ROLE OF INSULATION IN ENERGY CONSUMPTION IN COMMERCIAL AND OFFICE BUILDINGS

Submitted by

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Abstract

Buildings, as climate modifiers, are usually designed to shelter occupants and achieve thermal comfort in the occupied space backed up by mechanized cooling and heating systems as necessary. This heating and air-conditioning load can be reduced through many means; notable among them is the proper design and selection of building envelope components. The effect on reduction in energy consumption by using insulation materials is the major thrust of this project. The life cycle energy cost of a building has been realized to be critical to the energy consumption in buildings, which is reaching a serious proportion, as the energy needs have to be met for the fast growing population and also to sustain the development. The life cycle cost of a building, includes the initial cost, energy cost, other operation and maintenance cost. The effect of increase in the initial energy cost, constituted by the insulation materials to the energy savings that can be obtained, is studied by simulating two case buildings chosen, using eQUEST simulation tool. Parametric studies were carried out with different insulation materials at different climatic conditions in Indian context. Correlation between the resistance and thickness of the insulation material, to the percentage of energy savings were found to obey a logarithmic relationship. The life cycle energy cost analysis showed that energy savings up to 47% could be achieved during a 50 year life span of a building, with a very negligible increase in embodied energy due to the insulation materials.

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Summary of the contents of the report

Chapter 1 presents the ingenious constructive solutions developed in the past that could fulfill several assignments simultaneously. The construction industry at present has brought forward new architectural concepts, which need performance assessment of buildings. It also presents the overview on the objectives, scope and work methodology of the project.

Chapter 2 reports different potential approaches to assess the buildings performance. This chapter analyses the capabilities of available integrated simulation programs, which leads to the conclusion to choose one of the software to perform the assessment of the building performance (thermal, lighting, ventilation), the occupant comfort.

Chapter 3 focuses on the model developed in the software for existing buildings, with sufficient information to support the software, and its assessment. The model developed is simulated in accordance to the actual materials used in the construction of the building with the actual climatic file referring to the original location of the buildings. Further, the simulated output values are compared with the actual data collected, to assess the capability of the software used.

Chapter 4 presents the life cycle energy calculation done for both the case buildings, which specifies the embodied energy of the building envelope components and the different insulation materials.

Chapter 5 presents the analysis done with the same buildings, by varying different parameters at different climatic regions in India. The aim is to check whether insulation material is the only key factor in energy consumption of the buildings. It also presents the evaluation of the life cycle energy of the buildings pertaining to the embodied energy and the energy consumed every year during its entire life span. The results of all the parametric studies and life cycle energy costing done are discussed.

Chapter 6 presents the conclusions derived from the analysis performed in the previous chapter and strategy developed to minimize the sum total of energy consumed during the entire life span of the building.

CHAPTER – 1 INTRODUCTION

Every major civilization has developed an architecture with characteristic lines as specific as its language, costumes or folklore. For thousands of years, the humans has developed architectural concepts to provide acceptable comfort in a specific environment, taking into account local climatic conditions, available for construction materials, as well as cultural and religious aspects.

With modern architecture an important concern of the scientific community, is to resolve specific problems the building industry is confronted with. But the necessity for an efficient construction industry has brought forward new architectural concepts, which need performance assessment of buildings. This chapter presents several ingenious systems developed through time that could fulfill several assignments and illustrates the consequences resulting of a lack of building assessment in appraising the building performance in modern architecture. It also presents the objectives, Scope and work methodology of this project.

1.1 CONSTRUCTIVE SOLUTIONS OF THE PAST

Vernacular architecture, which can be regarded as a sustainable and natural contract between man and nature, is the fruit of imagination, years of evolution and climatic requirements. It was limited to the local materials and techniques available at a given time. Transport was limited, which reduced the use of imported materials. This led to constructive concepts that took into account not only occupant comfort but also the local resources and the environmental impacts of the use of the construction. Vernacular architecture was able to provide many concepts to maintain comfortable conditions while striking a balance with the environment as it can be illustrated with the following examples.

Providing daylight and ventilation simultaneously was an important issue, which was solved in different ways. In ancient Egyptian period (2635-2155BC), it was not conceivable to bore through thick temple roof and walls. To solve the problem, small slots were pierced at the junction of the flat roof and the temple wall (sphinx temple). Because of their size and location, these slots faintly lighted the upper part of the walls.

In small temples or in dwellings, where the roof was thinner, small apertures were bored through the roof-terrace, to improve day lighting and ventilation. The new empire (1550-1080BC) found a way to improve the efficiency of these apertures, by taking into advantage of the level difference between roof-terraces. For instance, in the Ammon temple in Karnak, louvers were pierced into vertical slabs (walls) to provide better ventilation and allow the light to enter obliquely, which avoided glare problems as shown in figure 1.1.

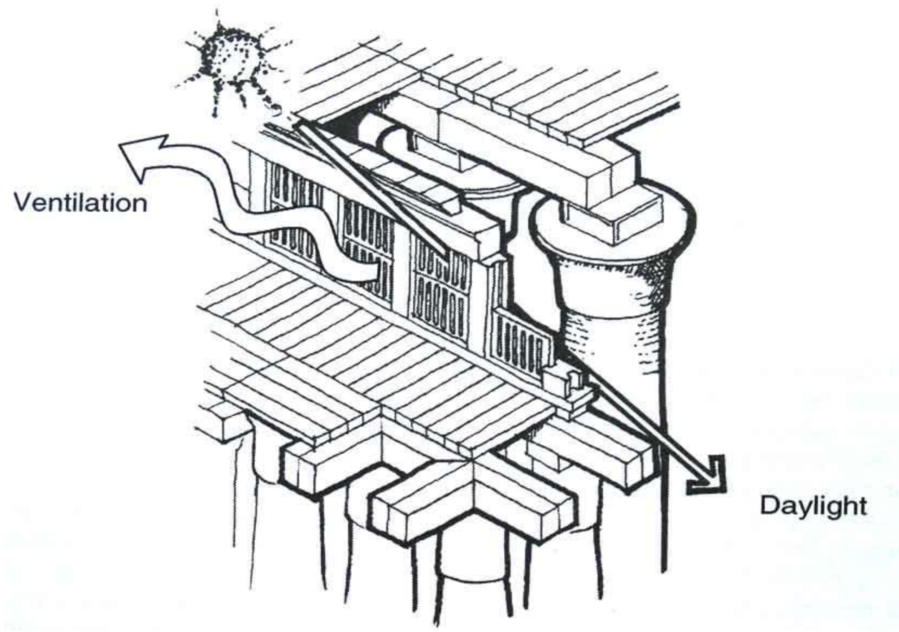


Figure 1.1: Clerestory of the hypostyle hall of the AMMON temple, Karnak.(source: Moore F)

The summerians (Mesopotamia, 3000-2000BC) are at the origin of several of the most outstanding human inventions, such as the wheel, the cuneiform writing or architectural concepts such as the vault. To avoid, overheating, they covered roofs with about 1 meter of earth. But the load induced by the weight on the roof reduced its span, because palm-tree was used for the structure. Therefore, houses were narrow and long, which complicated their natural ventilation. Thus, the occupants comfort was directly related to the structure. The evolution of this roof-terrace concept led to the famous suspended gardens of Babylon. They were located near wells, from which an astute system raised water to the roof construction for the irrigation of the gardens. Water evaporation reduced the ambient temperature and the roof cover reduced house overheating.

For many centuries, vernacular architecture has been seen as the product of an evolutionary process in which most suitable forms have survived by designing comfortable architectural spaces that respect local climatic conditions.

In the evolution of time, the occupants' necessity for buildings serving for their specific purpose has been evolved. Among them Office and commercial buildings have more significance in the present.

1.2 OFFICE AND COMMERCIAL BUILDINGS OF THE PRESENT

Office buildings provide the working environment for a large and increasing proportion of the Indian workforce. There are considerable diversity in the type and location of buildings used as offices throughout India. The principal requirement of office buildings is to provide comfortable, healthy and productive conditions for the workers. However costs, both capital and running, play an increasingly important part in decision-making for design, fitting out, etc. With increasing international concern about energy use and its environmental consequences, another dimension is becoming increasingly important, that of energy consumption in offices and the component production of carbon dioxide, and other ways in which offices can affect local and global environments.

New buildings are frequently thought to provide more prestigious and efficient offices than older buildings. There are basically two different approaches to achieving good internal conditions in an office-using natural force as far as possible, or relying on mechanical equipment. Natural methods include day lighting, thermal insulation, solar gain, opening windows, solar shading, and free cooling using thermal mass. On the other hand, modern offices in many countries are built to rely on artificial lighting, heating cooling, and ventilation using mechanical equipment and sophisticated automatic control systems, and this trend also affects refurbishment. The energy consumption of offices with sophisticated mechanical systems is always many times higher than that of climate respecting buildings which minimize such equipments by use of natural forces.

However it must be remembered that 'comfort' can be defined in a number of ways and has different meanings to different people. Whilst an air-conditioned office can provide temperatures within a closely defined range (typically 19 to 23degree Celsius(66.2F to 73.4F), a naturally ventilated office will have much higher temperatures in summer, though the effects of an open window and moving fresh air can make these equally or more acceptable. Similarly, an artificial lit office with tinted windows to reduce glare and solar gain will provide a consistent light level, but the changing light levels and clear views from a day lit office may provide a more pleasant and stimulating environment. Some research has demonstrated the importance to a person's perceived level of comfort, of individual control over the local environment, a concept becoming known as 'adaptive opportunities'.

To maintain external and visual comfort level there is a large amount of energy need, in offices with sophisticated mechanical systems. Moreover, these buildings demand energy in their life cycle, both directly and indirectly. Directly, for their construction, operation (operating energy), rehabilitation and eventually demolition. Indirectly through the production of materials they are made of and the materials technical installations are made of (embodied energy). There has been always a need to know the building performance in such cases during its life span, in its construction phase and operation phase.

1.3 NEED FOR BUILDING ASSESSMENT

The building sector is responsible for a large share of the worlds total energy consumption. The international Energy Agency (IEA 2005) estimates that buildings account for 30-40% of the worldwide energy use, which is equivalent to 2500 Mtoe (million tons of oil equivalent) of energy every year. Buildings are large users of materials with a high content of embodied energy.

Energy is also used for heating, cooling, lighting, cooking, ventilation and so on during the period that the building is in use. Over the years this adds up to significantly more energy than is used for manufacturing building materials and for constructing the building itself. In some of literatures, however, lowering the overall energy consumption has a direct positive impact upon life cycle costs. For which, there is a need to assess the performance of the building during its operation stage and at the construction stage.

1.4 OBJECTIVES OF THE PROJECT

As climate modifiers, buildings are usually designed to shelter occupants and achieve thermal comfort in the occupied space backed up by mechanized cooling and heating systems as necessary. Significant energy savings could be realized in buildings if they are properly designed and operated. The energy consumed can be reduced through many means: notable among them is the proper design and selection of building envelope and its components. Studies have been carried out on the building envelope and its components. The impact of operating temperature on the thermal performance of insulation materials has been the subject of some studies. Optimization of insulation thickness for building using life cycle costs has been discussed by T.M. Mahlia [1]. Performance characteristics of thermal insulation materials have been studied by Dr. Mohammad [5].

Further, studies indicate that opportunities for energy efficiency in buildings, is achievable by many means. The diversity of buildings and their distinct use imply major differences of energy conservation models. No single legislative rule can be effective in all case. The energy sources used, methods applied and equipment added are to be tailored according to individual needs. The same applies to building codes, operation guidelines and the monitoring of their implementation. There is no study made on the relative importance of operating and embodied energy in a building life cycle, in specific to Indian context, in office and commercial buildings, with the building codes taken into account. Hence this study is focused towards the same with the following objectives:

1. To evaluate the role of thermal insulation in energy consumption in office and commercial buildings.
2. To analyze the role of thermal mass and storage in relation with the energy consumption of a building.
3. To evaluate the Life cycle energy of a building pertaining to the embodied energy (pre-occupation) and the energy consumed every year (post occupation).
4. To prepare a strategy to minimize the sum total of the energy consumed during pre-occupation and post occupation.

1.5 SCOPE AND WORK METHODOLOGY OF THE PROJECT

With the above objectives in consideration the project had been phased into two. The first phase of the project is to choose appropriate software to perform the simulation of namely two buildings. The second phase is to obtain a methodology or develop a model to calculate the Life cycle energy cost of a building.

PHASE – I

In the first phase of the project work data on two buildings were collected, and the simulation was performed for the same using the appropriate software. As the first step, soft wares available for simulation were studied and an appropriate one for the same was chosen. As the Second step data on the two buildings such as their plans, sections and elevations and their actual energy consumption data was collected. As the third step the chosen buildings was modeled and the simulation was performed for the same. In the fourth step the results were compared with the actual data to validate the software chosen. And in the fifth step simulations were performed with different insulating materials for the same buildings, to analyze the fact that if insulation is the only key factor affecting the energy consumption of these buildings.

PHASE - II

The second phase was focused on to obtain a methodology or develop a model to evaluate the life cycle energy cost of the building. Life-cycle costing accounts for initial cost, energy cost, other operating and maintenance cost (including labor), life of each component forming the system; discount rate, inflation and escalation of some cost items such as energy cost, and salvage value of each component when its life is expired. The first two items dominate in our case. In the application of life cycle costing principle to determine the role of insulation, to analyze if it is the key factor affecting the energy performance, or is there other building systems that play an important role in minimum performance, extensive examples of alternative insulating materials and systems of different performance had to be simulated and their life cycle energy costs had to be evaluated.

In summary, this chapter has shown that through time, architecture has developed ingenious constructive solutions that could fulfill several assignments simultaneously. The limitation of available materials and construction process was compensated by long experience leading to a constructive balance between occupant requirements and environmental impact. The significance of reducing the overall energy consumption of a building necessitates the need for building performance assessment and to analyze the factors affecting the energy consumption. This complexity calls for to focus on the objectives of the project. The next chapter presents the review of available tools for building performance assessment, and describes the eQUEST simulation tool.

CHAPTER – 2 LITERATURE REVIEW

At all times, the analysis of physical phenomena was dependent on technical developments and scientific knowledge. In the past, performance assessment relied on thumb rules and hand calculation. At present, the advent of building simulation programs has enabled non-trivial performance appraisals. The current generation of application for the assessment of building performance ranges from simple spreadsheets based on simplified calculation methods to advanced programs, which allow the simulation of transient physical processes using complex numerical methods. In general, these programs deal, however, only with a small of the overall problem.

Advanced architectural developments require an integrated approach to design. The domains of heating, lighting, ventilation and acoustics, for example, are often closely related and it is only by taking into account their interactions that a complete understanding of building behavior can be obtained. This chapter begins with a comparison of various methods developed to perform a multiple-view appraisal of building performance. The chapter follows with an analysis of the different simulation program types that support multiple-view assessment. Finally, the most common simulation tools available on the market are compared.

Over the past 50 years, literally hundreds of building energy programs have been developed, enhanced, and are in use throughout the building energy community. The core tools in the building energy field are the whole-building energy simulation programs that provide users with key building performance indicators such as energy use and demand, temperature, humidity, and costs.

2.1 FACTORS AFFECTING ENERGY CONSUMPTION

Modern buildings consume energy in a number of ways. Energy consumption in buildings occurs in five phases, as shown in figure 2.1.

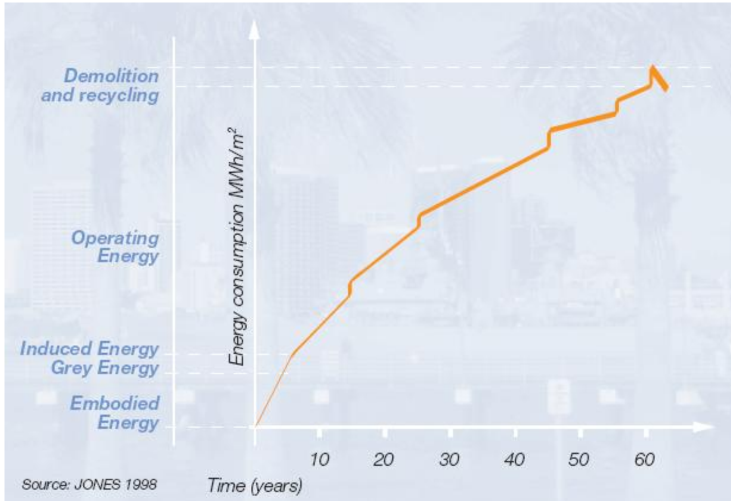


Figure 2.1: Energy consumed in the life of a building (source: UNEP)

The first phase corresponds to the manufacturing of materials and a component, which is termed, embodied energy. The second and third phases correspond to the energy used to transport materials from production plants to the building site and the energy used in the actual construction of the building, which are respectively referred to as grey energy and induced energy. Fourthly, energy is consumed at the operational phase (operation energy), which corresponds to the running of the building when it is occupied – estimated till 50 years. Finally, energy is consumed in the demolition process of buildings as well as in the recycling of their parts, when this is promoted (demolition – recycling energy). The major factors that affect the energy consumption of a building at the first four phases are:

a. Building envelope

The building wall is affected by all three heat transfer mechanisms; conduction, convection, and radiation. The incoming solar radiation into the outer wall surface will be converted to heat by absorption and transmitted into the building by conduction. At the same time, convective thermal transmissions occurs from air outside of the building to the outer surface of the wall and the inner surface of the wall to the air inside of the building. It makes portion of heat gains from the outside of the building wall occurs and by air leakage since the inner building area has lower temperature. K.S. Al-Jabri [ ] has reviewed his research on use of insulating materials is not popular, despite their long term financial benefit. His research is concerned with the development of light weight concrete blocks for thermal insulation either by using different hole arrangements or by using indigenous and by-product materials. T.Nussbaumer, as part of research programme on

“High performance Thermal Insulation in buildings and building systems” of IEA agency, determined the thermal performance of vacuum-insulation panels applied to walls I building constructions.

b. Building Materials

Y.G.Yohanis, in his studies [12] has concluded that initially embodied energy in a building could be as much as 67% of its operating energy over a 25 year period. The building materials used initially directly constitute to the embodied energy, which includes extraction, processing, manufacture and transport of the materials and its components. The relative significance of embodied energy forms a higher proportion of the total amount of energy used over the lifetime of a building. Potential to reduce energy consumption at the initial stages, in the materials selection plays a vital role.

c. Lighting systems

Reduction in energy use in one system can affect the energy use in another system. In Bangkok, lighting savings lead to significant reductions in energy used for cooling and ventilation systems [15]. Even in extreme cases of Sweden, commercial buildings enjoy a net HVAC benefit from lighting savings. According to studies at Chalmers university, typical modern Swedish buildings require cooling even at an out door temperature of -10degree Celsius. This is because of considerable internal heat generated by people, lighting and other energy-using equipment.

d. Energy supply systems

The operational energy normally accounts for the major part of the total energy used in buildings [12]. Therefore it is of great importance to have energy efficient system, that which provides good indoor conditions without consuming too much energy. These can include energy saving appliances, lighting controls and thermostats, activated blinds, fans, efficient heating systems and cooling systems. It should be noted that energy systems are usually designed for 20 to 40 years and if they are not chosen carefully, the potential to change to a different energy source may be lost for that period.

The pattern of the energy use of a building first and foremost depends on the building type and the climate zone where it is located. In addition, the level of economic development in the area is also influential in shaping the energy use-pattern. Shares of different energy uses during the operational phase of the building are shown in figure 2.2.

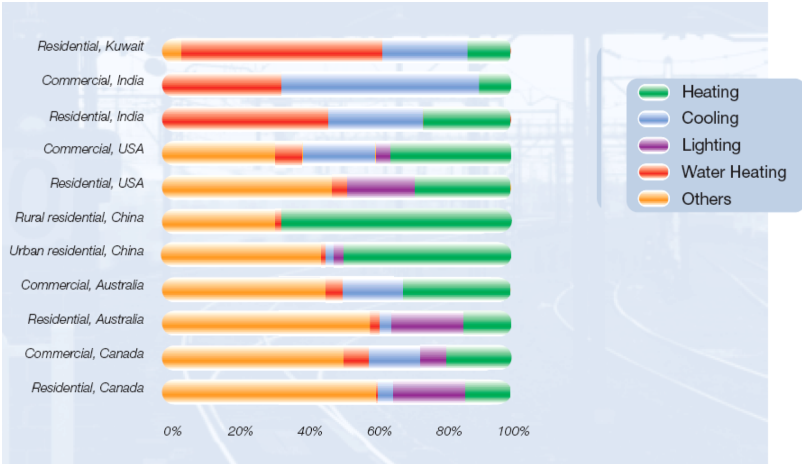


Figure2.2: Shares of different end-use purposes in some countries. (Source: Department of energy 2006, U.S, office of energy efficiency, natural resources Canada, 2006.)

It shows that in terms of international averages, most residential energy in developed countries is consumed for space heating. Building type usually sets different requirements for the indoor climate and internal loads. The impact of climate differences also affects the energy demand in a building. In order to achieve large scale energy efficiency improvements, a range of different approaches have been studied. Researches carried out in different countries are focused to the local needs.

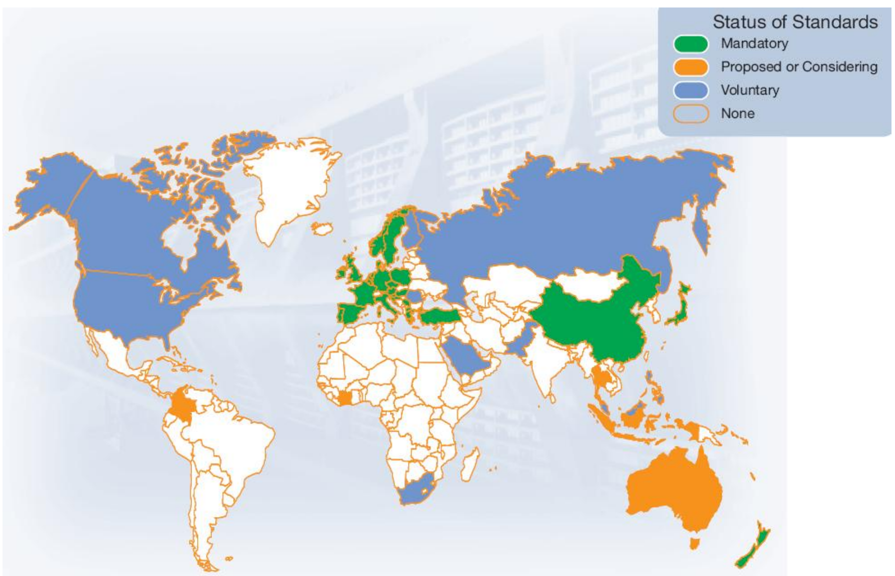


Figure2.3: status of Building standards (Source UNEP)

There are different strategies for using legislative instruments to control energy consumption level of buildings. Scandinavian countries generally use national building codes and standards, which regulate physical, thermal and electrical requirements of building components, service systems and equipment. The regulations also cover indoor conditions, health and safety standards, operation and maintenance procedures and energy calculation methods. Some codes accept limited compensation between building components; for instance, the glass area may for instance be increased, if the exterior wall insulation is also improved. Building codes are crucial to help induce the improvement of the energy efficiency of the building sector. A number of building codes currently include energy performance standards, limiting the amount of energy that buildings can consume. In India the codes that are specific to energy consumption are ECBC standards 2006 [2], and ASHRAE 90.1.-2004 [6] is followed for LEED rating system of buildings. The LEED Green building Rating System is a voluntary, consensus-based, market-driven building rating system based on existing proven technology. It evaluates environmental performance from a whole building perspective over a building's life cycle, providing a definitive standard for what constitutes a "green building". Both these standards have given importance and strategies of use of thermal insulation materials in buildings. In AHRAE 90.1-2004, sections 5.4 and 5.5 gives the mandatory provisions of insulation materials to provided for the walls, roofs, and floor. Section 5.8 specifies the insulation product information and installation requirements. ECBC standards specify the prescriptive requirements of insulations in section 4.3 for roofs, opaque walls.

2.2 THERMAL INSULATION

Thermal insulation is a material or combination of materials, that, when properly applied, retard the rate of heat flow by conduction, convection, and radiation. It retards heat flow into or building due to its high thermal resistance.

Thermal insulating materials resist heat flow as a result of the countless microscopic dead air cells, which suppress convective heat transfer. It is the entrapped air within the insulation, which provides the thermal resistance, not the insulation material.

2.2.1 Available types of Insulation

Many types of insulation are available which fall under the following basic materials and composites:

1. **Inorganic materials:**
    a. Fibrous materials such as glass, rock, and slag wool.
    b. Cellular materials such as calcium silicate, bonded perlite, vermiculite, and ceramic products.
2. **Organic materials**
    a. Fibrous materials such as cellulose, cotton, wood, pulp, cane, or synthetic fibers.
    b. Cellular materials such as cork, foamed rubber, polystyrene, polyethylene, polyurethane, polyisocyanurate and other polymers.
3. **Metallic or metallized reflective membranes**. These must face an air-filled, gas-filled, or evacuated space to be effective.

Accordingly, insulating materials are produced in different forms as follows:

a. Mineral fiber blankets: batts and rolls (fiberglass and rock wool)
b. Loose fill that can be blown-in (fiberglass, rock wool) , poured in, or mixed with concrete (cellulose, perlite, vermiculite)
c. Rigid boards (polystyrene, polyurethane, polyisocyanurate, and fiberglass).
d. Boards or blocks (perlite and vermiculite).
e. Insulated concrete blocks.
f. Reflective materials (aluminum foil, ceramic coatings).

2.3 THERMAL MASS

Massing of the building structure is influenced by the seasonal and daily temperature variations, which determine the need for thermal resistance and mass of the building structure. Thermal mass reduces heat gain in the structure by delaying the entry of heat into the building. Building thermal mass plays a more significant role in dry climates with

a. High daily summer temperatures.
b. Large diurnal ranges.

2.4 TOOLS AVAILABLE FOR ASSESSMENT OF BUILDINGS AND THEIR COMPARISONS

A number of comparative survey of energy programs have been published, most recently, "Contrasting the capabilities of Building Energy Performance Simulation programs" published by Drury B.Crawley, Jon W. Hand, Michael Kummert and Brent T. Griffith, gives an up-to-date comparison of the features and capabilities of major building energy simulation programs: BLAST, BSim, Dest, DOE-2.1E, ECOTECT, Ener-Win, Energy Express, Energy-10, Energy Plus, eQUEST, ESP-r, IDA ICE, IES, HAP, HEED, PowerDomus, SUNREL, Tas, TRACE and TRANSYS. The comparison is given in appendix 1. The conclusion of this report is that, who have specific simulation tasks or technologies in mind should be able to identify the likely tool. Hence, with objective of the project in mind, eQUEST was chosen to use it for modeling the chosen buildings.

2.5 eQUEST VERSION 3.55

eQUEST is an easy to use building energy use analysis tool which provides professional-level results with an affordable level of effort. This is accomplished by combining a building creation wizard, an energy efficiency measure (EEM) wizard, and a graphical results display module with an enhanced DOE2.2 – derived building energy use simulation program.

eQUEST features a building creation wizard that walks through the process of creating an effective building energy model. This involves following a series of steps that describe the features of the design that would impact energy use, such as architectural design, HVAC equipment, building type and size, floor plan layout, construction materials, area usage and occupancy, and lighting system.

After compiling a building description, eQUEST produces a detailed simulation of the building, as well as an estimate of how much energy it would use. Although these results are generated quickly, this software utilizes the full capabilities of DOE-2.2.

Within eQUEST, DOE2.2 performs an hourly simulation of the building design for a one year period. It calculates heating or cooling loads for each hour of the year, based on the factors such as walls, windows, glass, people, plug loads, and ventilation. DOE-2.2 also simulates the performance of fans, pumps, chillers, boilers, and other energy consuming devices. During the simulation, DOE-2.2 also tabulates the building's projected use for various end uses.

eQUEST produces several graphical formats for viewing the simulation results. For instance, graphing the simulated overall building energy on an annual or monthly basis or comparing the performance of alternative building designs. In addition, eQUEST allows performing multiple simulations and viewing alternative results side-by-side graphics. It produces energy cost estimating, day lighting and lighting system control, and automatic implementation of common energy efficiency measures (by selecting preferred measures from a list). This reasons for selecting this software was, the ease to interface with auto cad drawing, user interface to input the data, and the tool being a free tool.

Input to the program consists of a detailed description of the building being analyzed, including hourly scheduling of occupants, lighting, equipment, and thermostat settings.

CHAPTER – 3 CASE STUIES & SIMULATIONS

The previous chapters have described in detail the necessity, the elaboration and finally the implementation of a data model that enables assessment of building performance. The present chapter, which is a significant part of the study, presents the overall performance obtained for an office and a commercial building as modeled in eQUEST. The simulation results have been compared with the actual energy consumption metered in the building during the occupancy of the building for the year 2006. This chapter also presents the validation of the simulation performed using eQUEST.

3.1 THE INFOTECH BUILDING

The INFOTECH building, one of the IT buildings in Chennai, was selected as a case study because: (1) the wall and floor slab sections were different from other buildings, and (2) for the proximity and the ease of collection of data for the same.

3.1.1 BUILDING DESCRIPTION

The INFOTECH building is a four story office building, constructed in 2003-04 in Chennai, a city in southeast coast of India (Latitude 13.04 N, Longitude 80.17E, altitude- 6m). The building comprises seminar halls, conference rooms and museum in ground floor, and open offices in the top four floors (2400 Sqm each floor). The open office space is built as a column free space; the concrete floor slab is supported by the 6" thick shear concrete walls at the periphery, and by the central service core of the building.

Figure 3.1: Exterior 3-d View of INFOTECH building.

