THESIS

A REAL-TIME BUILDING HVAC MODEL IMPLEMENTED AS A TOOL FOR DECISION MAKING IN EARLY STAGES OF DESIGN

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ABSTRACT

A REAL-TIME BUILDING HVAC MODEL IMPLEMENTED AS A TOOL FOR DECISION MAKING IN EARLY STAGES OF DESIGN

Construction of buildings is one of the major sources of greenhouse gases (GHGs) and energy consumption. It would therefore be beneficial to improve the design of new buildings so that they consume less energy and reduce GHG emissions over their lifecycle.

However, the design of these "green buildings" is challenging because the analyses required to design and optimize these buildings is time intensive and complicated. In response, numerous software applications have been developed over the years by various government agencies, organizations and researchers. But, recent surveys of architects have found that these energy simulation programs are used irregularly and by very few architectural firms. The utility of these programs is limited by three main factors. First, these software applications are complicated, stand-alone programs that require extensive training to be effective. Second, there are a large set of energy simulation programs available, all of which have differing metrics of building performance with differing degrees of accuracy. And lastly, these applications do not fit into the conventional workflow that architects follow for a majority of projects. To address these issues, this thesis focuses on the development of a simplified HVAC model that not only gives sufficiently accurate results but also can be easily integrated into the conventional design workflow.

There are some key challenges in developing such a model.

- Early in the design process (when many irreversible energy impacting design decisions are made) there is very limited information available about the building materials, heat loads, and more.
- The simulation must be integrated into the design software and workflows that are currently being used by architects. This requires a near-instantaneous calculation method that can extract information from the only available data at the initial design (sketching) phase, the computer aided design (CAD) models and the location.

To achieve these objectives, the Radiant Time Series (RTS) method was supplemented with real data from National Solar Radiation Database to enable a near-instantaneous annual HVAC load calculation to be integrated into preliminary CAD modelling software. This model was integrated in to the Trimble Sketch-up™ software. The combined software system is demonstrated to enable effective design feedback in early design decisions including building orientation, construction material and design of fenestration.

ACKNOWLEDGEMENTS

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Secondly I would like to thank all my teammates of the Carbon Footprint Metric (CFM) Research Working Group for all their insight and technical guidance for the implementation of my research into their SketchUp® plugin. Their comments and feedback were instrumental in helping me shape this thesis and carrying out the research for it.

I would also like to thank my graduate committee for their valuable time and effort in editing my thesis and making it possible to submit within the deadline.

Lastly my sincere thanks goes to my friend and colleague Spencer Vore for his invaluable help with the Matlab® code that helped me in the implementation, testing and validation of my research.

PREFACE

Environmental change due to human activity has been a major concern for the last couple of decades. Of these activities, construction is a major player responsible for the emission of greenhouse gases. Keeping this in mind, a Carbon Footprint Metric [CFM] Research Working Group [RWG] was put together at Colorado State University in the spring of 2011 which aimed at developing a metric for architects that would help them in designing better and energy efficient buildings.

The metric is to be implemented as a plugin for the commercial software SketchUp® since it is used widely by architects for the initial 3D drafting of their projects.

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LIST OF SYMBOLS/ACRONYMS

ASHRAE	American Society of Heating, Refrigeration and Air conditioning Engineers
AST	Apparent (Actual) Solar Time, hours
$C_0, C_1 \ldots C_{23}$	Conduction time factors
DST	Daylight Saving Time, hours
E_b	Direct beam component of solar irradiance, Btu/hr
$E_{b,\,t}$	Incident direct beam solar radiation, Btu/hr
E_d	Diffused component of solar radiation, Btu/hr
$E_{d,\,t}$	Incident diffused solar radiation, Btu/hr
$E_{r,\,t}$	Incident reflected solar radiation, Btu/hr
E_t	Total incident solar radiation, Btu/hr
ET	Equation of Time, minutes
H	Hour Angle, degrees
IAC	Indoor solar Attenuation Coefficient
Lat	Latitude, degrees
Lon	Longitude, degrees
LSM	Local Standard Meridian, degrees
LST	Local Standard Time, hours

NSRDB	National Solar Radiation Database
SEER	Seasonal Energy Efficiency Rating
q_θ	Incident radiation at given hour θ, Btu/hr
$q_{i,\theta-n}$	Incident radiation $\theta - n$ hours ago, Btu/hr
$r_{0,}$ $r_{1\ldots}r_{23}$	Radiation time factors
TMY	Typical Meteorological Year
TZ	Time Zone, hours
Y	Diffusion factor
β	Altitude angle, degrees
γ	Surface-Solar azimuth
δ	Declination, degrees
θ	Soar incident angle, degrees
ρ_g	Ground reflectance
Σ	Wall inclination with the horizontal, degrees
ϕ	Solar azimuth, degrees
Ψ	Surface azimuth, degrees

INTRODUCTION

Global population growth coupled with the growth in economic and technological progress has left a deep impact on the environment. According to Reese, in the next 27 years the urban population is expected to increase by an amount equal to the total world population of 1930s. He further elaborates on the role of the built environment, by stating that buildings account for 40% of the materials and 33% of the total energy consumption of the world economy [Reese, 1999].

As such, it is no great surprise that governments world over have started to grant incentives for the construction of more environmentally-friendly buildings. For instance, the United Kingdom requires a mandatory Energy Performance Certificate (EPC) when a building is being sold, built or rented. However, despite the these types of government mandates, Hasegawa observes that only 25% of new offices (in terms of total floor area) had obtained an assessment label from BREEAM (LEED certification was inspired by this) since its inception in 1991 [Hasegawa, T., 2002].

The design of high performance, energy efficient buildings is a complicated process. Such designs must include consideration of unpredictable variables such as climate, technological advancement, and market conditions, and also involves complicated statistical and physical analysis that takes expertise to perform. Therefore various research organisations as well as commercial companies have come up with numerous software applications to automate this process and allow even those that do not have in-depth knowledge in the field to carry out a detailed life cycle and energy consumption analysis for buildings.

The consumer acceptance and impact of such applications has been limited owing to several factors such as their cost of implementation, training required to run them, and the time spent in carrying out the analysis. In a professional architecting and engineering environment, the high value of time makes the integration of time-intensive simulations into the general work flow difficult.

Conventional architectural design workflow

Before going into the specifics of the improvement of such building systems design, it is important to first understand the general workflow that architects follow in a firm for any typical project. This section describe this workflow as described to the CFM project team by numerous LEED-certified architects and project managers including Brian Dunbar (CSU Institute for the Built Environment) and Fred Patterson.

For demonstration purposes, let us assume that a customer comes to an architectural firm and asks for an office building to be designed. He gives his requirements to the architect and leaves. The architect now studies the land layout and requirements such as number of floors etc. and starts making an initial sketch of what the building will look like. At this stage of the design the main focus of the architect is to present an appealing design visually, functionally and economically. But in doing so he locks in many crucial elements that will affect the building's energy consumption. For instance, he might choose to have a large aesthetically-pleasing window on the side of the building that faces the main road. Later on in the design process when the engineering team discovers that it is causing an increase in the cooling loads they might not be able to change it since the elevation plans have been finalized. The only option now left would be to either use a reflective glass or provide shading. In this case, early design decisions that were made without explicit consideration of their energy costs have reduced the design options available to achieve economic and energy efficiency goals for the building.

Figure 1 shows the conventional workflow that is used in building design. The process to move from the project requirements to the project design selection is an iterative process. The initial modeling is performed in a CAD environment. Because this model is not generally compatible with the building energy simulation environment, the CAD data must be translated into a data type that is compatible with the energy simulation. When building energy goals are not met, the results are fed back into the initial design CAD model, and the process continues. In general, the initial conceptual and CAD models are developed by architects, and the structural modeling and other analyses are performed by trained professional engineers. The CAD models can be made in a variety of software applications which are then converted to another file format or, must be made again from scratch for the purpose of a detailed energy simulation. The file conversion process is a faster approach but has some credibility issues as demonstrated by Maile [Maile, T. et. al., 2007]. Maile and his team found that certain geometry is lost during conversion and requires additional work before the model can be effectively used for a simulation. This again increases the design lead time. Because of the computational intensity of the conventional workflow process and the large number of data type and personnel conversions, this process can often only be performed 2-3 times before the project deadline is reached.

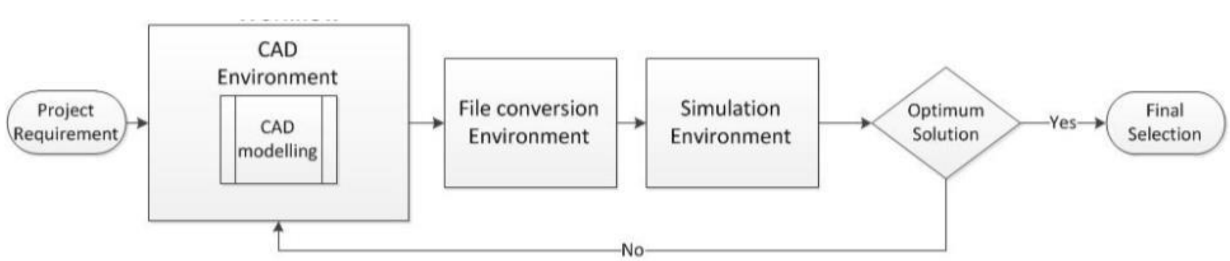

Figure 1 - Conventional Workflow

Proposed architectural workflow

The main aim of this thesis is to present a new process to address the design problems that prevent architects from implementing energy-simulation-informed building design in small scale projects. Figure 2 shows the workflow that this work proposes as a means to integrate the conventional workflow with a lightweight, low fidelity simulation model. In this case, the lightweight, low fidelity simulation would be directly integrated into the CAD software that will allow architects to run simulations without extensive training. Moreover, the simulation would be fast enough to allow architects to run it repetitively, in the background of their conventional CAD design process. The results would not be as accurate as a sophisticated software simulation but this work hypothesizes that an increasing the rate and number of energy system design feedback loops that are available to the architects will help the architects in making design decisions that can then be validated through the use of a detailed simulation application. In the case of smaller projects, where a costly high fidelity simulation is not possible, the low fidelity model can still be used as decision making tool.

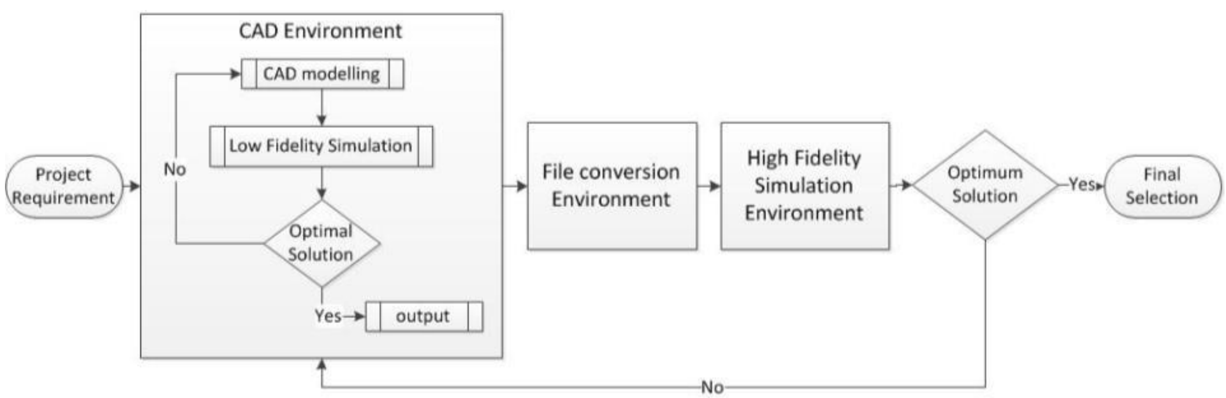

Figure 2 - Proposed Workflow

Trade-offs Between Design Options and Information Available

This project seeks to develop a new method of design to improve the performance of architects in building energy efficient buildings. This section provides the design process (requirements to decision making) context for our proposed process.

Any construction project starts by eliciting the requirement of a client. The client approaches a firm with his/her needs and asks the architects to draft an initial aesthetically pleasing design. Based on the client's requirements, the architect makes a conceptual 3D CAD model. But at this point, none of the crucial decisions such as material and equipment selection are done since it's too early in the design process and such decisions require more information (such as building usage, costing, landscaping and more) to be able to take decisions effectively and permanently. As design time progresses, the available information increases, at the expense of design options. These early decisions effect the options via a cascading effect.

This inverse relationship between design options and information is represented in Figure 3 which is based on the framework proposed by Malmqvist [Malmqvist, T. et. al., 2009]. As can be seen from the graphic below, many of the options are available in the initial design phase i.e. when the initial CAD models are being drafted. As the process moves from the initial design phase, the amount of information that can be elicited from the client, from simulation, and from the engineering team increases. At the same time, the design freedom associated with the building design decreases. As illustrated in Figure 3, if a design process increases the amount of knowledge available early in the design process, then it would be possible for architects to make better-informed higher-certainty decisions.

