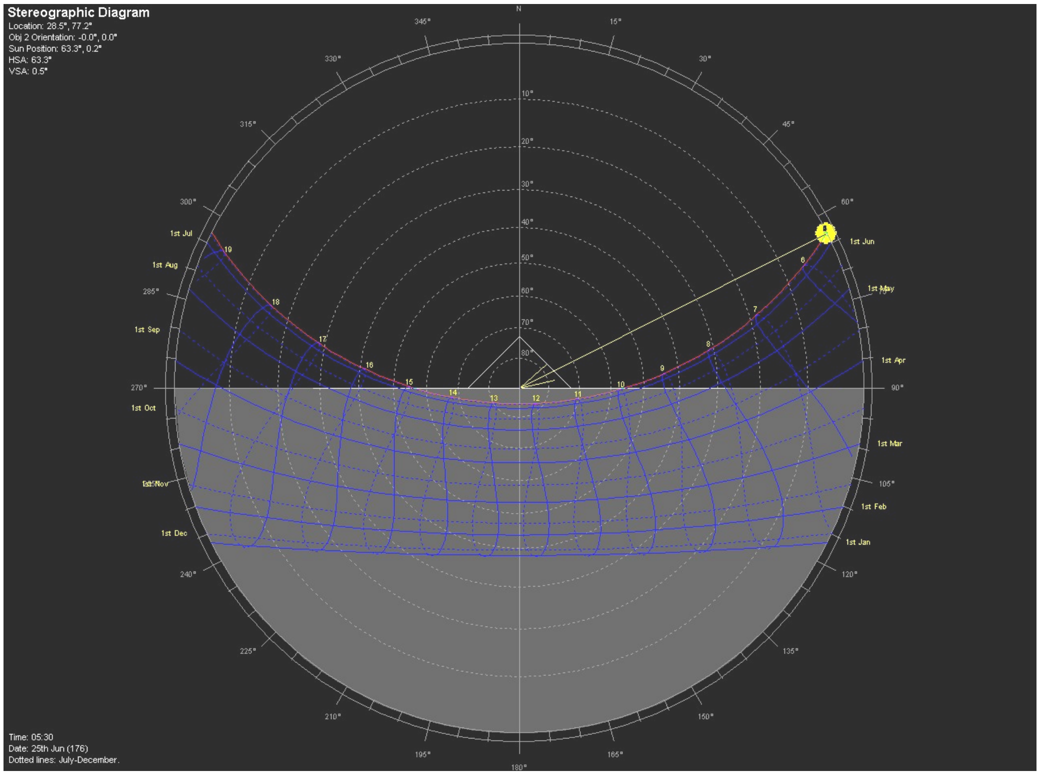

Fig. C-5 Sunpath Analysis for Façade Oriented to North: Delhi (28.6 N), India

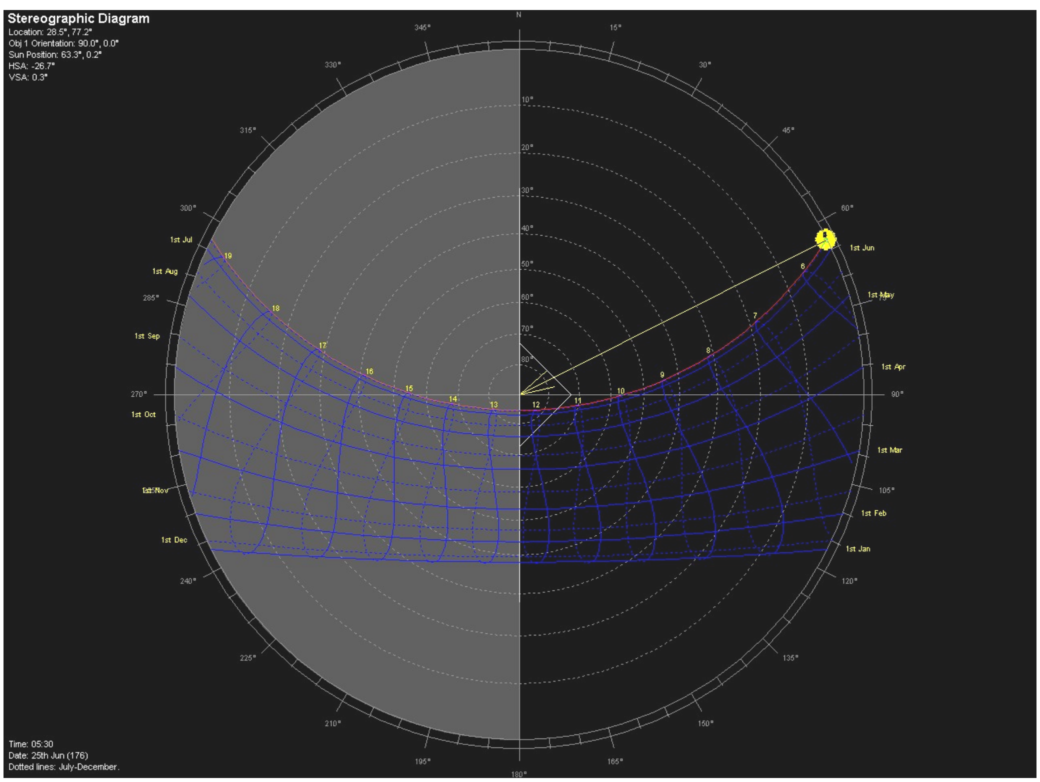

Fig. C-6 Sunpath Analysis for Façade Oriented to East: Delhi (28.6 N), India

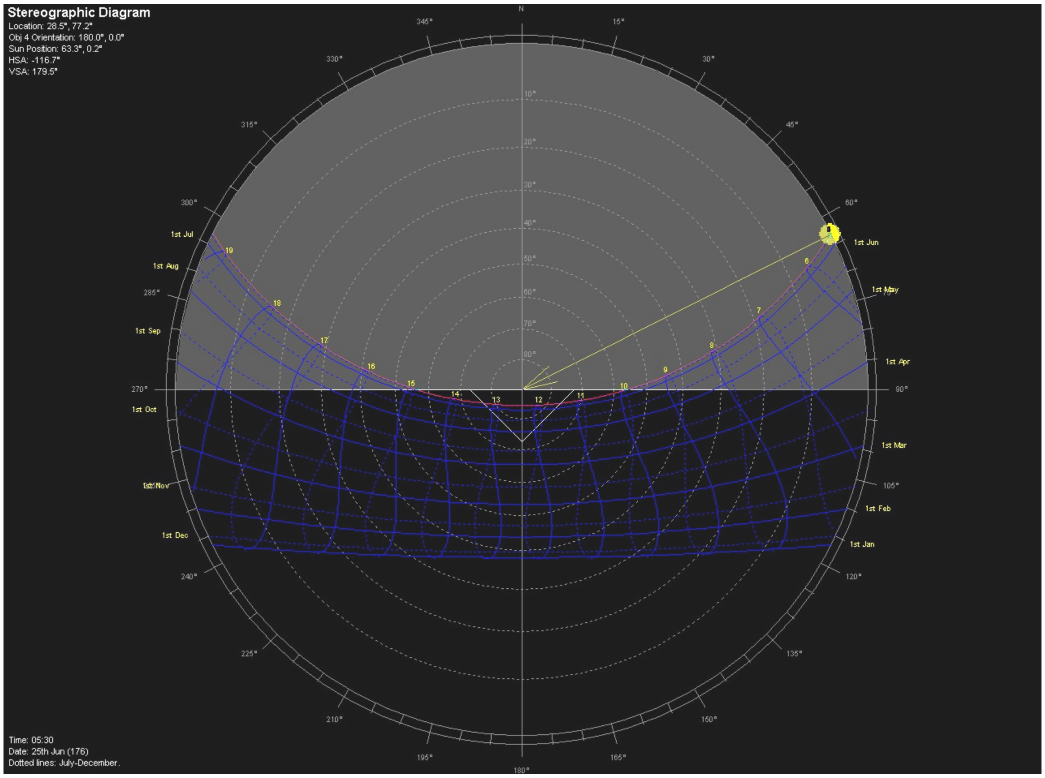

Fig. C-7 Sunpath Analysis for Façade Oriented to South: Delhi (28.6 N), India

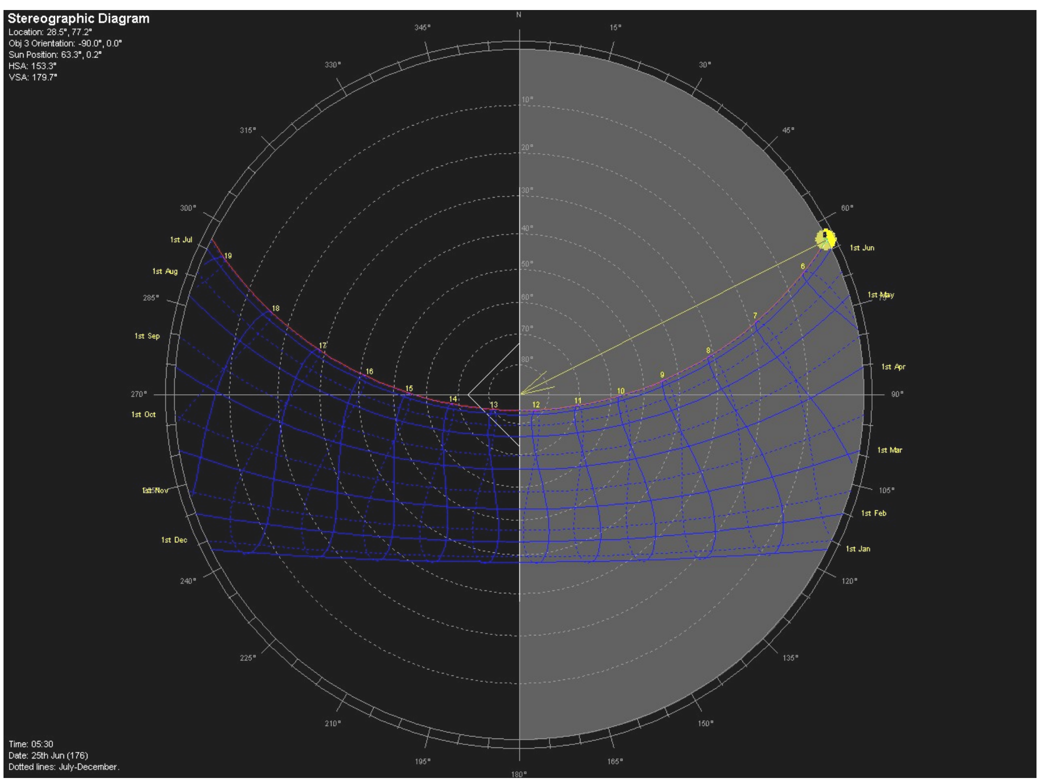

Fig. C-8 Sunpath Analysis for Façade Oriented to West: Delhi (28.6 N), India

APPENDIX D

WEATHER DATA

Table D-1