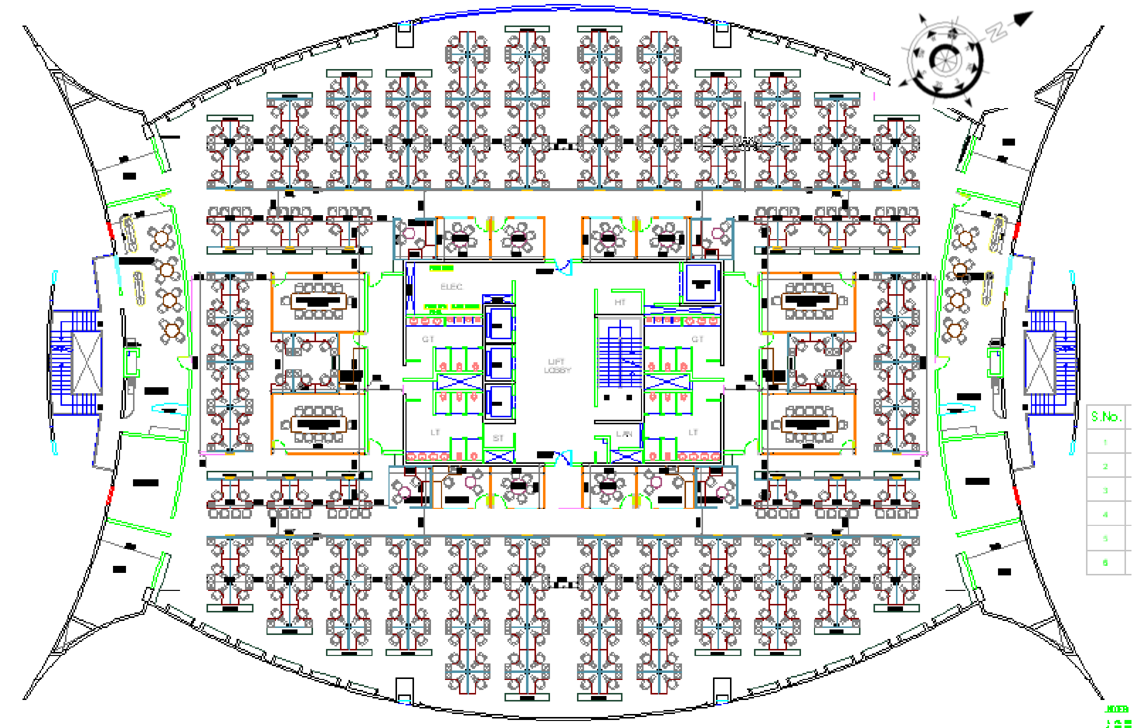


Figure 3.2: Plan of INFOTECH Building (typical open office plan)

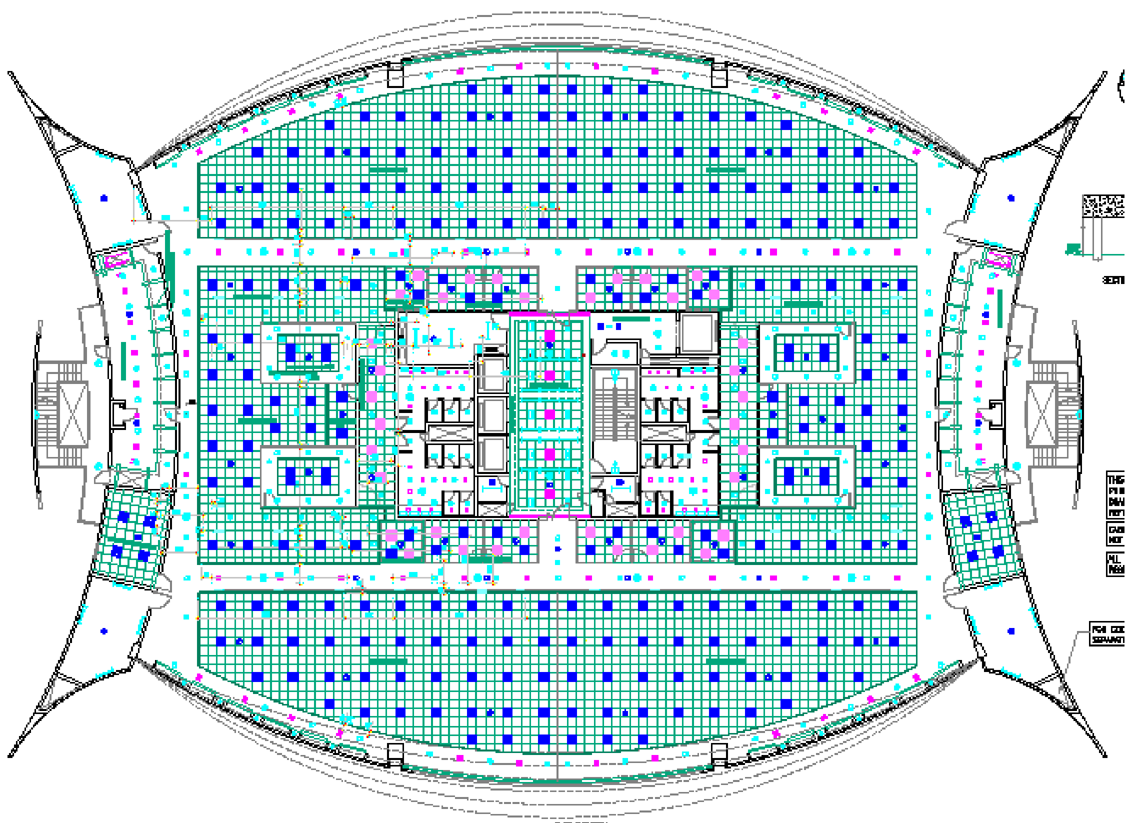


Figure 3.3: False ceiling Plan of typical office floor, INFOTECH Building

5m 10m

Figure 3.4: Different views of INFOTECH Building.

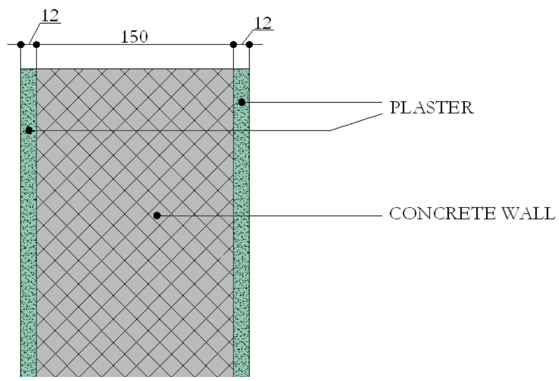
3.1.2 SPACE SUMMARY

The building use spaces are classified into major zones as: (1) office – open plan, (2) Auditorium (3) Corridor (4) Lobby (5) Restrooms (6) Conference Rooms (7) Mechanical / Electrical room (8) All others. The table 3.1 gives the space summary.

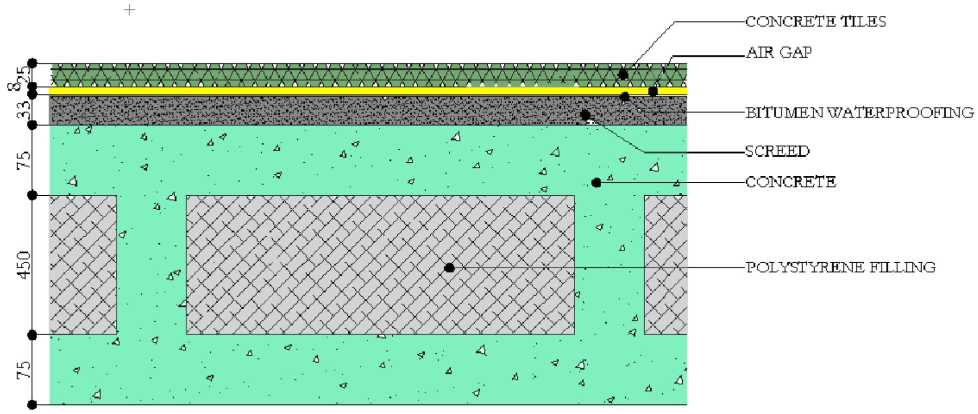
Building Use	Conditioned Area (Sqm)	Unconditioned Area (Sqm)	Total (Sqm)
Office (open plan)	**8848.32**		**8848.32**
Auditorium	**712.75**		**712.75**
Corridor	**414.77**		**414.77**
Lobby	**370.44**		**370.44**
Restrooms		**545.31**	**545.31**
Conference Rooms	**874.38**		**874.38**
Mechanical/Electrical rooms		**196.68**	**196.68**
All others	**26.35**		**26.35**
Total	**11247.04**	**742.00**	**11989.05**

Table 3.1: Summary of the building use spaces of INFOTECH building.

3.1.3 BUILDING ENVELOPE COMPONENTS



Section of external wall (dimensions in mm)



Roof slab section detail

Figure 3.5 Details of constructions, Roof slab & External Wall.

The envelope of the building is 6" thick shear concrete walls, plastered on both sides, with a u-value of 4.33 W/m^2K (0.763 $Btu/h.ft^2.F$). The details of construction of the external wall, and roof slab are shown in figure 3.5. The roof slab has a u-value of 0.028 W/m^2K (0.005 $Btu/h.ft^2.F$).

3.1.3.1 WINDOWS

The INFOTECH building has Double glazing systems of Saint Gobain, for the facade. They are made of double clear float panes with air gap in between. The properties of the glazing are

1. Shading coefficient = 0.23
2. U-value = 2.895 W/m^2K (0.51 $Btu/h.ft^2.F$).
3. Visual Light transmittance = 0.15
4. Emissivity = 0.84

The table 3.2 summarizes the window area in the external fazard of INFOTECH building, and the glass details.

Description	South East	North West	North East	South West	Total
Wall Area	13869.36	14245.2	17416.08	17416.08	62946.72
Total Window Area	4460.882	1594.437	1594.437	4282.585	11932.341
Fixed Window Area	3904.202	943.367	1179.347	3867.495	9894.411
% of Window area	37.385	13.362	13.362	35.891	

Table 3.2: Details of window area in the fazard of the INFOTECH building.

3.1.3.2 Artificial Lighting

The Open office spaces are lit with Compact fluorescent lamps (2 X 36 W), and the corridors with Compact fluorescent lamps (2 X 18 W). There is no control at every desk, but for they are controlled in different zones.

3.2.3.3 Occupancy Density and Design Ventilation

The INFOTECH building uses Multi zone Air handler, with chilled water coils as its HVAC systems. The Fan control is of Variable speed drive. Four Screw type chillers of 163 ton each, which gives output at 1.407kW/ton full load efficiency. The more detailed data of the HVAC system type used is tabulated in table 3.3.

Mechanical systems	
HVAC System Type(s)	1. Multi Zone Air Handler. 2. Chilled Water Coils
Design Supply Air Temperature	20 ºF
Fan Control	VSD Control
Fan Power	4 in WG, Standard Supply.
Economizer Control	No
Chiller Type, Capacity, and Efficiency	4, 163 ton VSD, Screw Type chiller: 1.407 KW/ton full load efficiency, Variable Speed control for part load operation.
Chilled Water Loop and Pump Parameters	Variable Primary Flow with 647 gpm variable speed pump. Chilled Water Fixed temperature at 45ºF
Condenser Water Loop and Pump Parameters	Constant Flow with 484 gpm, single speed pump, Condenser water temperature 75ºF

Table 3.3: Details of HVAC systems.

3.1.4 COMPUTER MODEL

In order to setup a realistic computer model, it was necessary to find and gather relevant information on the building geometry, construction, usage details. The INFOTECH building was modeled in eQUEST by using the gathered information and the physical properties that were determined from the architectural drawings, and manufacturer data. With the help of these sources, a detailed computer model was setup, representing the whole building. The zones were classified as same as given in the table 3.1 and shown in the figure 3.6.

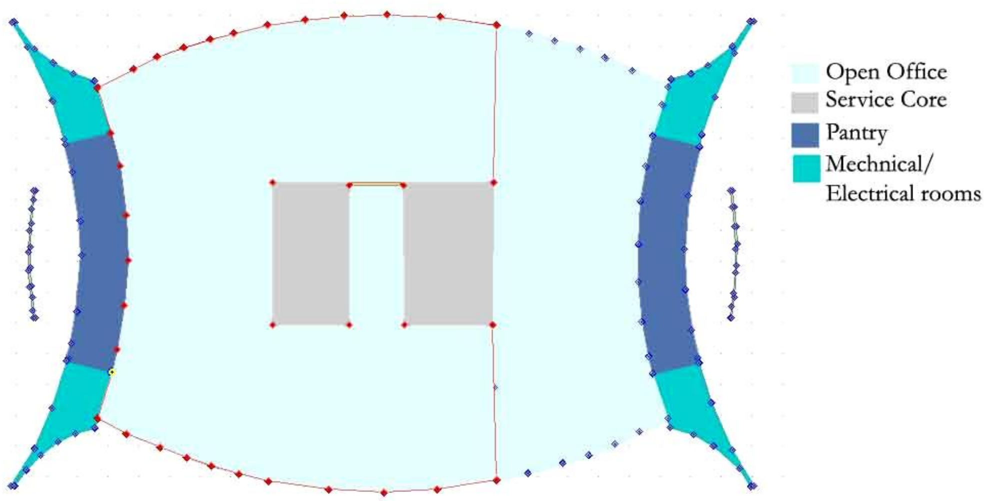


Figure 3.6: Zoning done in a typical floor in INFOTECH building.

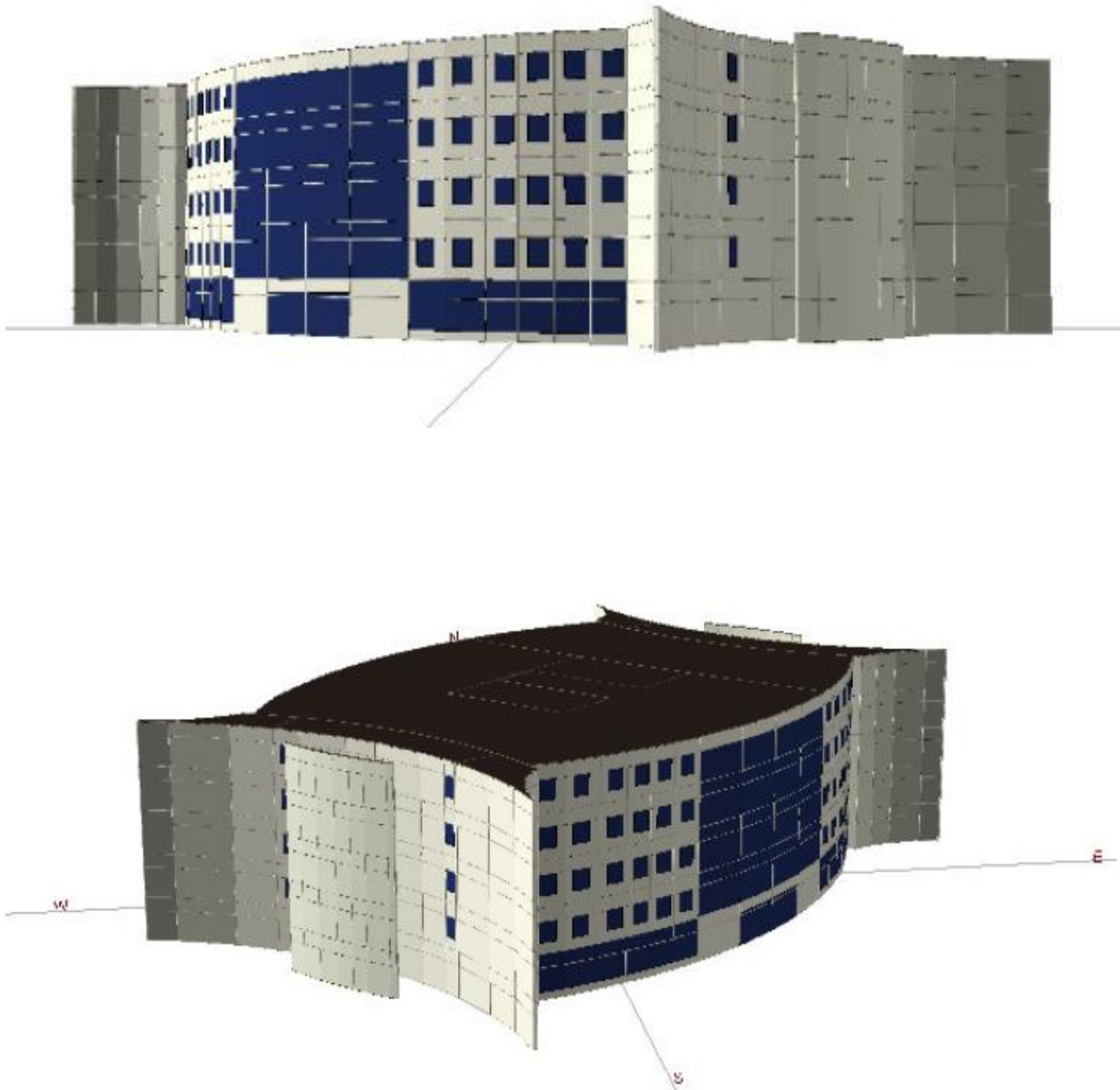


Figure 3.7: Computer model in eQUEST of INFOTECH Building.

The exterior curved walls on the north east and southwest have a tilt of 78º with the ground, which couldn't be modeled in eQUEST. Hence they could be modeled with a tilt of 90º to the ground. Further, the pergolas and other features constructed for aesthetic purpose could not be modeled in eQUEST. The materials used in the buildings, were defined in eQUEST using certain pre defined materials in its library, and also from manufacturers data. The data are documented in appendix C.

3.1.4.1 Occupancy Schedule

The occupancy density for each zones classified are as per the table 3.4. and the people occupy these spaces on weekdays, from Monday to Friday from 9:00AM to 6:00PM, and the office is closed in the weekends. The list of holidays in the year 2006 is also considered. The occupancy profile considered on a weekday is shown in the figure 3.8.

Building Use	Area Percentage	Design Maximum Occupancy (Sqft/Person)	Design Ventilation (CFM/Person)
Office (open plan)	71.9	47	17
Auditorium	5.7	750	5
Corridor	3.3	82	6
Lobby	2.1	163	7
Restrooms	2.6	275	17
Conference Rooms	12.9	47	6
Mechanical/Electrical rooms	1.3	360	17
All others	0.2	275	15

Table 3.4: Occupancy density in different zones.

3.1.4.2 Occupancy Profile

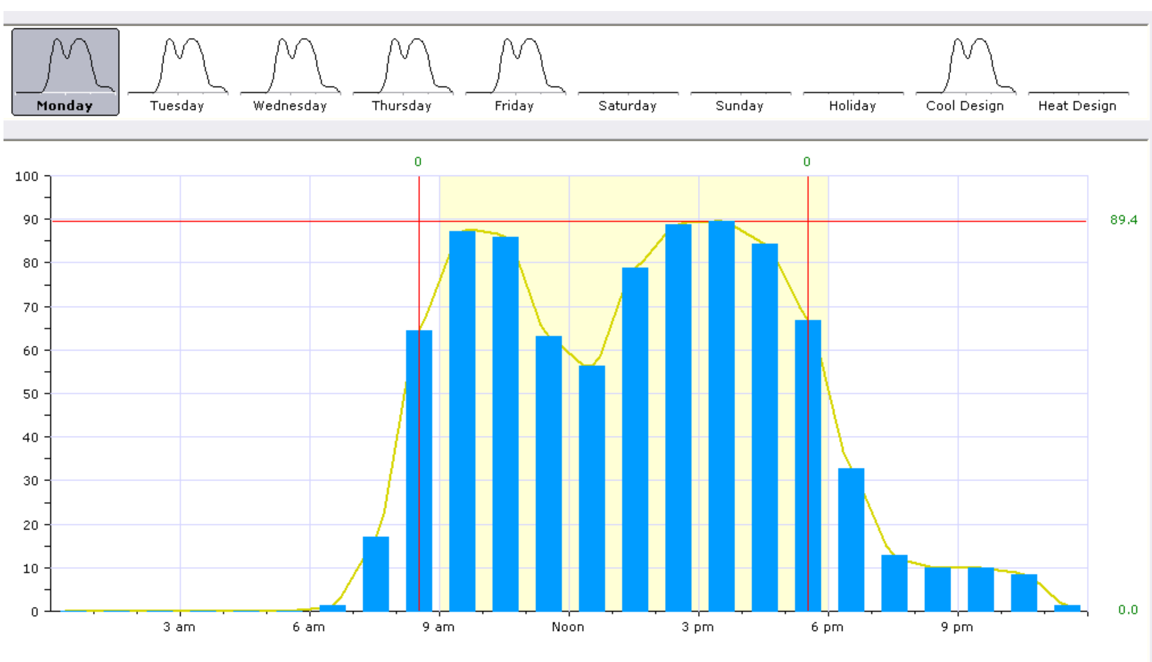


Figure 3.8: Occupancy schedule during a typical working day.

3.1.4.3 Lighting Schedule

The office spaces were lit with ceiling mounted Compact Fluorescent Lamps (2 X 36 W), the corridors were lit with CFL's (2 x 18 W). The Interior Lighting power illuminance was calculated from the as built false ceiling drawings in the classified zone. The lighting power density in the classified zones is as tabulated in table 3.5 and shown in figure 3.9.

Building Use	Area (Sqft)	Lighting Density (Watt/Sqft)	AHSRAE (9.6.1)	Interior Lighting power (Watt)
Office (open plan)	8848.32	10.1	11.1	98644.40
Auditorium	712.75	10.0	9.3	6621.72
Corridor	414.77	10.0	4.6	1926.70
Lobby	370.44	7.0	13.0	4818.19
Restrooms		6.0	9.3	5066.14
Conference Rooms	874.38	18.3	13.0	11372.62
Mechanical/Electrical rooms		8.1	14.9	2923.68
All others	26.35	7.0	9.3	244.84
Total	11247.04	(average) 10.4		131618.29

Table 3.5: Lighting power density at different zones.

3.1.4.4 Lighting profile

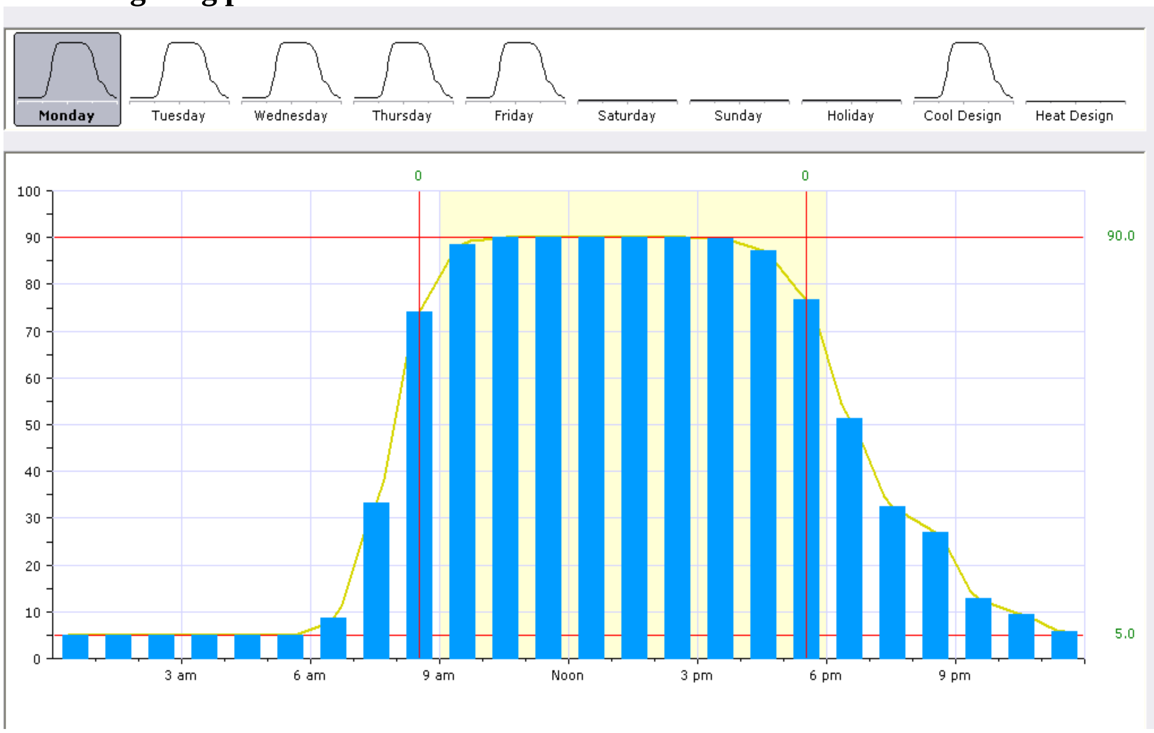
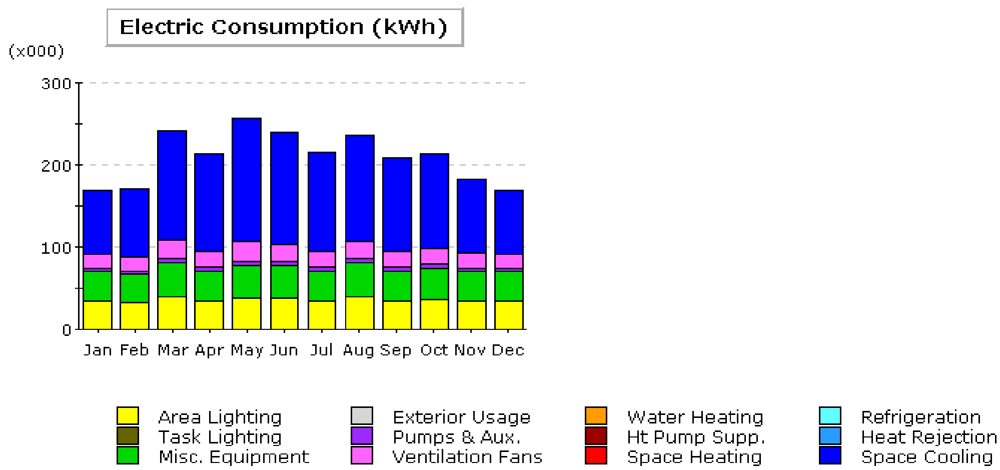


Figure 3.9: Lighting profile of a typical working day.

3.1.5 SIMULATION OUTPUT

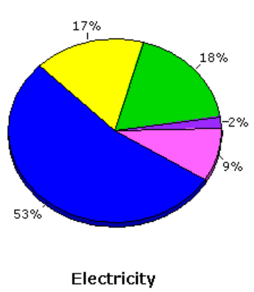
Once established, the computer model was simulated to obtain monthly Energy consumed for space cooling, Area lighting, miscellaneous equipments, ventilation fans and the pumps. They are shown in figures



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	77.1	81.9	133.8	118.2	150.0	136.5	121.7	128.9	114.4	115.7	89.6	78.1	1,345.8
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	16.9	17.5	22.1	19.8	23.7	21.8	19.1	21.4	19.6	19.7	17.5	16.9	236.1
Pumps & Aux.	3.6	3.6	4.9	4.3	4.8	4.7	4.3	4.9	4.3	4.4	3.9	3.6	51.5
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	36.9	34.8	41.8	36.8	40.1	40.0	36.9	41.8	36.7	38.5	36.7	36.9	457.9
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	34.3	32.5	39.2	34.2	37.5	37.5	34.3	39.2	34.2	35.9	34.2	34.3	427.3
Total	168.8	170.3	241.8	213.2	256.2	240.5	216.4	236.2	209.3	214.2	182.0	169.7	2,518.7

Annual Energy Consumption by Enduse



	Electricity kWh (x000)	Natural Gas Btu	Steam Btu	Chilled Water Btu
Space Cool	1,345.8	-	-	-
Heat Reject.	-	-	-	-
Refrigeration	-	-	-	-
Space Heat	-	-	-	-
HP Supp.	-	-	-	-
Hot Water	-	-	-	-
Vent. Fans	236.1	-	-	-
Pumps & Aux.	51.5	-	-	-
Ext. Usage	-	-	-	-
Misc. Equip.	457.9	-	-	-
Task Lights	-	-	-	-
Area Lights	427.3	-	-	-
Total	2,518.7	-	-	-

Plate 3.1: Annual energy consumption by enduse under various parameters.

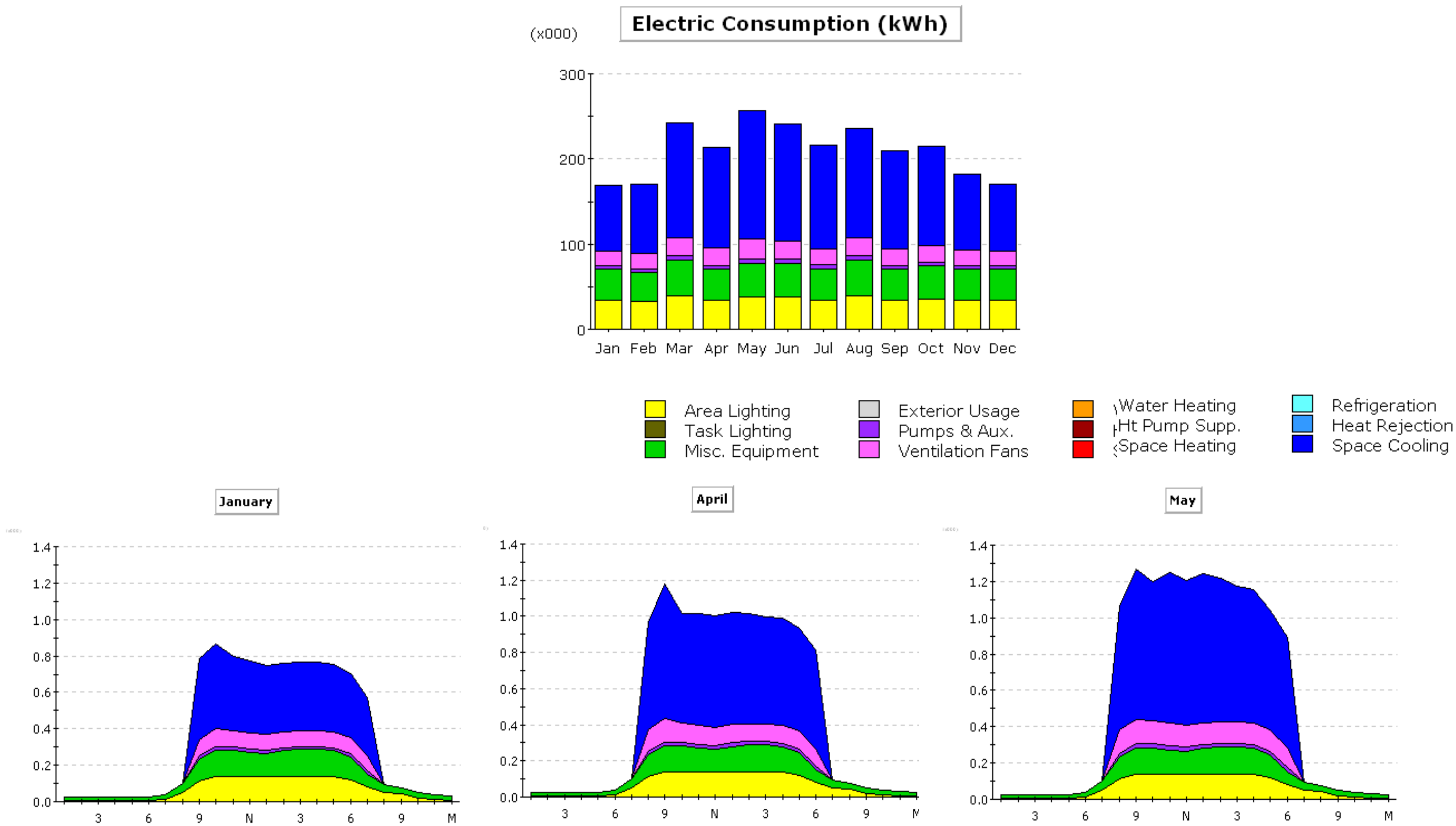


Plate 3.2: Simulation results showing annual electrical energy consumption under various parameters for the year 2006.