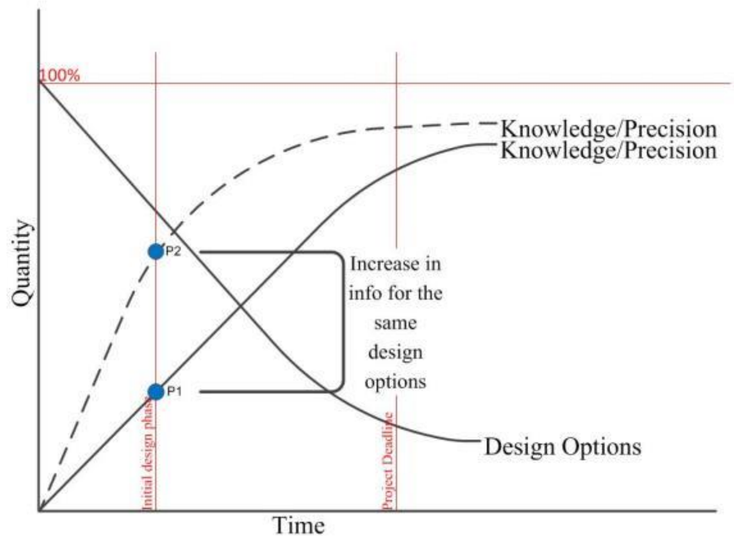

Figure 3 - Design Options vs Available Information

Design Decisions Based on HVAC Loads

Minor decisions in the early stages can have a major impact on the overall energy consumption of the building. It has been observed that just by orienting the building in the correct direction, architects can reduce the energy consumption of a building by 30-40% [Cofaigh et.al. 1999]. Similarly, fenestration design also effects the energy consumption since it is directly related to HVAC loads. As a general rule of thumb it is known that maximum solar gain occurs at the west facing features including windows and heat absorbing walls. But architects find it difficult to quantify these values or make informed trade-offs among conflicting objectives. In this research, we seek to develop a simulation model to give the architects a valuation and comparison of these characteristics so that they can analyze their design's impact on the HVAC load. The design decisions that we would like to influence as early as possible in the building design process include building/wall orientation, window properties (size, shading, glazing type) and construction material.

HVAC LOAD CALCULATION METHODS

Previously Used ASHRAE Methods

ASHRAE is the one of the world's leading organization that has been carrying out extensive research in the field of refrigeration and air conditioning since its induction in 1959. ASHRAE has developed various methods for calculating building HVAC loads. Most of these require a detailed set of input data. Some of the pre-existing methods that have been developed by ASHRAE include:

- Total equivalent temperature differential method with time averaging (TETD/TA) [ASHRAE, 1967]
- Transfer function method (TFM) [ASHRAE, 1972]
- Cooling load temperature differential method with solar cooling load factors (CLTD/CLF) [ASHRAE, 1977]

This work does not seek to discredit these three methods in any way. They are accurate to a degree, and are still being used by professional engineers worldwide. However, the main drawback of these methods is the dependency on purely subjective input such as determining a proper time averaging method for TETD/TA, determining safety factors for the rounded off TFM results, and determining whether the cooling load factors are accurate for a specific application in case of CLTD/CLF method [ASHRAE, 2013].

Heat Balance Method and Radiant Time Series Method

Currently the most advanced and sophisticated methods for carrying out HVAC load analysis by ASHRAE are the Heat Balance [HB] (Pederson et.al., 1997) method and the Radiant Time Series [RTS] method (Spitler et.al., 1997) method. The HB method is more direct in terms of calculations and inputs, and takes into consideration a surface-by-surface heat balance approach involving conduction, convection and radiation at every surface/air interface. The system of equations of a HB method can be calculated in a computer program using successive substitution, Newtonian techniques or (with linearized radiation) matrix methods. This renders the baseline method unsuitable for use with the tool being developed since it requires extensive simulation time and cumbersome user input.

The RTS method on the other hand is a simplified form of the HB method and effectively replaces all of the previously described methods. It does not involve simulated calculations and is based on a time delay effect in the heat transfer process. These time delay factors are derived using heat balancing principles using the program *Hbfort* (Pederson et. al., 1998). These factors apply to both direct heat sources such as lighting and solar radiation, as well as indirect heat sources such as heat absorbed by walls and furniture. This heat dissipates to the environment over time and thereby affects the overall cooling load even after the primary heat source is removed.

In the RTS method, these delayed responses are calculated using pre-calculated time series factors (solar and non-solar radiant time factors and conduction time factors) which gives a distributed heat gain profile of a given instantaneous heat source for the next 24 hours.

RADIANT TIME SERIES METHOD

Overview

Figure 4 shows an overview of the RTS method. The steps involved can be summarized as:

1. Calculate hourly heat gain through fenestration (windows): heat gain via conduction, direct beam radiation, and diffused radiation using solar radiation time factors.
2. Calculate hourly heat gain through opaque surfaces(walls/roof): heat gain via conduction using conduction time factors and taking into account elevated surface temperature.
3. Calculate hourly internal heat gain (equipment, lighting and occupancy) by applying non-solar radiation factors
4. Split hourly gains into radiative and convective portions
5. Apply radiant time series to radiant loads
6. Add infiltration heat to convective portion
7. Sum the heat gain to obtain total hourly loads

The heat that is absorbed by a surface is dissipated to the atmosphere over time by both radiation and convection. These are in-turn dependant on the emissivity and surface temperature respectively. Thus to segregate these two processes, the RTS method uses fixed fractions to split the heat gain into radiative and convective portions. These fractions are different for different heat sources and types. Some of these fractions (not all conditions) are tabulated in Table 1 (Nigusse, 2007).

Table 1 - Recommended radiative/convective splits

	Heat Gain Type	Radiative Fraction	Convective Fraction
Internal	Occupants	0.6	0.4
	Equipment	0.1 to 0.8	0.9 to 0.2
	Lighting	varies	varies
Conduction	Walls and roof	0.46	0.54
	Roof	0.6	0.4
	Windows	0.33 (SHGC > 0.5) 0.46 (SHGC < 0.5)	0.67 (SHGC > 0.5) 0.54 (SHGC < 0.5)
Fenestration (Solar)	Without interior shading	1	0
	With interior shading	varies	varies
Outside air	Infiltration	0	1

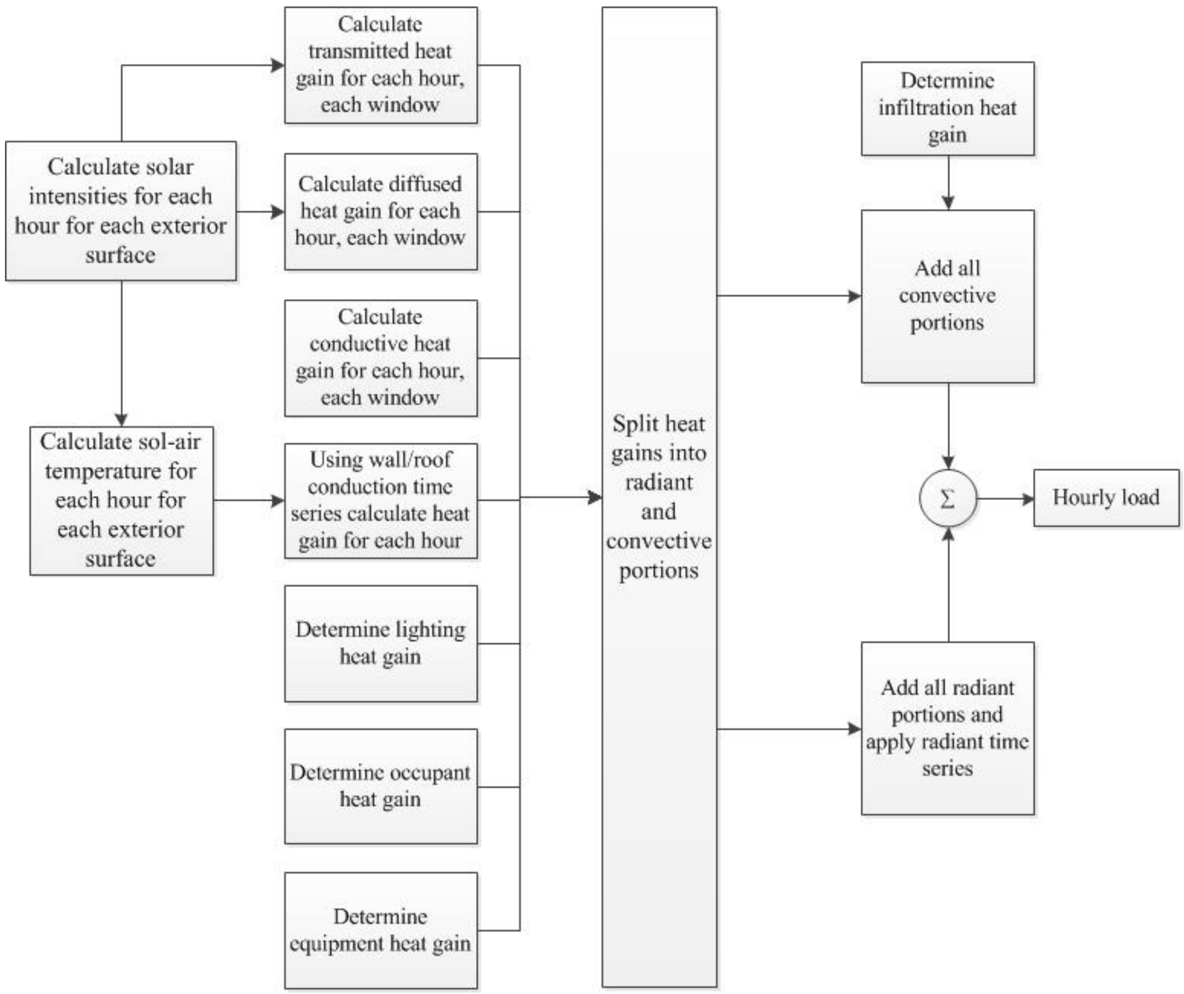

Figure 4 - Overview of RTS method

Time Series Factors

There are three types of time series factors in RTS method:

- Conduction Time Factors
- Solar RTS Factors
- Non Solar RTS Factors

The time factors are dependent on material and type of radiation and are derived using the HB method. The delayed time effect is applied using the following equations in RTS method:

$$q_\theta = c_0 q_{i,\theta} + c_1 q_{i,\theta-1} + c_2 q_{i,\theta-2} \dots \dots + c_{23} q_{i,\theta-23}$$

$$Q_{r,\theta} = r_0 Q_{r,\theta} + r_1 Q_{r,\theta-1} + r_2 Q_{r,\theta-2} \dots \dots + r_{23} Q_{r,\theta-23}$$

These factors are dependent on the material and type of construction. By definition, the sum of all factors in a series is unity. The ASHRAE handbook (ASHRAE, 2013) gives us the CTS values for 35 wall types, 19 roof types and RTS values for light to heavy construction.

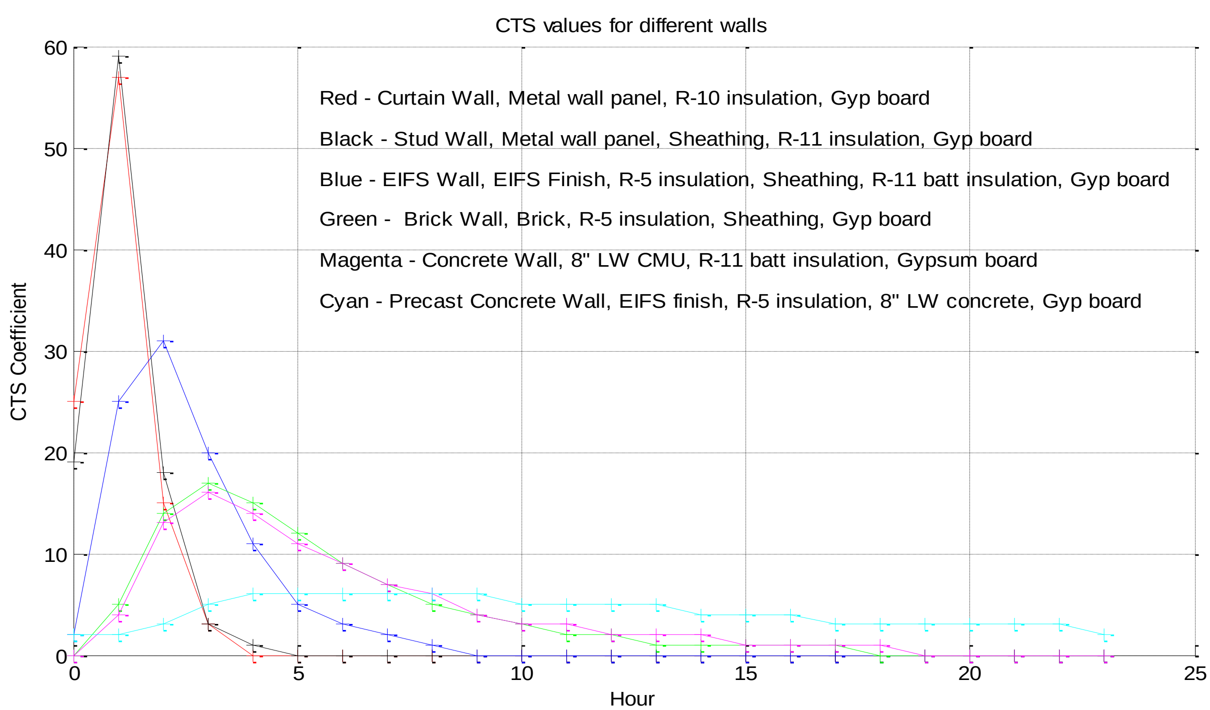

Figure 5 - CTS values for light to heavy walls

Figure 5 shows the CTS coefficients for six different wall types. As may be observed, curtain walls and stud walls lose majority of their heat in the first five hours whereas the other walls retain it much longer.

Sol-Air Temperature and Exterior Opaque Surface Heat Gain

The RTS method does not include detailed surface/air heat balance models. To overcome this drawback, conduction through exterior walls is modelled using an equivalent wall temperature called sol-air temperature. Sol-air temperature is the outdoor air temperature that, in the absence of all radiation changes gives the same rate of heat entry into the surface as would the combination of incident solar radiation, radiant energy exchange with the sky and other outdoor surroundings, and convective heat exchange with outdoor air (ASHRAE, 2013). The simplified sol-air temperature formula as given in ASHRAE Handbook of Fundamentals (2013) is:

$$t_e = t_o + \frac{\alpha E_t}{h_o} - \frac{\varepsilon \Delta R}{h_o}$$

The long wave correction factor ($\varepsilon\Delta R/h_o$) is calculated to be about 7^{o}F for horizontal surfaces and 0^{o}F for vertical surfaces (Bliss, 1961). Thus the sol-air temperature depends mainly on the absorptance of the wall material and the incident radiation on the surface. In general α/h_o values of 0.15 for a light coloured surface and 0.3 for a dark coloured surface are considered a reasonable approximation. Thus the conduction heat gain through exterior opaque surfaces is calculated as:

$$q_{i,\theta-n} = UA\left(t_{e,\theta-n} - t_{room}\right)$$

Once the hourly heat gain profile is obtained, it is split into radiant and convective portions and the radiant portion multiplied with non-solar RTS values to obtain total cooling load.