Weather Data Obtained from Ener-Win Simulation of the Base Case for Hyderabad

LOCATION: Hyderabad Airport, INDIA

WEATHER DATA YEAR: 2002

TEMPERATURES****
THE MAXIMUM TEMPERATURE FOR THIS YEAR WAS 108. DEGREES DATE: MAY 11
THE MINIMUM TEMPERATURE FOR THIS YEAR WAS 56. DEGREES DATE: DEC 20

SOLAR****
THE MAXIMUM SOLAR INSOLATION ON A HORIZONTAL SURFACE WAS 373. Btus/hr/sq.ft.
TIME: 12 ON MAY 2

THE TOTAL SOLAR INSOLATION ON A HORIZONTAL SURFACE WAS 582057. Btus/sq.ft.
LONG TERM AVERAGE SOLAR INSOLATION IS 575534. Btus/sq.ft.
TOTAL HOURS OF SUNSHINE = 2585

WIND****
WINTER DESIGN CONDITIONS 4. mph
SUMMER DESIGN CONDITIONS 7. mph

DEGREE DAYS (Fahrenheit)****

```
BASE=  41  43  45  47  49  51  53  55  57  59  61  63  65  67  69  71  73  75  77  79
----------------------------------------------------------------------------------------------------
HTG =  0.  0.  0.  0.  0.  0.  0.  0.  0.  0.  0.  0.  0.  1.  10.  46.  134.  281.  490.  777.
CLG =14222.13492.12762.12032.11302.10572. 9842. 9112. 8382. 7652. 6922. 6192. 5462. 4733. 4012. 3319. 2677. 2094. 1572. 1129.
```

