LIFE CYCLE ASSESSMENT OF THERMAL INSULATING BUILDING MATERIALS USING BUILDING INFORMATION MODELLING

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ABSTRACT

This paper discusses the integrated whole-building process of achieving the most economic and energy efficient design of a common residential building through the sustainable design. This involves positioning and orientation of the building with respect to the annual sun path, adjusting the percentage of openings in the building, usage of the low energy impact materials in non-load bearing structures. Life cycle Analysis of the materials to be used in the non-load bearing members has been integrated in this analysis. Energy analysis of the materials to determine the lower impact on the environment is computed by the SimaPro software. The results thus obtained are used to analyze the heating and cooling demand graphs using CASAnova. The real time analysis and modelling of the typical building is computed by Autodesk® AutoCAD® 2014, Autodesk® Revit® 2013, and Autodesk® Ecotect® Analysis 2010 by trial and error method. All the dimensions are followed as prescribed in the National Building Code 2005-Part 8.

Keywords: whole-building process. Autodesk® AutoCAD® 2014, Autodesk® Revit® 2013, Autodesk® Ecotect® Analysis 2010, BIM, CASAnova, LCA, SimaPro, sustainable, sun path.

INTRODUCTION

The construction industry accounts for major part of emissions and also has high energy demand. Insulation is the most cost effective way to conserve energy and also prevent greenhouse gas emissions. To maintain particular and comfortable temperature, energy is required and insulation reduces the use of this energy.

Thermal insulation envelops the building and helps reducing the heat transfer. Heat transfer through insulation materials is possible due to conduction. The rate at which this occurs depends on the material properties, density and the techniques with which they are implemented in the building. Thermal insulation materials should be selected in such a way that it reduces heating or cooling demand and also ensures savings on more energy than it consumes throughout its life cycle or span. Embodied energy materials may consist of high energy input levels during the construction process but they also ensure high future energy conservation.

To calculate the input energy quantity, the Life Cycle Assessment (LCA) of the material is highly essential. Using the energy values, the thermal conductivity and thermal resistivity of the material can also be calculated. The temperature varies at different climates and due to this the thermal comfort levels also change. If the building is warmed up then it is in cooling demand stage and if it is cooled up it is in heating demand stage. Both these demand changes according to the temperature. The insulation materials tend to reduce the demand and hence save energy. Other factors that govern the insulation of a building are the type of buildings, climatic zones, and density of the material, material properties, and techniques involved in construction (Active/Passive solar technology) and cost of the materials and so on. These can be studied theoretically using case studies.

Researchers conducted an annual comparative study of rock wool which involves the life cycle analysis [1]. From the earlier study it is proved that the direct emissions from the rock wool production have increased. The material intensity of the rock wool production as well as of the briquette production (i.e., cement) have decreased. Later this study was extended to different types of energy created by thermal insulation materials namely different types of foam.

In the comparative analysis made Bio-foam proved to be the most flexible material and also easy to compose. Research was carried out on the insulation materials used in the exterior walls of buildings and researchers concluded that the Poly urethane has large impacts in consumed energy and Mineral wool has lowest energy consumption [2].

The main objective of this research is to develop optimal design strategies for a building using BIM-based simulations and LCA of the materials used in the design of the building. For this research, a single storied residential building with an area of 1800 ft^2 is considered. The architectural design variables include glazing material, thickness; wall material, etc. are also incorporated.

OPTIMAL ENERGY EFFICIENT DESIGN

Optimal design on energy needs to be a goal-directed activity in order to achieve the objectives of making decisions about components and various physical forms of building. Standards for building performance assessments have multi-objective functions such as energy consumption (cooling and heating), PMV, CO_2 concentration, initial cost, etc. The above-mentioned assessment standards are affected by many design variables (for instance, window-wall ratio, form, materials).

Consequently, architectural optimal design involves searching for a solution set of optimal designs

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that have multi-objective functions rather than one objective function [3]. Genetic algorithm (GA) is one method of searching for the optimal solution for repeated generations of initial population, selection, crossover, and mutation based on the principles of Charles Darwin's, "Survival of the fittest".

BUILDING INFORMATION MODELLING (BIM)

The Building Information Modelling (BIM) is a process involving the generation and management of digital representations of physical and functional characteristics of a building and other construction facilities. The resulting 3D BIM models become shared knowledge resources to support decision-making about a facility from earliest conceptual stages, through design and construction, through its operational life and eventual demolition [4].

ENERGY PERFORMANCE SIMULATION

It is known that interoperability requires data exchange and decision-making between the domains experts involved in the building project by using a shared data model. Some of the techniques involved in achieving the efficiency are active day lighting, cool roofing, double envelope walls, passive day lighting, providing with high levels of insulation, windows of high energy efficiency, low levels of air filtration inside the building, heat and air circulation enhancing and various sustainable design, usage of low impact materials.

Thus the virtual modelling of the typical building with all the climatic, zonal factors with the properties of building materials are required for the efficient usage of the available energy and this should be in agreement with the standards prescribed in National Building Code 2005-Part 8. The National Building Code of India (NBC), a comprehensive building Code, is a national instrument providing recommendations for regulating the building construction process across the country.