Fenestration Heat Gain

Instantaneous heat gained through fenestration consists of three components: direct beam radiation, diffused radiation and conduction heat gain. The equations for the above are as follows:

$$q_b = A * E_{t,b} * SHGC(\theta) * IAC(\theta, \Omega)$$

$$q_d = A * \left(E_{t,d} + E_{t,r}\right) * < SHGC >_D * IAC_D$$

$$q_c = U * A * (T_{out} - T_{in})$$

$$Q = q_b + q_d + q_c$$

These instantaneous heat gains have to be split into radiant (direct beam component treated as 100% radiant) and convective components and further multiplied with the time factors to obtain the effective cooling load. The solar RTS values are applied to the direct beam component and the non-solar RTS values are applied to the diffused and conduction components.

Assumptions and parameters in RTS method

As with all calculation models, the RTS method has some inherent assumptions that must be discussed to evaluate the efficiency of the RTS methods to our application (McQuiston et. al., 2000 and ASHRAE, 2013). Some of the most relevant assumptions are as follows:

- Steady periodic condition: All internal and external heat gain conditions are periodic with time period of 24 hours

- No internal temperature gradient: The zone air is well mixed and at a constant temperature
- Adiabatic zone: No heat escapes the system at a later point of time
- Time delay effects:
    - Conductive heat gain delay due to opaque surfaces
    - Radiative heat gain delay to cooling load
- Exterior walls and roof conduct heat due to temperature difference between outside and inside air
- In addition to conduction, solar energy on exterior surfaces is first absorbed by the surface then transferred by conduction to the interior of the building. RTS method does not have detailed surface air heat balance models. Instead radiation and convection on exterior walls are modelled together using an equivalent temperature called sol-air temperature
- The time factors are pre-calculated coefficients
- Solar transmitted beam radiation is dissipated on the floor only, while other radiations are uniformly distributed on all surfaces.
- The convective part of heat is directly converted to cooling load
- The radiative part of heat gain must first be absorbed by interior surfaces and only adds to cooling load at a later time via convection

ANNUAL CLIMATIC DATA

Need for Annual Climatic Data

Due to the first assumption of steady state periodic conditions, the RTS method is only valid for peak load calculations and is not valid for predicting annual load. For the purpose of creating a decision making tool, annual weather data has to be considered in place of peak climate data. The data that is required for the RTS method includes solar radiation and temperature.

To apply the data into the calculation we need the geographic location of the place the building is being constructed. The National Solar Radiation Database (NSRDB) files provides our RTS model with meteorological data for 1020 locations in the United States collected over a period of 15 years (1991-2005) to develop a typical meteorological year (TMY) climatic data. This TMY database contains real life values for all required parameters on an hourly basis for the entire year. These can be applied in the RTS procedure to obtain HVAC cooling loads throughout the year on an hourly basis.

NSRDB TMY3 database

The method for generating a typical meteorological year (TMY) data was developed in 1978 by Sandia National Laboratories (hall et. al., 1978). However this method was later updated to account for weighting factors and missing data to generate TMY2 and TMY3 databases (Marion et.al. 1995 and Wilcox et.al. 2007). The method involved a statistical analysis of the data collected by weather stations over a long period of time. From the acquired data, one typical month is selected statistically that represents a typical climatic month for that location. Table 2 shows the months that showed a typical climatic representation for Denver international airport (USAF site identifier number - 725650TY).

Table 2 - Denver International Typical Meteorological Year

January	1995
February	1994
March	1991
April	1999
May	1991
June	1994
July	1991
August	2001
September	2005
October	2000
November	2002
December	1994

The TMY3 database files include 68 hourly parameters for 1020 locations along with area information (latitude, longitude, time zone and altitude) in csv file format which can be easily read by a computer program for simulation. These parameters include everything from dry bulb temperature to wind speed and humidity. Of these, the ones that are of importance for our calculations are:

- Latitude
- Longitude
- Time Zone
- Direct Normal Irradiance
- Diffuse Horizontal Irradiance

SOLAR POSITION CALCULATION

For calculating the solar intensities on various wall orientations it is necessary to find the position of the sun. Since the earth's orbit is elliptical and also slightly inclined with the axis of revolution the sun's position is unique at every hour throughout the year at different locations on the planet.

Solar Position

From a fixed point of reference on the earth's surface, the sun appears to travel along an arc in the sky. This path shifts every day of the year due to earth's declination and elliptical orbit which in turn causes a change in net solar output received at the surface. The procedure for calculating the sun's position has been extensively explained in the book by Iqbal (Iqbal, M; 1983). The following procedure describes how the incident angle of the solar radiation is calculated. This is required to calculate direct beam and diffused radiation. Figure 6 shows the path that the sun follows during the day.

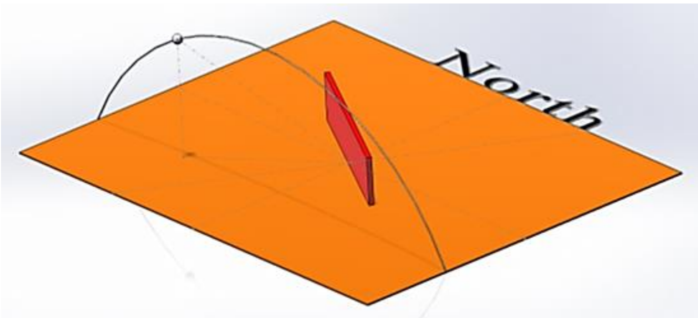

Figure 6 - Solar path through the day

Equation of Time

The time maintained by the clocks (mean solar time) differs from the apparent (actual) solar time by a value that is called as the equation of time. This discrepancy occurs due to two factors, the eccentricity of the earth's orbit and the obliquity of the ecliptic (due to declination of earth's axis). These two factors lead to variation in the orbital velocity and hence apparent solar time. Figure 7 shows the equation of time values for different days of the year. The equation below gives an approximation to evaluate the equation of time [Spencer, 1971, cited by Iqbal, 1983].

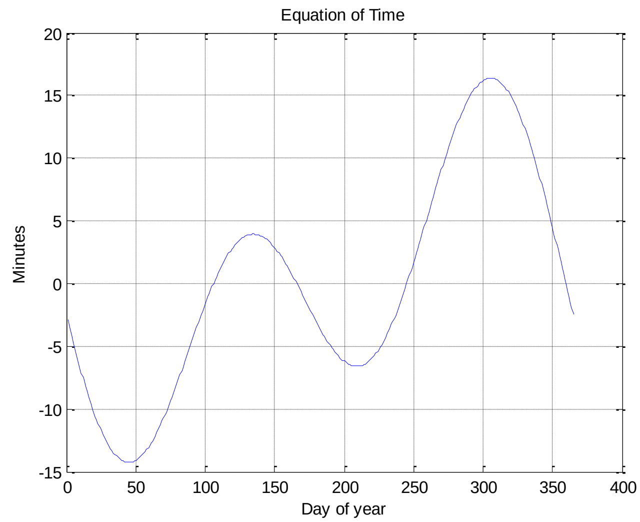

Figure 7 - Equation of Time

$$ET = 229.18 * [0.000075 + 0.001868 * \cos(N) - 0.032077 * \sin(N) - 0.014615 * \sin(2N) - 0.04089 * \cos(2N)]$$

$$N = 2\pi * \frac{n-1}{365}$$

$$n = Day\ of\ year$$

Apparent Solar Time

The apparent time can now be calculated by adding the equation of time to the local standard time. A longitude correction factor too has to be accounted for.

$$AST = Local\ Time + Equation\ of\ Time + Longitude\ Correction$$

$$AST = LST + \frac{ET}{60} + \frac{Lon - LSM}{15}$$

$$LST = DST - 1$$

$$LSM = 15 * TZ$$

Declination

Solar declination is the angle between earth sun line and equatorial plane (Figure 8). Due to the earth's tilt of 23.45^o, the declination of the sun changes throughout the year. Equation below is a Fourier series representation of the declination that has maximum error of less than 3 degrees [Spencer, 1971, cited by Iqbal, 1983]

$$\delta = 57.296[0.006918 - 0.399912 * \cos(N) + 0.070257 * \sin(N) - 0.006758 * \cos(2N) + 0.000907 * \sin(2N) - 0.002697 * \cos(3N) + 0.001480 * \sin(3N)]$$

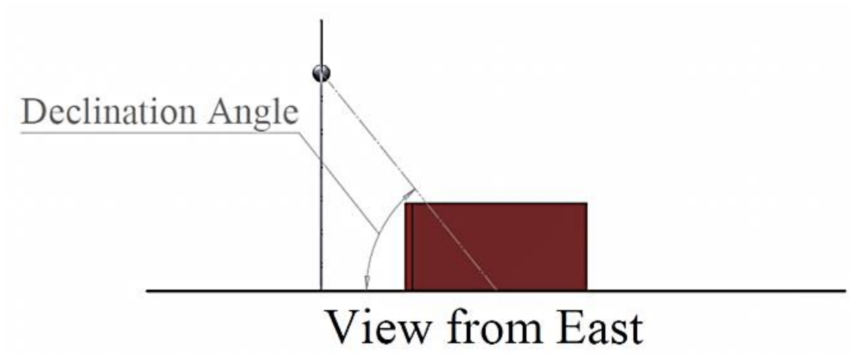

Figure 8 - Declination angle

Hour Angle

The hour angle is the angular displacement of the sun west or east of the local meridian due to the rotation of the earth.

$$H = 15(AST - 12)$$

Solar Altitude Angle

The solar position is expressed in terms of solar altitude angle and azimuth angle. The solar altitude angle is the angle between the horizontal plane and the line joining the sun to the surface (Figure 9). It depends on the latitude, declination and hour angle.

$$\beta = \sin^{-1}[\cos(Lat) * \cos(\delta) * \cos(H) + \sin(Lat) * \sin(\delta)]$$

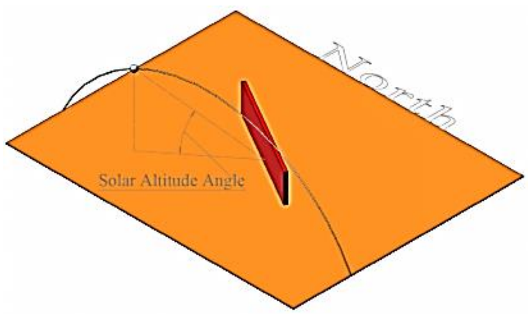

Figure 9 - Solar altitude angle

Solar Azimuth Angle

The solar azimuth angle is approximated using the following inverse cosine function. However, it is to be noted that these values are always positive. Therefore, when hour angle is negative (morning) the azimuth angle is between 0^o and 180^o and between 180^o and 360^o when hour angle is positive (afternoon).

$$\phi = \cos^{-1}\left[\frac{\sin(\delta) - \sin(\beta) * \sin(Lat)}{\cos(\beta) * \cos(Lat)}\right]$$

Incident Angle onto Surface

Surface Azimuth Angle

The azimuth of the surface is taken in reference to the south and incremented anti clockwise. Table 3 shows the 8 standard orientations and their azimuth values.

Table 3 - Surface Azimuth Angles

	N	***NE***	***E***	***SE***	***S***	***SW***	***W***	***NW***
Ψ	180	-135	-90	-45	0	45	90	135

Surface-Solar Azimuth

The surface-solar azimuth angle is the angle between the normal to the surface and the projection of the sun on the ground i.e. the difference between the solar azimuth and the surface azimuth as shown in Figure 10.

$$\gamma = \phi - \Psi$$

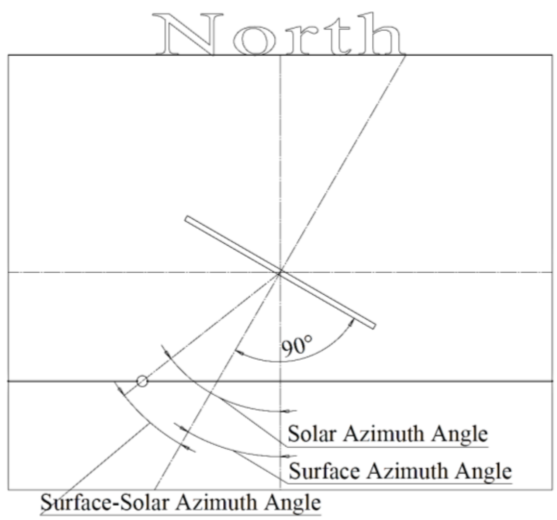

Figure 10 - Azimuth Angles

Incident Angle

Using all the above angles, the incident angle onto the surface can be calculated using the following equation:

$$\theta = \cos^{-1}[\cos(\beta) * \cos(\gamma) * \sin(\Sigma) + \sin(\beta) * \cos(\Sigma)]$$

Radiation

The next step after calculating the incident angle is to transpose the solar radiation into three components: direct beam radiation, diffused radiation, and ground reflected radiation. These values are directly dependant on the incident angle. The final radiation received by any surface is sum total of these components.

$$E_t = E_{t,b} + E_{t,d} + E_{t,r}$$

Direct Beam Radiation

The direct beam radiation is computed directly from a geometric relation as shown in equation below. This component of the radiation originates from the solar disk directly.

$$E_{t,b} = E_b * \cos(\theta)\, , if\ \cos(\theta) > 0$$

$$= 0\, , if\ \cos(\theta) \leq 0$$

Diffused Radiation

The diffuse component is harder to compute due its non-isotropic nature. For a vertical surface this can be computed by the following relation (Stephenson, 1965 and Threlkeld, 1963):

$$E_{t,d} = E_d * \cos(Y)$$

$$Y = \max[0.45, 0.55 + \cos(\theta) + 0.313 * cos^2(\theta)]$$

In case of inclined surfaces the following formula can be used for calculating the diffused component:

$$E_{t,d} = E_d[Y * \sin(\Sigma) + \cos(\Sigma)]\, , if\ \Sigma \leq 90^o$$

$$= E_d * Y * \sin(\Sigma)\ , if\ \Sigma > 90^o$$

The diffusion factor is calculated for a vertical surface having the same azimuth as the given surface. However, it is to be noted that the above relations for diffused radiation apply to clear sky radiation only.