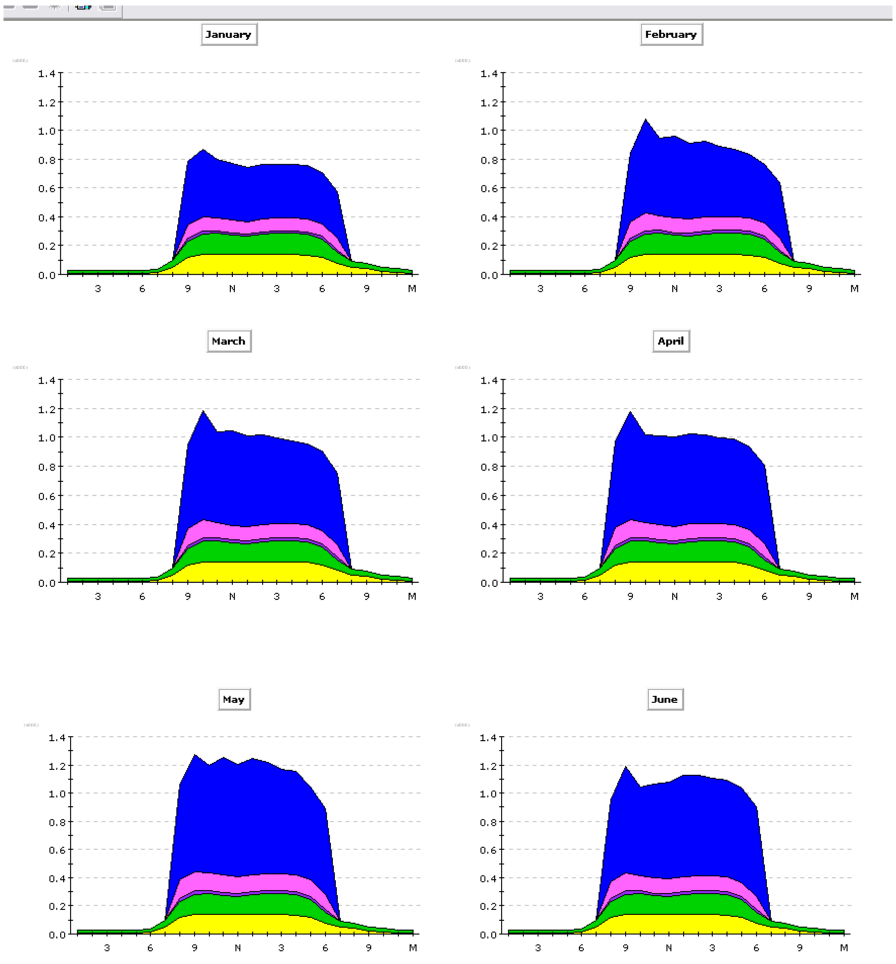


Plate 3.3: Monthly Electric Peak loads for the year 2006.

In the simulation output shown in above plates, it is observed that energy consumed for space cooling is 53% of the total energy consumed. The miscellaneous equipments used in office, computers which contribute the major percentage in it, constitutes 18% to the overall energy consumption. 17% is consumed by the lighting systems installed in the office. Ventilation fans consume 9% of the total annual energy consumption. Space cooling consumes the maximum percentage of the total energy consumption which has huge potential to reduce energy consumption. The area lighting and equipments have a same uniform consumption throughout the year, where as the space cooling demand is considerably less during the January and February, November and December in comparison with the other eight months. There is considerably higher demand in March, May, June and August.

3.2 THE ASCENDAS BUILDING

The ASCENDAS building, one of the commercial buildings in Chennai, was selected as a case study because of the proximity and the ease of collection of data.

3.2.1 Building Description:

The ASCENDAS building is a ten story office building, spread over an area of 6,00,00sqm; constructed in 2004-05 in Chennai, a city in southeast coast of India (Latitude 13.04 N, Longitude 80.17E, altitude- 6m). The building comprises of shopping complexes in ground and first floor, the second and third floor used for car parking, and open offices in the top eight floors (60,00 Sqm per floor).

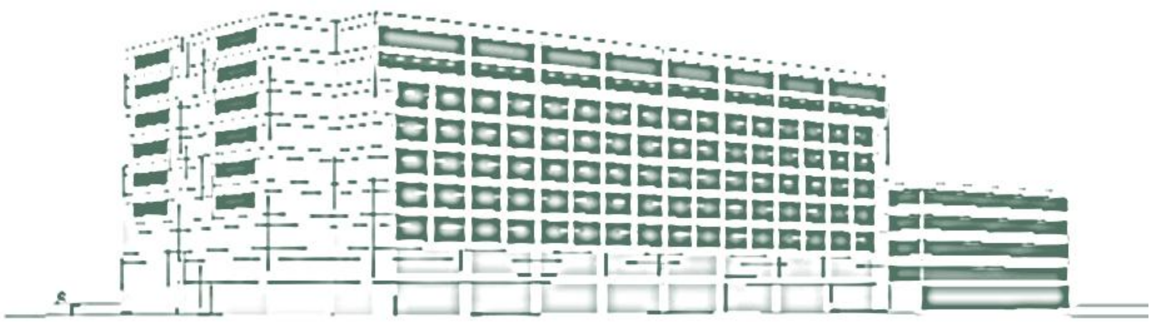


Figure 3.10: Exterior 3-d view of ASCENDAS building.

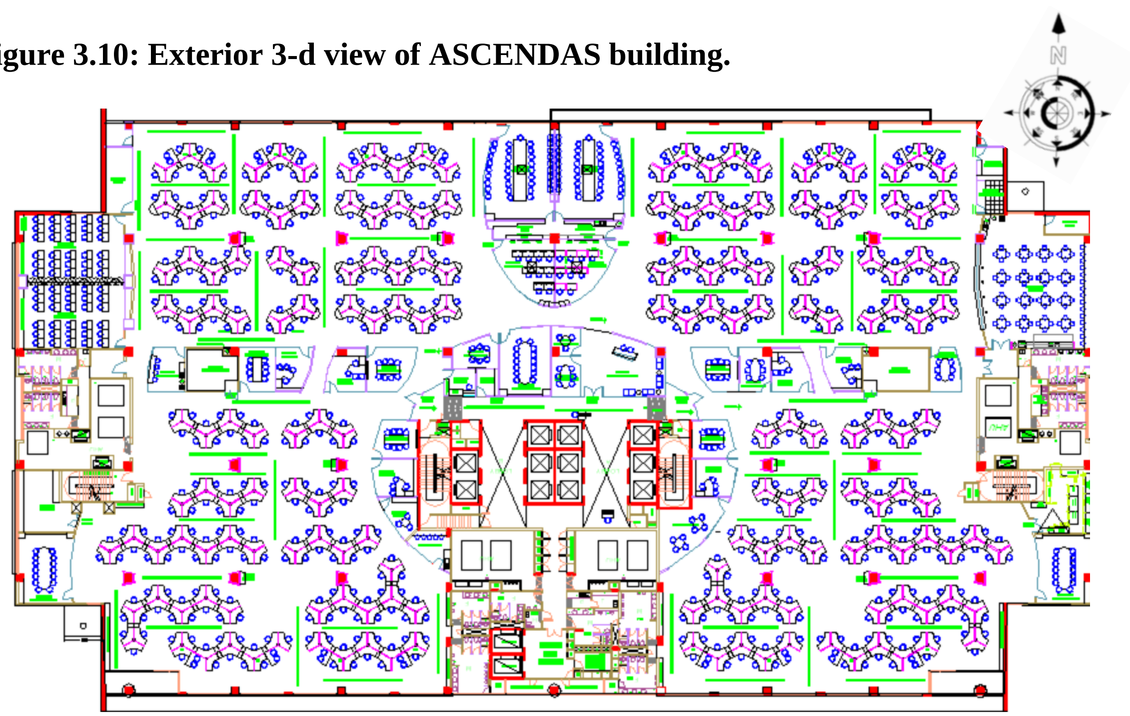


Figure 3.11 Plan of a typical office floor in ASCENDAS building.

5m 10m

Figure 3.12 Exterior and interior views of ASCENDAS building.

3.2.2 Space Summary:

The building use spaces are classified into major zones as: (1) office – open plan, (2) Lobby (3) Restrooms (4) Conference Rooms (5) Mechanical/Electrical rooms. The following table 3.6 gives the space summary.

Building Use	Conditioned Area (Sqft)	Unconditioned Area (Sqft)	Total (Sqft)
Office (open plan)	**438000**		**438000**
Lobby	**24000**		**24000**
Restrooms		**63000**	**63000**
Conference rooms	**45000**		**45000**
Mechanical/Electrical room		**30000**	**30000**
Total	**507000**	**93000**	**600000**

Table 3.6: Summary of the building use spaces of ASCENDAS building.

3.2.3 Building Envelope Components:

The exterior walls of the building are of 200mm thick solid concrete block with Aluminium composite panels used for exterior cladding the section of the exterior wall which has a u-value of 0.55 W/m^2K (0.098 $Btu/h.ft^2.F$)is shown in the figure 3.13. The roof slab and floor slab are of 150 mm thick concrete slab, constructed as a flat slab construction. The roof slab has been given a 3” thick under deck insulation with polystyrene. The overall u –value of the roof slab is 0.232 W/m^2K (0.041 $Btu/h.ft^2.F$).

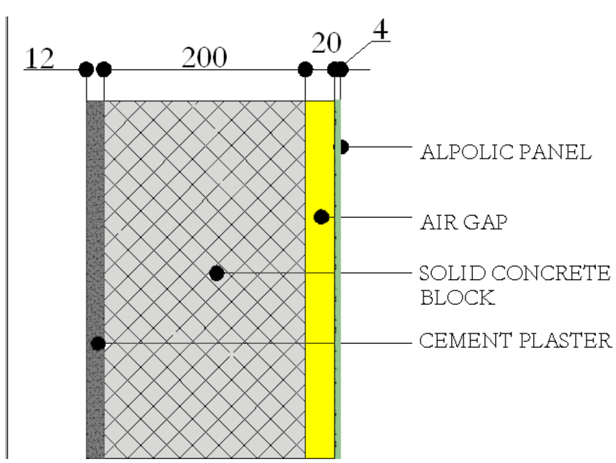


Figure 3.13: Section of exterior wall

3.2.3.1 Windows:

The ASCENDAS building has different types of glazing of Saint Gobain, used in the fazard. The glass types used, their area and their characteristics are tabulated in table 3.7. The window has aluminium frames.

Glass Type	Area (Sqm)	Perimeter (m)	Specifications
Glass type VS1	483	15.19	6mm +12mm air gap +6mm clear float glass
Glass type VS2	1938	15.19	6mm +12mm air gap +6mm clear float glass
Glass type VS3	686	31.6	6mm thick clear float glass
Glass type VS4	1554.6	37.2	12mm thick clear float glass

Table 3.7: Glass details used in the fazard of ASCENDAS building.

Glass Type	U-value W/m^{2}K (Btu/h.ft^2.F)	SHGC (%)	Reflectance (%)	Visual Light Transmittance (%)
Glass type VS1	2.83 (0.498)	0.41	0.23	0.28
Glass type VS2	2.83(0.498)	0.26	0.39	0.16
Glass type VS3	5.73(1.009)	0.77	0.21	0.63
Glass type VS4	5.73(1.009)	0.76	0.21	0.63

Table 3.8 Specifications of the glass types.

3.2.3.2 Artificial Lighting:

The Open office spaces are lit with Compact fluorescent lamps (2 X 36 W), and the corridors with Compact fluorescent lamps (2 X 18 W). There is no control at every desk, but for they are controlled in different zones.

3.2.3.3 Occupancy Density and Design Ventilation:

The ASCENDAS building uses Multi zone Air handler, with chilled water coils as its HVAC systems. The Fan control is of Variable speed drive. Six Screw type chillers of 296 ton each, which gives output at 1.26 KW/ton full load efficiency. The more detailed data of the HVAC system type used is as follows:

Mechanical systems	
HVAC System Type(s)	1. Single Zone Air Handler (cooling only). 2. Chilled Water Coils
Design Supply Air Temperature	20 ºF
Fan Control	VSD Control
Fan Power	4 in WG, Standard Supply.
Economizer Control	No
Chiller Type, Capacity, and Efficiency	6, 296 ton VSD, Screw Type chiller: 1.26 KW/ton full load efficiency, Variable Speed control for part load operation.
Chilled Water Loop and Pump Parameters	Variable Primary Flow with 1800 gpm variable speed pump. Chilled Water Fixed temperature at 44ºF
Condenser Water Loop and Pump Parameters	Constant Flow with 1800 gpm, single speed pump, Condenser water temperature 75ºF

Table 3.9: Details of HVAC systems.

3.2.4 Computer Model

In order to setup a realistic computer model, it was necessary to find and gather relevant information on the building geometry, construction, usage details. The ASCENDAS building was modeled in eQUEST by using the gathered information and the physical properties that were determined from the architectural drawings, and manufacturer data. With the help of these sources, a detailed computer model was setup, representing the whole building. The zones were classified as same as given in the table 3. 1. and shown in figure 3.14.

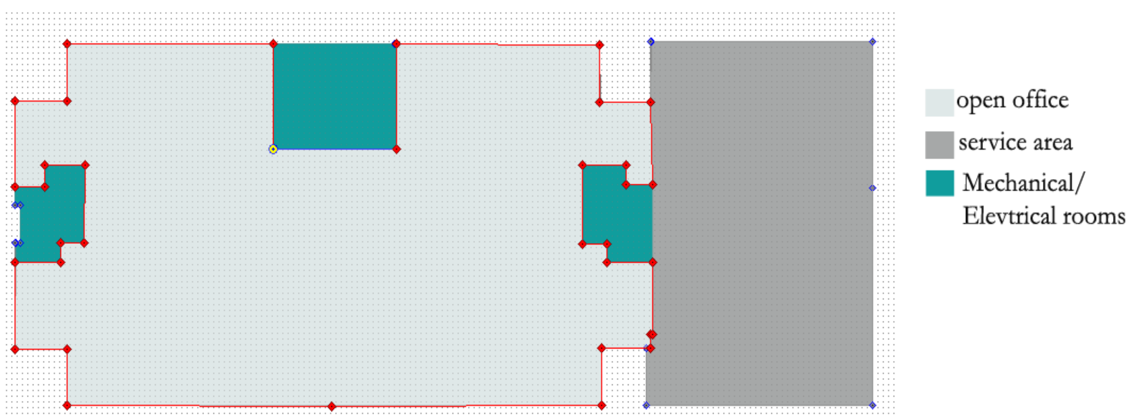


Figure 3.14: Zoning of Spaces in a typical office floor in ASCENDAS building.

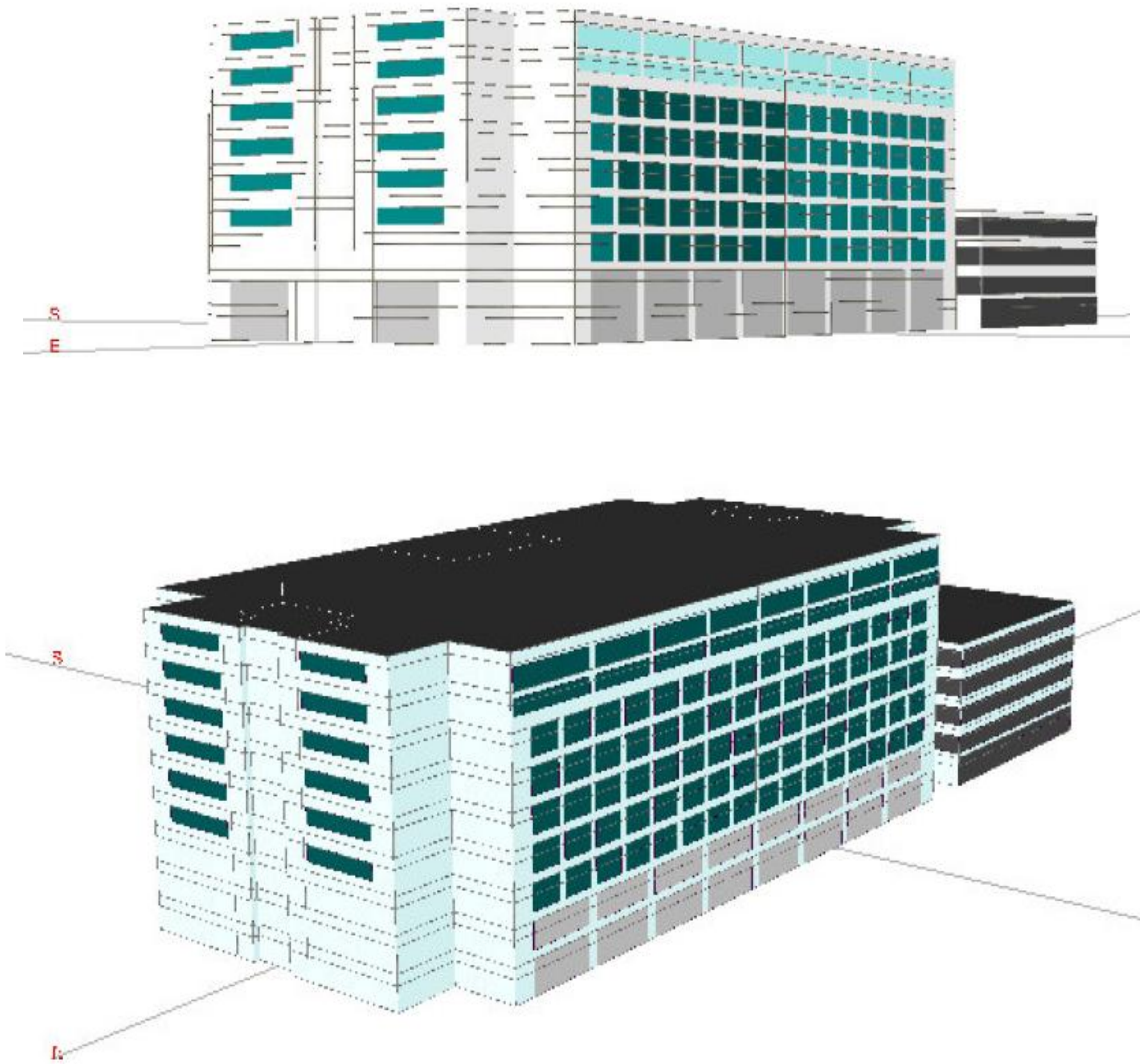


Figure 3.15: Computer model in eQUEST of ASCENDAS Building.

The model developed shown in figure 3.15, has taken into account all basic features of the building envelope except for few aesthetic features that could not be modeled in eQUEST. The materials used in the buildings, were defined in eQUEST using certain pre defined materials in its library, and also from manufacturers data. The data are documented in appendix C.

3.2.4.1 Occupancy Schedule:

The occupancy density for each zones classified are as per the table 3.6, and the occupancy in the different offices, vary, but mostly the occupancy on weekdays, from Monday to Friday is from 8:00AM to 11:00PM, and in the weekends from 10:00AM to 10:00PM. The list of holidays considered in the year 2006, is also considered. The occupancy profile considered on a weekday is shown in figure 3.16.

Building Use	Area Percentage	Design Maximum Occupancy (Sqft/Person)	Design Ventilation (CFM/Person)
Office (open plan)	73	200	20
Lobby	4	100	15
Restrooms	10.5	300	50
Conference rooms	7.5	50	20
Mechanical/Electrical rooms	5	2000	100

Table 3.10: Occupancy density in different zones.

3.2.4.2 Occupancy Profile:

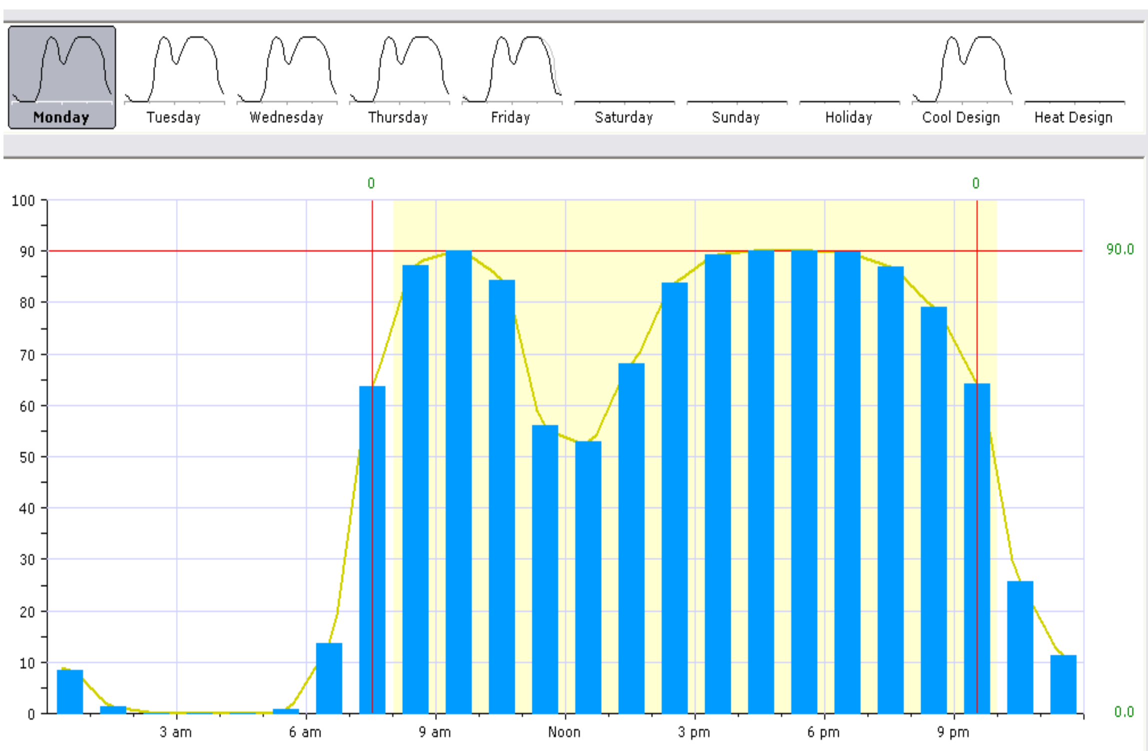


Figure 3.16: Occupancy Schedule during a typical working day.

3.2.4.3 Lighting Schedule:

The office spaces were lit with ceiling mounted Compact Fluorescent Lamps (2 X 36 W), the corridors with CFL's (2 x 18 W). The Interior Lighting power luminance was calculated from the as built false ceiling drawings in the classified zone. The lighting power density in the classified zones is as shown in the table 3.11.

Building Use	Area (Sqm)	Lighting Density (Watt/Sqft)	AHSRAE (9.6.1)	Interior Lighting power (Watt)
Office (open plan)	43800	12.4	11.1	543120
Lobby	2400	15.2	13.0	36480
Restrooms	6300	7.7	9.3	48510
Conference rooms	4500	9.2	13.0	41400
Mechanical/Electrical rooms	3000	8.1	14.9	24300
Total	60000	(average) 11.5		693810

Table 3.11: Lighting power density at different zones.

3.2.4.4 Lighting profile:

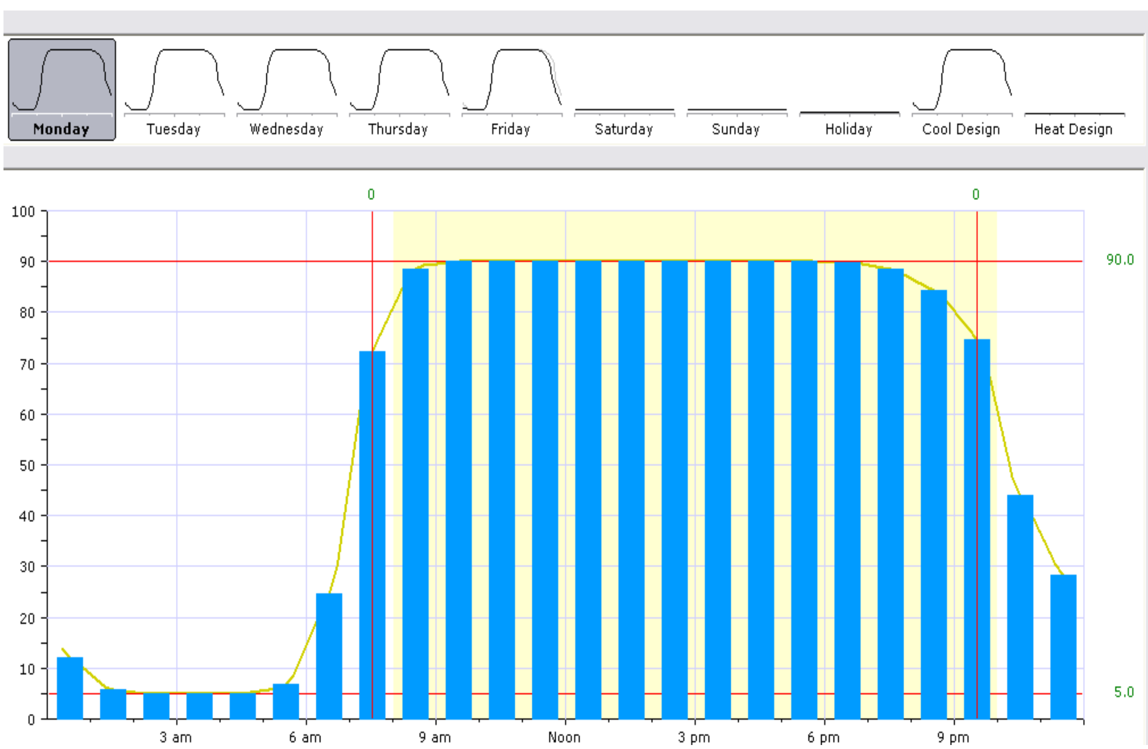
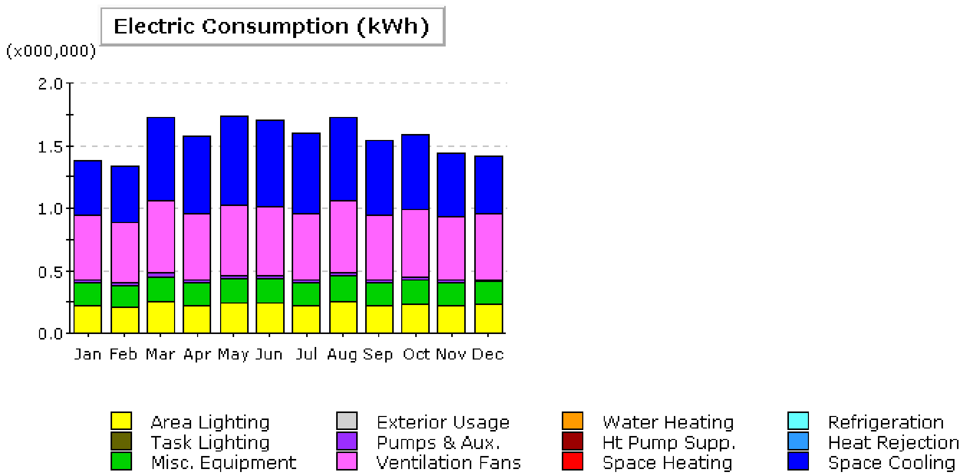


Figure 3.17: Lighting profile of a typical working day.

3.2.5 Simulation output

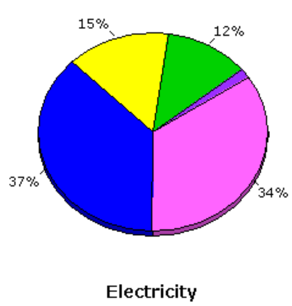
Monthly Energy consumed for space cooling, Area lighting, miscellaneous equipments, ventilation fans and the pumps are obtained by simulating the model developed, it is as follows:



Electric Consumption (kWh x000,000)

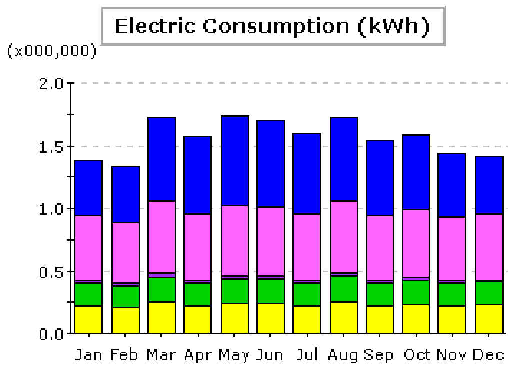
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.44	0.45	0.67	0.62	0.71	0.68	0.64	0.67	0.59	0.60	0.50	0.46	7.02
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	0.52	0.49	0.58	0.53	0.56	0.56	0.53	0.58	0.52	0.54	0.51	0.53	6.42
Pumps & Aux.	0.02	0.02	0.03	0.02	0.03	0.03	0.02	0.03	0.02	0.02	0.02	0.02	0.28
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	0.18	0.17	0.20	0.18	0.19	0.19	0.18	0.20	0.18	0.19	0.18	0.19	2.25
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	0.22	0.21	0.25	0.22	0.24	0.24	0.22	0.25	0.22	0.23	0.22	0.22	2.77
Total	1.38	1.33	1.72	1.58	1.73	1.70	1.59	1.72	1.54	1.58	1.43	1.42	18.73

Annual Energy Consumption by Enduse

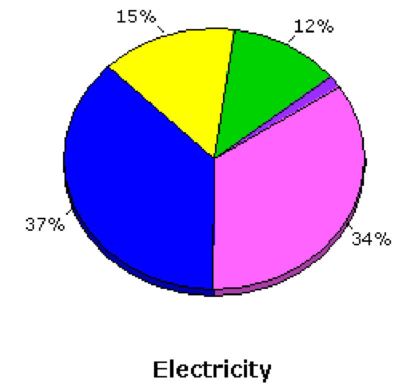


	Electricity kWh (x000)	Natural Gas Btu	Steam Btu	Chilled Water Btu
Space Cool	7,020	-	-	-
Heat Reject.	-	-	-	-
Refrigeration	-	-	-	-
Space Heat	-	-	-	-
HP Supp.	-	-	-	-
Hot Water	-	-	-	-
Vent. Fans	6,415	-	-	-
Pumps & Aux.	280	-	-	-
Ext. Usage	-	-	-	-
Misc. Equip.	2,247	-	-	-
Task Lights	-	-	-	-
Area Lights	2,765	-	-	-
Total	18,728	-	-	-

Plate 3.4: Annual energy consumption by endues under various parameters.