The National Building Code of India (NBC), Part 8, consists of various guidelines in the lighting and ventilation, orientation of the building, solar radiation, correction for glazing, artificial lighting, sensible heat, sky components, air conditioning, heating and mechanical ventilation, acoustic and noise control etc.,

Researchers carried out experiments on the Building Energy Simulation analysis which proved to be very innovative and time saving than the conventional energy analysis [5]. Later many researches were implemented and investigated on the theories of environmental adaptability in architecture, passive adaptability index and thermal comforts in a building were formulated in the recent days with the use of the computers [6].

The decision models for improvement of energy efficiency and other objectives such as cost reduction, minimal maintenance of buildings were proved to be advantageous by various analysts [7]. Recent researches reveal that the orientations of the building, its structure, the choice of materials, windows and other openings have great potential in terms of contribution to sustainable development [8].

ENERGY EFFICIENT DESIGN

Energy Efficient Design is a methodology that assists to design, construct and manage projects to achieve minimum energy consumption. One of the main approaches to low energy design in the building construction is to invest in the building's design form and enclosure so that the loads of heating, cooling, and lighting are reduced. Passive solar design strategies also require that particular attention be paid to building orientation and glazing [9].

For a particular project, the specific energy saving techniques, strategies, and mechanisms to be deployed will vary greatly, depending on building and space type. Their selection and configuration will also be influenced by:

- Size of the building
- Climate of the location
- Hours of operation
- Sun-space
- Annual sun-path
- Low-impact materials

BUILDING DIMENSIONS AND PROPERTIES

The building is oriented 90° from the North to have the maximum exposure to the Sun light throughout the day and to have a better Wind direction intruding inside the building. It is located at the latitude 13.0810° N and longitude 80.2740° E which are the geographical co-ordinates of Chennai region. Typical floor plan is represented in Figure-1.

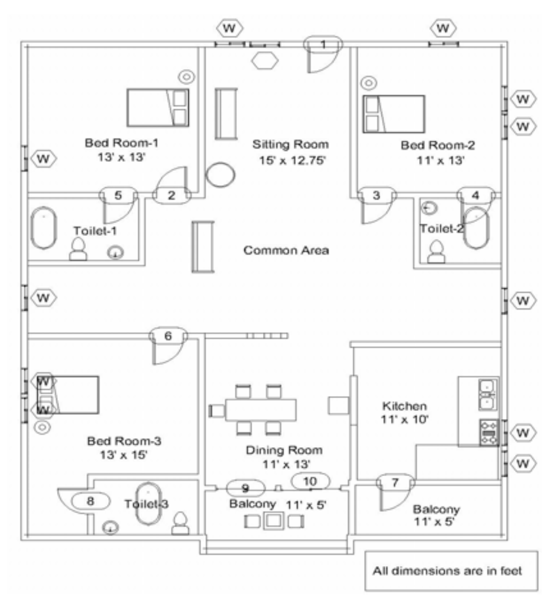

Figure-1. Typical floor plan of the selected building.

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Table-1. Room dimensions.

Type	Dimension (Sq. ft.)		
	Length	Breadth	Area
Sitting Room	15	12.75	191.2
Bed Room-1	13	13	169
Bed Room-2	11	13	143
Bed Room-3	13	15	195
Dining	11	13	143
Kitchen	11	10	110
Common Area	21	15	315
Restroom-1	10	8	80
Restroom-2	8	7.5	60
Restroom-3	10	8	80
Balcony-1	5	11	55
Balcony-2	5	11	55
Store Room	6	5	30
Pooja Room	5	2.5	12.5
Floor Area	40	45	1800

LIFE CYCLE ASSESSMENT

Life Cycle Assessment (LCA) is defined as the analysis of a product and the evaluation of its environmental impacts throughout its life cycle or 'Cradle-to-grave' analysis which include raw material collection, manufacturing, usage, waste flow and disposal. The energy required for each of these processes is taken as the input. The use of this energy will create an impact on the environment and this is taken as the output. Compilation and evaluation of the inputs and outputs and their potential environmental impact, throughout the life cycle of a product gives us the total energy consumed by it. This process is used to compare different materials and arrive at the best. The LCA is carried out in accordance with ISO 14040 [10]. SimaPro 7.3 is used as the LCA modelling and analysis tool for the different materials.

The LCA process comprises of four phases:

- The goal and scope definition phase
- The inventory analysis phase
- The impact assessment phase
- The interpretation phase

GOAL AND SCOPE DEFINITION PHASE

It is the phase where the work plan of the entire LCA project is determined. The goal of the study is formulated in terms of intended applications. The scope is expressed in terms of the level of sophistication of the study in relation to its goal. The goal of this LCA study is to assess the impacts of the different materials and thus to determine the most suitable material in terms of less energy consumption. The scope is limited to five materials namely Rock wool, Mineral wool, Glass wool, Polyurethane foam and cotton fiber.

CREATING THE MATERIAL NETWORKS PHASE

A model for each material is first created in SimaPro for analyzing and creating the inventory and impact assessment charts as in Figure-2 and Figure-3 which shows the LCA model network of Rock wool. Similarly the network charts for Mineral wool, Polyurethane foam and cotton fiber are drawn.