Reflected Radiation

The reflected component of the radiation depends on the reflectivity of the ground surrounding the building. The reflectivity of the ground varies from as low as 0.05 for asphalt to 0.7 for an isolated rural site with snow cover (Thevenard and Haddad, 2006). A typical value taken into consideration for ground reflectance is 0.2. The following equation shows the reflected component of irradiance.

$$E_{t,r} = [E_d \sin(\beta) + E_d] * \rho_g * \frac{1 - \cos(\Sigma)}{2}$$

CAD MODEL

The method presented in this thesis requires two primary inputs from the user. The CAD model and the geographic location coordinate. The CAD model provides the following data:

- Total volume of the building envelope
- Surface areas of all surfaces through which heat is gained/lost
- 3D spatial orientation of surfaces
- If the CAD environment has a Building Information Modeling (BIM) interface, then the CAD model can also provide the material properties.

Figure 11 represents an example CAD drawing of a building that can be modeled in SketchUp®. There are other software applications available that can provide the same functionality but that will not be discussed in this dissertation.

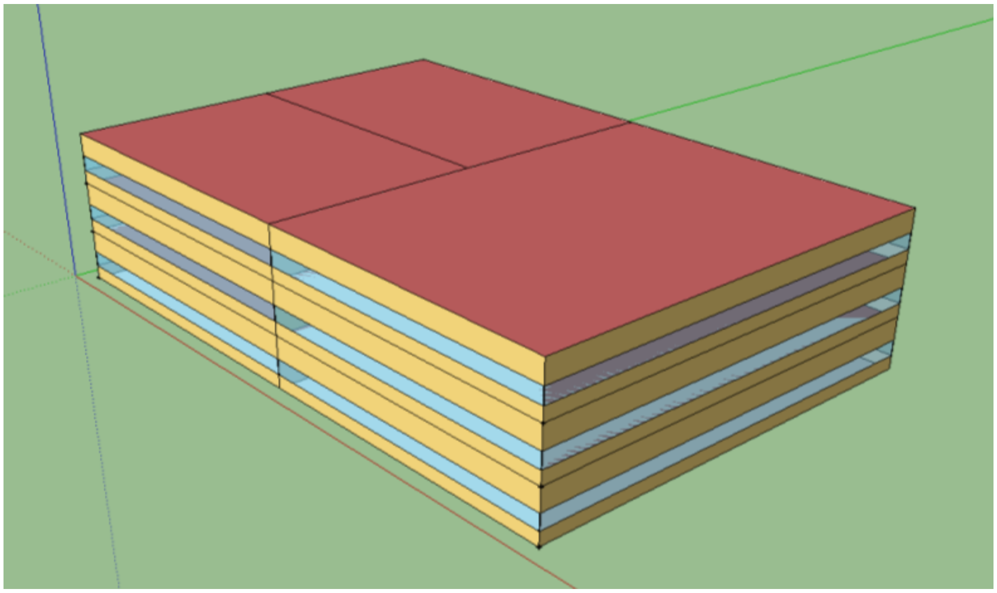

Figure 11 - CAD Model (SketchUp)

EXAMPLE CALCULATION

The example calculation for this dissertation is being demonstrated via a MATLAB® code. All the CAD data and material properties are fed into program as variables or user inputs and calculations are carried out to achieve final results. Figure 12 shows the overview of the design process and how the RTS method is integrated with the user input.

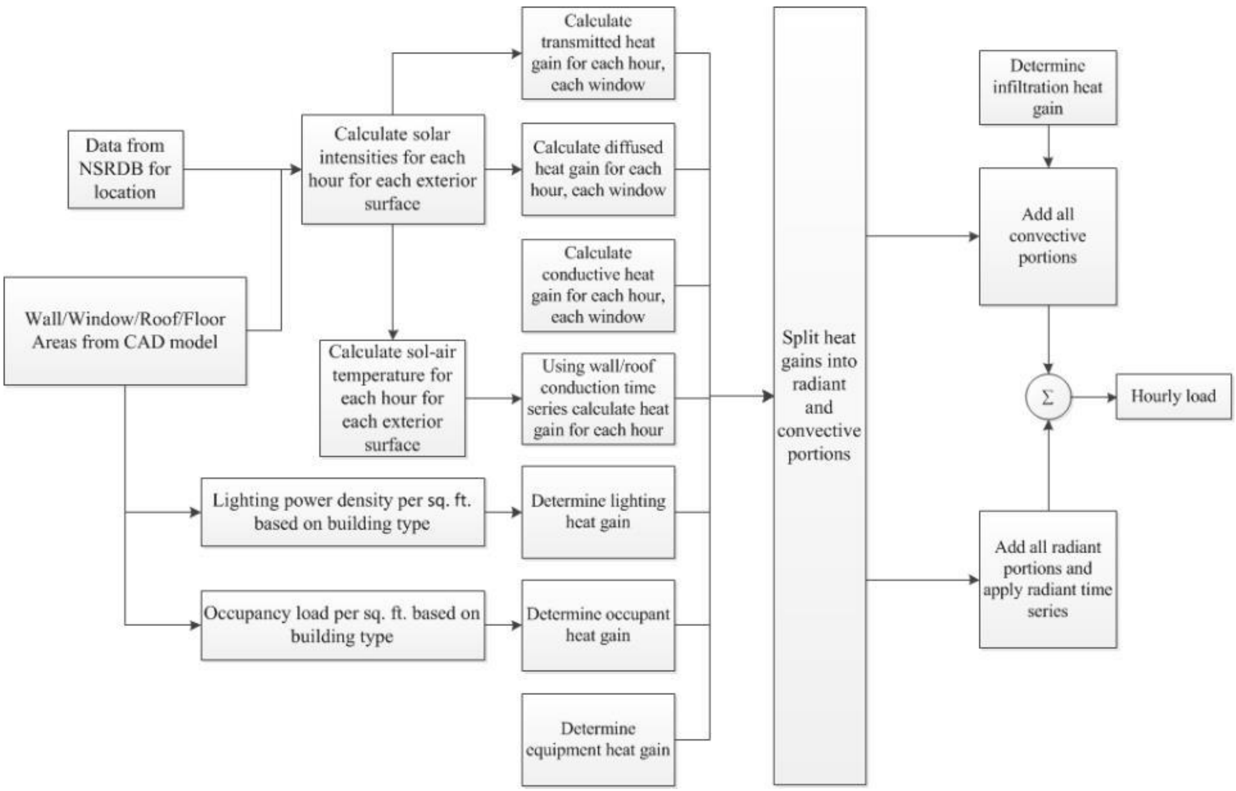

Figure 12 – RTS integrated with NSRDB and CAD

Problem Statement

For the purpose of demonstration, we can assume that a client has approached an architectural firm with the plot details of a project based near Denver and seeks to lease it after construction. The client does not specify any other details of the building's use except that it will be an office. Based on this assumption the architect drafts a sketch of a three storied office as shown in Figure 13.

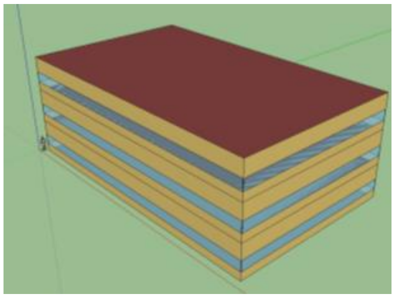

Figure 13 - CAD model of example office building

Building Type and Surface Areas

From the CAD model the various surface areas with orientations can be extracted and are tabulated here in Table 4. According to research by NREL (NREL, 2011) commercial buildings can be classified into 16 types. Based on the number of stories and floor area it can be concluded that the building falls under a small office building category. The window area is calculated using a window to wall ratio of 0.25 i.e. 25% of the wall surface consists of windows.

Table 4 - Surface areas of example office building

Floor Area = 3*100*80 ft^2		**Slab Height = 12 ft.**	
Surface Areas (ft^2)			
North	**South**	**East**	**West**
Walls (Opaque Portion)			
2700	2700	2160	2160
Windows (window to wall ratio – 0.25)			
900	900	720	720

Internal Loads

Because this project is in a very early stage of architecting, the internal loads are not known, and they must be estimated on a per square foot basis from standards set by ASHRAE and DoE (ASHRAE Standards 90.1-2010 and NREL, 2011). These standards have data based on similar building structures and are a reasonable guideline in most cases. Table 5 lists the internal loads applied to the model.

Table 5 - Internal loads per square feet

Lighting	1.11 W/ft^2
Equipment	1 W/ft^2
People	200 ft^2/person

Again, because this project exists at an early stage of design the operating schedule of the building must be estimated. The operating schedule for this example is taken to be a 12 hour shift from 7:00 AM to 7:00 PM with 100% load during the operating hours.

Geographical Information

The building is to be constructed in Denver. Based on this the files that can be used from the NSRDB database are:

- Denver International Airport (USAF number 725650TY)
- Denver/Centennial [Golden-NREL] (USAF number 724666TY)

Table 6 - NSRDB data header for Denver Intl AP

Site Identifier Code	725650
Station Name	Denver Intl AP
Station State	CO
Site Time Zone	-7
Site Latitude	39.833
Site Longitude	-104.65

Table 6 shows the data pulled from the csv file for Denver International Airport. All these values are needed for the RTS method to be implemented. Apart from this the other parameters that have to be extracted from the csv file are the dry bulb temperature and solar irradiances. These values are arranged in a column by column manner, so that they can be easily accessed.

Construction Material

The construction material is important in terms of heat energy transmitted and stored in the building. The type of glazing and insulation determine the amount of heat transmitted between the inner and outer environment whereas the thermal capacity of the material decides the radiant time series factors. Table 7 lists the materials applied to the model.

Table 7 - Example Calculation Material Properties

	Type	Material Properties
Window	Reflective glazing	SHGC = 0.17 SHGC for diffused = 0.16 Conduction coefficient = 0.56 Btu/h.ft^2.°F
Walls	Exterior Insulation Finishing System [EIFS]	Conduction coefficient = 0.092 Btu/h.ft^2.°F Conduction Time Factors [CTF] = 0.01; 0.02; 0.06; 0.09; 0.09; 0.09; 0.08; 0.07; 0.06; 0.06; 0.05; 0.05; 0.04; 0.04; 0.03; 0.03; 0.03; 0.02; 0.02; 0.02; 0.02; 0.01; 0.01; 0.00
Solar RTS Values	Medium construction with carpet and 50% glass	0.54; 0.16; 0.08; 0.04; 0.03; 0.02; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.00; 0.00; 0.00; 0.00; 0.00
Non-Solar RTS Values	Medium construction with carpet and 50% glass	0.49; 0.17; 0.09; 0.05; 0.03; 0.02; 0.02; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.00; 0.00; 0.00; 0.00

RESULTS

Example Calculation Results

Figure 14 through Figure 19 show the results obtained by running the MATLAB® code with the above set constraints. This also serves as a default for comparison with varying parameters as will be discussed in later sections. Table 8 shows the peak load values for a typical year due to windows on different building faces along with the hour at which the peak occurs. It may be observed that the highest load occurs on the south and west faces of the building.

Table 8 - Peak Cooling Loads due to Windows

Window (zero azimuth)	N	E	S	W
Peak Value (x10^4 Btu/hr)	1.55	1.96	3.37	3.07
Peak Index(hour)	4240	4449	4240	4242

Table 9 shows the peaks of the cooling load due to the walls. When compared to the heat load attributable to the windows there is much less heat entering the building since these are opaque faces. Similarly, the heat gain is highest on south and west faces. But the variation is not as high as the previous case. This can be attributed to the fact the heat does not enter the building directly. Instead it goes through a process of conduction and then convection through the wall surfaces.