	Electricity kWh (x000)
Space Cool	7,020
Heat Reject.	-
Refrigeration	-
Space Heat	-
HP Supp.	-
Hot Water	-
Vent. Fans	6,415
Pumps & Aux.	280
Ext. Usage	-
Misc. Equip.	2,247
Task Lights	-
Area Lights	2,765
Total	18,728



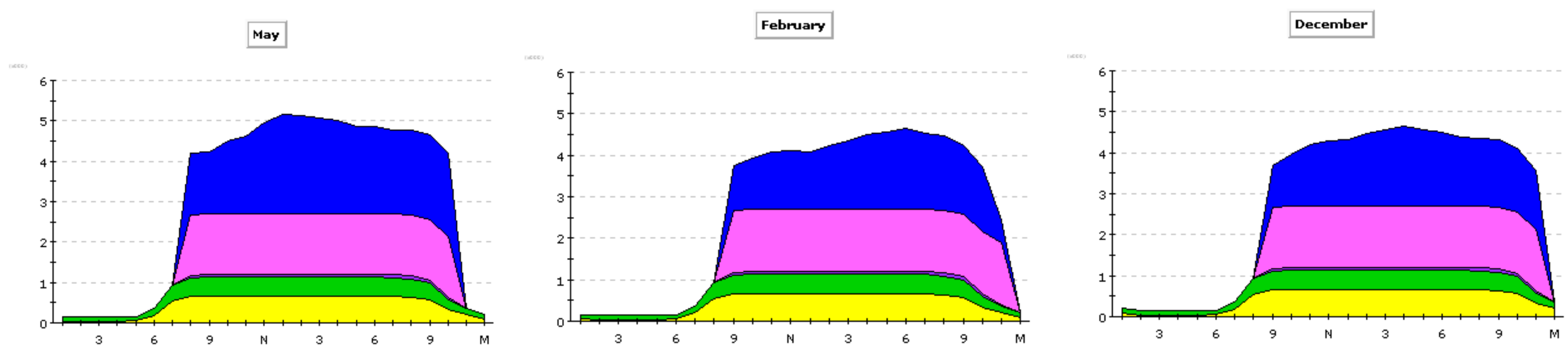


Plate 3.5: Simulation results showing annual electrical energy consumption under various parameters for the year 2006.

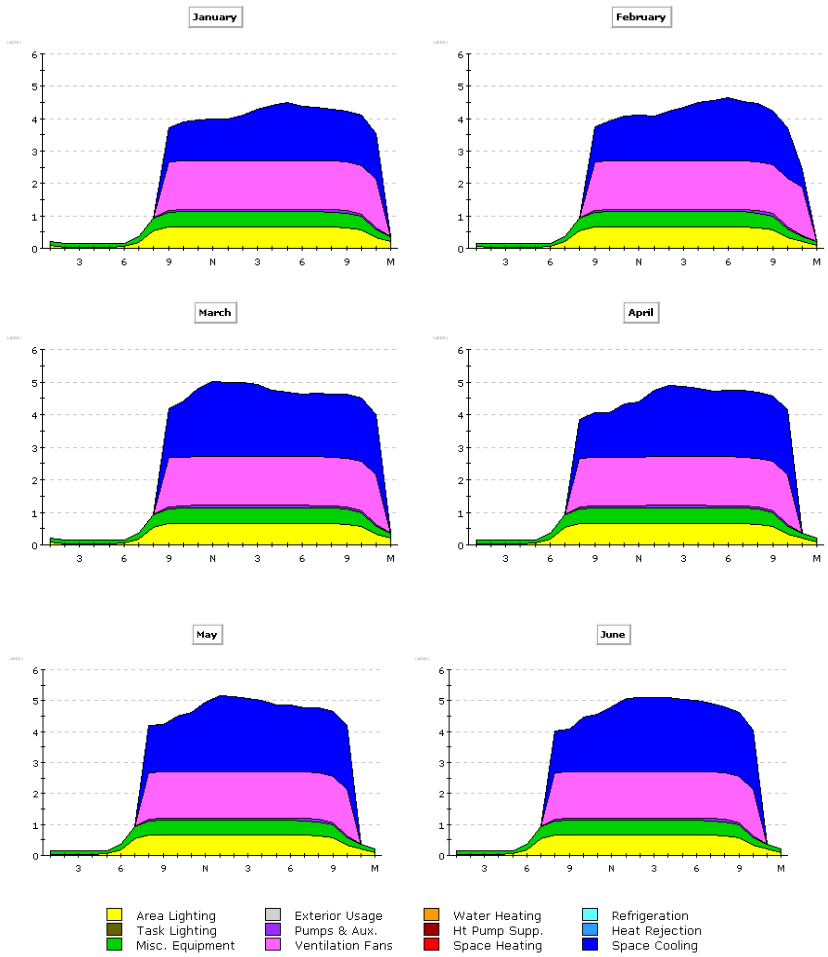


Plate 3.6: Monthly Electric Peak loads for the year 2006.

In the simulation output shown in above plates, it is observed that energy consumed for space cooling is 37% of the total energy consumed. The miscellaneous equipments used in office, computers which contribute the major percentage in it, constitutes 12% to the overall energy consumption. 15% is consumed by the lighting systems installed in the office. Ventilation fans consume 34% of the total annual energy consumption. Space cooling consumes the maximum percentage of the total energy consumption and equally the ventilation fans, which has a huge potential to reduce energy consumption. The area lighting and equipments have a same uniform consumption throughout the year, where as the space cooling demand is considerably less during the January and February, November and December in comparison with the other eight months. There is considerably higher demand in March, May, June and August.

3.3 VALIDATION OF THE MODEL DEVELOPED IN EQUEST

The model developed and its simulation results got, the monthly energy consumption for the year 2006, was compared with the actual monthly energy consumption for the same year, as recorded in the electric meters in the building. The following table 3.12 gives the actual and simulated energy consumption values in Kilo Watt hour, and their percentage difference and plotted in figures 3.18 and 3.19.

Months	Actual Billing Data (KWh)	Simulated Values from eQUEST(KWh)	Percentage Difference
Jan	818613	1380000	40.68
Feb	935390	1330000	29.67
Mar	1225450	1720000	28.75
Apr	1535582	1580000	2.81
May	1821384	1730000	-5.28
Jun	1737225	1700000	-2.19
Jul	1843659	1590000	-15.95
Aug	1666434	1720000	3.11
Sep	1764524	1540000	-14.58
Oct	1688254	1580000	-6.85
Nov	1542173	1430000	-7.84
Dec	1517753	1420000	-6.88
Total	18096441	18720000	3.33

Table 3.12: Actual and Simulated values of monthly energy consumption, year 2006.

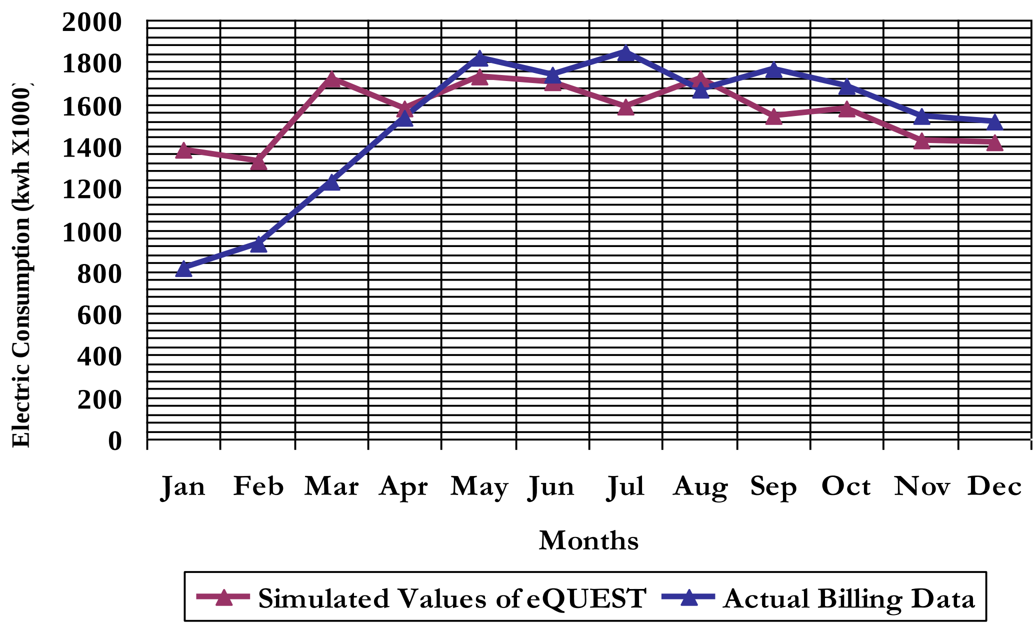


Figure3.18: Comparison of building simulation result and actual billing data

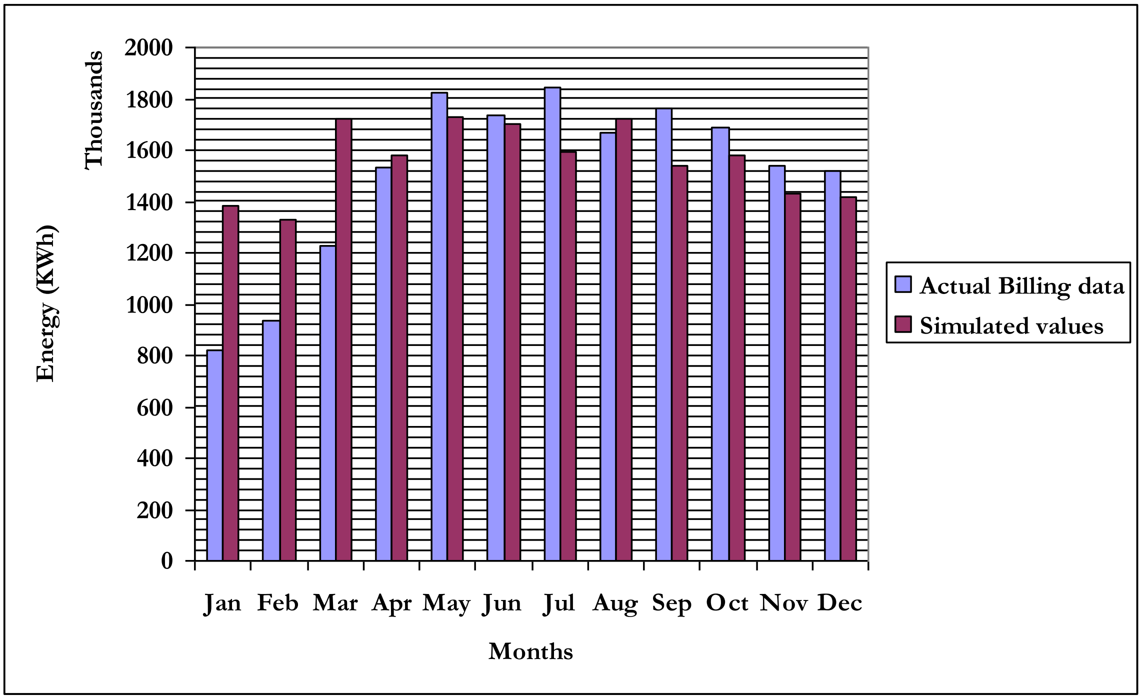


Figure 3.19: Comparison of the actual billing data and building simulation results.

The result shows that energy simulation program predicts the energy use pattern of the building fairly well. The higher difference in January, February and March is significant as all the floors of ASCENDAS building was not fully occupied by the tenants. The Table 3.12 shows that there is less than 8% difference for the months of April, May, June, August, October, November and December and a maximum of 15% difference for months of July and September between the simulation results and the actual billing data of ASCENDAS for the year 2006.

CHAPTER - 4 LIFE CYCLE ENERGY CALCULATION

Embodied energy corresponds to energy consumed by all of the processes associated with the production of building materials and components. This includes the mining and manufacturing of materials and equipments. Embodied energy is proportional to the level of processing required by a material. The more complex the material is and the greater the amount of energy consumed. High levels of embodied energy imply higher levels of pollution at the end of the production line, as the consumption of energy usually results in emissions. Every building is a complex combination of many processed materials, each of which contributes to the building's total embodied energy. This chapter presents the calculations done for embodied energy for the structural and the envelope components are considered, as the focus is on the building envelope components and it would be more complex to consider the finishing materials used inside the building.

4.1 EMBODIED ENERGY CALCULATION

Embodied energy can be calculated on an industrial sector basis (i.e., total embodied energy divided by the total material used in a sector, e.g., manufacture of steel) or by process analysis in which the embodied energy of a particular material is tracked from extraction to end-use. The figures produced by each approach differ, particularly for low-volume commodities [12]. The figures used in this study, are referred from Embodied energy of common and alternative building materials and technologies by B.V.Venkatarama Reddy, K.S.Jagadish [11] and Eco balance assessment tool (Eco – BAT,www.eco-bat.ch) developed by Stephane Cithrelet [16].

Embodied energy can be split into: (1) energy consumed in the production of basic building materials, (2) energy needed for transportation of the building materials, and (3) energy required for assembling the various materials to form the building.

4.1.1 Energy in building materials:

Energy consumed during production of basic building materials is given in table 4.1. (Reference)

Type of material	Thermal Energy (MJ/Kg)
Cement	**5.85**
Lime	**5.63**
Lime- pozzolana	**2.33**
Steel	**42.00**
Aluminium	**236.80**
Glass	**25.8**

Table 4.1: Energy in basic building materials

4.1.2 Energy in transportation of building materials

Transportation of materials is a major in the cost and energy of a building. Bulk of the building materials in urban and semi-urban centers are transported using trucks in India. The transportation distance may vary depending upon the location of construction activity. In urban areas, the materials travel anywhere between 10 to 100 km in the Indian context. Materials such as sand are transported from a distance of 70-100 Km in cities like Bangalore, India. Similarly bricks/blocks crushed aggregate, etc. travel about 40-60 km before reaching a construction site, in urban and semi-urban centers.

Cement and steel travel even longer distances, of the order of 500 Km or more. Long haul of cement and steel is handled through rail transport. Building materials such as marble, paints, etc. are sometimes transported from great distances (>1500Km) in India. Table 4.2 gives diesel energy spent during transportation of various building materials, along with energy consumed in production.

Type of material	Energy (MJ/Kg)		
	Production	Transportation	
		50 Km	100 Km
Sand (m^3)	0.0	87.5	175
Crushed aggregate (m^3)	20.5	87.5	175
Burnt clay bricks (m^3)	2550	100	200
Portland Cement (tonnes)	5850	50	100
Steel (tonnes)	42000	50	100

Table 4.2: Energy in transportation of building materials

4.1.3 Energy in Mortars

Mortar is a mixture of cementitious material and sand. It is used for the construction of masonry as well as plastering. Details of mortar type, their proportions and energy content /m^3 of mortar is given in the table 4.3.

Type of Mortar	Proportions of materials			Energy (MJ)/ m^3
	Cement	Soil	Sand	
Cement Mortar	1	0	6	1268
	1	0	8	1006
Cement pozzolana mortar	0.8:0.2[b]	0	6	918
	0.8:0.2[b]	0	8	736
Cement-soil mortar	1	2	6	849
	1	2	8	773
Lime pozzolana mortar	1 (1:2)[c]	0	3	732

Table 4.3: Energy in mortars [a]

[a] Energy content: Portland cement = 5.85MJ/Kg; and sand=175MJ/m^3

[b] Cement: Pozzolana (0.8: 0.2)

[c] Lime: Pozzolana (1: 2)

4.1.4 Energy in flooring/roofing systems:

There are many alternatives available for the construction of roof/floor of a building. Energy content of different types of floor/roofing systems are given in table 4.4. The table gives the energy/ m^2 of plan area of roof/floor and an equivalent of RC slab energy.

Type of roof/floor	Energy (MJ/m^2)
RC slab	730
Stabilized mud block filler slab	590
RC ribbed slab roof	491
Ferroconcrete roof	158

Table 4.4: Energy in different floor/roofing systems

The information from the tables 4.2.1, 4.2.2, 4.2.3 and 4.2.4 was used to calculate the embodied energy for the two buildings in this study. As there a huge number of materials used in the interiors of the two buildings, in this study only the building envelope components were considered, they are, Concrete wall, Floor slab, Roof slab and Glass. Their corresponding embodied energy during the life span is shown in the figure 4.1, and tabulated for INFOTECH building in table 4.5.

Building Component	First year (MJ)	20 years (MJ)	40 years (MJ)	60 years (MJ)	80 years (MJ)
Wall	**3267576.30**	**3267576.30**	**3267576.30**	**3267576.30**	**3267576.3**
Floor Slab	**18207431.7**	**18207431.70**	**18207431.70**	**18207431.7**	**18207431**
Glass	**1464499.01**	**1464499.01**	**1464499.01**	**29335106.4**	**3682936**
Roof Slab	**5096349.00**	**5096349.00**	**5641660.97**	**5641660.97**	**6186972**

Table 4.5: Embodied energy for INFOTECH building during its life span.

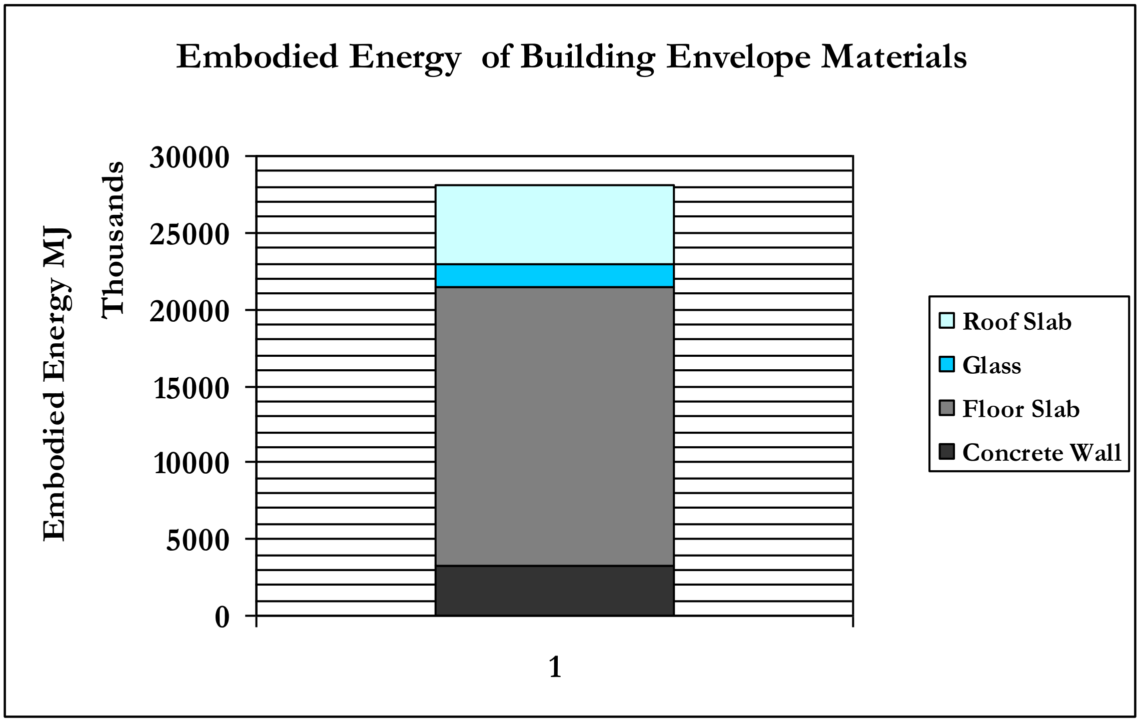


Fig 4.1: Initial Embodied energy of INFOTECH building

The building envelope components considered for ASCENDAS building are the Exterior wall, Floor slab, Roof slab and Glass. Their corresponding embodied energy during the life span, is shown in the figure 4.2, and tabulated for ASCENDAS building in table 4.6.

Building Components	Initial Embodied Energy (MJ)	20 years (MJ)	40 years (MJ)	60 years (MJ)	80 years (MJ)
Exterior Wall	**15899847.39**	**15899847.39**	**15899847.39**	**15899847.39**	**15899847.39**
Floor Slab	**34952400.00**	**34952400.00**	**34952400.00**	**34952400.00**	**34952400.00**
Glass	**7676435.32**	**7676435.32**	**7676435.32**	**12917355.76**	**19859780.59**
Roof Slab	**5096349.00**	**5545528.10**	**6722906.20**	**6722906.20**	**7900284.30**

Table 4.6: Embodied energy of ASCENDAS building in its life span

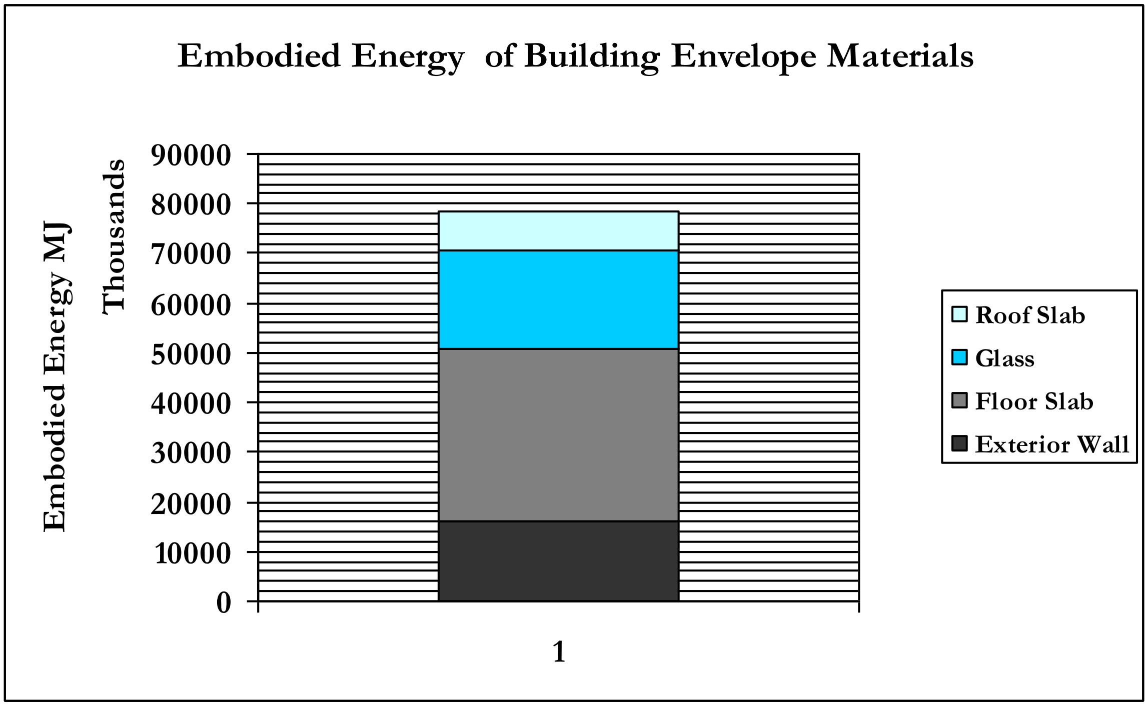


Fig 4.2: Initial Embodied energy of ASCENDAS building

The embodied energy of the building materials of the above mentioned envelope components are shown in the figure 4.3.

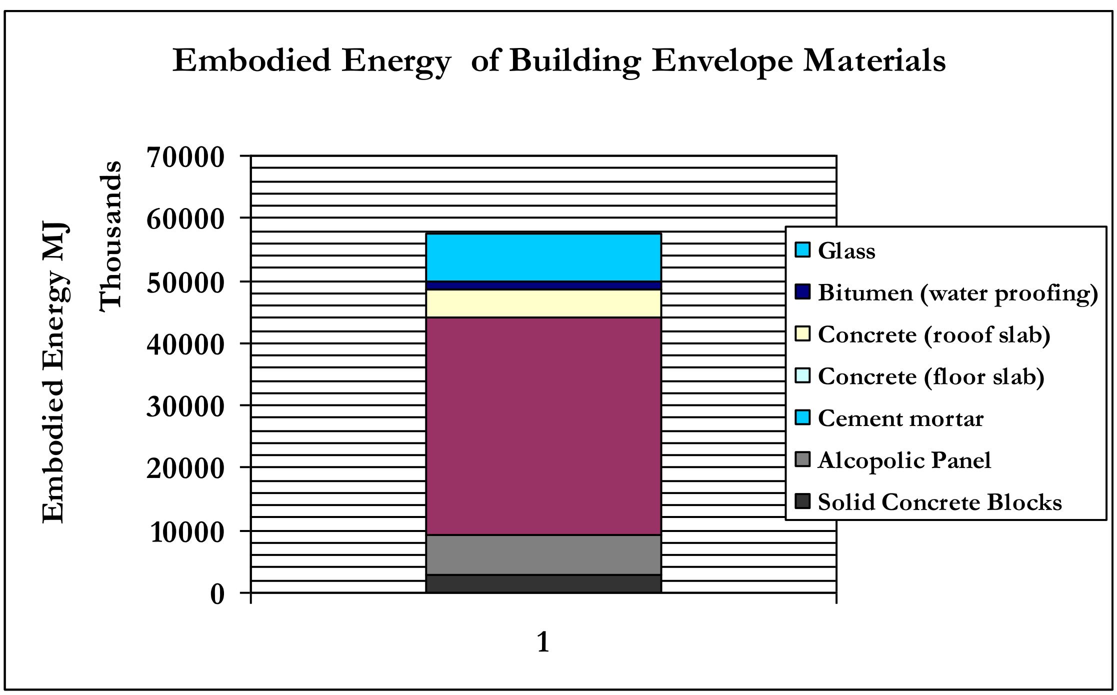


Fig 4.3: Embodied energy of building materials used in the envelope components of ASCENDAS building.

4.2 Insulation materials:

Thermal insulation is material or combination of materials, that, when properly applied, retard the rate of heat flow by conduction, convection, and radiation. It retards heat flow into or out of a building due to its high thermal resistance. Thermal insulation materials like other natural or man-made materials exhibit temperature dependant properties that vary with the nature of the material and the influencing temperature range.

Thermal insulating materials resist heat flow as a result of the countless microscopic dead air-cells, which suppress (by preventing air from moving) convective heat transfer. It is the air entrapped within the insulation, which provides the thermal resistance, not the insulation material.

Creating small cells (closed cell structure) within thermal insulation across which the temperature difference is not large also reduces radiation effects. It causes radiation ‘paths’ to be broken into small distances where the long-wave infrared radiation is absorbed and /or scattered by the insulation material (low-e materials can also be used to minimize radiation effects). However, conduction usually increases as the cell size decreases (the density increases).

Typically, air-based insulation materials cannot exceed the R-value of still air. However, plastic foam insulations (e.g., polystyrene and polyurethane) use fluorocarbons gas (heavier than air) instead of air within the insulation cells, which gives higher R-value.

Therefore, the interaction of the three modes of heat transfer of convection, radiation, and conduction determines the overall effectiveness of insulation and is represented by what is called the apparent thermal conductivity which indicates the lack of pure conduction especially at higher temperatures.

Both vapor passage and moisture absorption are more critical in open cell structure insulation as compared to closed cell structure. Vapor retarders are commonly used to prevent moisture penetration into low-temperature insulation. Vapor retarders are used inside of insulation in cold climates and to outside of insulation in hot and humid climates (allowing moisture escape from the other side). Vapor retarders placement, however, is a challenge in mixed climates.

The embodied energy of different insulation materials of varying thickness are tabulated in table 4.7.

Insulation material	Thickness (cm)	Embodied energy (80 years)
Polystyrene	**2.5**	**652992.35**
	5	**1305984.71**
	7.5	**1958977.06**
	10	**2611969.41**
	20	**5223938.83**
	30	**7835908.24**
Polyurethane Foam	**2.5**	**1010367.26**
	5	**2020734.51**
	7.5	**3031101.77**
	10	**4041469.03**
	20	**8082938.05**
	30	**12124407.10**
Glass wool	**2.5**	**371432.03**
	5	**742864.06**
	7.5	**1114296.10**
	10	**1485728.13**
	20	**2971456.26**
	30	**4457184.39**
Rock wool	**2.5**	**334217.85**
	5	**668435.69**
	7.5	**1002653.55**
	10	**1336871.40**
	20	**2673742.80**
	30	**4010614.20**

Table 4.7: Embodied energy of different insulation materials of varying thickness

4.3 OPERATING ENERGY

Energy used in buildings during their operational phase, as for cooling, ventilation, hot water, lighting, heating, and other electrical appliances. It might be expressed either in terms of end-use or primary energy. End-use energy is measured at final use level, so it somehow expresses the performance of a building. Primary energy is measured at the natural resource level, including losses from the processes of extraction of the resources, their transformation and distribution, and so it expresses the real load on the environment caused by a building.

In other words, the same building placed in different countries but with similar climates is likely to have similar figures about end-use energy. The difference in terms of primary energy, however, can be significant because of the different energy carriers available for thermal purposes (like cooling, heating, electricity) and /or because of the different ways to produce electricity. For example, India, Thermal 66%, Hydropower 26.5%, Nuclear 3%, renewable 4.8% [Ministry of Power, India].

Concerning Operating energy, eQUEST tool used in this study gives the end use energy consumption. A linear relationship exists between operating and total energy consumed by a building [14]. Life cycle assessment, provide better understanding and better estimation of energy aspects in the life cycle of any sort of good. Hence, this study focuses only on operating energy and embodied energy in the life cycle of buildings.