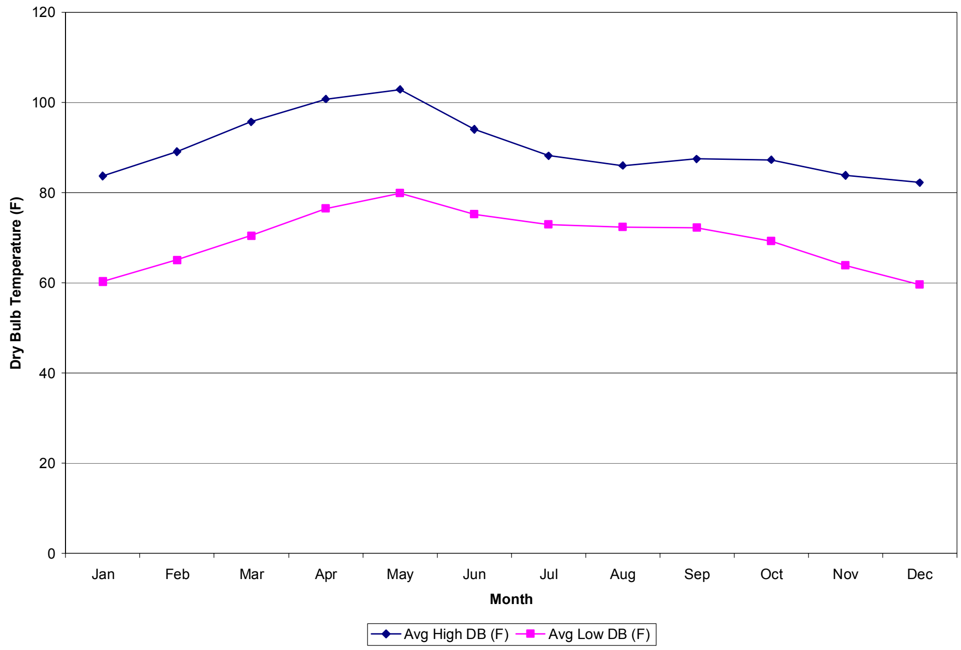

Fig. D-1. Monthly Average High and Low Dry Bulb Temperatures for Hyderabad

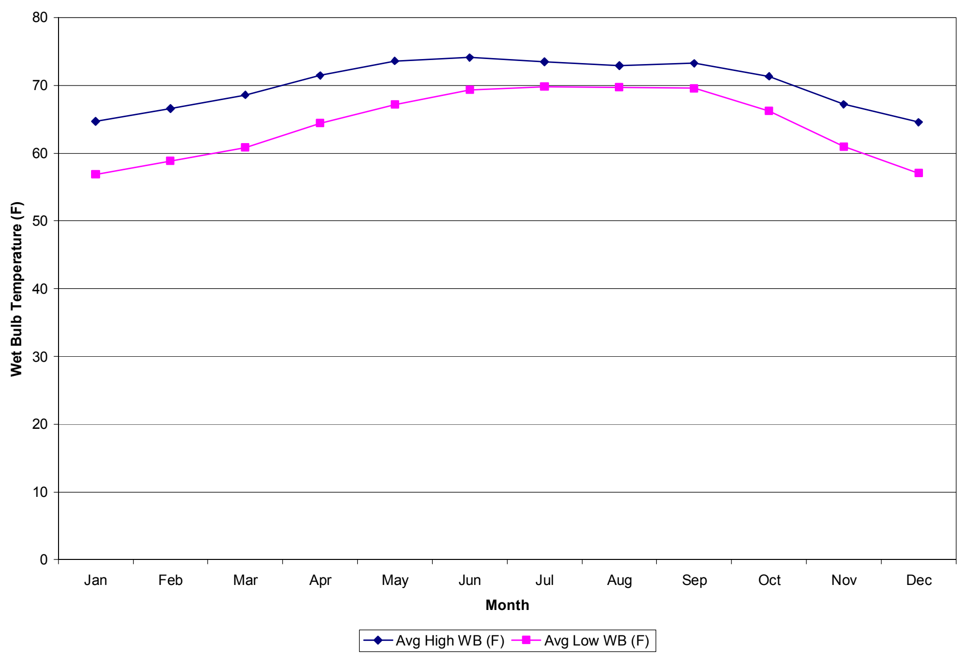

Fig. D-2. Monthly Average High and Low Wet Bulb Temperatures for Hyderabad

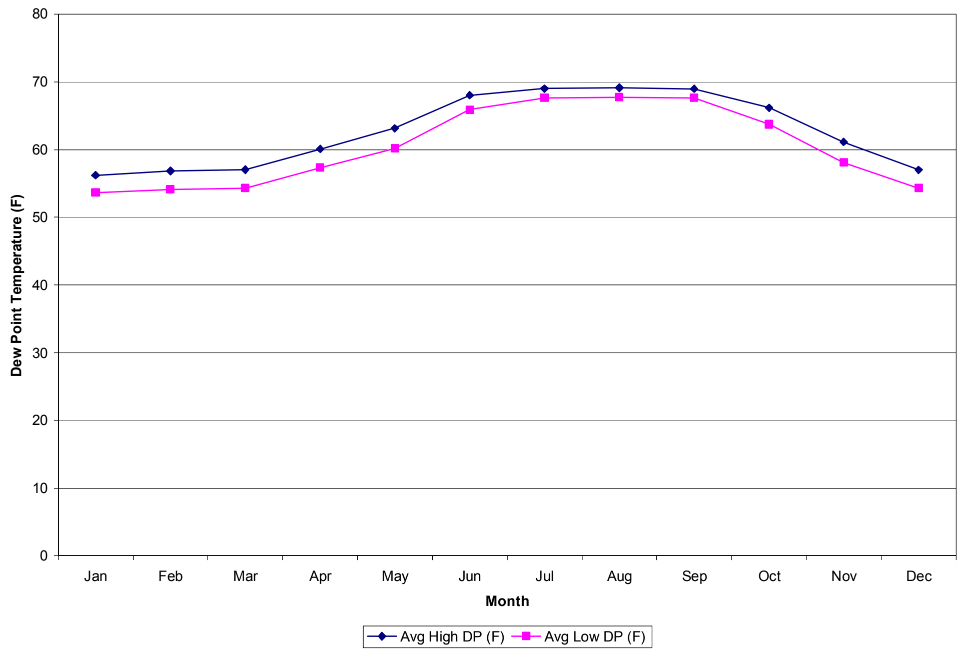