Table 9 - Peak Cooling Loads for Walls

Wall (zero azimuth)	N	E	S	W
Peak Value (x10^3 Btu/hr)	5.17	4.65	8.44	6.89
Peak Index(hour)	3953	4242	4241	4242

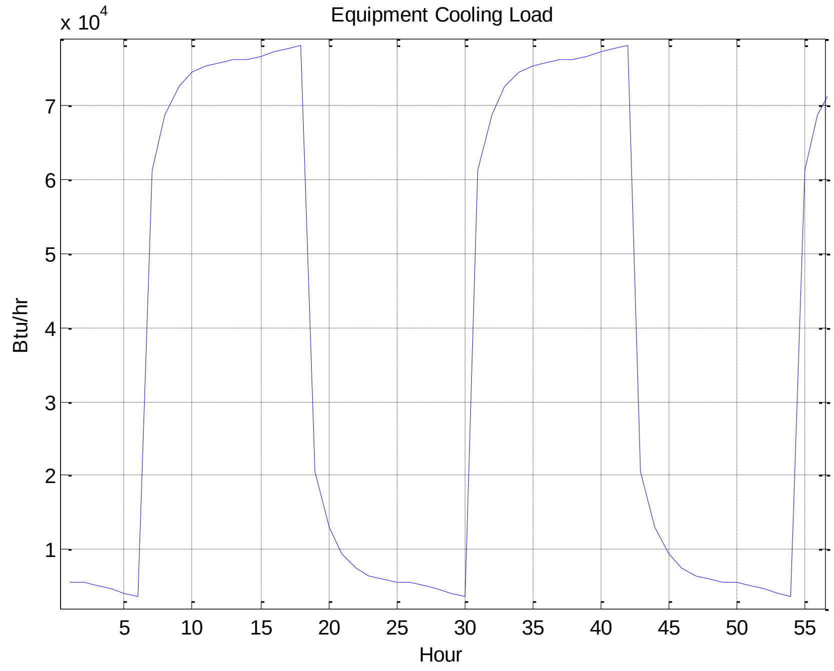

Figure 14 - Equipment Cooling Load

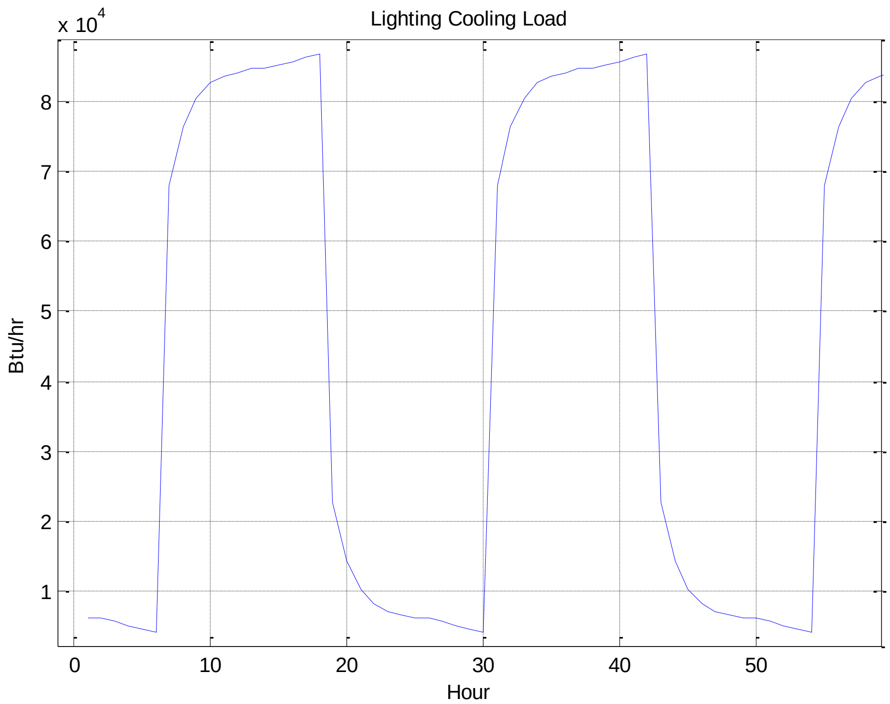

Figure 15 - Lighting Cooling Load

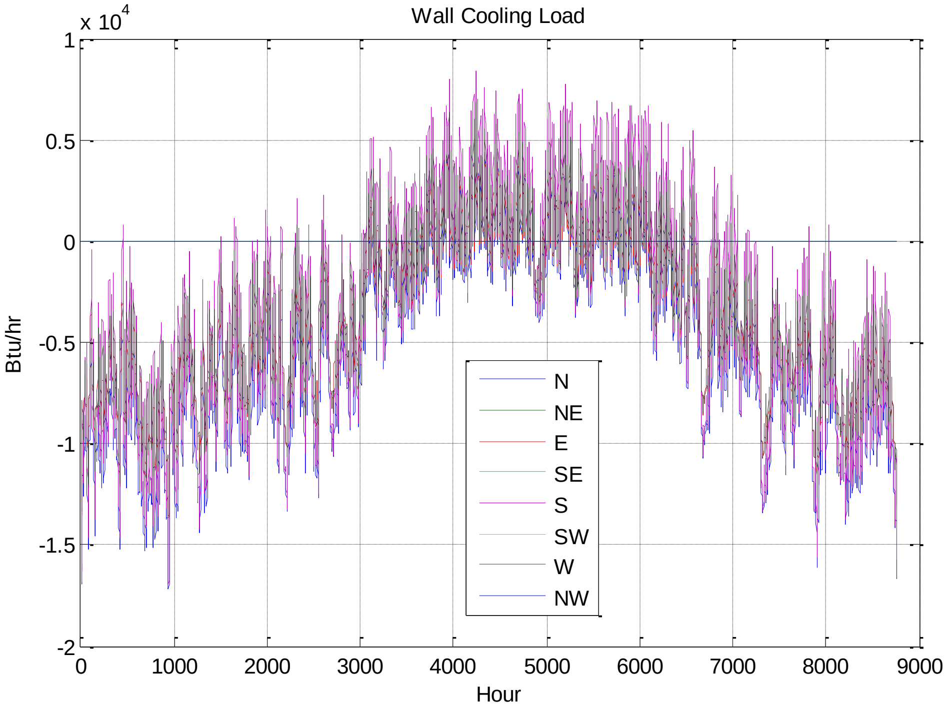

Figure 16 - Wall Cooling Load

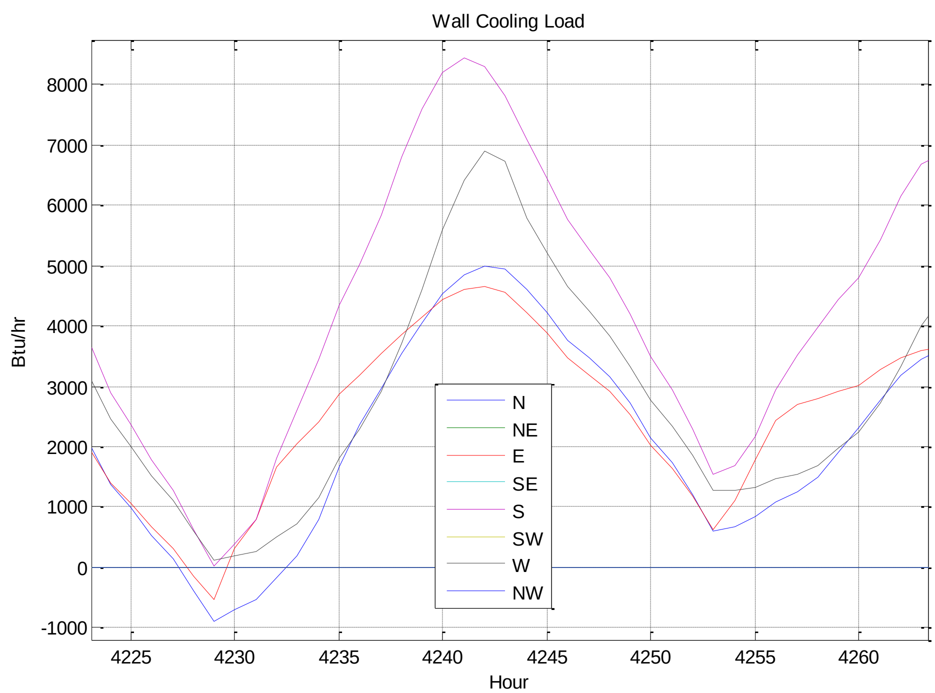

Figure 17 - Wall Cooling Load Peak for Building South

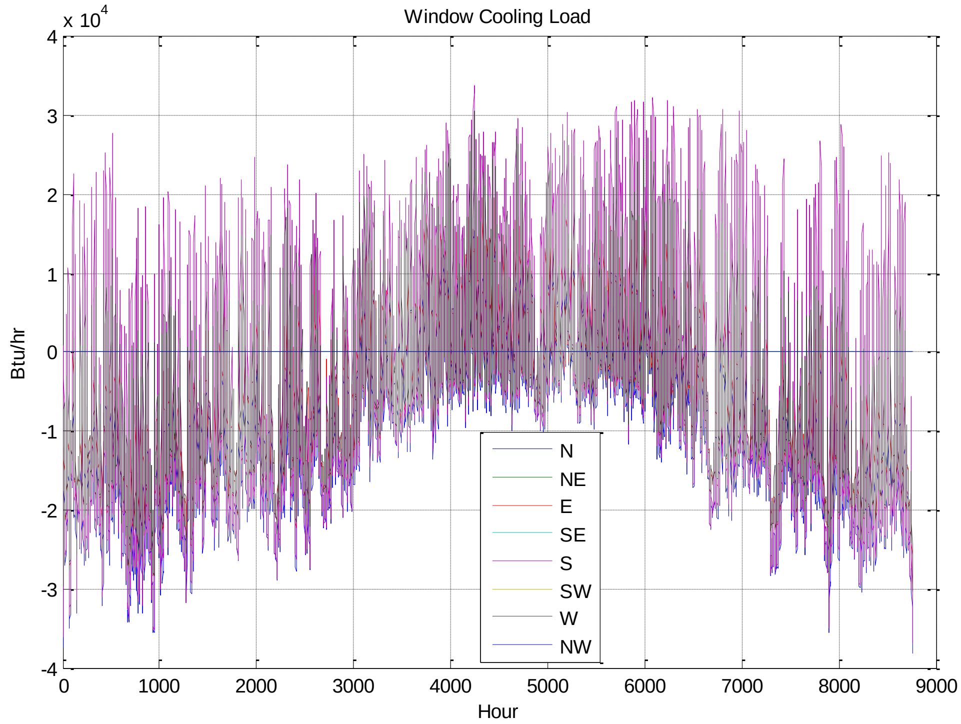

Figure 18 - Window Cooling Load

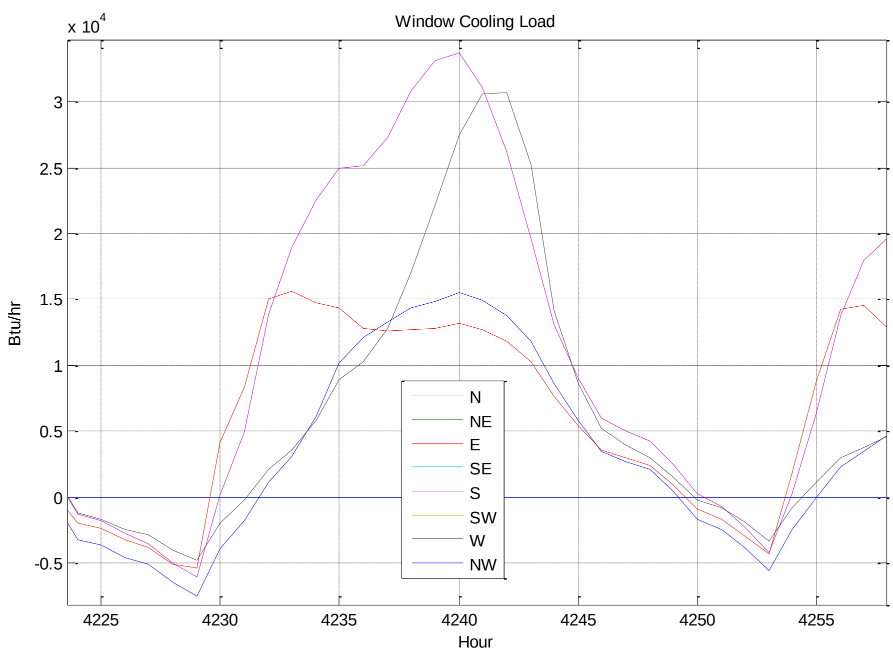

Figure 19 - Window Cooling Load Peak for Building South

Effect of Location

So as to compare between possible locations for this building, the same code was run for the location of JKF International Airport, New York with other parameters unchanged. It is seen that the period of time when cooling is needed is significantly different and lower than in the case of Denver. The results of the simulation were as follows:

Table 10 - NSRDB data header for JFK Intl AP

Site Identifier Code	744860
Station Name	JFK Intl AP
Station State	NY
Site Time Zone	-5
Site Latitude	40.65
Site Longitude	-73.8

Table 11 - Peak Cooling Loads for Windows - JFK

Windows	N	E	S	W
Peak Value ($x10^4$ Btu/hr)	1.58	1.77	3.46	2.19
Peak Index(hour)	4068	4664	5510	5513

Table 12 - Peak Cooling Loads for Walls - JFK

Walls	N	E	S	W
Peak Value ($x10^4$ Btu/hr)	0.6277	0.4946	1.0256	0.6243
Peak Index(hour)	4071	4071	5512	4074