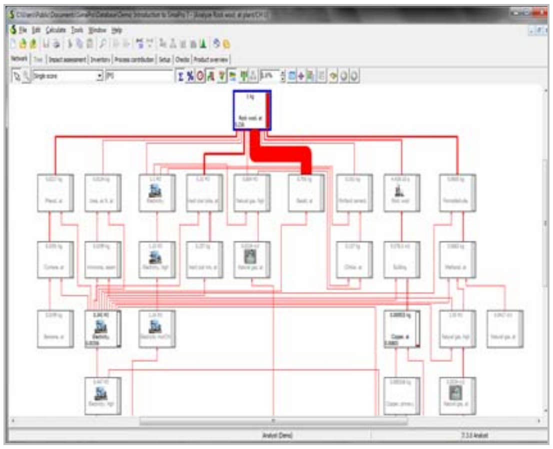

Figure-2. Model material analysis for rockwool.

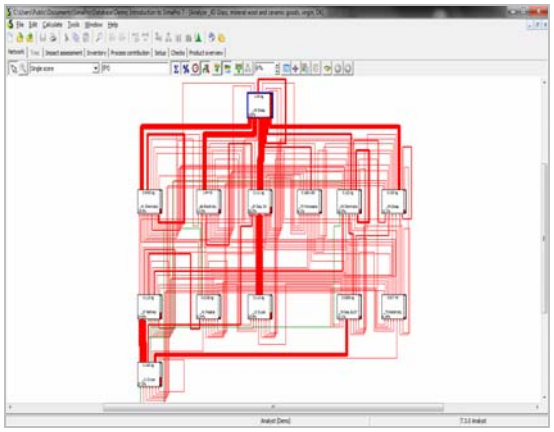

Figure-3. Model material analysis for glass wool.

THE INVENTORY ANALYSIS PHASE

The inventory analysis includes the inputs of the entire energy required by the material throughout its life cycle. It will provide a quantitative catalogue of energy, resource requirements, atmospheric and waterborne emissions and solid waste for a material which form the output of the analysis. The inputs are given in SimaPro in three ways i.e. raw materials, fuel and heat or electricity. The inputs and outputs for each sub-division of the process can be drawn in the form of flow chart.

For example when inventory charts are drawn for cotton fiber, separate flow charts can be computed for each of the output. That is the energy emissions for raw

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materials and Air borne emissions as in Figure-4 and Figure-5, Water borne emissions and Soil emissions as in Figure-6 and Figure-7. In this case cotton fiber does not have any emissions due to waste flow or non-material factors. Similarly the inventory flow charts for the other material charts are also drawn.

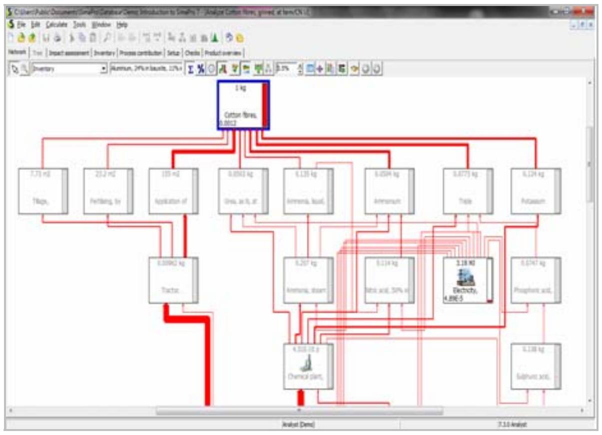

Figure-4. Energy emissions for raw materials.

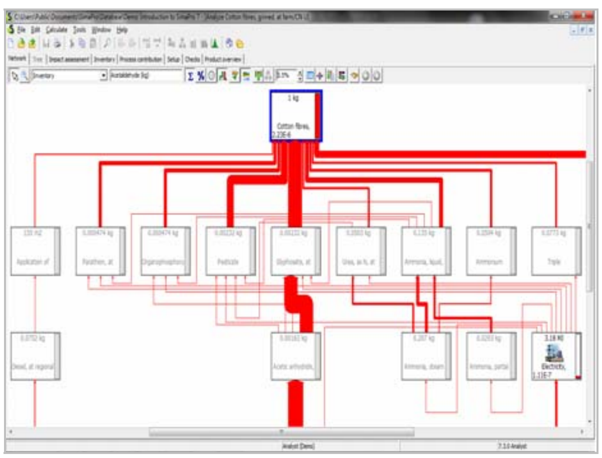

Figure-5. Air borne emissions of cotton fiber.

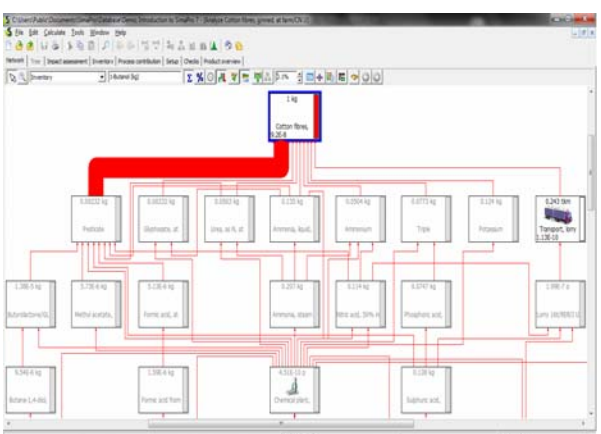

Figure-6. Water borne emissions of cotton fiber.