4.4 LIFE CYCLE ENERGY CALCULATION

The total energy used in a building over its life is the sum of the operational energy and embodied energy. The embodied energy of the building envelope components is tabulated in table 4.2, and the operating energy (end-use) of the buildings, obtained from the simulation carried out in eQUEST (3.2.6), is sum totaled to obtain the Life cycle energy of the building from 20 years till the life span of the building. The sum total energy calculation for INFOTECH building is tabulated in table 4.8 as follows:

Year	Embodied Energy (MJ)	Operational Energy (MJ)	Total Energy (MJ)
1	28092894.12	9067320	37160214.12
5	28092894.12	45336600	73429494.12
10	28092894.12	90673200	118766094.1
15	28092894.12	136009800	164102694.1
20	28092894.12	181346400	209439294.1
40	28638206.09	362692800	391331006.1
50	29335106.49	453366000	482701106.5

Table 4.48: The total energy consumed during the life span of INFOTECH building.

The sum total energy calculation for ASCENDAS building is tabulated in table 4.9 as follows:

Year	Embodied Energy (MJ)	Operational Energy (MJ)	Total Energy (MJ)
1	64075110.82	67392000	131467110.8
5	64075110.82	336960000	401035110.8
10	64075110.82	673920000	737995110.8
15	64075110.82	1010880000	1074955111
20	64075110.82	1347840000	1411915111
40	65252488.92	2695680000	2760932489
50	70493409.35	3369600000	3440093409

Table 4.9: The total energy consumed during the life span of ASCENDAS building.

The life cycle energy of the two buildings, tabulated above is shown in the figure 4.4 and 4.5 .

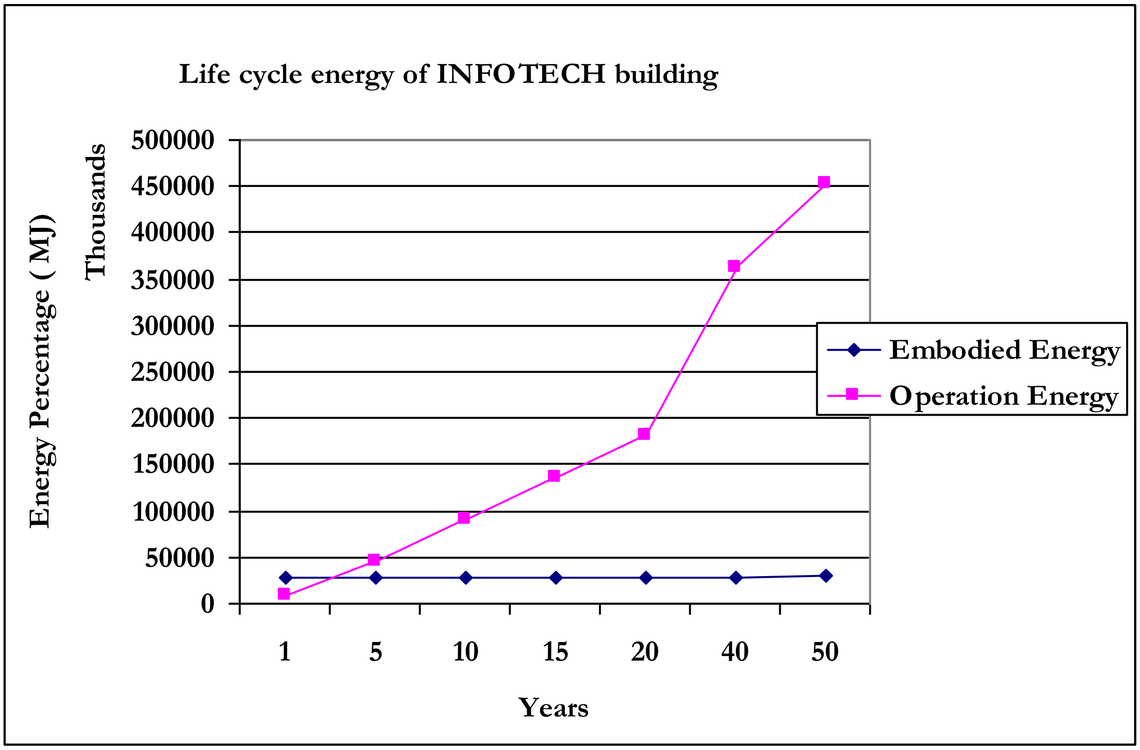


Fig 4.4: The life cycle energy of INFOTECH building

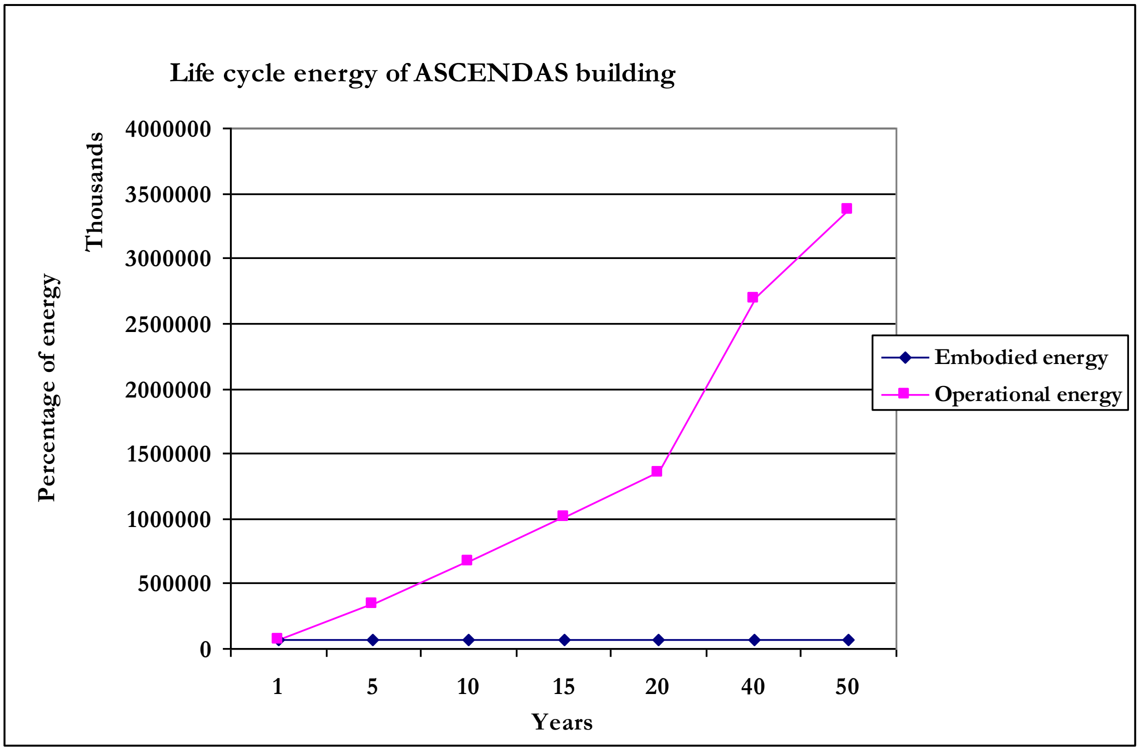


Fig 4.5: The life cycle energy of Ascendas building

4.5 Life cycle impact assessment

The life cycle impact assessment of the two case buildings presented in this study were done using Eco Balance Assessment tool, ECO-BAT 2.4 developed by stephane cithrelet, HES.SO[16]. The environmental effects used as the environmental indicators are as follows:

1. Non-Renewable Energy (NRE).
2. Global warming potential over a 100 year period (GWP 100)
3. Acidification potential (AP)
4. Photochemical Ozone Creation Potential (POCP)

These indicators are related to global external environment. However, a part of the environmental problems related to the building sector might arise locally n connection with the indoor environment, such as Volatile organic compounds (VOCs), these are not considered in this tool. The building materials data according to Indian context were modified and fed in ECO-BAT.

The results of the life cycle impact assessment are shown in figures 4.6 till 4.10.

Figure 4.6 Life cycle impact assessment of Materials and Energy (INFOTECH)

The figure 4.6 shows the building life cycle impact caused by all the materials used in the envelope and structure of the building, and the energy consumed during operation of the building. It is seen that the materials used, has a negligible quantity in comparison with the impact of energy consumed. Energy used for space cooling is dominant in all the four indicators. Hence, potential to reduce this energy consumption is more significant, which would help in considerable reduction in the impact on the environment.

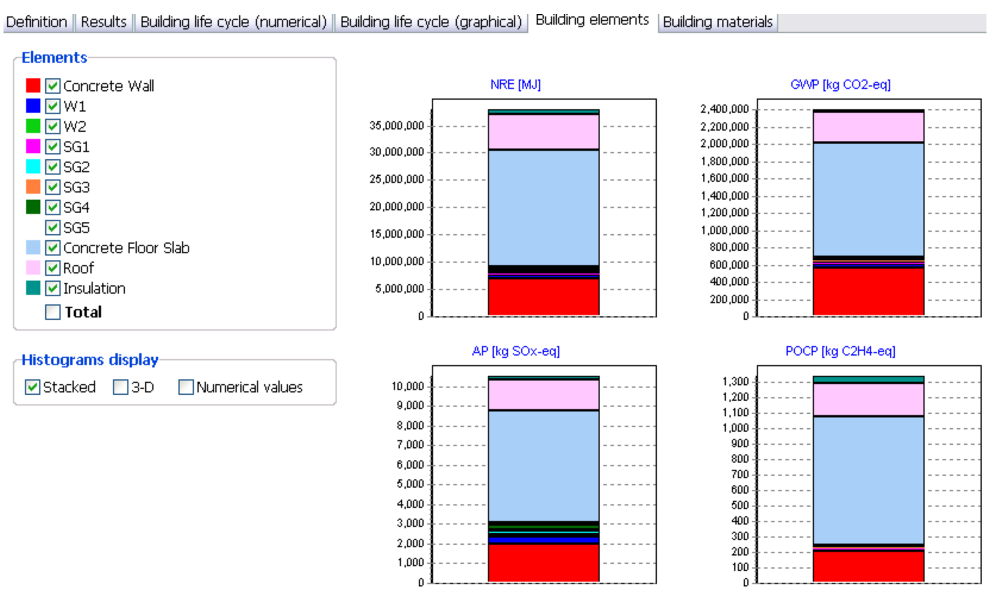


Figure 4.7: Life cycle impact assessment of the building elements (INFOTECH)

The figure 4.7 shows the NRE (MJ), GWP (kg Co2), AP (kg Sox), POCP (kgc$_2$H$_4$) indicators of the Building elements in INFOTECH building. The building elements of the envelope considered for assessment are the concrete wall, glazing, concrete floor slab, and roof slab and insulation material if applied on the exterior walls. It is seen that, concrete floor slab element is dominant in all the four indicators. Concrete used for walls and roof slab are again more dominant in all the four indicators. Glazing shows a very less percentage of impact in comparison with the other elements. Thermal Insulation materials used for the exterior walls also have a negligible impact in comparison with the other elements. They have more impact on POCP, in comparison with the other indicators.

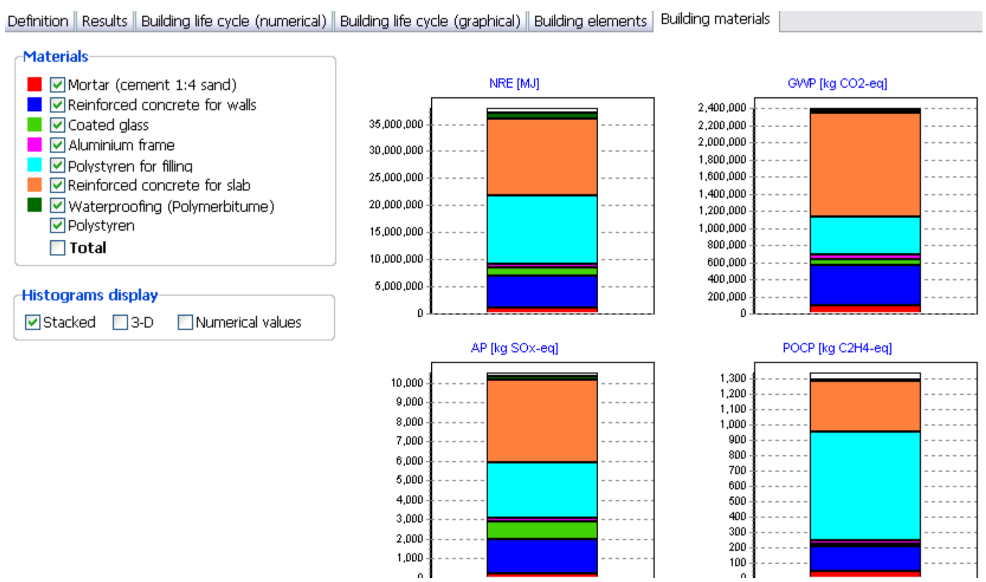


Figure 4.8: Life cycle impact assessment of building materials (INFOTECH)

The figure 4.8 shows the impact on environment caused individually by each building material used in INFOTECH building. It is seen that, the reinforced concrete and polystyrene used in floor slabs, are dominant in all the four indicators. Polystyrene has a major impact on POCP, ozone creation potential.

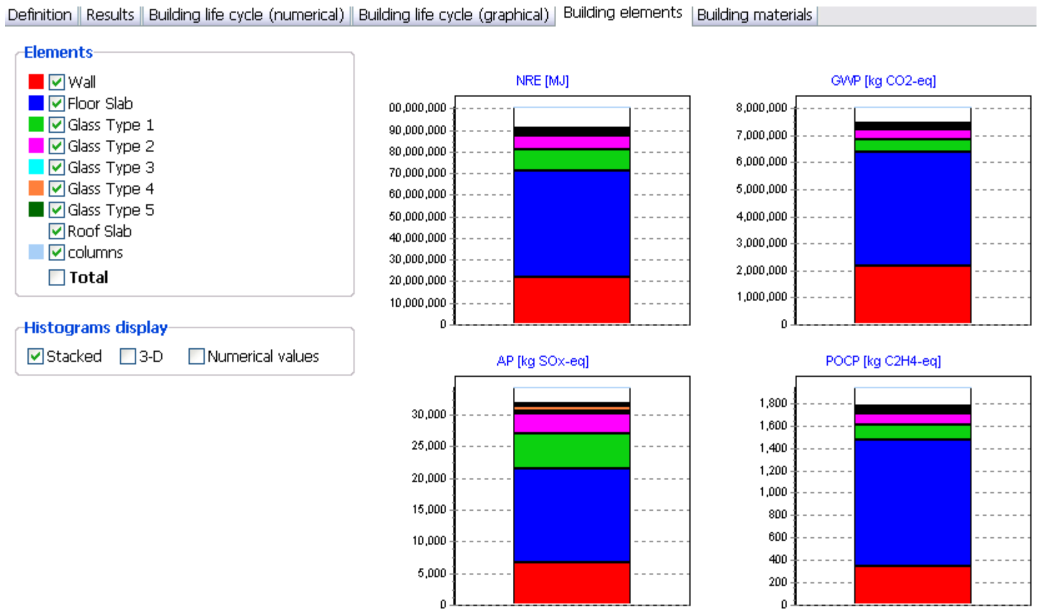


Figure 4.9: Life cycle impact assessment of the building elements (ASCENDAS)

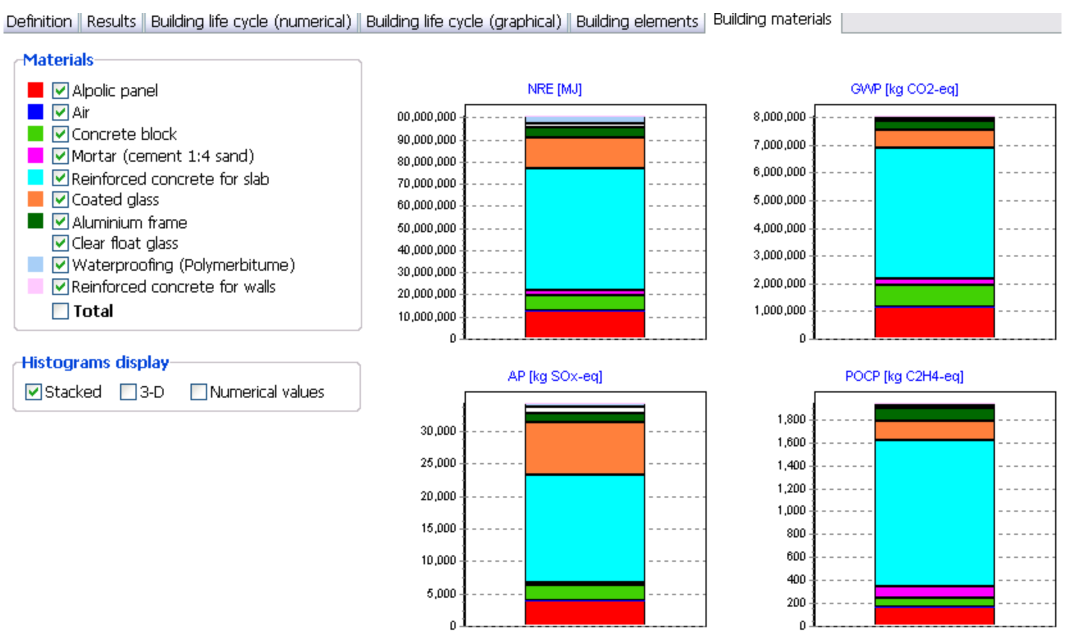


Figure 4.10: Life cycle impact assessment of building materials (ASCENDAS)

The figure 4.9 and 4.10 shows that NRE (MJ), GWP (kg Co2), AP (kg Sox), POCP (kgc_2H_4) indicators of the Building elements in ASCENDAS building. The building elements of the envelope considered for assessment are the exterior wall, glazing, concrete floor slab, roof slab, columns and insulation material if applied on the exterior walls. It is seen that, concrete floor slab element is dominant in all the four indicators. Glazing shows a very less percentage of impact in comparison with the other elements.

CHAPTER – 5 ANALYSIS & DISCUSSIONS

With the objectives of the project in focus, this chapter presents the analysis and discussions on the results obtained in the previous chapter. Firstly, the performance of the existing buildings in reference with the standards was analyzed to check if the two buildings comply with the same. Secondly, the role of the building envelope components and the key role of insulation in Energy consumption are analyzed. Finally, the life cycle energy consumption of the buildings is analyzed to derive conclusions and strategies to minimize the total energy consumption of the buildings.

5.1 COMPARISON OF THE MODEL WITH ECBC & ASHRAE STANDARDS:

The developed computer model in eQUEST for both the buildings, INFOTECH & ASCENDAS, was compared with the ANSI/ASHRAE/IESNA Standard 90.1-2004 (Energy standard for buildings except for low rise residential buildings), and Energy conservation Building Code,2006 (Bureau of Energy Efficiency, ECBC). The INFOTECH building showed 25% of energy consumption more than the ASHRAE 90.1-2004 standards, shown in figure 5.1, and the figure 5.2 shows the same building consumes 3.5% of more energy than ECBC standards. The ASCENDAS building showed 9.6% of energy consumption more than ECBC standards as shown in figure 5.3.

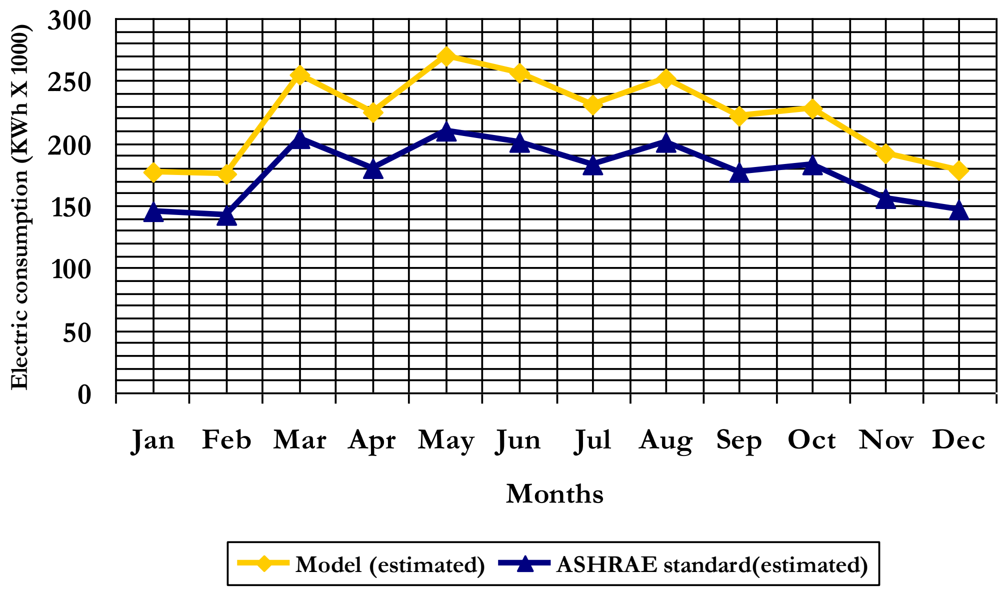


Fig 5.1: Comparison with ASHRAE standard (INFOTECH building)

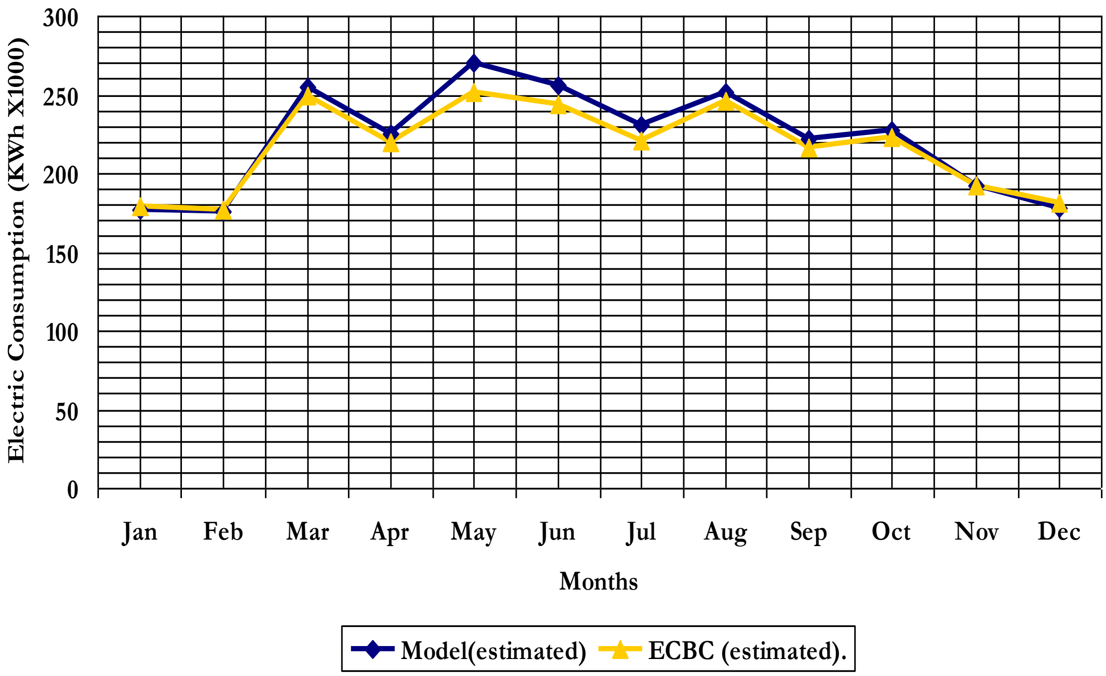


Fig 5.2: Comparison with ECBC standards (INFOTECH building)

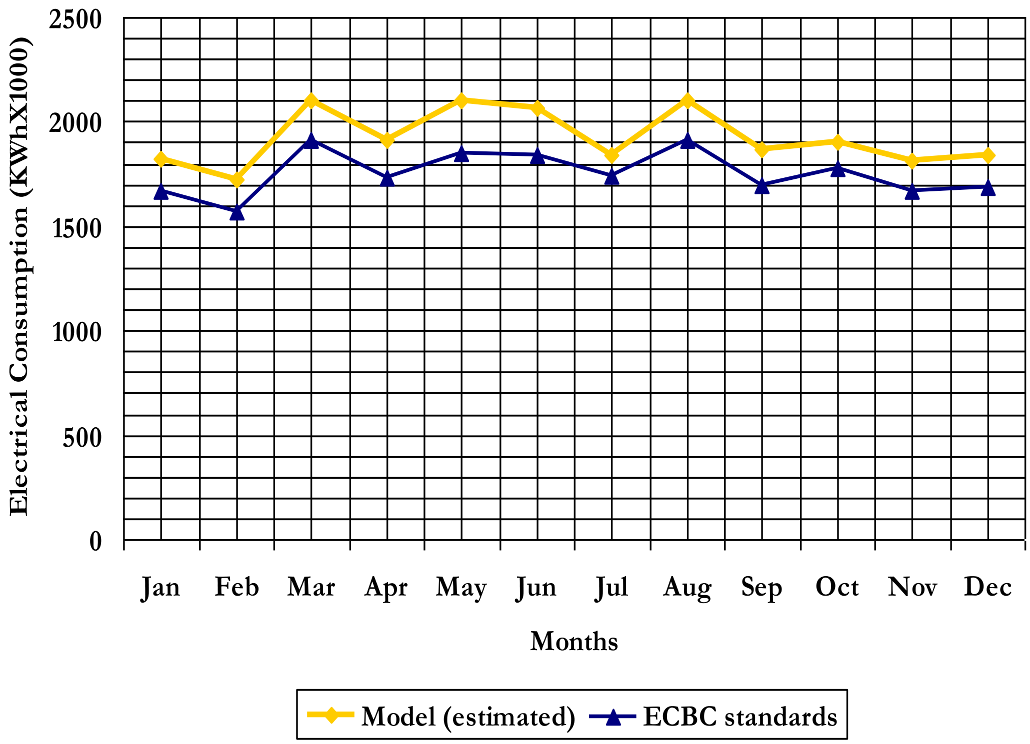


Fig 5.3: Comparison of with ECBC standards (ASCENDAS building)

The above comparisons with the standards show that, either of the building is not satisfying the codal requirements of ECBC standards, and ASHRAE standards. Hence the influence of different parameters on the buildings to reduce the energy consumption is significant, which lead to further analysis.

5.2 ANALYSIS OF BUILDING ENVELOPE COMPONENTS IN ENERGY CONSUMPTION

The energy consumption of a building is affected by different parameters, the climate of the region where the building is located, the physical properties of materials used in the building envelope, the internal loads, the HVAC systems installed etc., To analyze these parameters and check whether the insulation application on the building envelope is the only key factor, affecting the energy consumption of a building, the analysis of building envelope components were done.

5.2.1 ROLE OF INSULATION MATERIAL IN ENERGY CONSUMPTION

The amount of energy required for cooling or heating a building depends on how well the envelope of that building is treated thermally [5]. The thermal performance of a building envelope is determined by the thermal properties of the materials used in construction characterized by its ability to absorb or emit solar heat in addition to the overall U-value of the corresponding component including insulation. The placement of the insulation materials within the building component can affect its performance under transient heat flow. The best performance can be achieved by placing the insulation material close to the point of entry of heat flow [5]. This means placement of insulation to the inside for climatic regions where winter heating is dominant and to the outside where summer cooling is dominant. To estimate the amount of energy savings that could be obtained by the application of insulation, Simulations were performed by applying different insulation materials on the exterior walls of INFOTECH building, under different climatic conditions in India.

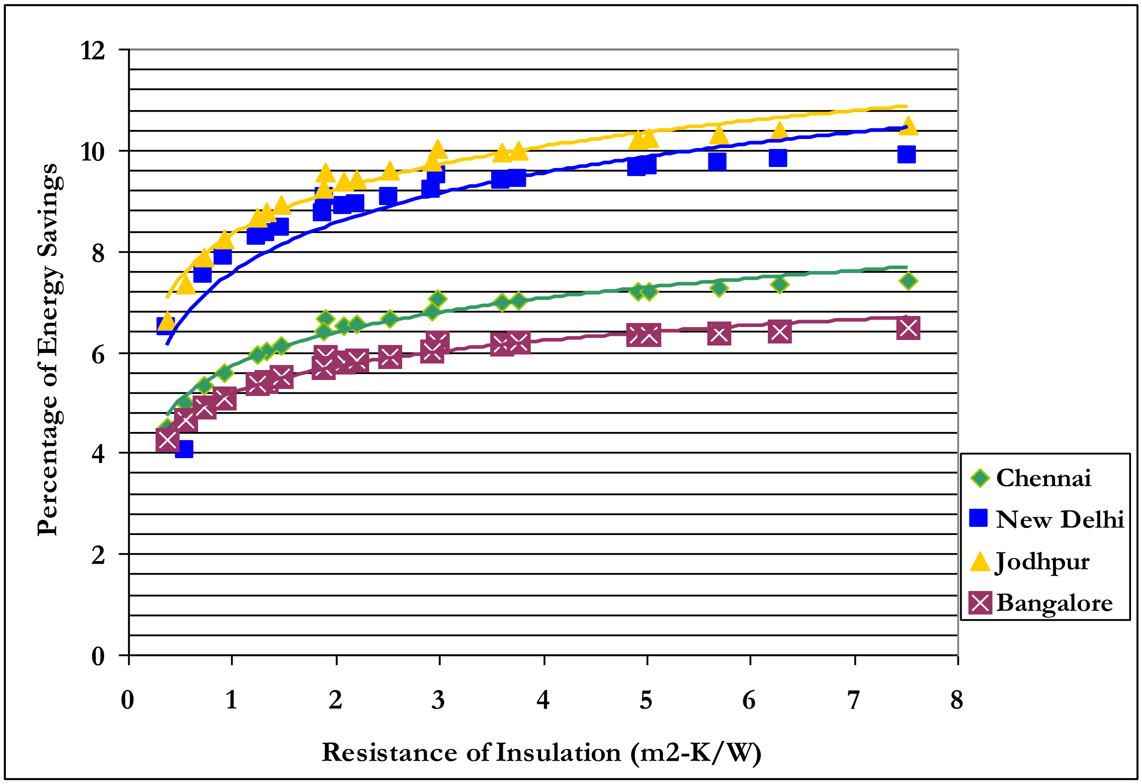


Fig 5.4: Energy savings after application of insulation material on the exterior wall surface.