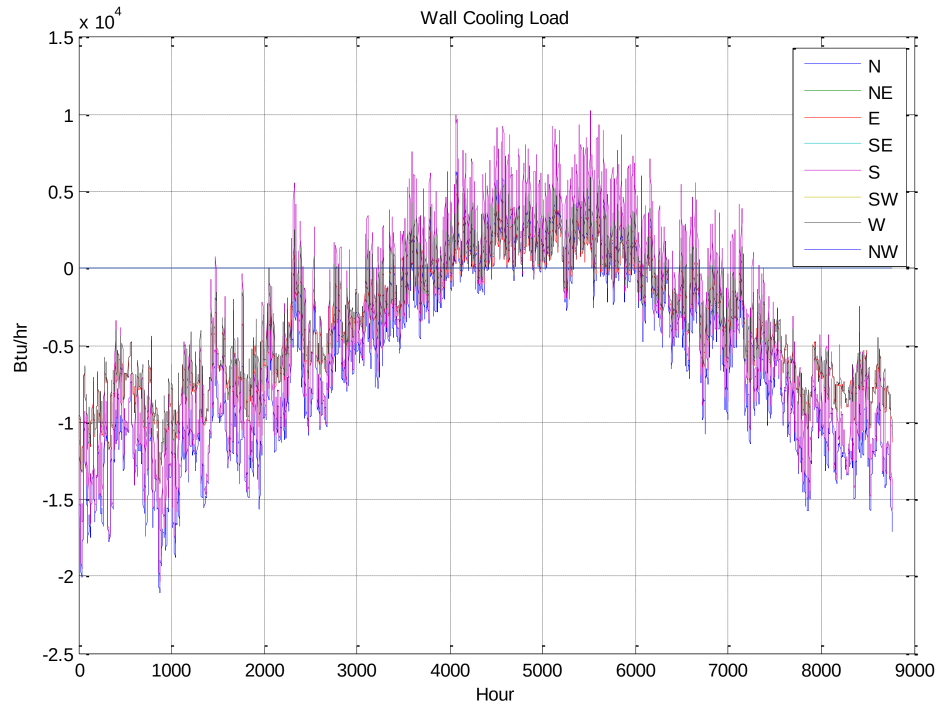

Figure 20 - Wall Cooling Load for JFK Intl Airport

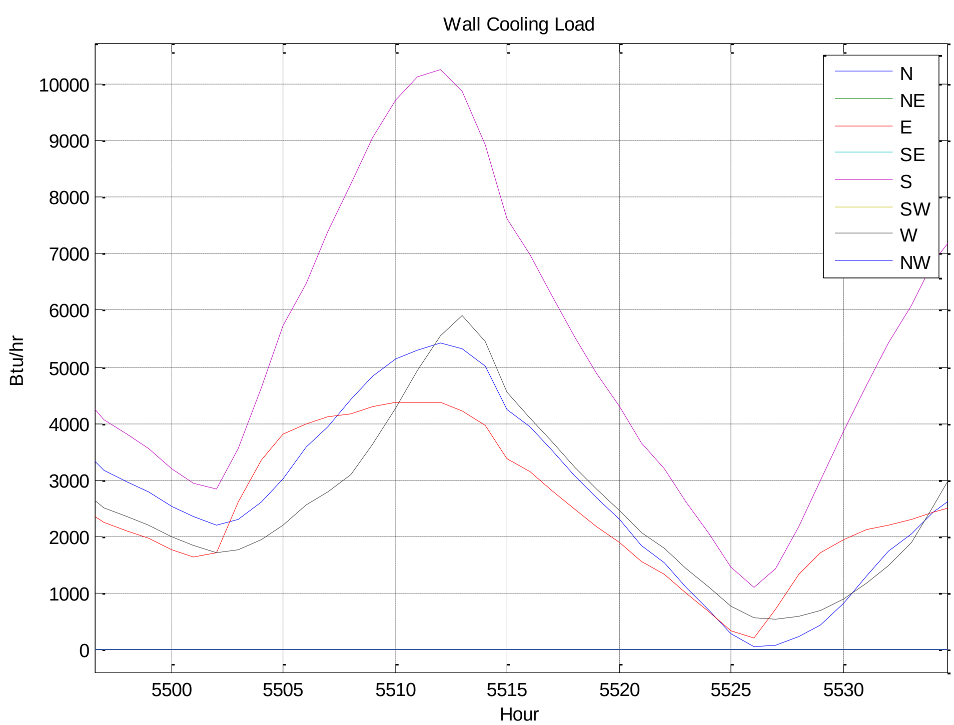

Figure 21 - Wall Cooling Load Peak for JFK Intl Airport (South Wall)

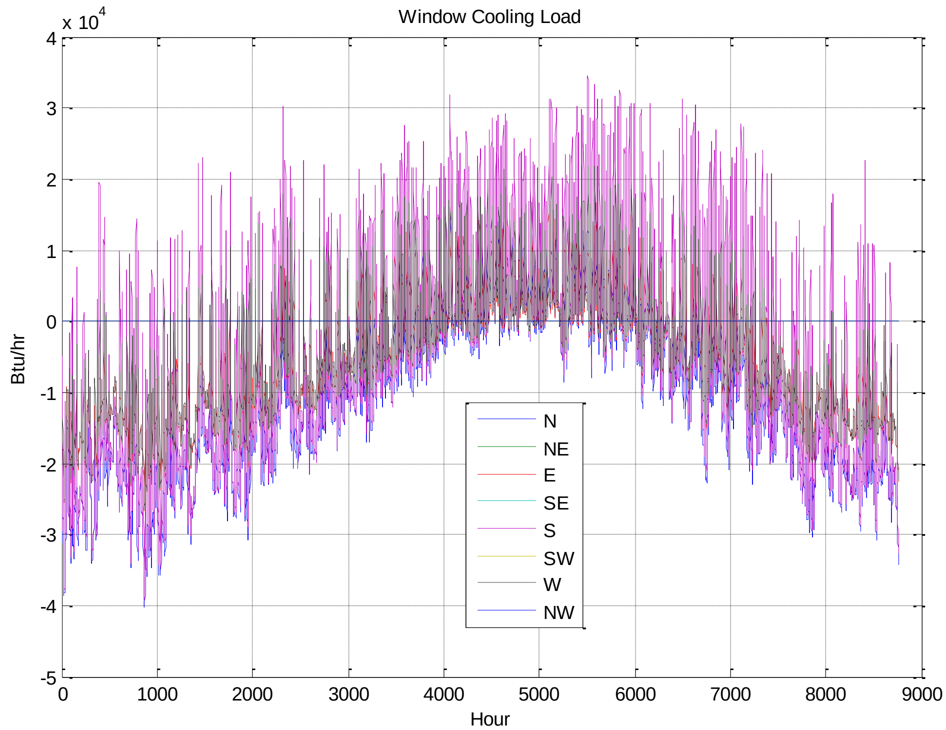

Figure 22 - Window Cooling Load for JFK Intl Airport

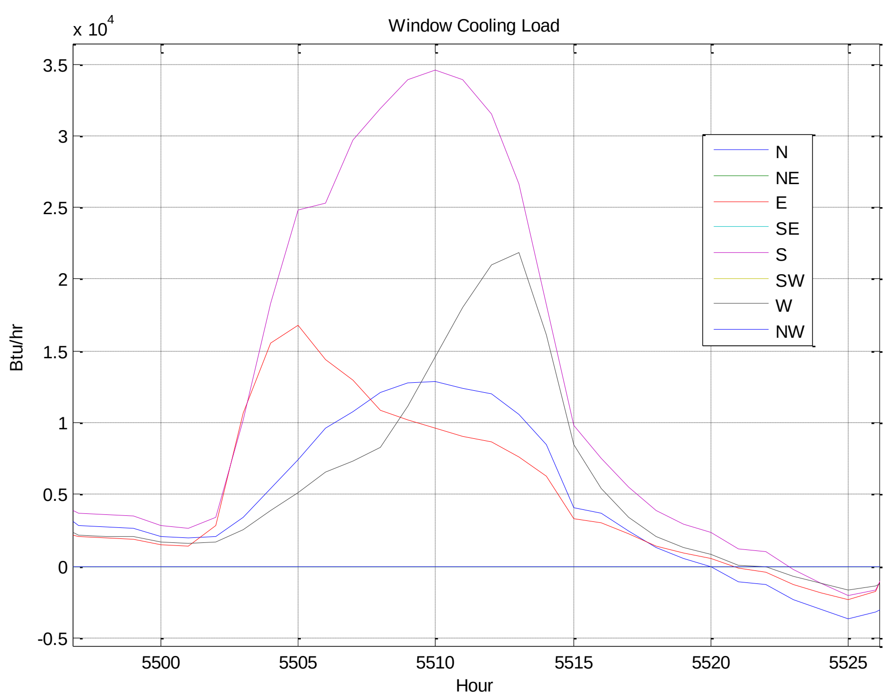

Figure 23 - Window Cooling Load Peak for JFK Intel Airport (South Wall)

Effect of Orientation

Table 13 shows the peak loads for the building at incrementing azimuth orientations in steps of 5 degrees anticlockwise. The total cooling load for the walls and windows is summed together to obtain the net Peak cooling load due to solar radiation. The relationship between building orientation and solar cooling can thus be determined and is shown in Figure 24. From the graph it can be deduced that the optimum orientation to maintain a low cooling load is 25^o counter clockwise. The total time for all the orientations to be simulated was under 15 minutes.

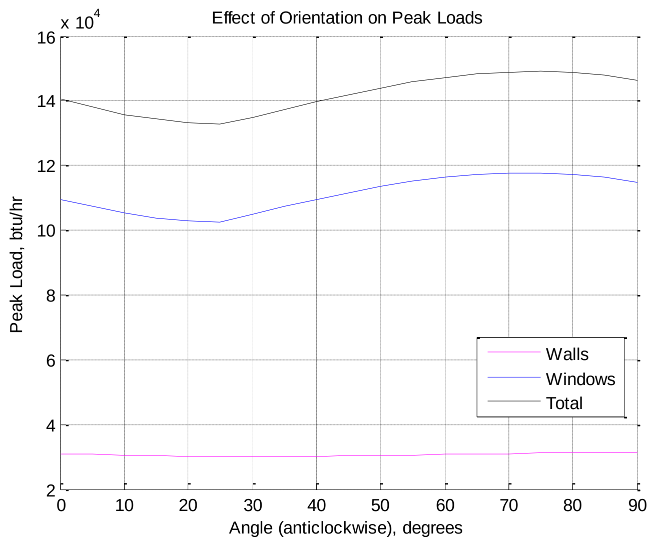

Figure 24- Orientation v/s Peak Load

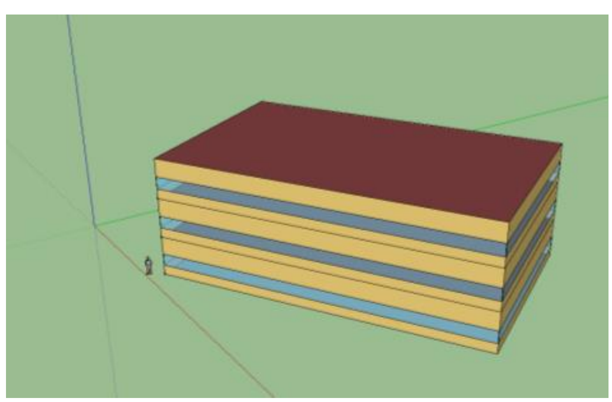

Figure 25 - Optimum Orientation of the Building

Table 13 – Peak Load (Btu/h) Variation with Orientation (5 degree steps)

	Walls					Windows				
Azimuth	N	E	S	W	Total	N	E	S	W	Total
0	6894	5177	11261	7659	30991	18606	19645	40499	30685	109435
-5	6895	5108	10984	7838	30825	18606	18465	38561	31604	107240
-10	6898	5036	10676	7994	30604	18606	17187	36997	32450	105240
-15	6910	4973	10342	8122	30347	18606	15952	36209	33140	103910
-20	6927	4929	10029	8234	30119	18627	14657	35990	33678	102950
-25	7140	4884	9729	8319	30071	19051	13275	36316	34052	102690
-30	7394	4838	9402	8374	30010	21118	12751	36696	34258	104823
-35	7668	4798	9108	7416	29999	23413	12688	36897	34308	107300
-40	7995	4757	8934	8428	30115	25824	12623	36920	34187	109550
-45	8331	4721	8780	8419	30250	28283	12567	36909	33905	111660
-50	8675	4689	8638	8390	30390	30704	12519	36912	33466	113600
-55	9036	4659	8518	8337	30549	33096	12478	36710	32870	115150
-60	9399	4636	8389	8298	30692	35368	12450	36290	32218	116330
-65	9794	4617	8293	8174	30878	37560	12427	35653	31678	117320
-70	10165	4606	8191	8060	31030	39607	12413	34806	31001	117830
-75	10527	4600	8078	7925	31130	41482	12406	33755	30189	117830
-80	10879	4598	7983	7807	31266	43202	12405	32508	29149	117360
-85	11200	4597	7878	7669	31344	44721	12404	30175	28183	116380
-90	11488	4596	7765	7507	31354	46028	12404	29467	27000	114899

Effect of Fenestration Size

To study the effect of fenestration sizing, multiple windows to wall ratios were considered. Table 14 shows the surface areas for a window to wall ratio of 0.4. If the fenestration size is reduced, the cooling load due to the windows decreases, but the cooling load of the wall increases, and vice versa. Table 15 shows the change in cooling load that occurred due to these modifications.

Table 14 - Surface areas of example office building – varying fenestration

Floor Area = 3*100*80 ft^2		**Slab Height = 12 ft.**	
Surface Areas (ft^2)			
North	**South**	**East**	**West**
Walls (Opaque portion)			
2160	2160	1728	1728
Windows (Window to wall ratio – 0.4)			
1440	1440	1552	1552

Table 15 - Change in Cooling Load due to Fenestration Size Change

Cooling Load (Btu/h)	**Window Ratio 0.2**		**Window Ratio 0.25 (Original)**		**Window Ratio 0.3**	
	Walls	Windows	Walls	Windows	Walls	Windows
North	5516	12404	5171	15505	4826	18606
East	4970	15716	4659	19645	4349	2357
South	9009	27000	8446	33749	7883	40499
West	7352	24548	6893	30685	6433	36822
Total	26847	79668	25169	99584	23491	119501
Net Total	104216(-19%)		124753		142992(+14%)	

From the results it can be observed that as fenestration size increases the cooling load increases. This is because the load due to the windows is greater than the walls. By calculating the net total cooling due to the walls and windows for different fenestration size a trend was plotted. The relation is relatively linear as is shown in Figure 26.

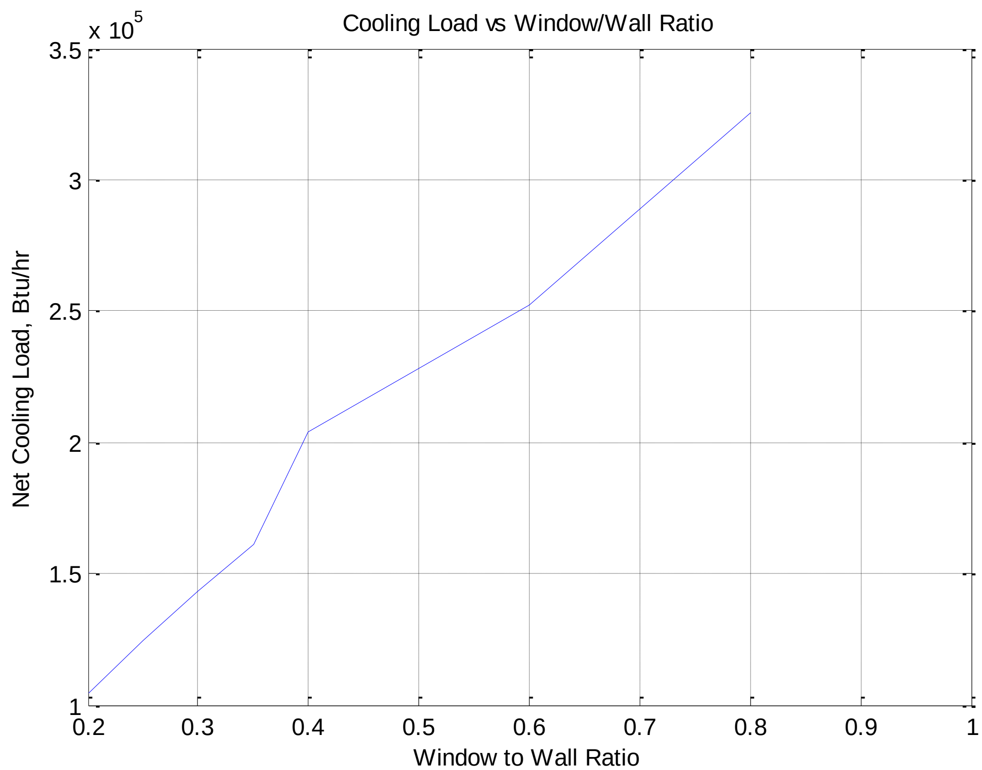

Figure 26 - Effect of Fenestration on Cooling Load

Effect of Material

Material has significant impact on heat transfer. To study its effect the following material (Table 16) was applied to the model for a comparison. The walls and windows were taken to be bricks and uncoated glass and a heavy type construction was used in place of medium construction as in the case of the original calculation. Table 16 shows the material properties of this new material. This can be compared with materials listed in Table 7.