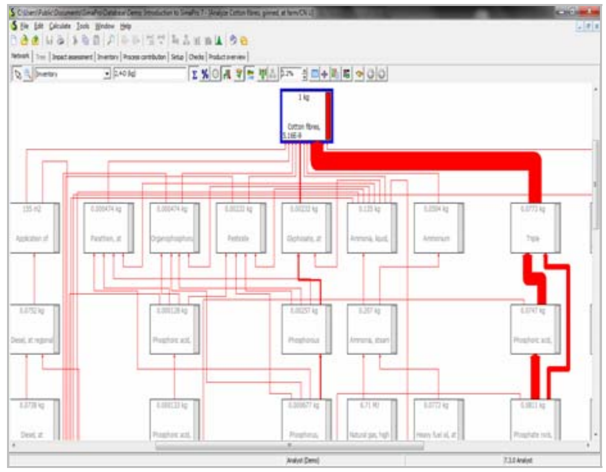

Figure-7. Soil emissions of cotton fiber.

As it is a residential building, the level of comfort should be maintained to the maximum when compared to the other type of buildings. Hence usage of more number of low energy materials is avoided. Also for the stability of the building, the load bearing members such as the beams and the columns are left undisturbed. The non-load bearing members are designed with low energy impact materials and materials which are favorable for the enhancing the energy efficiency of the building.

INTERPRETATION PHASE

From the comparative analysis as in Table-2, Cotton fiber has high usage of land; Mineral wool has negligible amounts while the other materials have none. It also has 1.43U of carcinogenic effects while rock wool and mineral wool have 0.0129 and 0.0106, respectively which are negligible.

Only Cotton fiber has impacts to Eco-toxicity and Acidification/Eutrophication, and only mineral wool has impacts to ozone layer, but both are of almost negligible amounts. Mineral wool has moderate impacts on respiratory inorganics.

Rock wool and glass wool have almost negligible impacts to climate change while the other materials have less impact to the same. None of the materials have effects on respiratory organics and radiation while all the materials have impacts on fossil fuels, respiratory inorganics and climate change and all the materials have negligible impacts to minerals.

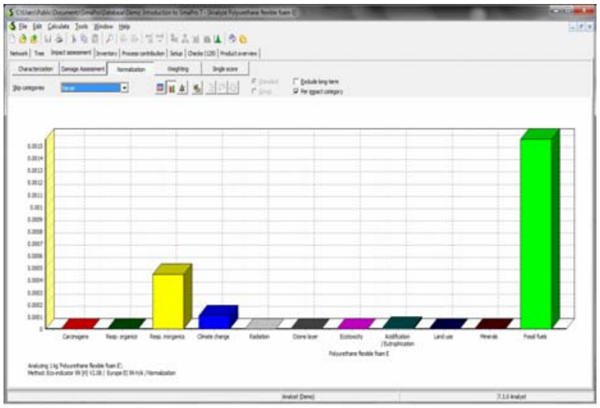

Figure-8. Impact assessment of polyurethane foam.

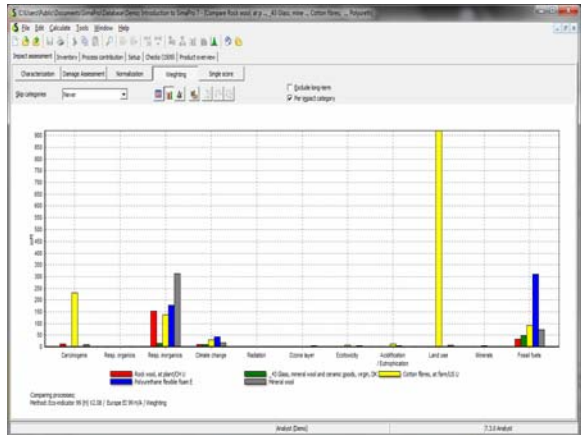

Figure-9. Comparison between materials.

Table-2. Thermal analysis of materials.

Materials	Energy Emitted (Pt)	Thermal Conductivity W/(m.K)	Thermal Resistivity M^2K/W	U W/m^2K
Rock Wool	0.262	0.045	4.44	0.225
Glass Wool	0.282	0.040	5.00	0.200
Mineral Wool	0.437	0.040	5.00	0.20
Poly Urethane Foam	0.540	0.030	6.67	0.150
Cotton Fiber	1.430	0.029	6.90	0.145

From the above LCA analysis as in Figure-8 and Figure-9 the following materials are used in the building design and analyzed.

- Wall insulation by expanded polyurethane foam
- Cold roofing
- Foamed Glass wall divisions

VIRTUAL MODELING USING AUTODESK® REVIT® 2013

Autodesk Revit is Building information modeling software which allows users to design a building and its components in 3D, visualize the model with 2D drafting elements and in turn access building information from the building models database.