The results of the simulations are tabulated in table 5.1, and displayed in figure 5.4. It shows that, increasing the resistance value of insulation material does not yield proportional return in percentage of energy saving (Y) beyond a certain point. The relationship between the percentage of energy savings (Y) and the resistance of insulation material (X) is not linear. It obeys a logarithmic function of y = 1.2612 Ln (x) + 8.3158, R^2 =0.9588, with respect to Hot-dry climate (Jodhpur). In respect with composite climate (New Delhi), it obeys Y = 1.4302 Ln (x) +7.559, R^2 =0.7476, Warm-Humid climate (Chennai) it obeys Y=0.9732 Ln (x) + 5.7066, R^2 =0.9692, and in Moderate Climate (Bangalore) it obeys Y= 0.7547 Ln (x) +5.1813, R^2 =0.97.

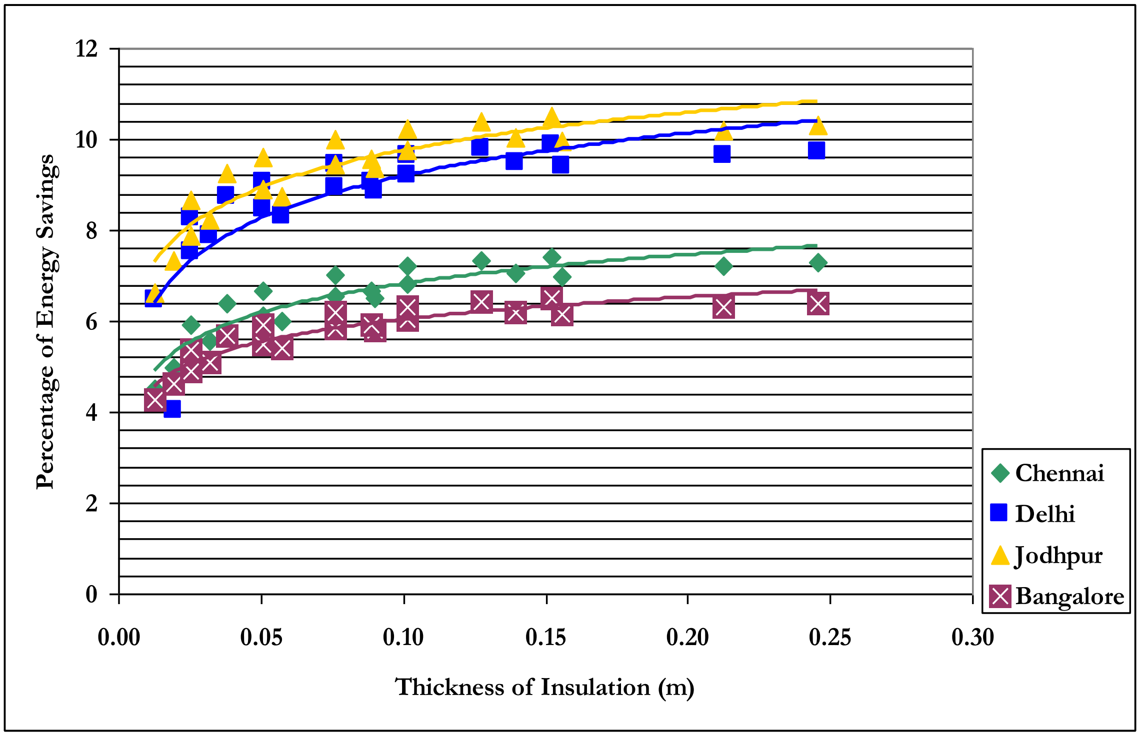


Fig 5.5: The energy savings in reference with the thickness of insulation.

Increasing the resistance value of insulation materials is achieved by increasing the thickness of the insulation material. The results on the percentage of energy savings, in relation with the thickness of insulation materials, shows that beyond a certain level, there is no considerable savings even after increasing the thickness of the insulation. Which means additional insulation thickness is not effective anymore. It shows that the relationship between the percentage of energy savings (Y) and thickness of insulation (x) is non-linear as shown in figure 5.5. It obeys a logarithmic function of Y= 1.2001 Ln (x) + 11.09, R^2 =0.8506, in Hot dry climate (Jodhpur). In respect with composite climate (New Delhi), it obeys Y = 1.3584 Ln (x) +10.701, R^2 =0.6607, Warm-Humid climate (Chennai) it obeys Y= 0.9259 Ln (x) + 7.847, R^2 =0.8594, and in Moderate Climate (Bangalore) it obeys Y= 0.709 Ln (x) +6.8207, R^2 =0.8592. The following table shows the different insulation material and their properties, which were applied to the exterior surface of the buildings. It also shows the corresponding energy savings obtained in different climatic conditions.

Insulation Material	L (ft)	K (Btu/hr-ft2-F)	P lb/ft3	C Btu/lb-F	R hr-ft2-F/Btu	Overall u-value	Chennai % of Savings	Delhi % of Savings	Jodhpur % of Savings	Bangalore% of Savings
Min Wool Batt R7	0.1882	0.025	0.6	0.2	7.530	0.101	6.011	8.332	8.761	5.419
Min Wool Batt R11	0.2957	0.025	0.6	0.2	11.830	0.071	6.503	8.867	9.373	5.785
Min Wool Batt R19	0.5108	0.025	0.6	0.2	20.430	0.044	6.972	9.397	9.958	6.157
Min Wool Batt R24	0.6969	0.025	0.6	0.2	27.880	0.033	7.198	9.639	10.215	6.323
Min Wool Batt R30	0.8065	0.025	0.6	0.2	32.360	0.029	7.278	9.735	10.321	6.383
Min Wool Fill 3.5 in R11	0.2917	0.025	0.6	0.2	10.800	0.061	6.670	9.051	9.582	5.911
Min Wool Fill 5.5 in R19	0.4583	0.025	0.6	0.2	16.970	0.04	7.047	9.481	10.044	6.212
Polystyrene, Expanded										
Polystyrene ½ in	0.0417	0.02	1.8	0.29	2.080	0.226	4.518	6.468	6.616	4.259
Polystyrene ¾ in	0.0625	0.02	1.8	0.29	3.120	0.183	4.995	4.043	7.343	4.645
Polystyrene 1 in	0.0833	0.02	1.8	0.29	4.160	0.154	5.324	7.538	7.864	4.891
Polystyrene 1.25 in	0.1042	0.02	1.8	0.29	5.210	0.132	5.582	7.867	8.227	5.097
Polystyrene 2 in	0.1667	0.02	1.8	0.29	8.330	0.094	6.130	8.455	8.907	5.504
Polystyrene 3 in	0.25	0.02	1.8	0.29	12.500	0.067	6.559	8.928	9.437	5.825
Polystyrene 4 in	0.3333	0.02	1.8	0.29	16.660	0.053	6.817	9.209	9.766	6.031
Polyisocyanurate										
Polyisocyanurate 1"	0.083	0.0117	2	0.22	7.094	0.106	5.940	8.262	8.676	5.373
Polyisocyanurate 1.5"	0.125	0.0117	2	0.22	10.684	0.077	6.400	8.753	9.244	5.700
Polyisocyanurate 2"	0.167	0.0117	2	0.22	14.274	0.06	6.678	9.064	9.595	5.921
Polyisocyanurate 3"	0.25	0.0117	2	0.22	21.368	0.042	7.008	9.437	9.997	6.182
Polyisocyanurate 4"	0.333	0.0117	2	0.22	28.462	0.032	7.210	9.656	10.232	6.333
Polyisocyanurate 5"	0.417	0.0117	2	0.22	35.641	0.026	7.329	9.801	10.390	6.428
Polyisocyanurate 6"	0.5	0.0117	2	0.22	42.735	0.022	7.420	9.902	10.497	6.498

Table 5.1: Insulation materials, their properties and the corresponding energy savings.

5.2.2 ROLE OF THERMAL MASS AND STORAGE

Thermal mass reduces heat gain in the structure by delaying the entry of heat into the building. Internal mass stores excess heat, whether from the sun or internal loads of the building, for release during unoccupied or cooler periods. Material thermal mass is characterized by its time lag which is the length of time from when the outdoor temperature reaches its peak until the indoor temperature reaches its peak.

The heat capacity per unit surface area of a structure is the product of density, thickness and specific heat of its components. Any increase in the heat capacity achieved by higher density is accompanied by a decrease in the thermal conductivity, reducing thermal resistance. Replacement of heavy weight with lighter materials of higher thermal resistance, with no change in wall thickness, reduces the heat capacity, moderately improve thermal conditions. If wall thickness is increased to raise heat capacity, the overall thermal resistance increases proportionally, greater thermal effect.

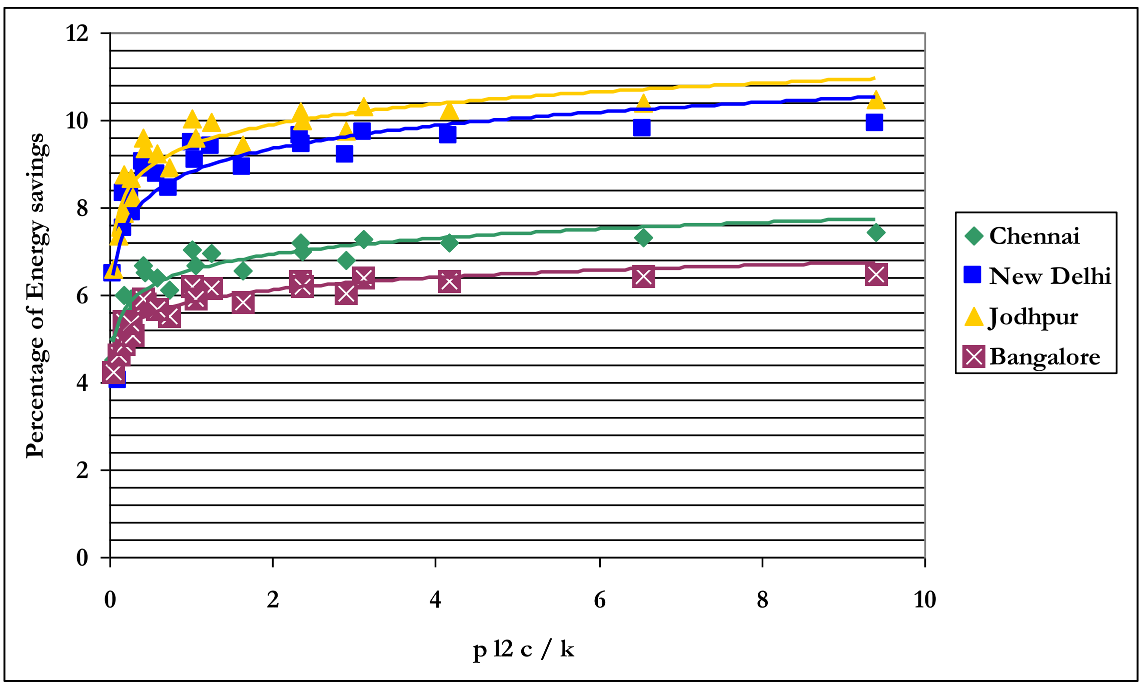


Figure 5.6: Effect of increase in thermal capacity to the percentage of energy savings.

In multi-layer walls the combined effect of thermal resistance and heat capacity depends not only on the overall thermal transmittance and heat capacity but also on the specific order of the various layers, which may differ in thickness and thermo physical properties. To analyze this, the product of (ρLc/k) (L), where L is the thickness, c is the specific heat, ρ is the density and k the thermal conductivity was plotted against the percentage of energy savings. The figure 5.6 shows that the equivalent thermal resistance-capacity product(x) has logarithmic relationship with the percentage of energy savings(y). It does not give proportional return to percentage of energy savings.

The figure 5.7 shows that there is a linear relationship between percentage of energy savings (Y) and overall U-value (x) of the wall. Hence there is always increase in percentage of energy savings with the reduction in overall u-value.

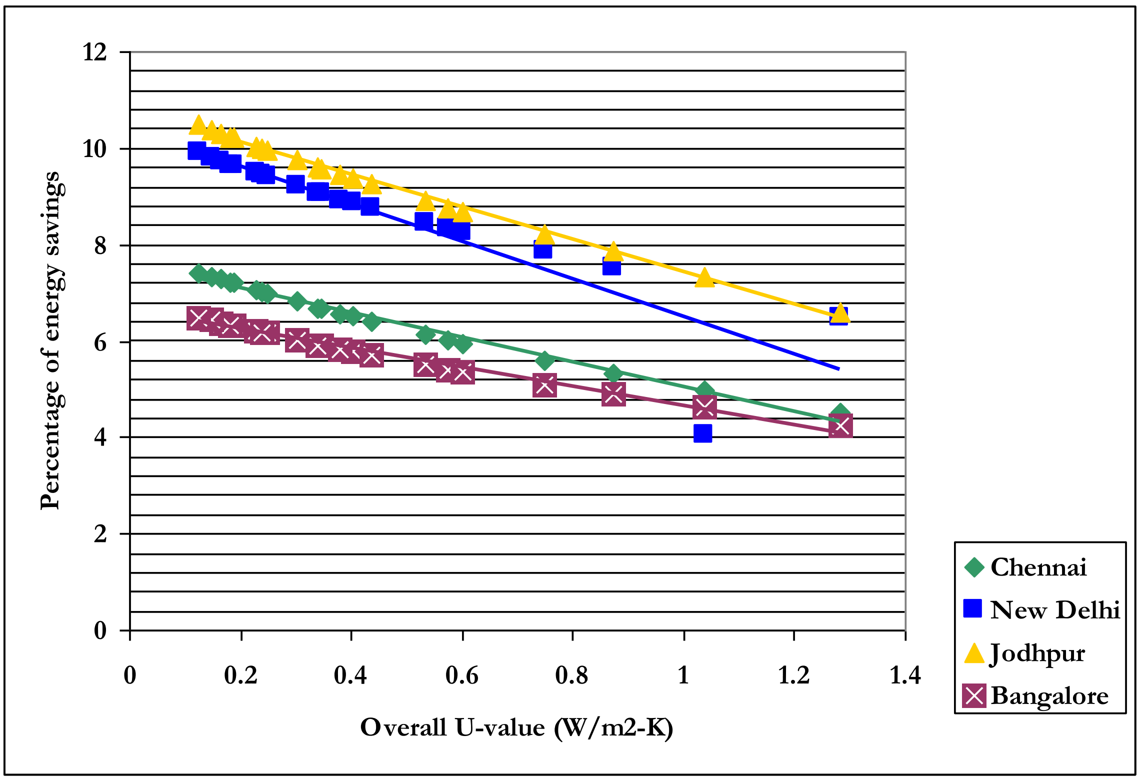


Figure 5.7: Overall thermal u-value of wall to the percentage of energy savings

5.2.3 ROLE OF WINDOWS IN ENERGY CONSUMPTION

The table 5.2 shows the energy savings achieved by applying exterior movable blinds over the windows. It shows that the energy savings due to the external blinds is as much as only 1%. This is because the ratio of the glass area to the floor area, in INFOTECH building is 10.6% and in ASCENDAS building it is 12.97%.

Window (Exterior Movable blinds)	Chennai % of Savings	Delhi % of Savings	Jodhpur % of Savings	Bangalore % of Savings
Shade - Thin - T20-R70	1.084	1.316	1.684	1.080
Shade - Thin - T30-R30	1.004	1.342	1.684	1.356
Shade - Thin - T30-R50	1.004	1.342	1.684	1.356
Shade - Thin - T30-R60	1.004	1.342	1.684	1.356

[a] – Movable window shades, appendix ( )

Table 5.2: Percentage of energy savings due to parameters of window.

Type Of Glass [a]	U-Value	Shading coefficient (%)	Visual Light Transmittance (%)	Percentage of Energy Savings
2204	0.48	0.57	0.47	5.034
2205	0.45	0.56	0.47	4.998
2210	0.48	0.57	0.66	5.084
2211	0.45	0.57	0.66	5.048
2216	0.48	0.54	0.38	4.768
2217	0.45	0.54	0.38	4.717
2219	0.48	0.57	0.5	5.012
2220	0.45	0.56	0.5	4.973
2411	0.4	0.15	0.05	-0.056
2412	0.36	0.15	0.05	-0.267
2414	0.41	0.18	0.08	0.336
2415	0.38	0.17	0.08	0.139
2434	0.41	0.22	0.12	0.842
2435	0.37	0.21	0.12	0.651
2634	0.31	0.65	0.75	6.029
2635	0.26	0.66	0.75	6.054
2637	0.31	0.43	0.44	3.387

Table 5.3: percentage of energy savings due to various parameters of glass type.

The significant parameters of the glass type are, the U-value, shading coefficient, and visual light transmittance. Shading coefficient is the ratio of solar heat gain at normal incidence through glazing to that occurring through 3 mm thick clear, double-strength glass. Shading coefficient, as used herein, does not include interior, exterior, or integral shading devices. These parameters from the Saint Gobain glass manufacturers (appendix) were simulated to see their effect in reduction in energy consumption. The figure5.8 shows the linear relationship between the shading coefficient and the visual light transmittance with the percentage of energy savings.

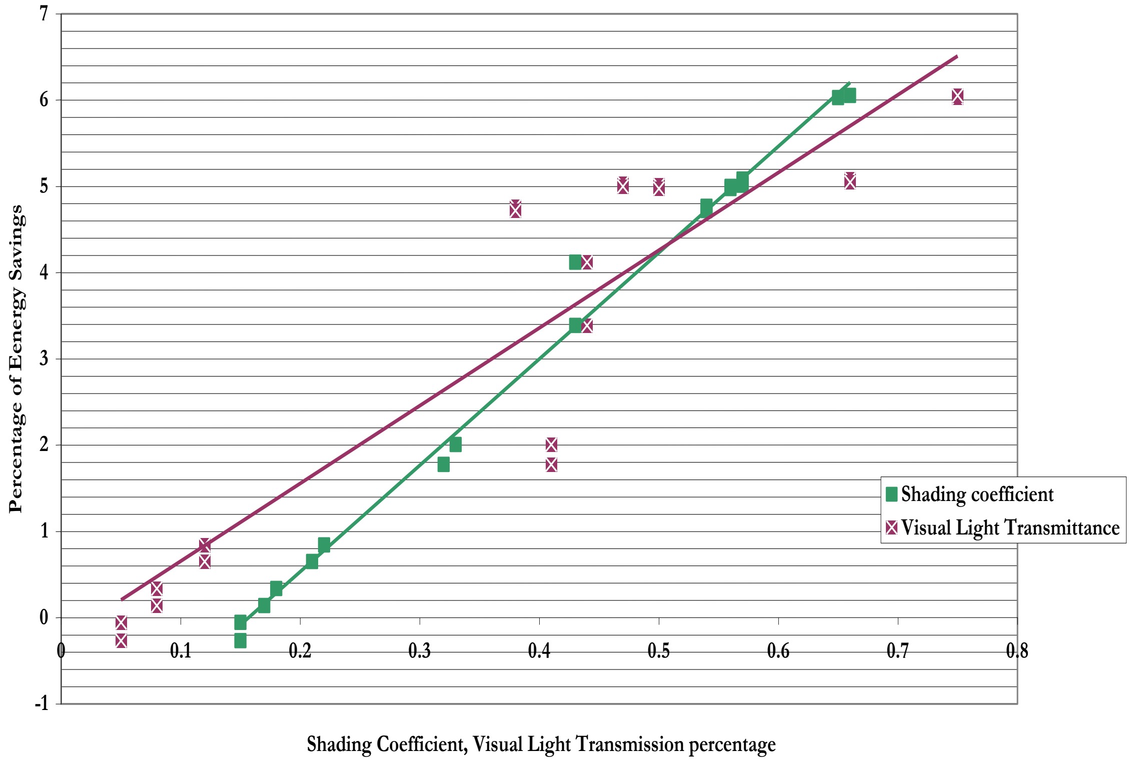


Figure 5.8: Effect of Parameters of glass, Shading coefficient and Visual light transmittance

5.3 EVALUATION OF LIFE CYCLE ENERGY

The application of different insulation materials showed significant energy savings in yearly energy consumption. To see the additional embodied energy imparted into the insulation material, if it is effective during the operation phase of a building, the life cycle energy cost has to be determined. The figure 5.9 shows the embodied energy of different thickness of polyurethane foam, polystyrene, and mineral wool insulations like glass wool and rock wool, which have applications mostly on walls in buildings. It shows that Polyurethane foam and polystyrene has higher embodied energy in comparison with the mineral wool insulations.

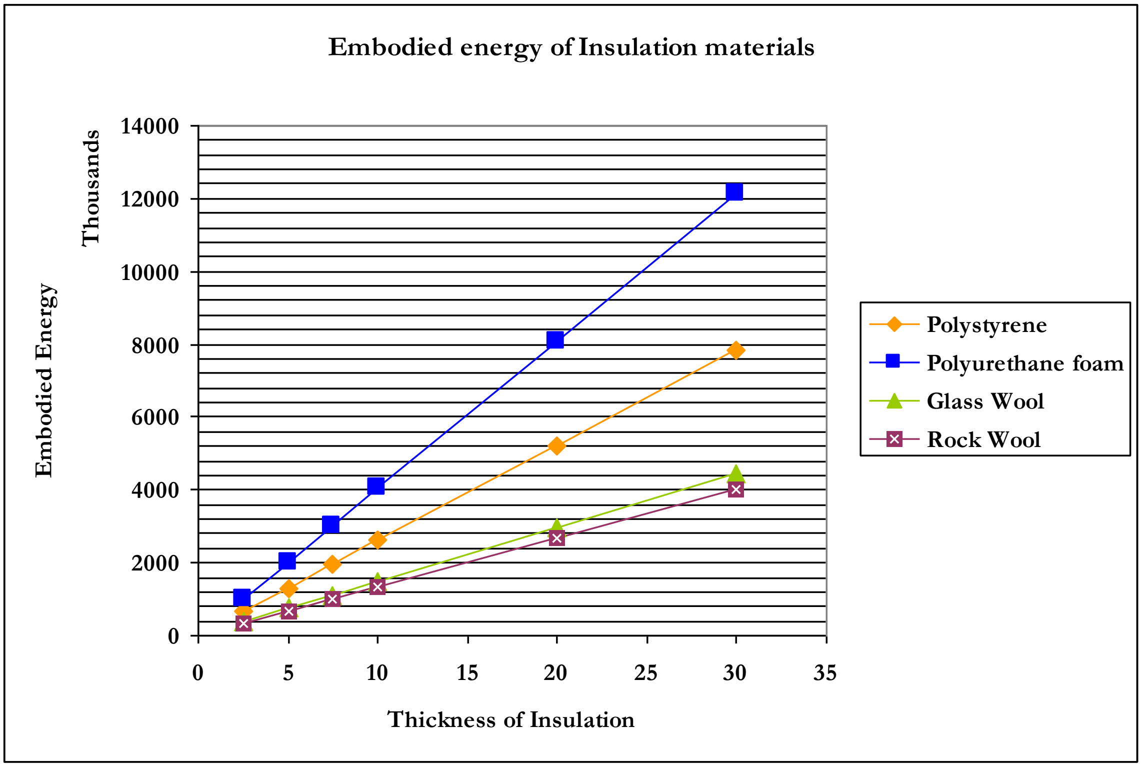


Fig 5.9: Embodied energy of the insulation materials of different thickness

The energy initially embodied in a building could be as much as 67% of its operating energy over a 25 year period [12]. In the figure 5.4.2, it is seen that the initial embodied energy of the envelope and structural components constitutes as mush as 76% of the operating energy at the first year of operation phase in INFOTECH building, and 49% of the operating energy in ASCENDAS building shown in figure 5.10 and 5.11 respectively. The difference in the two buildings is because of the main constituent of concrete wall and polystyrene filling in the roof slab, used in INFOTECH building as seen in fig 5.12. In further years it is observed that the operating energy constitutes higher percentage to the total energy consumption in comparison with the embodied energy.

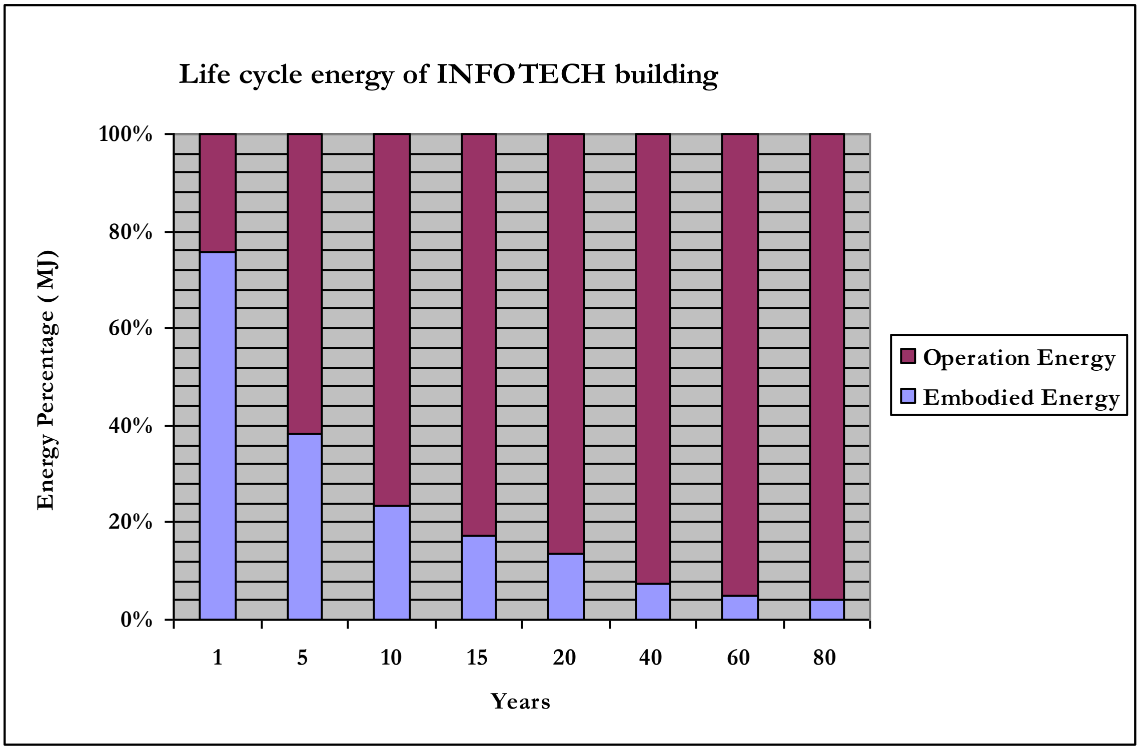


Fig 5.10: Life cycle energy consumption of INFOTECH building

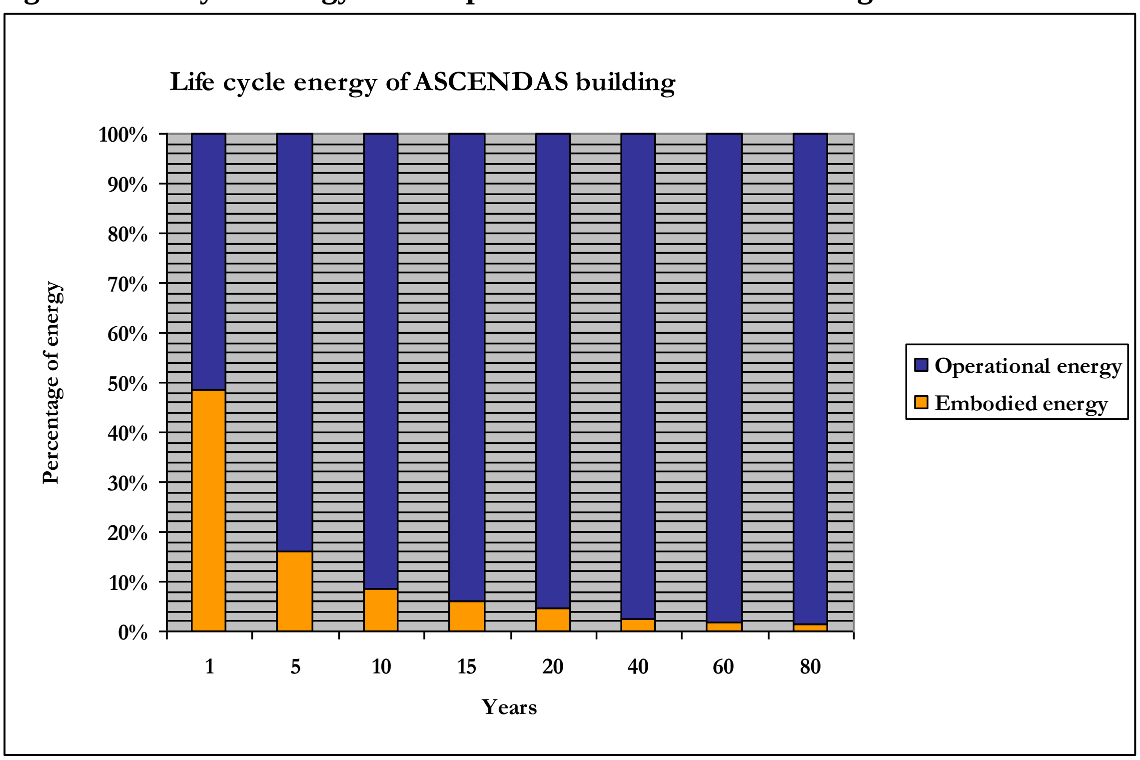


Fig 5.11: Life cycle energy consumption of ASCENDAS building

The figure 5.12, below shows the embodied energy of the envelope and structural components, in addition to it, the polystyrene insulation which has comparatively higher embodied energy constitutes as much as only 6% to it.