Fig. D-3. Monthly Average High and Low Dew Point Temperatures for Hyderabad

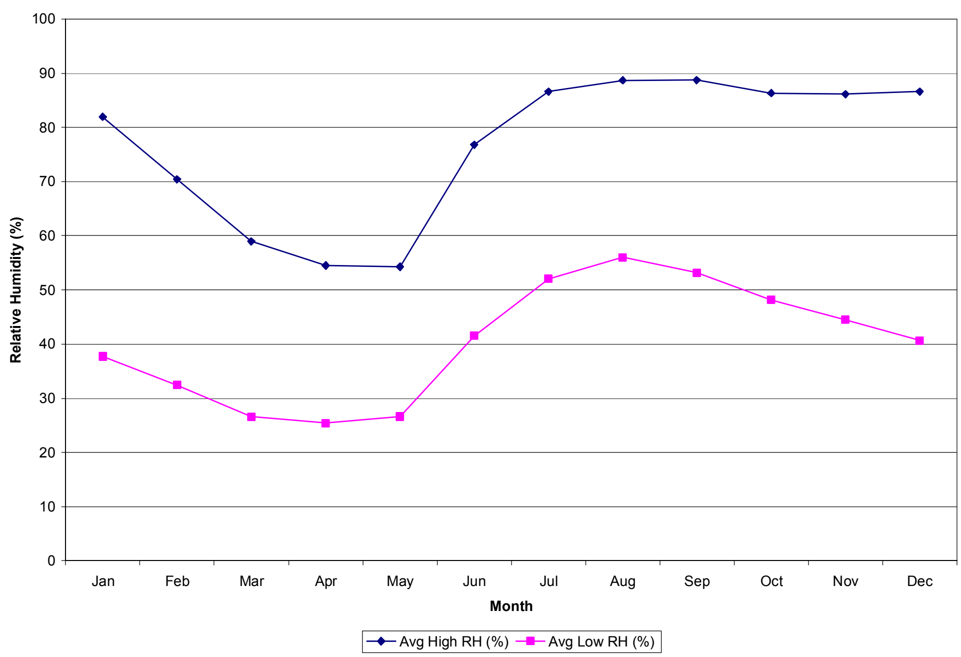

Fig. D-4. Monthly Average High and Low Relative Humidity for Hyderabad

Table D-2
Weather Data Obtained from Ener-Win Simulation of the Base Case for New Delhi