Earlier BIM software products are considered not to be in line with the practical approach in the view of designing and cost efficiency. In contrast to that, the recent introduction of the evolutionary software products such as the Revit 2013 and Ecotect Analysis 2010 from the Autodesk, Inc., an American multinational software Company provides the accurate and economical results in the design of the building and also provides the user to achieve the energy simulation and analysis to any type of building and materials regardless of the location and climatic conditions of the building site.

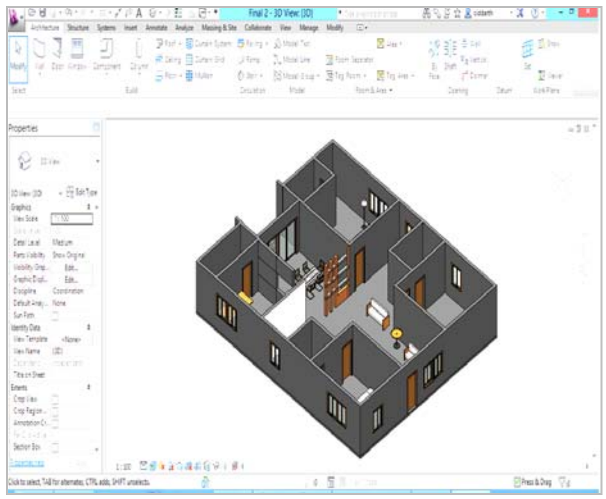

Figure-10. Virtual modeling using Autodesk® Revit® 2013.

The actual building model with the above mentioned dimensions in Table-1 and with the material properties resulted from the LCA are incorporated in the Autodesk® Revit® 2013 and all other required dimensions and components of the building such as the cold roof, floor and the glass wall divisions are modelled using the family files of Revit and are edited according to the above mentioned conditions as in Figure-10.

The phase of the building should be maintained and all the components including the spaces, rooms, windows, doors, walls should be tagged in the building model so that it can be exported to the Autodesk® Ecotect® 2010.

Then the location and silver tolerance value including the type of the building, occupant's profile, and thermal properties are included in the model. Then the project file should be converted to the native Ecotect format by exporting the rooms, windows, spaces, and all other room components and converting to the .xml format.

MODEL ANALYSIS USING AUTODESK® ECOTECT® 2010

Autodesk Ecotect Analysis is an environmental analysis tool that allows designers to simulate building performance right from the earliest stages of conceptual design.

It combines a wide array of detailed analysis functions with a highly visual and interactive display that presents analytical results directly within the context of the building design, enabling it to revise complex concepts and more number of databases in intuitive and effective ways [11].

Initially the orientation of the building with respect to the north direction and the annual sun-path are computed for the selected project and then the rooms and spaces are calculated in the Ecotect software as in Figures 11 and 12.

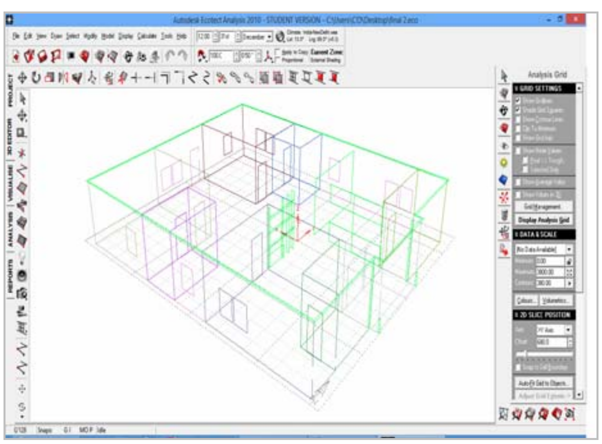

Figure-11. 3D analysis using Autodesk® Ecotect® 2010.

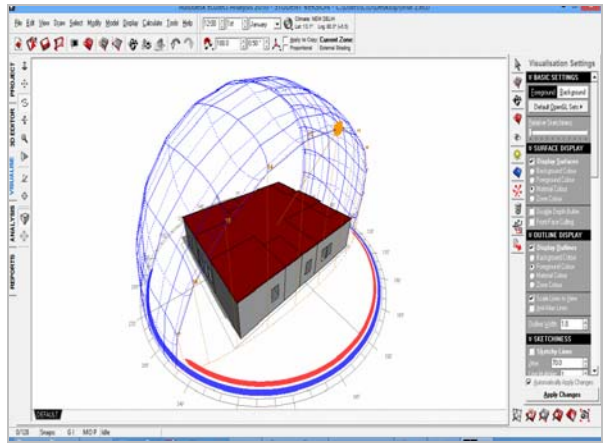

Figure-12. Annual sun-path computation.

ENERGY OPTIMIZATION USING AUTODESK® ECOTECT® ANALYSIS 2010

SUN PATH DIAGRAM

Sun path refers to the apparent significant seasonal-and-hourly positional changes of the sun (and length of daylight) as the Earth rotates, and revolves around the sun. The actual position of the sun is a major factor in the heat gain of buildings and in the performance of solar energy systems [12].