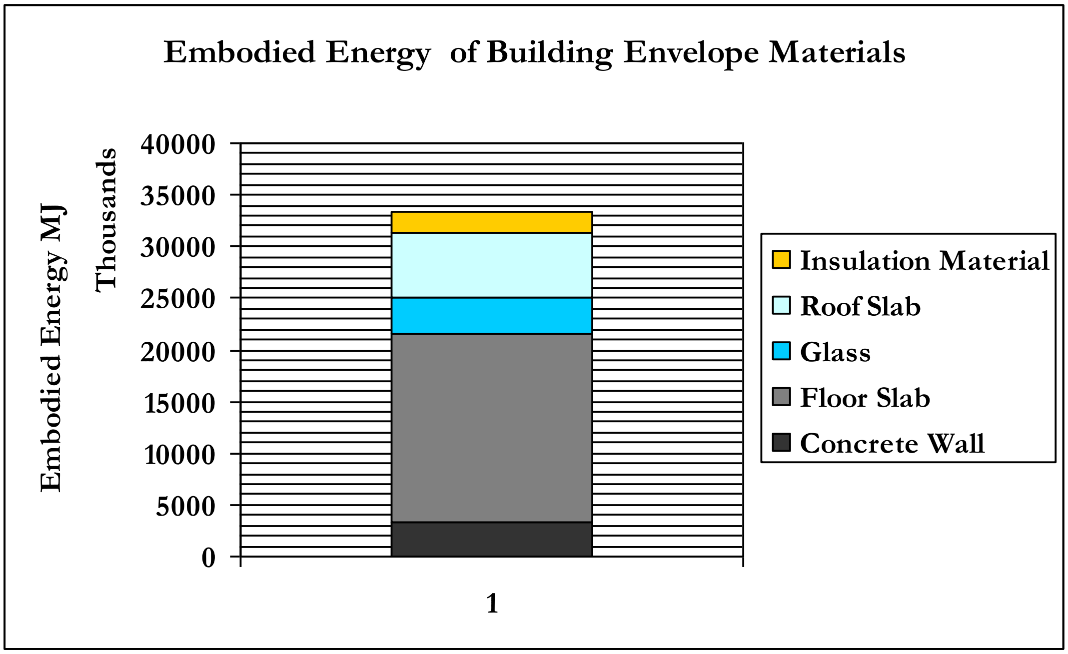


Fig 5.12: Embodied energy of the building materials and the additional insulation material.

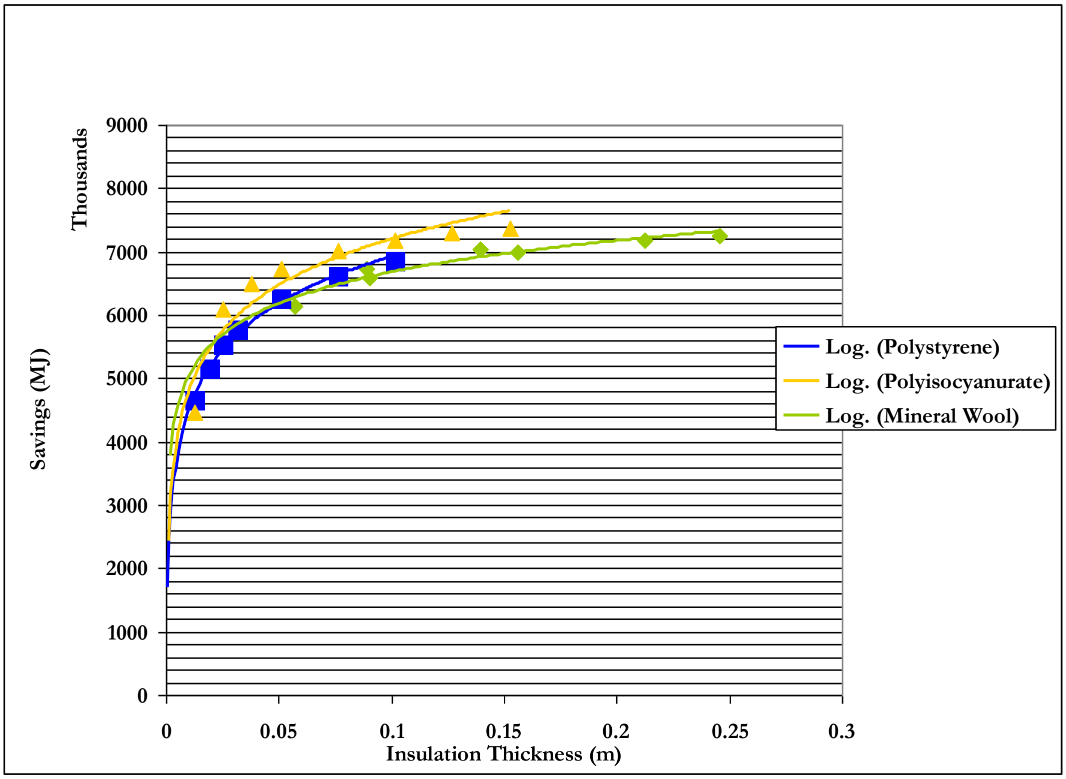


Fig 5.13: Comparison saving for insulation material studied.

The energy savings in specific with the different insulation materials of varying thickness is shown in figure 5.13. It shows that poysicocyanurate insulation which has higher embodied energy gives higher energy savings than polystyrene or mineral wool insulations. It also shows that with the increase of insulation thickness, there is significant energy savings but not beyond a certain point. The relationship between percentage of energy savings (Y) and the thickness of insulation material (x) is non-linear.

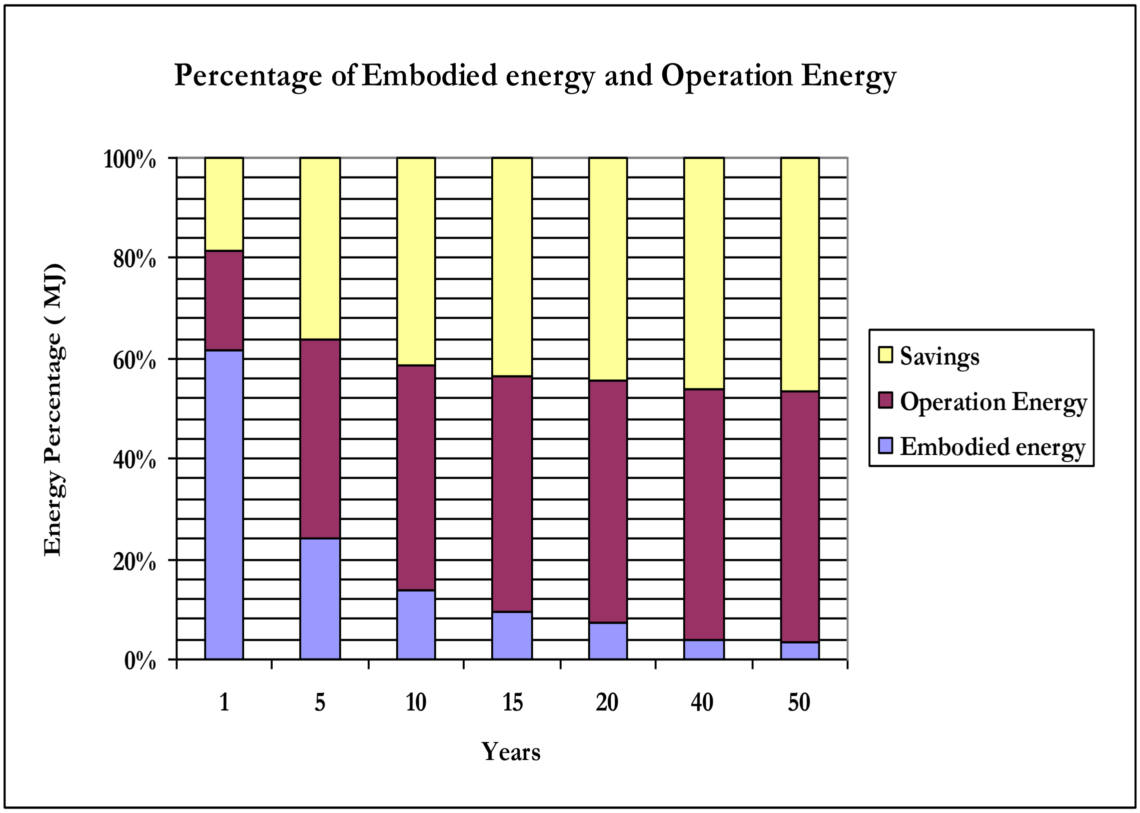


Fig 5.14: Energy Savings after the application of insulation materials of different thickness.

The replacement of the insulation materials (or) the life span of insulation materials varies from 15 to 30 years. The figure 5.14 shows the total embodied energy with additional insulation, operating energy and the energy savings achieved from the first year of operations phase of the building till the life span of 80 years of INFOTECH building. It shows that the energy savings due to installation of insulation is as much as 19% at the first year and reaches a maximum of 44% during the life span of 80 years.

CHAPTER 6 – CONCLUSION AND STRATEGIES

The work and analysis done in this project to evaluate the role of insulation in energy consumption in commercial and office buildings, has lead to the following conclusions.

1. ***The analysis of the case studies of the building on their performance shows that, they do not comply with the ECBC, 2006 and ASHRAE 90.1.2004, standards. INFOTECH building showed 25% of more energy consumption in comparison with ASHRAE standards and 3.5% more than ECBC standards. The ASCENDAS building showed 9.6% of energy consumption more than ECBC standards.***

2. The results of the analysis done on the influence of different parameters of the buildings that affect the energy consumption, shows that, firstly, in respect with the application of insulation materials on the exterior walls, shows that, ***the relationship between the percentage of energy savings(y) and the resistance of insulation materials(x) is non-linear. It obeys a logarithmic function in respect with all climates in India. Beyond a certain value of (X) the resistance value of the insulation material does not yield proportional return in percentage of energy savings. The thickness of the insulation material also obeys a logarithmic function with the percentage of energy savings.***

3. Secondly, ***the role of thermal mass in energy consumption showed that the equivalent thermal resistance-capacity product has logarithmic relationship with the percentage of energy savings. It does not give proportional return to percentage of energy savings. There is a linear relationship between percentage of energy savings and overall U-value of the wall. Hence there is always increase in percentage of energy savings with the reduction in overall u-value.***

4. Thirdly, the effect of window shades, ***movable interior or exterior do not have any considerable effect in the reduction, since the ratio of the glass area to the***

floor area in INFOTECH building is 10.6% and in ASCENDAS building it is 12.97%, which is very less percentage to have any considerable effect in reduction in energy consumption.

5. Fourthly, the result on analysis on the ***parameters of glass type***, ***the shading coefficient and visual light transmittance shows a linear relationship with the percentage of energy savings***. ***Energy savings as much as 6 to 7% with higher values of these parameters can be achieved. But higher the values of SC and VLT, the u-value of the glass increases. Hence, all the three parameters have to be considered simultaneously.***

6. Fifth, the results of analysis on the ***additional energy cost of insulation material to the initial embodied energy showed that the embodied energy of the insulation material is as much as only 6% of the total initial embodied energy of the building envelope components. The energy savings is specific with the insulation material with the highest embodied energy yield higher energy savings which exhibit a logarithmic function.***

7. Finally, the results of analysis on ***the lifecycle energy cost, sum total of the embodied energy and the operating energy, shows that the initially at the first year the energy savings is as much as 19% and reaches a maximum of 47% during the life span of 50 years with a very negligible increase in the embodied energy of the insulation material.***

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APPENDIX – A Comparison of simulation tools

Contrasting the Capabilities of Building Energy Performance Simulation Programs

Table 7 HVAC Systems	BLAST	BSim	DeST	DOE-2.1E	ECOTECT	Ener-Win	Energy Express	Energy-10	EnergyPlus	eQUEST	ESP-r	HAP	HEED	IDA ICE	IES <VE>	PowerDomus	SUNREL	Tas	TRACE	TRNSYS
Discrete HVAC components[135]			X				P		X		X			X	X	R	R	X		X
Idealized HVAC systems	X		X		X	X			X		X[136]			X	X		X			X[137]
User-configurable HVAC systems		X	X				P		X	X	X[138]	X[139]	X	X	X	X	R	X	X	X
Air loops[140]			X				P		X	P	X	X		X	X	X	R	X	X	X
Fluid loops[141]			X				P		X	X	X	X		X	X	P	R	X	X	X
Run-around, primary and secondary fluid loops with independent pumps and controls			X						P	X	X	X		X		P		X	X	X[142]
Fluid loop pumping power[143]										X	X[144]	X		X					X	
Pipe flow-pressure networks[145]											X			X						
Air distribution system[146]						X	P		X	X	X[147]	X	X	X	X		R			X
Multiple supply air plenums			P						X	P	X[147]				X					X
Simplified demand-controlled ventilation																				
▪ Ventilation rate per occupant and floor area			X			X			X	X			X	X[148]	X	X		X	P	X
▪ Ventilation air flow schedule		X	X			X			X	X	X		X[149]	X	X	X	X	X	X	X
▪ User-defined ventilation control strategy[150]		X[151]	X								X			X	X			X		X
CO_2 modeling																				
▪ CO_2 zone concentrations, mechanical and natural											X	X		X	X					O[151]

[135] Including part-load performance
[136] ESP-r users tend to use ideal zone controls to represent environmental controls as loops of sensors and actuators with a range of controls laws. These can be combined with flow networks to represent air distribution systems if increased resolution is needed. For projects where detailed component performance is required a network of detailed systems components can be defined.
[137] The multizone building model (Type 56) can optionally calculate the load from the temperature and humidity setpoints. A maximum power can be set and if that maximum is reached the model calculates the actual zone temperature
[138] See Table 14 for a general discussion of how ESP-r approaches detailed system components and for a list of component types.
[139] User selects a basic airside or waterside system type and then configures components permitted for that type of air loop or water loop.
[140] Connect fans, coils, mixing boxes, zones
[141] Hot water, chilled water and condenser loops connect equipment
[142] By combining available components
[143] Based on flow and pressure with 2/3-way valves with static head
[144] Static head not supported.
[145] Arbitrary structure with valves, pumps and controls
[146] Including conduction losses and air leakage
[147] Via plant components and/or flow network
[148] Via CO_2 based control
[149] Intelligent controller manages night flushing and daytime economizer for passive cooling
[150] Any combination of feed-forward/feedback controllers
[151] CO_2 controlled ventilation rates

Table 7 *HVAC Systems*	BLAST	BSim	DeST	DOE-2.1E	ECOTECT	Ener-Win	Energy Express	Energy-10	EnergyPlus	eQUEST	ESP-r	HAP	HEED	IDA ICE	IES <VE>	PowerDomus	SUNREL	Tas	TRACE	TRNSYS
air path transport																				
▪ CO_2 based demand-controlled ventilation		X[152]									X	X		X	X				P	EO[151]
Automatic sizing																				
▪ HVAC components		P	X	X		X	X	X	X	X		X	X	X[153]	X	P	R	X	X	P[154]
▪ Air loop flow, outside air, zone airflow		X	P			X			X			X		X	X			X	X	P
▪ Hot, cold, and condenser water loops			P						X	X		X[155]		X	X			X	X	P
Zonal air distribution unit											I[156]									OI[157]
▪ Constant volume reheat	X	X	X	X		X	X		X	X	X	X		X	X	X		X	X	
▪ Constant volume 4-pipe induction	X		X				P		X			X		X	X				X	
▪ Variable air volume reheat	X	X	X	X			X		X	X	X	X		X	X			X	X	
▪ Variable air volume no reheat	X	X	X	X		X	X		X	X	X	X		X	X			X	X	
▪ Variable air volume reheat/variable speed fan (UFAD)		X	X				P		X		R				X			X	X	
▪ Powered induction unit																		X		
o Series PIU reheat				X			P		X	X		X		X					X	
o Parallel PIU reheat				X					X	X		X		X					X	
▪ Dual duct constant volume	X	X		X		X	P		X	X	X	X		X	X				X	
▪ Dual duct variable air volume	X	X		X			P		X	X	X	X		X	X				X	
Zone forced air unit											I[156]									
▪ Fan coil (2 pipe)	X		X				P				X	X							P	O[158]
▪ Fan coil (4 pipe)	X	X	X	X		X	P		X	X		X		X	X			X	X	O[158]
▪ Unit heater[159]	X		X	X		X		X	X	X	X	X	X	X	X	X	R	X	X	O[158]
▪ Unit ventilator[160]	X		P	X		X		X	X	X	X	X	X	X	X			X	X	O[158]
▪ Window air-conditioner (cycling)			X	X		X	P	X	X	X		X	X	X	X	X	R	X	X	O[158]
▪ Energy recovery ventilator (stand-alone)									X			X		X	X			X	X	O[158]

[152] Detailed demand controlled ventilation with CO_2 mass balance and CO_2 sensor control
[153] Via unlimited capacity components
[154] The total power
[155] Hot and cold water loops
[156] Combinations of detailed system components and/or flow networks can be used to define a range of HVAC designs. Also see component descriptions in Table 14.
[157] Combinations of detailed system components, most of which are available in the optional TESS libraries
[158] Through additional components or combinations of components that are part of the additional TESS libraries
[159] Water, gas or electric heating coil
[160] Water, gas or electric heating coil, water cooling coil

Table 7 *HVAC Systems*	BLAST	BSim	DeST	DOE-2.1E	ECOTECT	Ener-Win	Energy Express	Energy-10	EnergyPlus	eQUEST	ESP-r	HAP	HEED	IDA ICE	IES <VE>	PowerDomus	SUNREL	Tas	TRACE	TRNSYS
Unitary equipment											I[158]									
▪ DX system																				
o Heating/cooling coils	X	X	X	X		X	P	X	X	X	X	X	X		X	X	R	X	X	X
o Coil latent capacity degradation[161]									X	X	X				X					X
▪ Furnace[162]	X		X	X		X	X	X	X	X	R	X	X		X		R	X	X	X
▪ Air-to-air packaged heat pump	X	X	X	X		X	P	X	X	X	R	X	X		X	X	R	X	X	X
▪ Water-to-air packaged heat pump	X		X	X		X	P		X	X	R	X			X		R	X	X	X

[161] At part load (cycling) conditions
[162] Gas or electric heating coil, DX cooling coil

Table 8 *HVAC Equipment*	BLAST	BSim	DeST	DOE-2.1E	ECOTECT	Ener-Win	Energy Express	Energy-10	EnergyPlus	eQUEST	ESP-r	HAP	HEED	IDA ICE	IES <VE>	PowerDomus	SUNREL	Tas	TRACE	TRNSYS
Coils											I[156]									
▪ Water heating coil	X	X	X	X		X	X		X	X	X	X		X	X	P	R	X	X	X
▪ Electric heating coil	X	X	X	X		X	X	X	X	X	X	X		R	X	X	R	X	X	X
▪ Gas heating coil	X			X		X	X		X	X		X			X	P	R	X	X	X
▪ Water cooling coil	X	X	X	X		X	X		X	X	X	X		X	X	X	R	X	X	X
▪ Detailed fin/tube water cooling coil	X[163]								X		X			X		X				X
▪ DX coil																				O[158]
o Bypass factor cooling empirical	X								X			X			X[164]					
o Multispeed cooling empirical	X								X						[164]					
o Heating empirical	X								X						[164]					
o Coil frost control									X	X	X	X			[164]				X	
▪ Water-to-air heat pump[165]	X		X	X			P		I	X		X			X			X	X	X
Radiative/convective unit											X[166]									
▪ Baseboard (electric)	X	X		X		X		X	X	X	X	X	X	X	X	X	X		X	
▪ Baseboard (hydronic)	X	X				X			X	X	X	X		X	X		R		X	O[158]
▪ Low temperature radiant																				
o Hydronic[167]	X[163]	X							X		X[168]			X	X					X
o Electric[169]	X[163]	X							X		X[168]				X					X[168]
▪ High temperature radiant (gas, electric)	X			P					X		X[168]			X[170]	X					X
Desiccant dehumidifier (solid)				X			P		X	X									X	X
Humidifier							P													
▪ Steam (electric)	X	X	X						X		X	X		X	X	X		X	X	O[158]
▪ Humidifier water consumption		X	X						X		X			X	X	X			X	O[158]
Humidity control[171]																				
▪ Cooling coils in combination with air-to-air heat exchanger for improved dehumidification performance		X							X		X			X	X	X			X	X

[163] Only in IBLAST, an unreleased, integrated simulation version of BLAST.
[164] Generic coil
[165] Reciprocating, rotary or scroll compressor, heating or cooling
[166] Various representations: as an ideal zone controller or via detailed plant components.
[167] Heating or cooling, floor, slab, wall, ceiling
[168] Via system components or heat injected into surfaces
[169] Floor, slab, wall, ceiling
[170] Electric
[171] Chilled water or DX cooling coils

Table 8 ***HVAC Equipment***	BLAST	BSim	DeST	DOE-2.1E	ECOTECT	Ener-Win	Energy Express	Energy-10	EnergyPlus	eQUEST	ESP-r	HAP	HEED	IDA ICE	IES <VE>	PowerDomus	SUNREL	Tas	TRACE	TRNSYS
▪ High humidity control (DX or chilled water coils)	X	X		X		X			X	X	X	X		X	X	X			X	X
Fans																				
▪ Constant volume	X	X	X	X		X	X	X	X	X	X	X		X	X	X	P	X	X	X
▪ Variable volume	X	X	X	X		X	X	X	X	X	X	X	X	X	X		R	X	X	X
▪ Exhaust	X	X	X	X					X	X	X	X	X	X	X	X		X	X	X
Pumps																				
▪ Constant speed	X		X	X		X	P		X	X	X	X		X	X	X	R	X	X	X
▪ Variable speed	X		X	X			P		X	X	X	X		X	X	P	R	X	X	X
▪ Multi-stage										X	X			X					P	X[172]
▪ Direct-couple to power source											X									O[158]
Heat exchangers[173]																				
▪ Plate frame									P	X	X			X					X	X
▪ Immersed coil														X						X
▪ Shell and tube											X			X						X
▪ User-defined effectiveness										X	X			X						X
Plant cooling equipment																				
▪ Electric chiller											X[174]									
o Centrifugal	X		X	X		X	P		X	X		X		O	X[175]	X			X	O[158]
o Centrifugal with VSD				X[176]					X[177]	X		X			[175]				X	O[158]
o Reciprocating	X		X			X	P		X	X		X		O	[175]				X	O[158]
o Double-bundle condenser/heat recovery	X		X	X			P		X	X					[175]				X	O[158]
o Screw			X	X[178]			P		X[179]	X		X		O	[175]				X	O[158]
o Scroll			X							X		X			[175]				X	O[158]
o Constant COP	X	X	X			X	P	X	X	X				X	[175]			X	X	O[158]
▪ Engine-driven chiller[180]	X		X	X			P		X			X			[175]				X	O[158]
▪ Combustion turbine chiller[181]	X		X				P		X			P			[175]				X	O[158]

[172] Through appropriate controller
[173] Various flow configurations
[174] Generic chiller representation.
[175] User can specify curves of chiller performance
[176] User can simulate VSD by substituting curves for centrifugal chiller.
[177] User can enter curves for VSD centrifugal chiller.
[178] User can replace compression chiller curves with curves for screw chiller.
[179] User can enter curves for screw chiller and use Chiller:Electric:EIR.
[180] Gas, diesel, gasoline, fuel oil
[181] With/without heat recovery, gas, diesel, gasoline, fuel oil

Table 8 HVAC Equipment	BLAST	BSim	DeST	DOE-2.1E	ECOTECT	Ener-Win	Energy Express	Energy-10	EnergyPlus	eQUEST	ESP-r	HAP	HEED	IDA ICE	IES <VE>	PowerDomus	SUNREL	Tas	TRACE	TRNSYS
▪ Absorption Chiller																				
o Steam absorption chiller	X		X	X			P		X	X		X[182]			[175]				X	O[158]
o Gas-fired absorption chiller							P					X			[175]				X	
o Gas-fired hot water absorption chiller heater	X			X					X	X									X	X[182]
▪ Free cooling chiller	X			X					X	X				X				X	X	X
▪ Air-to-water heat pump chiller			X			X				X				O	[175]			X	X	X
▪ Water-to-water heat pump chiller	X		X			X			X	X				X	[175]			X	X	X
Plant condenser/evaporator equipment																				
▪ Cooling tower																				
o Single speed	X		X	X		X	P	X	X	X	X	X				X			X	X
o Two speed									X		X	X							X	X
o Variable speed				X					X	X	X	X				P			X	X
▪ Air-cooled condenser	X		P	X		X	P	X	X	X	X	X				X			X	X
▪ Simple evaporative condenser	X		P	X					X	X									X	X
▪ Direct evaporative cooler	X		P			X			X										X	O[158]
▪ Indirect evaporative cooler	X								X										X	O[158]
▪ Free cooling, hydronic heat exchanger[183]			X	X					X	X		X		X					X	X
▪ Pond heat exchanger									X	X		X								X
▪ Ground surface heat exchanger									X	X										X
▪ Ground loop vertical borehole heat exchanger									I	X	R	X		X[184]					X	X
▪ DX cooling coil evaporative condenser																				
o Simple effectiveness model				X					X	X									X	X
o Water usage and water pump power									X											X
Seasonal heat and cold storage										X										
▪ Hot-/chilled-water/ice thermal energy storage	X		P				P		P										X	XO
▪ Ground heat exchangers										X										O[158]
▪ Stratified thermal storage tank	X									X										X
▪ Ground-coupled (uninsulated) stratified tank																				O[158]
▪ With phase change																				O[185]
Plant heating equipment																				
▪ Boiler[186]	X		X	X		X	P	X	X	X	I	X	X	X	X			X	X	XO

[182] Single- and double-effect chillers
[183] Water-side economizer
[184] As add-in. Vertical or slanted holes in user-specified configuration. 3D model.
[185] Additional component from Transsolar
[186] Gas, electric, diesel, gasoline, propane, fuel oil, coal, steam

Table 8 HVAC Equipment	BLAST	BSim	DeST	DOE-2.1E	ECOTECT	Ener-Win	Energy Express	Energy-10	EnergyPlus	eQUEST	ESP-r	HAP	HEED	IDA ICE	IES <VE>	PowerDomus	SUNREL	Tas	TRACE	TRNSYS
▪ Water heater[186]	X					X			X	X	I			X	X[187]				X	X
▪ Ground source water-to-water heat pump			P	P		P		X[188]	I	X	R			O	X[187]			X	X	X
Air-to-air energy recovery																				
▪ Generic sensible heat exchanger	X	X	X	P			P		X	X	X	X		X	X			X	X	X
▪ Flat plate sensible heat exchanger		X	X						X	X	X	X		X	X				X	X
▪ Sensible and latent energy exchanger	X	X	X				P		X	X	X	X		X	X				X	X
Domestic/service water heating																				
▪ User-configurable water piping network											X									X
▪ Domestic/service water heater[189]				X		X		X	X	X	R			X	X		R	X	X	X
▪ D/SHW water consumption								X	X		R			X					X	X
▪ Stratified water heater tank	X										R									X[190]
▪ Combi-tanks for space and water heating[191]																				XO[192]
Controls, thermostats and strategies																				
▪ Humidistat	X	X	X			P	P		X		R	X		X	X	P		X	X	O[158]
▪ Zone thermostat[193]	X	X	X	X		X	P	X	X	X	X	X	X	X	X	X	X	X	X	X
▪ Zone supply air setpoint[194]	X	X	X	X			P	X	X	X	X	X[195]		X	X			X	X	X
▪ Outside air control[196]	X	X		P			P		X	X	X	X		X	X	P		X	X	X
▪ System availability[197]	X	X	X	X			P	X	X	X	X	X[198]		X	X		R	X	X	X
▪ Plant heating/cooling load control for staging and sequencing plant equipment	X		X	X			P		X	X		X		X	X	P		X	X	X
▪ Condenser control[199]				X					X	X				O					X	X
▪ Nighttime flushing for passive cooling				X		X			X	X	X		X	X	X		X		X	X
▪ Economizer	X			X		X	P	X	X	X	X	X	X	X	X				X	X

[187] User can specify curves of boiler/heater performance
[188] Simple fixed efficiency model for ground-source heat pump
[189] Gas and electric
[190] Options include stratified water heater tank with up to 10 internal heat exchangers and 25 inlet/outlet ports, as well as multiple geometries (horizontal and vertical cylinder, rectangular cross-section, spherical)
[191] Multiple heat exchanger and or inlets/outlets with stratification devices
[192] Standard components as well as add-ons from Transsolar and components from the TESS libraries
[193] Single heating setpoint, single cooling setpoint, single heating/cooling setpoint, dual setpoint with deadband
[194] Scheduled, coldest, warmest, mixed air, outside air, minimum/maximum humidity
[195] Scheduled, coldest, warmest, outside air, min/max humidity
[196] Scheduled, outdoor dry bulb and wet bulb temperature, outdoor air flow
[197] Scheduled, night cycle control, differential thermostat, high/low temperature on/off
[198] Scheduled, high/low temperature on/off
[199] Uncontrolled, heating/cooling load range-based, outdoor range based (dry bulb, wet bulb, humidity, dew point), outdoor temperature difference based (dry bulb, wet bulb, dew point)

Table 8 HVAC Equipment	BLAST	BSim	DeST	DOE-2.1E	ECOTECT	Ener-Win	Energy Express	Energy-10	EnergyPlus	eQUEST	ESP-r	HAP	HEED	IDA ICE	IES <VE>	PowerDomus	SUNREL	Tas	TRACE	TRNSYS
▪ User-defined control strategy[200]		X								X				X	X					X
Refrigeration systems for warehouse and retail food storage																				
▪ Refrigerant loops[201]										X										
▪ Multiple staged refrigerant compressors										X										
▪ Refrigerated casework[202]				X					X	X						P				
▪ Refrigerant air/evaporative condensers with heat reclaim and control				X					X	X										
▪ User-selectable refrigerants										X										
▪ Ammonia chillers and low temperature brine										X										
▪ Brine and refrigerant loop fan coil for coolers/freezers										X										
Ice rink in building space																				
▪ Brine loop and chiller refrigeration system										X				O						
▪ Ice-to-ceiling radiative and ice-to-space air exchange										X				O						
▪ Under floor heating (with ice load)										X				O						
▪ Ice resurfacing										X				O						
Indoor/outdoor swimming pool											R			O						O[203]

[200] Any combination of feedback/feed-forward controllers
[201] Connects coils, casework, compressors, condensers
[202] Zone interaction, frost forming refrigerant coil and controls
[203] Additional component from Transsolar

Table 9 Environmental Emissions	BLAST	BSim	DeST	DOE-2.1E	ECOTECT	Ener-Win	Energy Express	Energy-10	EnergyPlus	eQUEST	ESP-r	HAP	HEED	IDA ICE	IES <VE>	PowerDomus	SUNREL	Tas	TRACE	TRNSYS
Power plant energy emissions	X		P	X	^{3}	X		X	X	X	X	X	X		X			X	X	I
On-site energy emissions	X	X	P	X	X	X		X	X	X	X	X	X		X			X	X	I
Major greenhouse gases (CO_2, CO, CH_4, NO_x)	X	P	P	X	^{3}	X		X	X	X	X	X[204]	X		X			X		
Carbon equivalent of greenhouse gases	X			X	^{3}				X						X			X		I
Criteria pollutants (CO, NO_x, SO_2, PM, Pb)					^{3}				X			X[205]			X					
Ozone precursors (CH_4, NMVOC, NH_3)					^{3}				X											
Hazardous pollutants (Pb, Hg)					^{3}				X											
Water use in power generation					^{3}				X											X
High- and low-level nuclear waste					^{3}				X											
Pollutant emissions factors[206]					^{3}				X				X							