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LOCATION: New Delhi/Safdarjung, INDIA

WEATHER DATA YEAR: 2002

TEMPERATURES****
  THE MAXIMUM TEMPERATURE FOR THIS YEAR WAS 110. DEGREES      DATE: MAY 11
  THE MINIMUM TEMPERATURE FOR THIS YEAR WAS  40. DEGREES      DATE: JAN 13

SOLAR****
  THE MAXIMUM SOLAR INSOLATION ON A HORIZONTAL SURFACE WAS  362. Btus/hr/sq.ft.
    TIME:  12 ON MAY  2

  THE TOTAL SOLAR INSOLATION ON A HORIZONTAL SURFACE WAS     560918. Btus/sq.ft.
  LONG TERM AVERAGE SOLAR INSOLATION IS     554930. Btus/sq.ft.
  TOTAL HOURS OF SUNSHINE = 2725

WIND****
  WINTER DESIGN CONDITIONS     5. mph
  SUMMER DESIGN CONDITIONS   7. mph

DEGREE DAYS (Fahrenheit)****
BASE=   41   43   45   47   49   51   53   55   57   59   61   63   65   67   69   71   73   75   77   79
-----------------------------------------------------------------------------------------------------------------------------
HTG =    0.    0.    0.    0.    0.    1.    5.   16.   45.  101.  193.  322.  478.  659.  863. 1097. 1358. 1636. 1931. 2248.
CLG =13210.12480.11750.11020.10290. 9561. 8835. 8117. 7415. 6741. 6103. 5502. 4928. 4379. 3854. 3357. 2888. 2437. 2001. 1589.
```

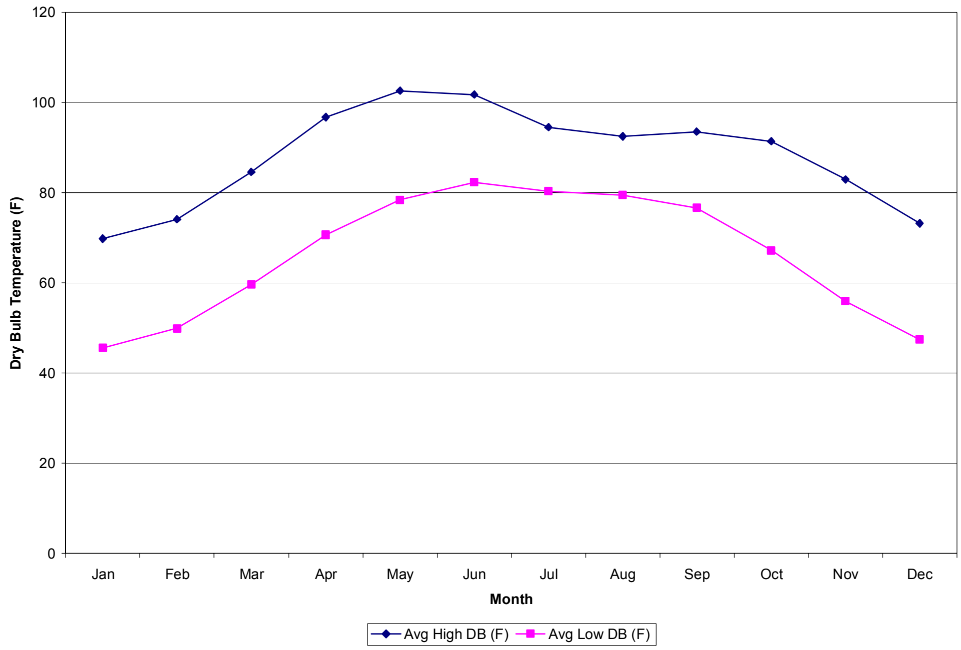