The Building is oriented in such a way that it is exposed to the maximum daylight throughout the year. The annual sun path diagram for the specified location of the building is drawn and analyzed for the effective thermal radiation and daylight factors by Autodesk® Ecotect® Analysis 2010.

Thus the stereographic sun-path for the whole year is traced and with that path the building is oriented along the East-West axis to have the maximum exposure to the sunlight as in Figure-13 and the results are tabulated in Table-3.

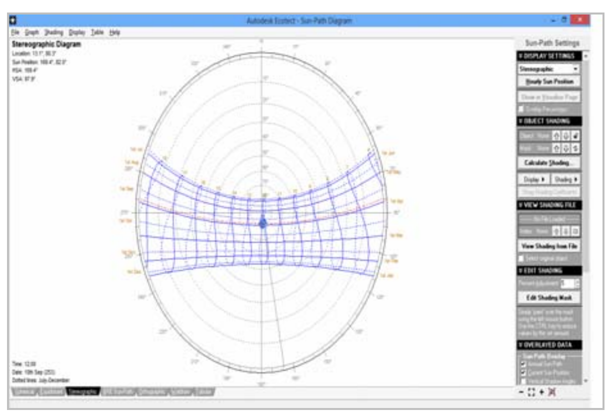

Figure-13. Annual sun-path traced at 13.0810° N and 80.2740° E.

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Table-3. Tabulated daily solar data.

Local	(Solar)	Azimuth	Altitude
06:30	(06:24)	86.2°	7.0°
07:30	(07:24)	89.5°	21.6°
08:30	(08:24)	93.1°	36.2°
09:30	(09:24)	97.9°	50.8°
10:30	(10:24)	106.2°	65.1°
11:30	(11:24)	130.8°	78.2°
12:30	(12:24)	-142.3°	80.1°
13:30	(13:24)	-108.8°	67.8°
14:30	(14:24)	-99.1°	53.6°
15:30	(15:24)	-93.9°	39.1°
16:30	(16:24)	-89.8°	24.5°
17:30	(17:24)	-86.9°	9.9°

HOURLY TEMPERATURE PROFILE

- Total Exposed Area: 462.997 m^2
- Total South Window: 4.465 m^2 (1.7% flr area)
- Total Window Area: 13.396 m^2 (5.2% flr area)
- Total Conductance (AU): 2262 W/°K
- Total Admittance (AY): 4839 W/°K

The following graph in Figure-14 is the diagrammatical representation of the hourly temperature profile of the selected building for the entire year.

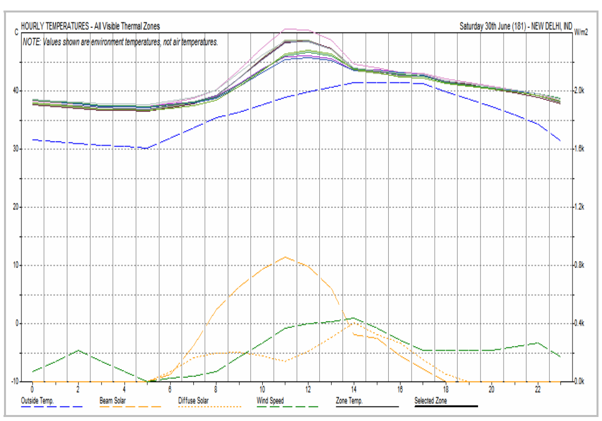

Figure-14. Hourly temperature profile.

PASSIVE ADAPTIVITY INDEX

The passive adaptivity index graph in Ecotect allows you to evaluate the passive performance of a structure. This thermal calculation calculates temperature of the selected zone against the prevailing outside temperature for the selected period, and then draws a line of best fit. This gives an index value between 0 and 1, where a lower index value depicts better passive performance.

As can be seen, the passive adaptivity index in Ecotect is an easy to use analysis tool for assessing the passive performance of a building. By making progress of alterations to the building model, the passive index can be used to assess the effectiveness of each change, without the need to analyze more detailed calculation data. This is greatly useful in the early stages of the design process. The color-coded temperature plots also make it simple to visually interpret the results the greener dots the better as in Figure-15 and the results are tabulated in Table-4.

$$Si = [(Q * S * T) + 1]/2 \quad (1)$$

$$Ai = Si + ((-Si) * Ai) \quad (2)$$

$$Pi = Si - Ai \quad (3)$$

Where,
Si = Stimulus value
Ai = Adaptive satisfaction
Q = Stimulus value
S = Spatial scale of the stimulus
T = Time scale
Pi = Passive adaptivity index

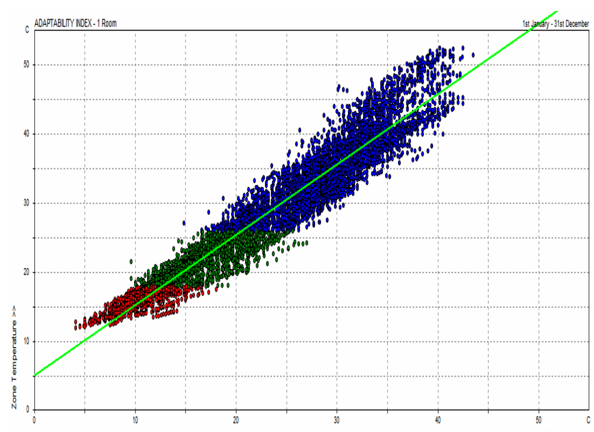

Figure-15. Passive adaptivity index.