[204] CO_2, NO_x
[205] NO_x, SO_2
[206] State/provincial/regional/national aggregation for major fuels: electricity, natural gas, residual fuel oil, distillates, residential oil, LPG, gasoline, diesel, and coal

Table 10 ***Climate Data Availability***	BLAST	BSim	DeST	DOE-2.1E	ECOTECT	Ener-Win	Energy Express	Energy-10	EnergyPlus	eQUEST	ESP-r	HAP	HEED	IDA ICE	IES <VE>	PowerDomus	SUNREL	Tas	TRACE	TRNSYS
Weather data provided																				
▪ With the program[207]	X	X	X		X	X	X	X	X[208]	X[209]	X	X		X	X	P		X	X	X[210]
▪ Separately downloadable		X			X	X			X[208]	X[209]	X	X		X	X			X	X	X
Generate hourly data from monthly averages			X[211]		X	X									X				X	X
Estimate diffuse radiation from global radiation			X	X	[3]	X			X						X			X		X
Weather data processing and editing	X		X	X	X	X		X	X	X	X					X		X		X
Weather data formats directly read by program																				
▪ Any user-specified format		X[214]			X	X	X		X[212]					X[213]	X[214]	X[214]	X			X
▪ EnergyPlus/ESP-r[215]		X			X				X		X		X					X		X
▪ European Test Reference Year[216]		X			X						X			X						X
▪ Typical Meteorological Year[217]	X		X[218]	X	X		P		X	X	X			X		X[219]	X		X	X
▪ Typical Meteorological Year 2[220]	X			X	X	X		X[221]	X	X	X			X		X[219]	X	X	X	X
▪ Solar and Wind Energy Resource Assessment[222]									X											
▪ Weather Year for Energy Calculations 2[223]			X	X	X	X	P		X	X				X						
▪ Solar and Meteorological Surface Observation Network[224]									X											
▪ International Weather for Energy Calculations[225]					X		P		X					X					X	X

[207] CD, DVD, distribution download
[208] Five weather files provided with EnergyPlus. More than 900 locations worldwide available for download
[209] Automatically downloads weather files from web site.
[210] More than 1000 locations worldwide including TMY2 data and Meteonorm-generated data
[211] From daily measured data (max, min, average)
[212] By specifying the data format
[213] C source code for weather data conversion utility supplied to enable easy implementation of various formats.
[214] Any weather data given as hourly values in text files can be converted to the internal file format as long as it includes dry bulb temperature, two solar data, humidity parameter, wind speed, and wind direction.
[215] Crawley, Hand, and Lawrie (1999)
[216] European Commission (1985)
[217] NCDC (1981)
[218] Based on measured data
[219] Through an additional program, Domus weather converter, which comes with PowerDomus
[220] NREL (1995)
[221] Use of TMY2 and other text formats possible using companion WeatherMaker utility.
[222] swera.unep.net/swera/
[223] ASHRAE (1997)
[224] NCDC (1993)
[225] ASHRAE (2001b)

Table 10 *Climate Data Availability*	BLAST	BSim	DeST	DOE-2.1E	ECOTECT	Ener-Win	Energy Express	Energy-10	EnergyPlus	eQUEST	ESP-r	HAP	HEED	IDA ICE	IES <VE>	PowerDomus	SUNREL	Tas	TRACE	TRNSYS
▪ Japan AMeDAS weather data[226]																				X
▪ DOE-2 text format				X	X				X	X									X	
▪ BLAST text format	X				X				X								X			
▪ ESP-r text format									X		X									
▪ ECOTECT WEA format					X				X											

[226] Akasaka et al. (2003)

Appendix - B

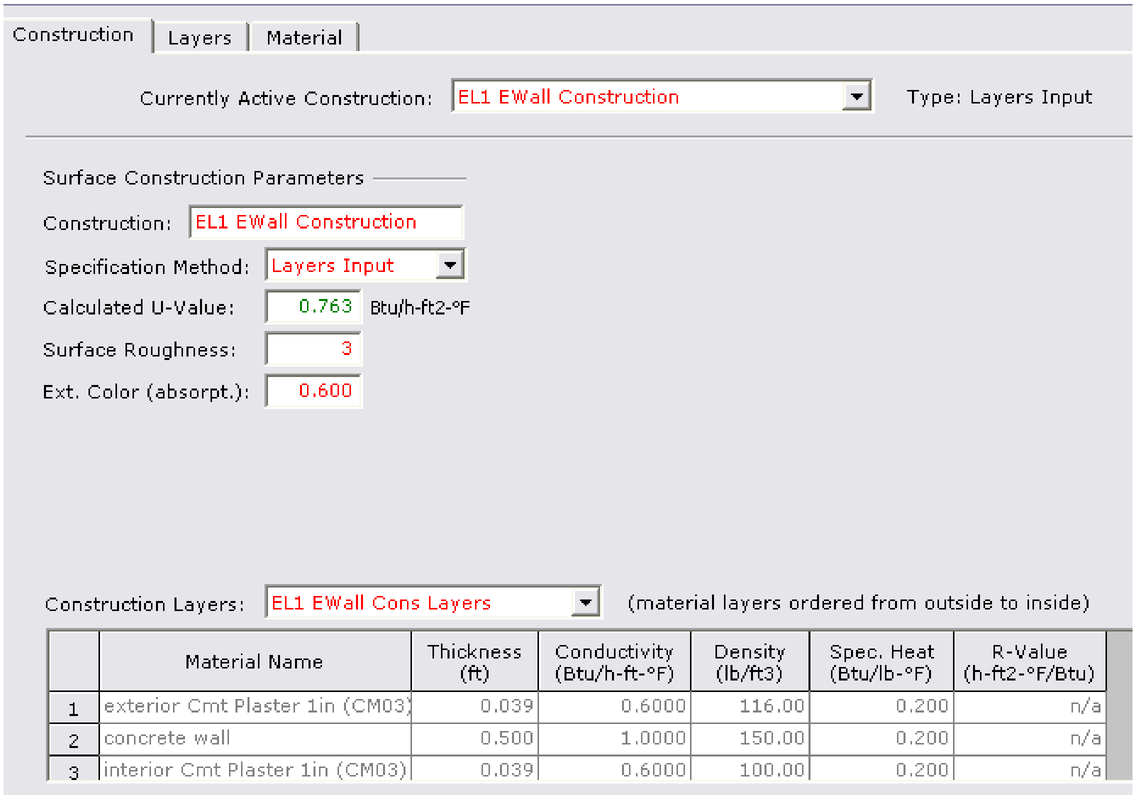
Insulating Materials

Table 1 Insulating Materials						
Code-Word	**Description**	**Thickness**	**Conductivity**	**Density**	**Specific Heat**	**Resistance**
		ft (m)	Btu/hr-ft^2-F (W/m-K)	lb/ft^3 (kg/m^3)	Btu/lb-F (kJ/kg-K)	hr-ft^2-F/Btu (K-m^2/W)
Mineral Wool/Fiber						
MinWool Batt R7 (IN01)	Batt, R-7*	0.1882 (0.0574)	0.0250 (0.043)	0.60 (10)	0.2 (837)	7.53 (1.327)
MinWool Batt R11 (IN02)	Batt, R-11	0.2957 (0.0901)	0.0250 (0.043)	0.60 (10)	0.2 (837)	11.83 (2.085)
MinWool Batt R19 (IN03)	Batt, R-19	0.5108 (0.1557)	0.0250 (0.043)	0.60 (10)	0.2 (837)	20.43 (3.600)
MinWool Batt R24 (IN04)	Batt, R-24	0.6969 (0.2124)	0.0250 (0.043)	0.60 (10)	0.2 (837)	27.88 (4.913)
MinWool Batt R30 (IN05)	Batt, R-30	0.8065 (0.2458)	0.0250 (0.043)	0.60 (10)	0.2 (837)	32.26 (5.685)
MinWool Fill 3.5in R11 (IN11)	Fill, 3.5 in (8.9 cm), R-11	0.2917 (0.0889)	0.0270 (0.046)	0.60 (10)	0.2 (837)	10.80 (1.903)
MinWool Fill 5.5in R19 (IN12)	Fill, 5.5 in (13.4 cm), R-19	0.4583 (0.1397)	0.0270 (0.046)	0.63 (11)	0.2 (837)	16.97 (2.991)
Cellulose Fill						
Cellulose 3.5in R-13 (IN13)	3.5 in (8.9 cm), R-13	0.2917 (0.0889)	0.0225 (0.039)	3.0 (48)	0.33 (1381)	12.96 (2.284)
Cellulose 5.5in R-20 (IN14)	5.5 in (13.4 cm), R-20	0.4583 (0.1397)	0.0225 (0.039)	3.0 (48)	0.33 (1381)	20.37 (3.590)
Insulation						
Insul Bd 1in (HF-B2)	1 in (2.5 cm)	0.0830 (0.0254)	0.0250 (0.043)	2.0 (32)	0.2 (837)	3.32 (0.585)
Insul Bd 2in (HF-B3)	2 in (3.1 cm)	0.1670 (0.0508)	0.0250 (0.043)	2.0 (32)	0.2 (837)	6.68 (1.177)
Insul Bd 3in (HF-B4)	3 in (7.6 cm)	0.2500 (0.0762)	0.0250 (0.043)	2.0 (32)	0.2 (837)	10.00 (1.762)
Insul Bd 1in (HF-B5)	1 in (2.5 cm)	0.0830 (0.0254)	0.0250 (0.043)	5.7 (91)	0.2 (837)	3.29 (0.580)
Insul Bd 2in (HF-B6)	2 in (3.1 cm)	0.1670 (0.0508)	0.0250 (0.043)	5.7 (91)	0.2 (837)	6.68 (1.177)
Insul Bd 3in (HF-B12)	3 in (7.6 cm)	0.2500 (0.0762)	0.0250 (0.043)	5.7 (91)	0.2 (837)	10.00 (1.762)
Preformed Mineral Board						
MinBd 7/8in R-3 (N21)	7/8 in (2.2 cm), R-3	0.0729 (0.0222)	0.0240 (0.042)	15.0 (240)	0.17 (711)	3.04 (0.536)
MinBd 1in R-3 (IN22)	1 in (2.5 cm), R-3.5	0.0833 (0.0254)	0.0240 (0.042)	15.0 (240)	0.17 (711)	3.47 (0.612)
MinBd 2in R-7 (IN23)	2 in (2.5 cm), R-7	0.1667 (0.0508)	0.0240 (0.042)	15.0 (240)	0.17 (711)	6.95 (1.225)
MinBd 3in R-10.4 (IN24)	3 in (7.6 cm), R-10.4	0.2500 (0.0762)	0.0240 (0.042)	15.0 (240)	0.17 (711)	10.42 (1.836)
Polystyrene, Expanded						

Table 1 Insulating Materials						
Code-Word	**Description**	**Thickness**	**Conductivity**	**Density**	**Specific Heat**	**Resistance**
		ft (m)	Btu/hr-ft^2-F (W/m-K)	lb/ft^3 (kg/m^3)	Btu/lb-F (kJ/kg-K)	hr-ft^2-F/Btu (K-m^2/W)
Polystyrene 1/2in (IN31)	1/2 in (1.3cm)	0.0417 (0.0127)	0.0200 (0.035)	1.8 (29)	0.29 (1213)	2.08 (0.367)
Polystyrene 3/4in (IN32)	3/4 in (1.9 cm)	0.0625 (0.0191)	0.0200 (0.035)	1.8 (29)	0.29 (1213)	3.12 (0.550)
Polystyrene 1in (IN33)	1 in (2.5 cm)	0.0833 (0.0254)	0.0200 (0.035)	1.8 (29)	0.29 (1213)	4.16 (0.733)
Polystyrene 1.25in (IN34)	1.25 in (3.2 cm)	0.1042 (0.0318)	0.0200 (0.035)	1.8 (29)	0.29 (1213)	5.21 (0.918)
Polystyrene 2in (IN35)	2 in (3.1 cm)	0.1667 (0.0508)	0.0200 (0.035)	1.8 (29)	0.29 (1213)	8.33 (1.468)
Polystyrene 3in (IN36)	3 in (7.6 cm)	0.2500 (0.0762)	0.0200 (0.035)	1.8 (29)	0.29 (1213)	12.50 (2.203)
Polystyrene 4in (IN37)	4 in (10.2 cm)	0.3333 (0.1016)	0.0200 (0.035)	1.8 (29)	0.29 (1213)	16.66 (2.936)
Polyurethane, Expanded						
Polyurethane 1/2in (IN41)	1/2 in (1.3cm)	0.0417 (0.0127)	0.0133 (0.023)	1.5 (24)	0.38 (1590)	3.14 (0.553)
Polyurethane 3/4n (IN42)	3/4 in (1.9 cm)	0.0625 (0.0191)	0.0133 (0.023)	1.5 (24)	0.38 (1590)	4.67 (0.823)
Polyurethane 1in (IN43)	1 in (2.5 cm)	0.0833 (0.0254)	0.0133 (0.023)	1.5 (24)	0.38 (1590)	6.26 (1.103)
Polyurethane 1.25in (IN44)	1.25 in (3.2 cm)	0.1042 (0.0318)	0.0133 (0.023)	1.5 (24)	0.38 (1590)	7.83 (1.380)
Polyurethane 2in (IN45)	2 in (3.1 cm)	0.1667 (0.0508)	0.0133 (0.023)	1.5 (24)	0.38 (1590)	12.53 (2.208)
Polyurethane 3in (IN46)	3 in (7.6 cm)	0.2500 (0.0762)	0.0133 (0.023)	1.5 (24)	0.38 (1590)	18.80 (3.313)
Polyurethane 4in (IN47)	4 in (10.2 cm)	0.3333 (0.1016)	0.0133 (0.023)	1.5 (24)	0.38 (1590)	25.06 (4.416)
* Nominal thickness is 2 to 2-3/4 in (3.1 to 7 cm). Resistance value is based on a thickness of 2.26 in (5.74 cm).						
Urea Formaldehyde						
Urea Formald 3.5in R19 (IN51)	3.5 in (8.9 cm), R-15	0.2910 (0.0887)	0.0200 (0.035)	0.7 (11)	0.3 (1255)	14.55 (2.564)
Urea Formald 5.5in R23 (IN52)	5.5 in (13.4 cm), R-23	0.4580 (0.1396)	0.0200 (0.035)	0.7 (11)	0.3 (1255)	22.90 (4.036)
Insulation Board						
Insul Bd 1/2in (IN61)	Sheathing, 1/2 in (1.3cm)	0.0417 (0.0127)	0.0316 (0.055)	18.0 (288)	0.31 (1297)	1.32 (0.232)
Insul Bd 3/4in (IN62)	Sheathing, 3/4 in (1.9 cm)	0.0625 (0.0191)	0.0316 (0.055)	18.0 (288)	0.31 (1297)	1.98 (0.348)
Insul Bd 3/8in (IN63)	Shingle Backer, 3/8 in (1 cm)	0.0313 (0.0096)	0.0331 (0.058)	18.0 (288)	0.31 (1297)	0.95 (0.167)
Insul Bd 1/2in (IN64)	Nail Base Sheathing, 1/2 in (1.3cm)	0.0417 (0.0127)	0.0366 (0.064)	25.0 (400)	0.31 (1297)	1.14 (0.200)

Table 1 Insulating Materials						
Code-Word	**Description**	**Thickness**	**Conductivity**	**Density**	**Specific Heat**	**Resistance**
		ft (m)	Btu/hr-ft^2-F (W/m-K)	lb/ft^3 (kg/m^3)	Btu/lb-F (kJ/kg-K)	hr-ft^2-F/Btu (K-m^2/W)
Roof Insulation, Preformed						
Roof Insul 1/2in (IN71)	1/2 in (1.3cm)	0.0417 (0.0127)	0.0300 (0.052)	16.0 (256)	0.2 (837)	1.39 (0.244)
Roof Insul 1in (IN72)	1 in (2.5 cm)	0.0833 (0.0254)	0.0300 (0.052)	16.0 (256)	0.2 (837)	2.78 (0.489)
Roof Insul 1.5in (IN73)	1.5 in (3.8 cm)	0.1250 (0.0381)	0.0300 (0.052)	16.0 (256)	0.2 (837)	4.17 (0.732)
Roof Insul 2in (IN74)	2 in (3.1 cm)	0.1667 (0.0508)	0.0300 (0.052)	16.0 (256)	0.2 (837)	5.56 (0.977)
Roof Insul 2.5in (IN75)	2.5 in (6.4 cm)	0.2083 (0.0635)	0.0300 (0.052)	16.0 (256)	0.2 (837)	6.94 (1.220)
Roof Insul 3in (IN76)	3 in (7.6 cm)	0.2500 (0.0762)	0.0300 (0.052)	16.0 (256)	0.2 (837)	8.33 (1.464)

APPENDIX – C
INPUT DATA IN eQUEST.



Construction | Layers | Material

Currently Active Construction: EL1 EWall Construction   Type: Layers Input

Surface Construction Parameters

Construction: EL1 EWall Construction

Specification Method: Layers Input

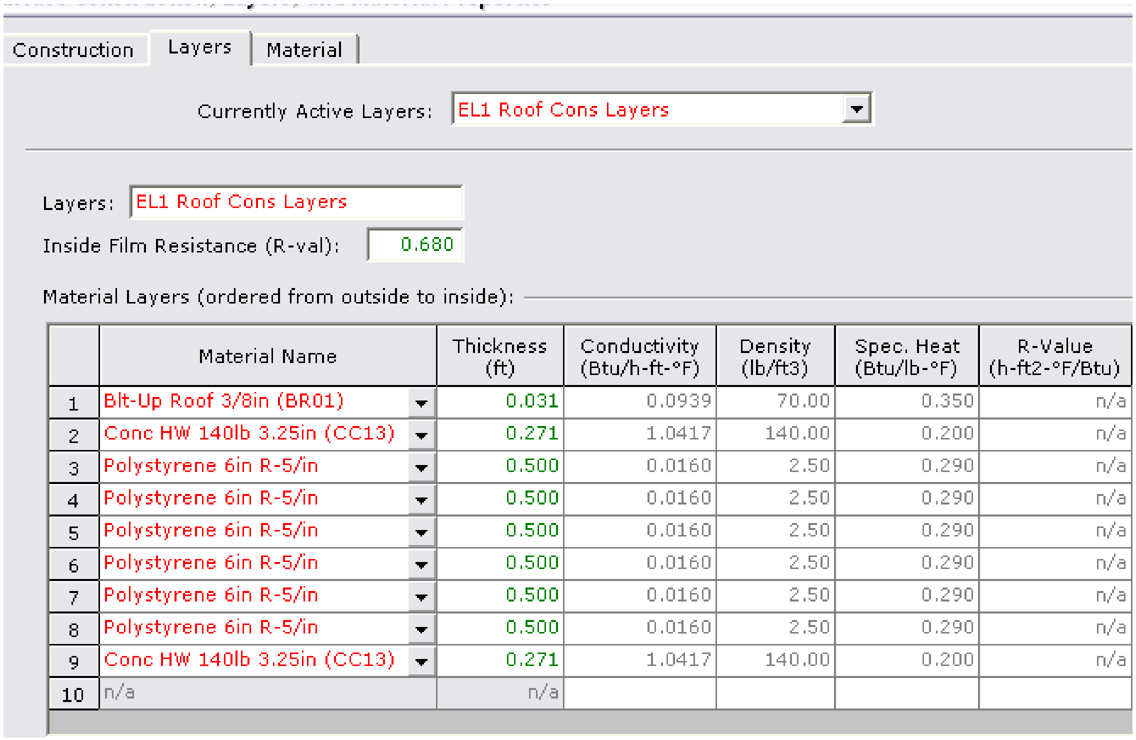
Calculated U-Value: 0.763 Btu/h-ft2-°F

Surface Roughness: 3

Ext. Color (absorpt.): 0.600

Construction Layers: EL1 EWall Cons Layers   (material layers ordered from outside to inside)

	Material Name	Thickness (ft)	Conductivity (Btu/h-ft-°F)	Density (lb/ft3)	Spec. Heat (Btu/lb-°F)	R-Value (h-ft2-°F/Btu)
1	exterior Cmt Plaster 1in (CM03)	0.039	0.6000	116.00	0.200	n/a
2	concrete wall	0.500	1.0000	150.00	0.200	n/a
3	interior Cmt Plaster 1in (CM03)	0.039	0.6000	100.00	0.200	n/a



Construction | Layers | Material

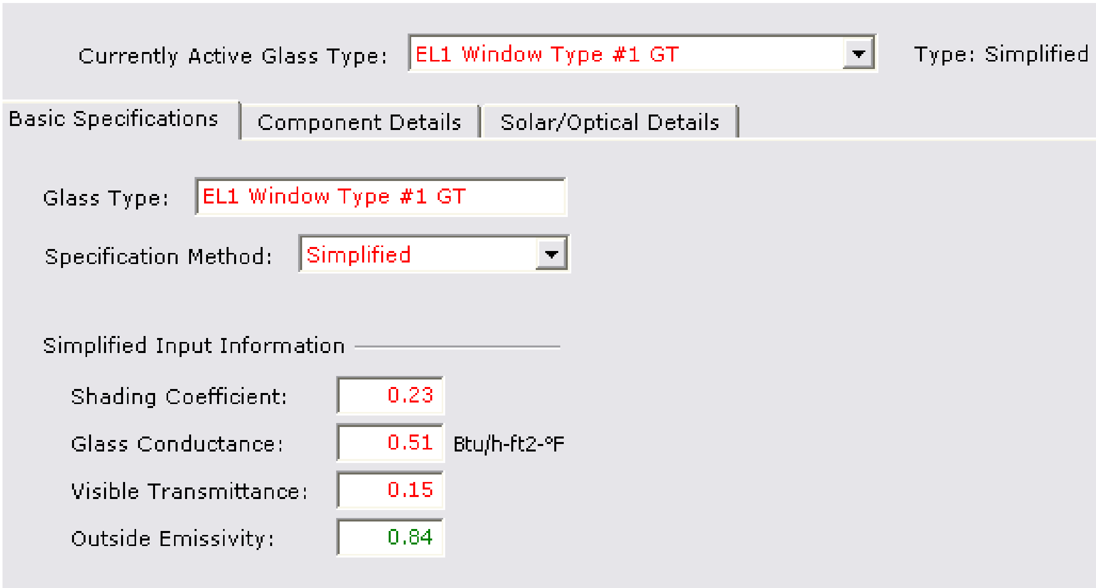
Currently Active Layers: EL1 Roof Cons Layers

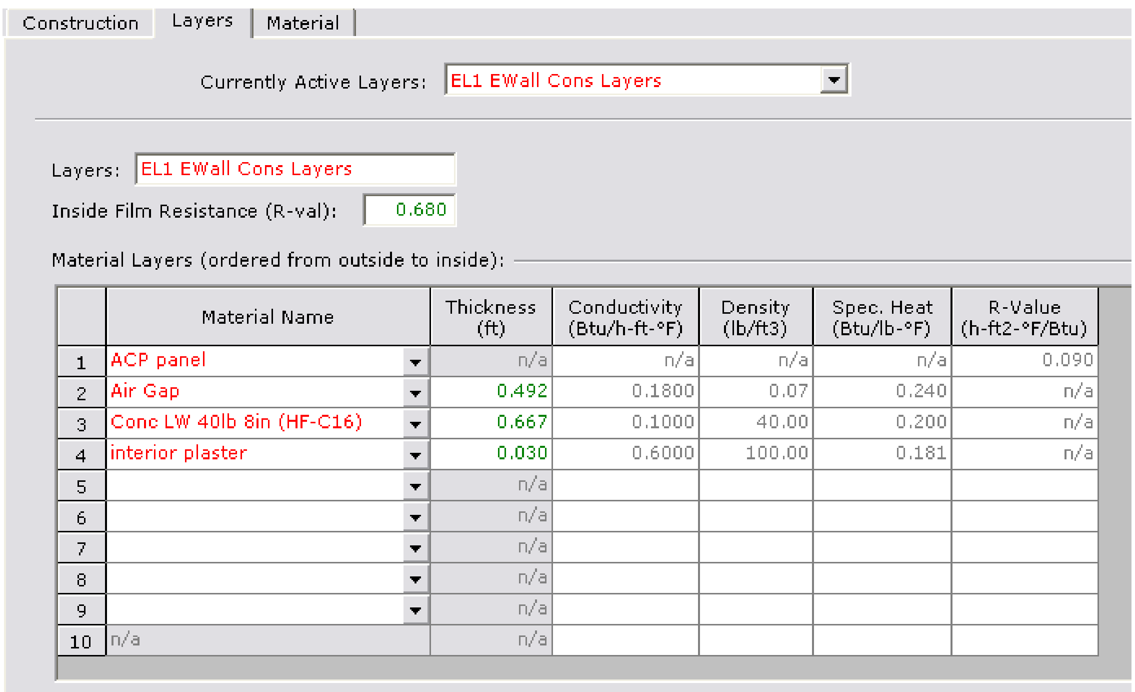
Layers: EL1 Roof Cons Layers

Inside Film Resistance (R-val): 0.680

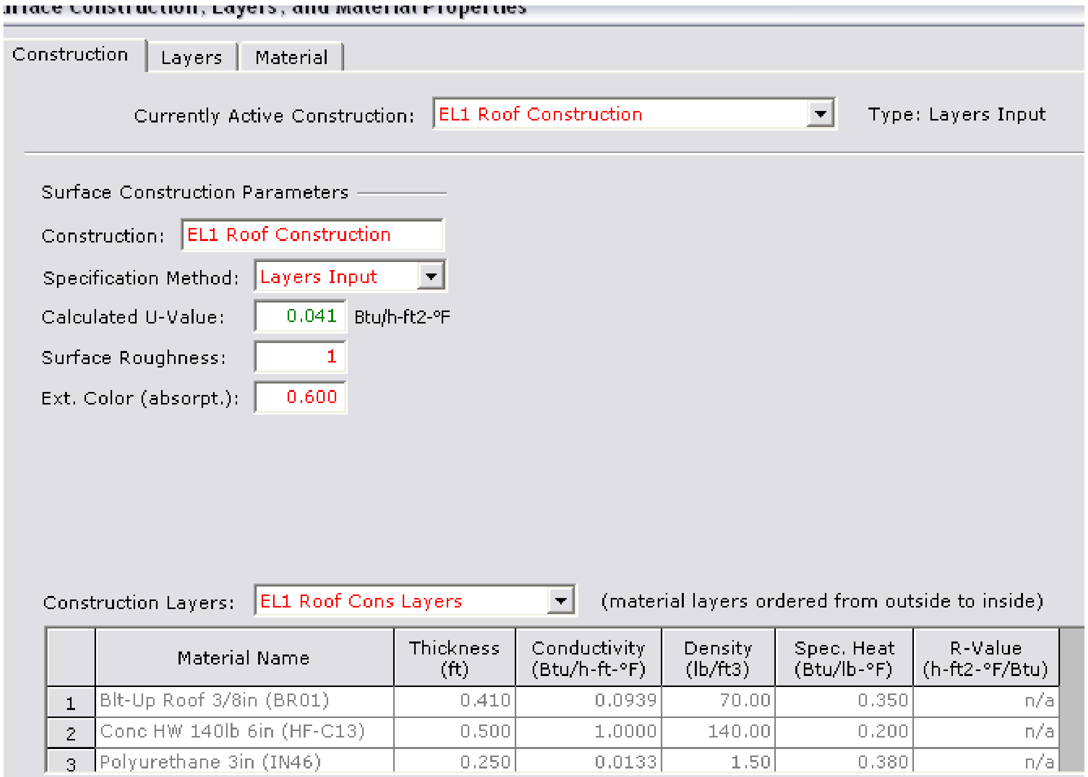
Material Layers (ordered from outside to inside):

	Material Name	Thickness (ft)	Conductivity (Btu/h-ft-°F)	Density (lb/ft3)	Spec. Heat (Btu/lb-°F)	R-Value (h-ft2-°F/Btu)
1	Blt-Up Roof 3/8in (BR01)	0.031	0.0939	70.00	0.350	n/a
2	Conc HW 140lb 3.25in (CC13)	0.271	1.0417	140.00	0.200	n/a
3	Polystyrene 6in R-5/in	0.500	0.0160	2.50	0.290	n/a
4	Polystyrene 6in R-5/in	0.500	0.0160	2.50	0.290	n/a
5	Polystyrene 6in R-5/in	0.500	0.0160	2.50	0.290	n/a
6	Polystyrene 6in R-5/in	0.500	0.0160	2.50	0.290	n/a
7	Polystyrene 6in R-5/in	0.500	0.0160	2.50	0.290	n/a
8	Polystyrene 6in R-5/in	0.500	0.0160	2.50	0.290	n/a
9	Conc HW 140lb 3.25in (CC13)	0.271	1.0417	140.00	0.200	n/a
10	n/a	n/a				





	Material Name	Thickness (ft)	Conductivity (Btu/h-ft-°F)	Density (lb/ft3)	Spec. Heat (Btu/lb-°F)	R-Value (h-ft2-°F/Btu)
1	ACP panel	n/a	n/a	n/a	n/a	0.090
2	Air Gap	0.492	0.1800	0.07	0.240	n/a
3	Conc LW 40lb 8in (HF-C16)	0.667	0.1000	40.00	0.200	n/a
4	interior plaster	0.030	0.6000	100.00	0.181	n/a
5		n/a				
6		n/a				
7		n/a				
8		n/a				
9		n/a				
10	n/a	n/a				



	Material Name	Thickness (ft)	Conductivity (Btu/h-ft-°F)	Density (lb/ft3)	Spec. Heat (Btu/lb-°F)	R-Value (h-ft2-°F/Btu)
1	Blt-Up Roof 3/8in (BR01)	0.410	0.0939	70.00	0.350	n/a
2	Conc HW 140lb 6in (HF-C13)	0.500	1.0000	140.00	0.200	n/a
3	Polyurethane 3in (IN46)	0.250	0.0133	1.50	0.380	n/a