Fig. D-5. Monthly Average High and Low Dry Bulb Temperatures for Delhi

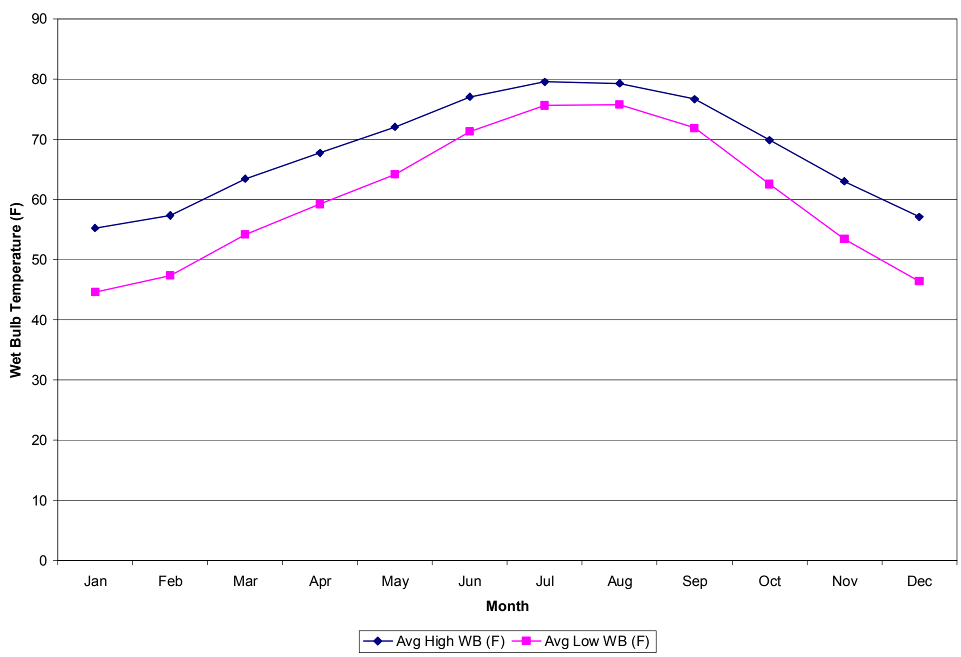

Fig. D-6. Monthly Average High and Low Wet Bulb Temperatures for Delhi

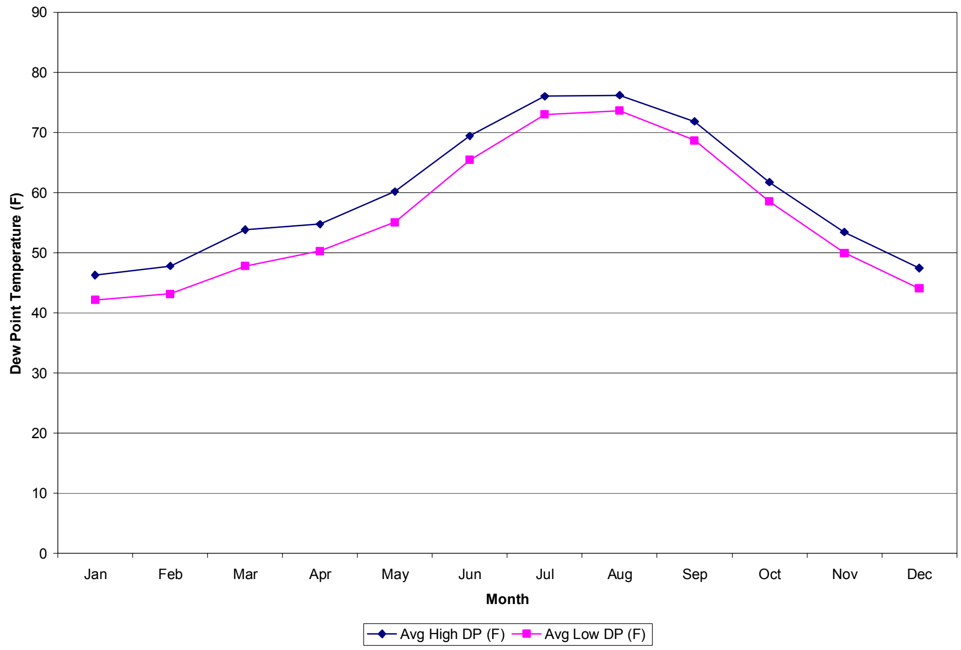

Fig. D-7. Monthly Average High and Low Dew Point Temperatures for Delhi

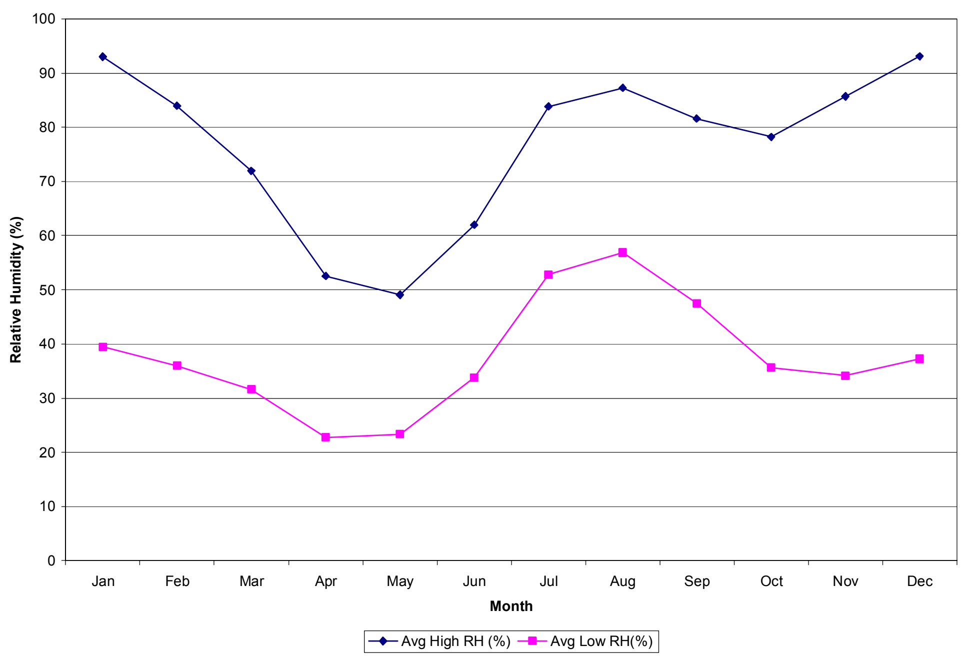

Fig. D-8. Monthly Average High and Low Relative Humidity for Delhi

VITA

Vijaya Yellamraju
5604 Southwest Parkway, Apt 1024,
Austin, TX, 78735
yvijaya@hotmail.com

EDUCATION

M.S. Architecture, Texas A&M University, College Station, Texas, 2004 GPA: 4.0
Dip. in Architecture (5yrs), Sushant School of Art and Architecture, India, 1995-2000

GRADUATE COURSEWORK

Data Processing in Environmental Design, Environmental Control Systems, Applied Solar Energy, Study of Intelligent Building Skins, Daylighting Seminar

WORK EXPERIENCE

Department of Architecture, Texas A & M University Jun'02 – Sep'03
Graduate Assistant: Designed and developed online courses with WebCT; created course websites using html editors; designed and commissioned a design studio class online.
Graduate Teaching Assistant: Assisted in teaching an undergraduate class on Design Methods and graded presentations of the students besides coordinating class work and interacting with students for their problems.

Lakeer Architects & Interior Designers, Secunderabad, India Jun'01-Dec'01
Junior Architect: Responsible for design and construction drawings, client presentations and site supervision, for a number of projects which included Sujata Schools, Ramoji Film City and National Games Village

Kanvinde Rai & Choudhury Architects and Planners, India Jan'00-April'01
Assistant Architect: Contributed at various levels of design-development: from concept to final commissioning of buildings; prepared working drawings, conducted site inspections, made client presentations, did market surveys and cost estimation; major projects include the Computer Science Engineering Block and the Girls Hall of Residence at the Indian Institute of Technology (IIT), Kanpur, India

HONORS

- Preston Green Scholarship from the Texas Architectural Foundation for 2003-04
- Paul & Katie Stein Scholarship from the Texas Architectural Foundation in 2002-03
- Ansals Gold Medal for academic performance and extracurricular activities in 1998-99
- Scholarship in 1999 from college, in recognition of academic merit
- Gold Medal in school for consistent academic performance in 1993