Table-4. Passive adaptability index.

Type	P_i
Sitting Room	0.54
Bed Room-1	0.49
Bed Room-2	0.89
Bed Room-3	0.8
Common Area	0.55

HEATING AND COOLING DEMAND

The purpose of insulation is to provide thermal comfort by reducing the heating or cooling demand. The variations of the demand curves can be analyzed by using the software CASAnova. The demand charts can be drawn with and without providing the insulation for the purpose of comparison. Figure-16 illustrates the heating and cooling demand chart without insulation. Demand curves for the U value of Rock wool, Glass wool and Mineral wool have been noted to reduce at a rate of 40% as in Figure-17. Similarly when the graph is drawn for Polyurethane foam and Cotton Fiber there is a decrement of 56% and 60% respectively as represented in Figure-18. Hence it is proved that Polyurethane foam and cotton Fiber have the highest and almost similar resistivity among the five materials.

Note: The scale for each graph shown in Figure-16, Figure-17 and Figure-18 varies from one another.

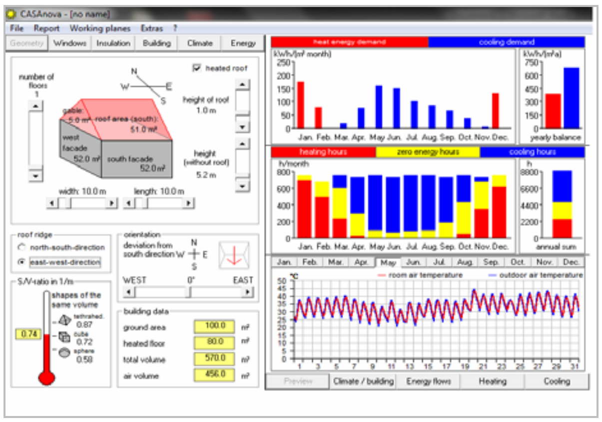

Figure-16. Heating and cooling demand chart-ithout insulation.

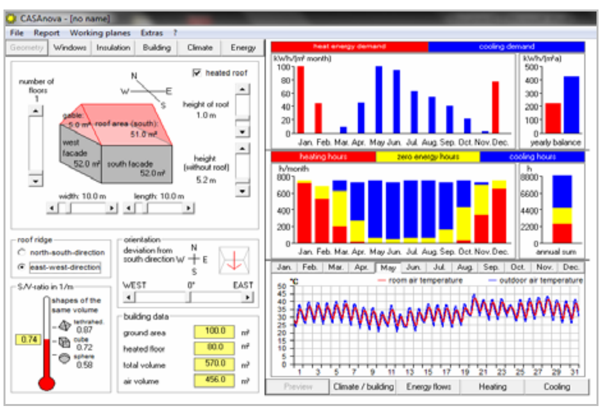

Figure-17. Heating and cooling demand charts-rock wool, glass wool and mineral wool.

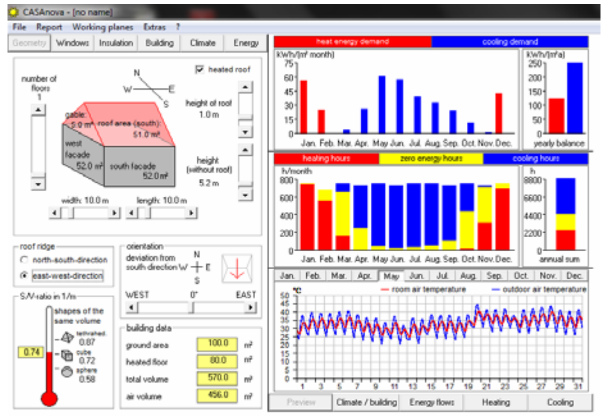

Figure-18. Heating and cooling demand charts-cotton fiber.

MONTHLY DEGREE DAYS

Heating degree day (HDD) is a measurement designed to reflect the demand for energy needed to heat energy a building. It is calculated from measurements of outside air temperature. The heating needs for a given structure at a specific location are considered to be directly proportional to the number of HDD at that location. An identical measurement, cooling degree day (CDD), reflects the amount of energy used to cool a home or business [13]. This can be calculated as the sum of the heat losses per degree of each element of the buildings' thermal envelope or as the average of the U-value of the building multiplied by the area of the thermal envelope of the building, or calculated directly for the whole building. This gives the buildings' specific heat loss rate Pspecific, generally given in Watts per Kelvin (W/K).
Total energy in kWh is then given by:

$$Q = (P_{specific} * 24 * D)/1000 \text{ [kWh]} \quad (4)$$

Where,

Pspecific = Specific heat loss rate
Q = Total energy
D = Number of heating/cooling degree days

The heating/cooling degree is calculated by the Ecotect software and is summarized in a graph for the entire year for the given building with all the conditions applied in the analysis. The graph below in Figure-19 depicts the actual heating and cooling degree days. The results are tabulated in Table-5.