Table 16 - Material Properties for Different Material

	Type	Material Properties
Window	Uncoated Double Glazing	SHGC = 0.7 SHGC for diffused = 0.6 Conduction coefficient = 0.59 Btu/h.ft^2.^{o}F
Walls	Brick, sheathing, R-11 batt insulation, gypsum board	Conduction coefficient = 0.066 Btu/h.ft^2.^{o}F Conduction Time Factors [CTF] = 0.00; 0.04; 0.13; 0.17; 0.15; 0.12; 0.09; 0.07; 0.05; 0.04; 0.03; 0.02; 0.02; 0.02; 0.02; 0.01; 0.01; 0.01; 0.00; 0.00; 0.00; 0.00; 0.00; 0.00
Solar RTS Values	Heavy construction with carpet and 50% glass	0.49; 0.12; 0.06; 0.04; 0.03; 0.02; 0.02; 0.02; 0.02; 0.02; 0.02; 0.02; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01; 0.01
Non-Solar RTS Values	Heavy construction with carpet and 50% glass	0.38; 0.09; 0.06; 0.04; 0.04; 0.03; 0.03; 0.03; 0.03; 0.03; 0.02; 0.02; 0.02; 0.02; 0.02; 0.02; 0.02; 0.02; 0.02; 0.02; 0.01; 0.01; 0.01; 0.01

By changing the material, the building's thermal properties including conduction and heat storage will also change. This leads to an overall shift in the cooling load including lighting and equipment. The following can be observed from the figures shown below:

- The lighting and equipment load decreases due to increase in thermal storage capacity of the building (medium construction to heavy construction)
- The wall peak cooling load decreases (since brick retains heat longer, refer Figure 5)
- The window cooling load decreases significantly on removing the reflective coating

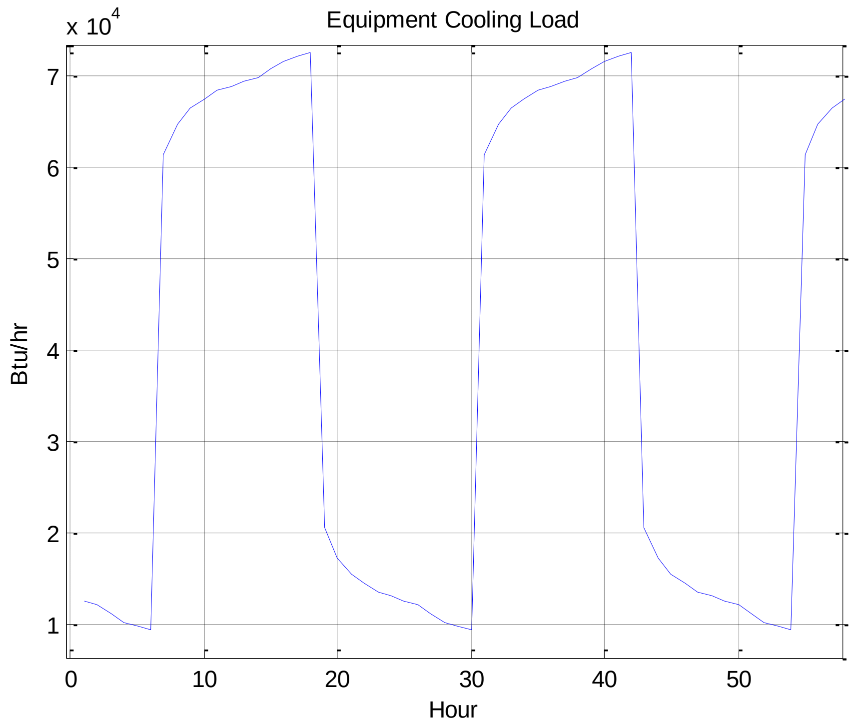

Figure 27 - Equipment Cooling Load (Different Material)

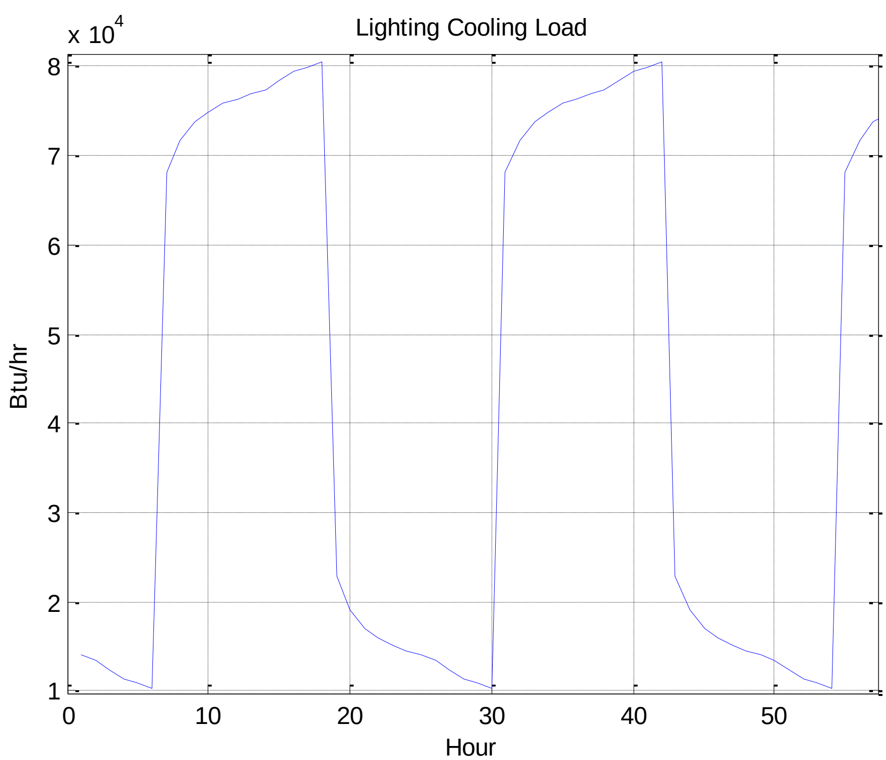

Figure 28 - Lighting Cooling Load (Different Material)

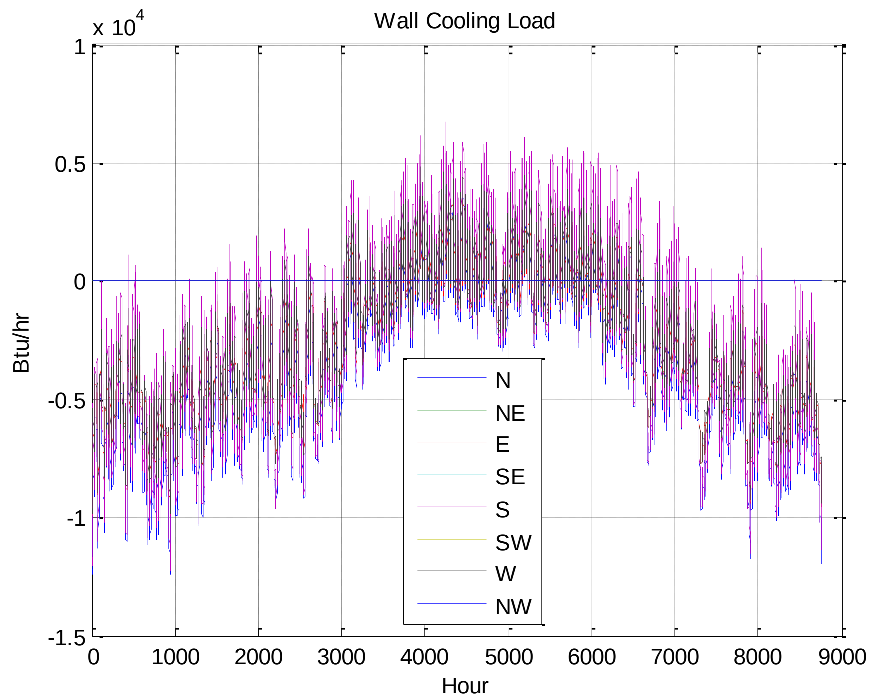

Figure 29 - Wall Cooling Load (Different Material)

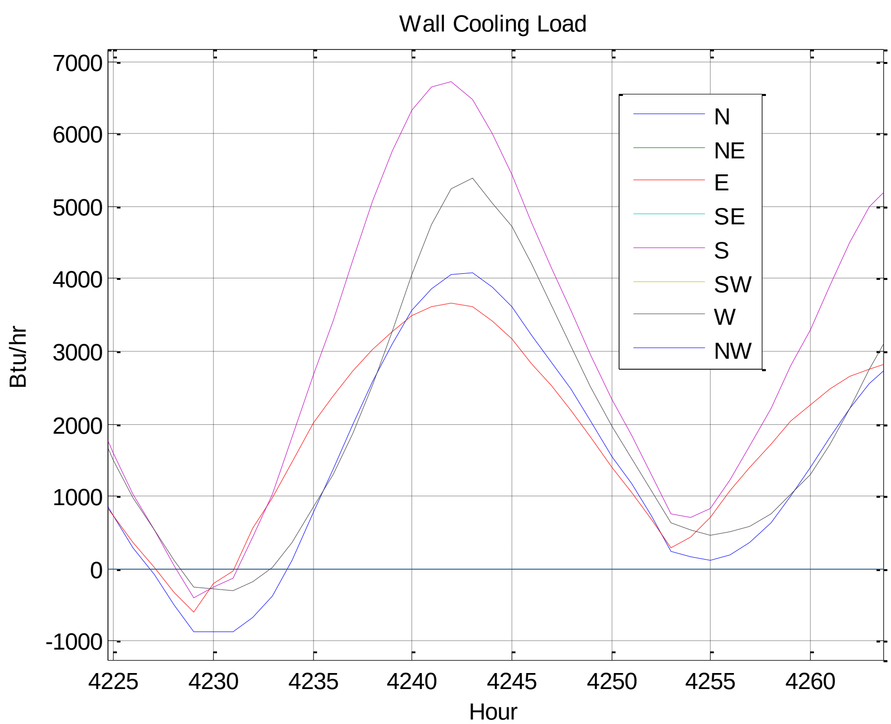

Figure 30 - Wall Cooling Load Peak for Building South (Different Material)

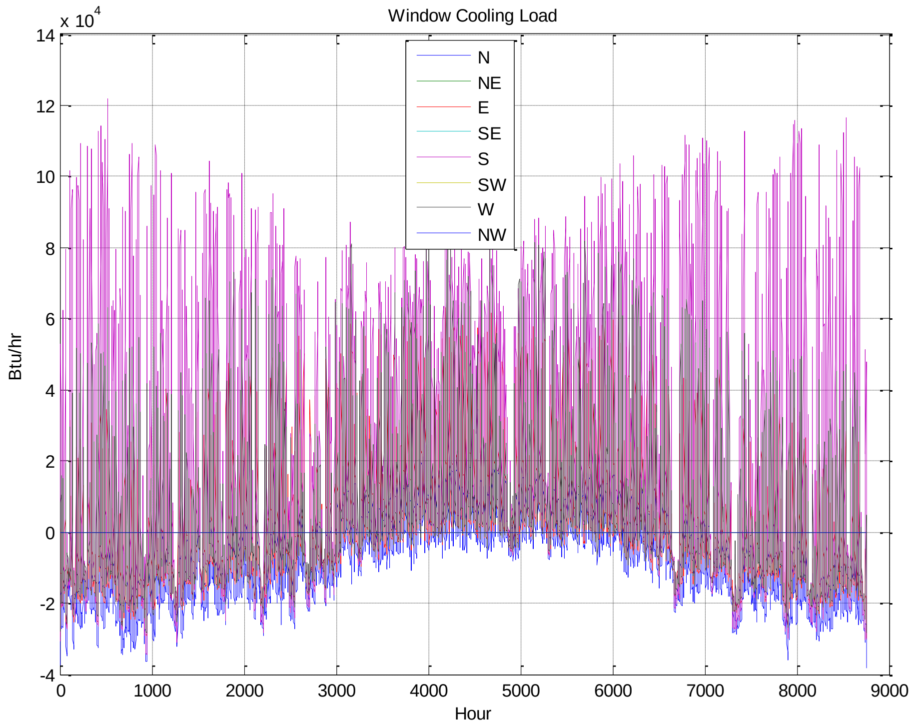

Figure 31 - Window Cooling Load (Different Material)

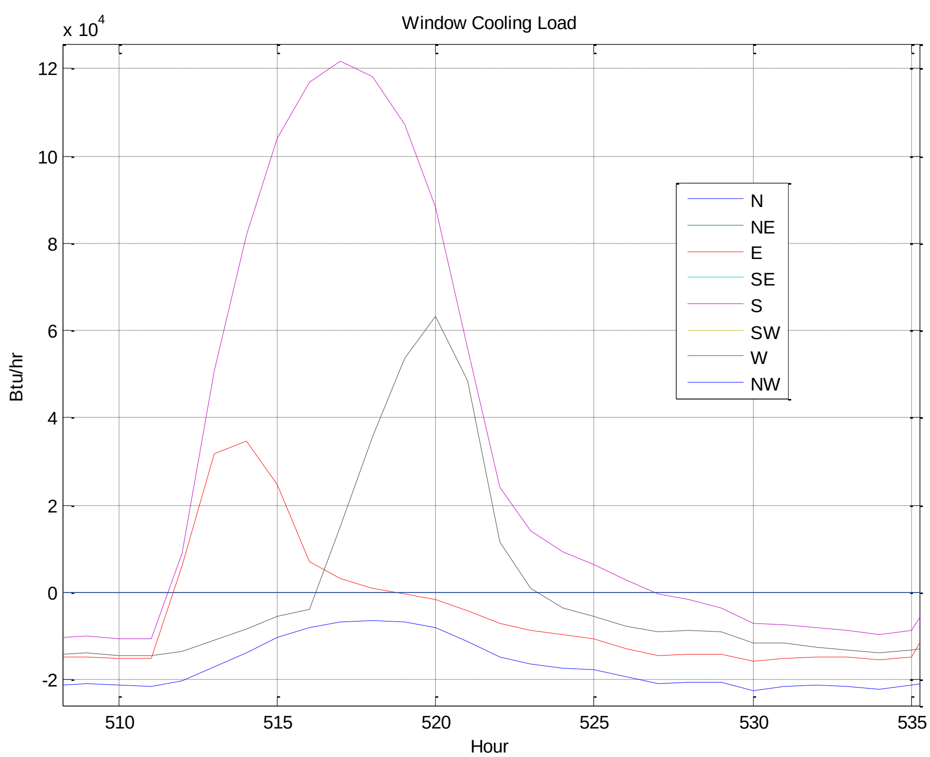

Figure 32 - Window Cooling Load Peak for Building South (Different Material)

Effect of Shading

Shading reduces the total amount radiation coming in from the fenestration. This impacts the overall cooling load significantly. Hence shading is provided both internally and externally. For this demonstration only internal shading is considered. The effect of shading varies at every hour leading to a varying IAC value for direct as well as diffused radiation.