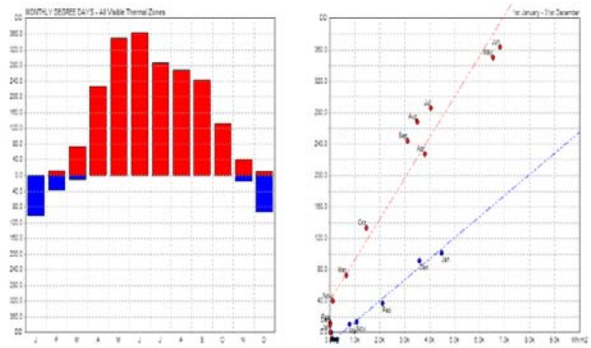

Figure-19. Monthly degree days chart.

Table-5. Monthly degree days.

Month	Heat	Cool	Losses	Gains
	(dd)	(dd)	(Wh)	(Wh)
Jan	102.1	0.7	4460	0
Feb	37.7	12.9	2093	4
Mar	10.7	73.2	784	646
Apr	7.9	227.3	28	3790
May	5.6	350	0	6535
Jun	4.2	363.8	0	6820
Jul	4.0	285.5	0	4039
Aug	2.5	268.3	0	3486
Sep	5.8	243.5	0	3096
Oct	13	133.9	39	1449
Nov	14.3	40.1	1067	112
Dec	92	9.5	3583	3

GAINS BREAKDOWN

The passive gains breakdown graph depicts the gains and losses that occur through the various heat transfer mechanisms that occur within a zone of the selected building. The optimal lighting and ventilation of the building assures the mechanism of improving the total gains and reduction of the energy losses [14].

These mechanisms include conduction, direct solar, ventilation, internal and inter-zonal gains and losses separated by the colors shown in the legend below in the Figure-20 with the results in Table-6.

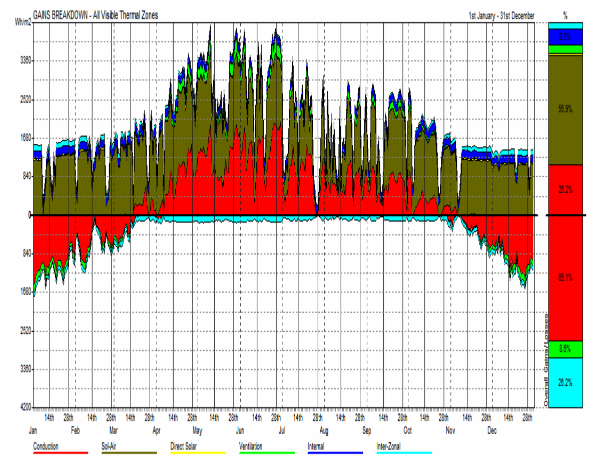

Figure-20. Gains breakdown graph.

Table-6. Passive gains breakdown.

Category	Losses	Gains
Fabric	5.10%	26.20%
Sol-air	2.5%	56.90%
Solar	9.5%	51.10%
Ventilation	8.60%	44.10%
Internal	6.20%	33.30%

CONCLUSIONS

The final results are interpreted from the total energy emissions evaluated using the SimaPro software, the heating and cooling demand curves, cost efficiency and some numerical facts and characteristics of the materials. Rockwool has excellent fire, water, acoustic and vibration and rot resistance. It has the least impact assessment when compared to other materials. It also has moderate cost. Because of its multiple resistivity property it is the most preferred. Glass wool also has good resistance to acoustics, corrosion, fire and water. Its properties are almost similar to that of Rockwool and it is most suitable for flat surfaces. It has lesser impact when compared to other materials but slightly more when compared to Rockwool and it is of lesser cost than Rockwool.

Mineral wool is durable, moisture and fire resistant hence it is considered as the most flexible and efficient material among the rest. It has moderate impacts and considerably alters the demand charts. Cotton fiber is the most easily installable material as it is very safe. Though it has high use of land and fossil fuels it is considered as the safest material for installation. It has the highest thermal resistivity among the five materials and is also cost efficient. It should be permeated with a fire retarder and vapour retarder for increasing durability. It's not exactly suitable for winter climate due to this reason.

Polyurethane foam has moderate impacts. It also has the highest thermal resistivity when compared to the other materials. It is combustible and should be handled carefully. It increases structural strength and also seals cracks efficiently. The foam is rigid and efficiently minimizes the air flow. It performs well in both hot and cold climate and has the best R-value. It is the costliest when compared to the other materials.

The efficiency improvements provide a platform for the designers to include the thermal properties beforehand and ensure the minimization of the loss of energy. The final results are interpreted from the total energy emissions evaluated using the SimaPro software, the heating and cooling demand curves, cost efficiency and some numerical facts and characteristics of the materials are some of the important factors to determine the energy efficiency of the buildings. The site specific design which involves the orientation of individual buildings enhances the energy usage to a maximum extent.

FURTHER RESEARCH

This can be extended to various other types of constructions such as factories, office buildings etc., which consists of more number of occupants than in the residential building. Usage of other energy concepts such as straw bale walls, adobe walls, can be included in the virtual model. Usage of artificial ventilators, mechanical systems can be used.

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