The only load that gets affected by internal shading is the load due to windows. Figure 33 shows the cooling load for the building with louvered shades with 45^o angle with other parameters unchanged.

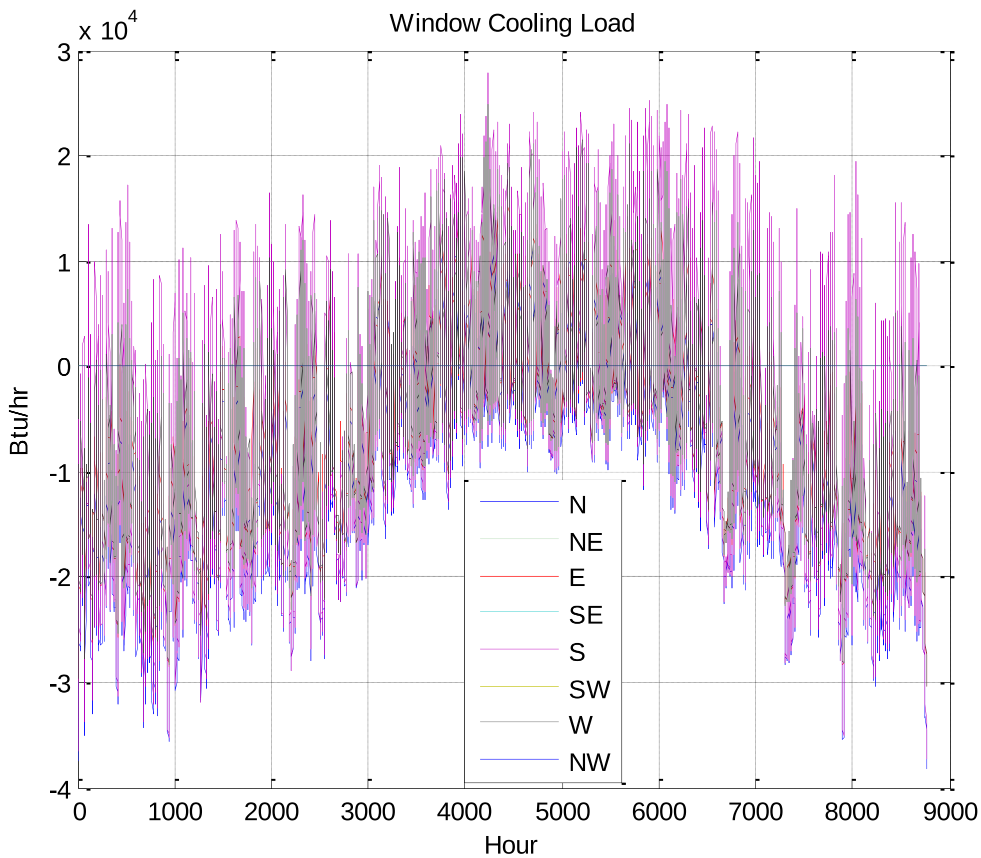

Figure 33 - Window Cooling Load (With Shading)

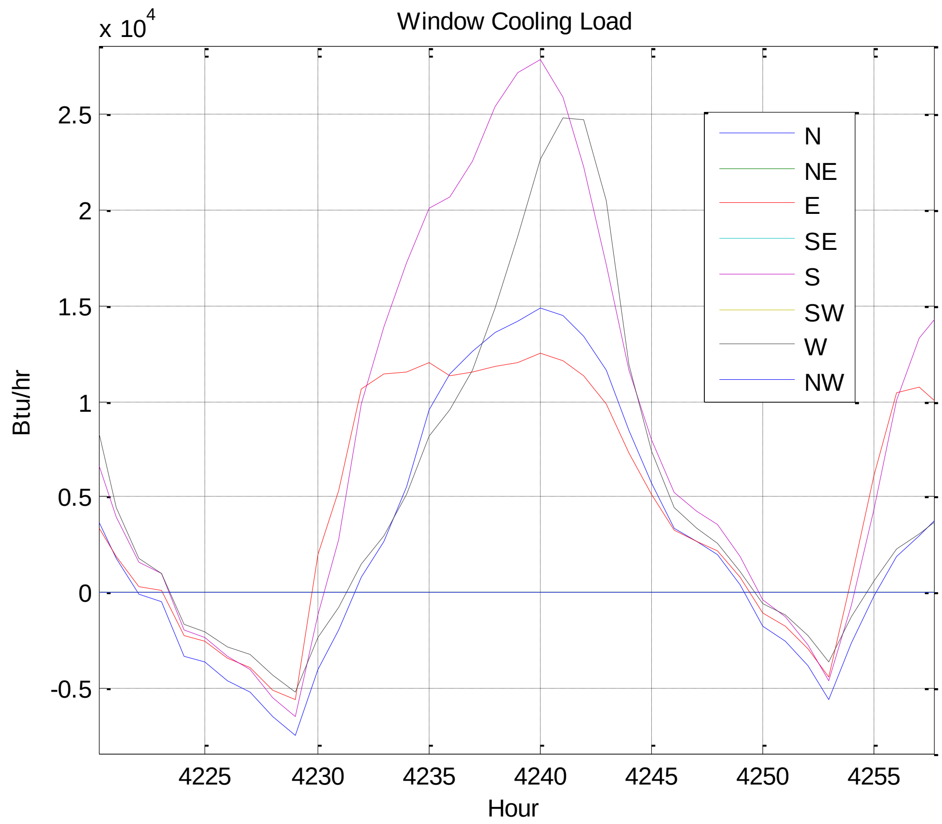

Figure 34 - Window Cooling Load Peak for Building South (With Shading)

On comparing Figure 34 with Figure 19 it can be observed that the peak cooling load reduced by approximately 10,000 Btu/hr. This is equal to 0.8 tons of cooling or 1000 W of electricity (for equipment with SEER of 10 Btu/W.hr). Thus a proper shading device can be selected using this simulation and these results.

VALIDATION IN OPEN STUDIO

To validate the calculations, a similar building was modelled in the software OpenStudio®. Calculations were also run for varying orientations to compare the output for optimizing the orientation of the building.

Example Model Calculation

OpenStudio® has a plugin for SketchUp® using which a building's energy can be simulated. The only drawback to it is that the plugin requires the entire CAD model to be remade from scratch before the plugin can be used. Figure 35 and Figure 36 show the results obtained by running a simulation with the same parameters as the example calculation. The results are tabulated in table on a per month basis. It is observed that at zero surface azimuth the cooling load is equal to 17568 kWh.

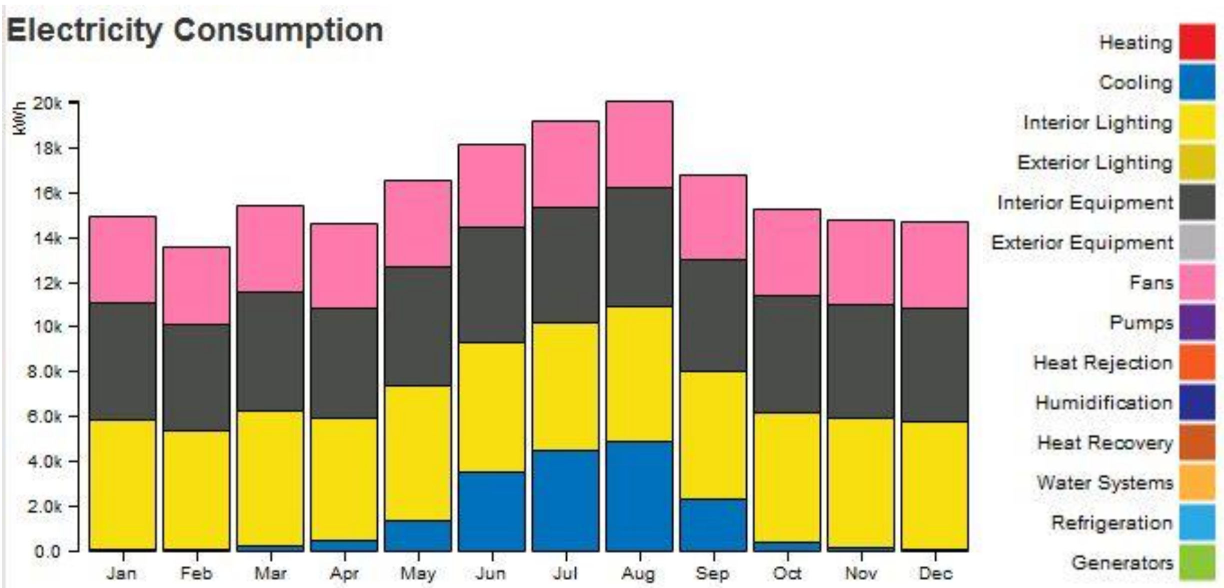

Figure 35 - OpenStudio Results - Cooling

The Air Conditioning and Refrigeration Institute (ARI) has estimated an average number of hours per year that people use their air conditioner to maintain comfort. This is depicted in Figure 37. By extrapolation, the number of hours that the air conditioning system has to be used in the Denver area is 628 hours/year [Krigger, J. - 1991].

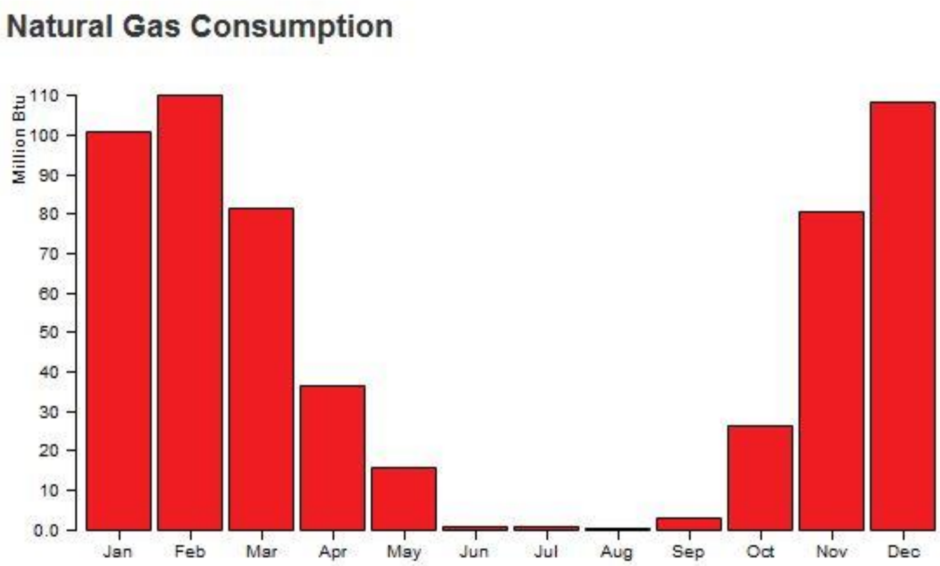

Figure 36 - OpenStudio Results – Heating

Table 17 - Monthly Cooling/Heating Load

Month	Cooling Load (kWh)	Heating Load (million Btu)
Jan	3.317	100.753
Feb	2.312	110.085
Mar	191.872	81.276
Apr	462.978	36.193
May	1314.6	15.517
June	3488.889	0.739
July	4504.306	0.55
Aug	4853.556	0.129
Sept	2333.592	2.907
Oct	323.892	26.175
Nov	84.987	80.634
Dec	4.357	108.353
Total	**17568.658**	**563.311**

On adding the cooling load due to lighting, equipment, walls and windows from the MATLAB® code the net cooling load was calculated as shown in Figure 38. The peak from this graph represents the peak HVAC load, and therefore the size of the HVAC equipment that has to be installed. The peak was found out to be 277,500 Btu/hr. The total electricity consumption for equipment with SEER of 14 Btu/W.hr is:

$$Cooling\ Electricity\ Consumption = \frac{277500\,\frac{Btu}{hr} * 628\,\frac{hr}{year}}{14\,\frac{Btu}{W.hr} * 1000\,\frac{W}{kW}}$$

$$= 12447\ kWh$$

Figure 37 - Cooling hours per year in the US

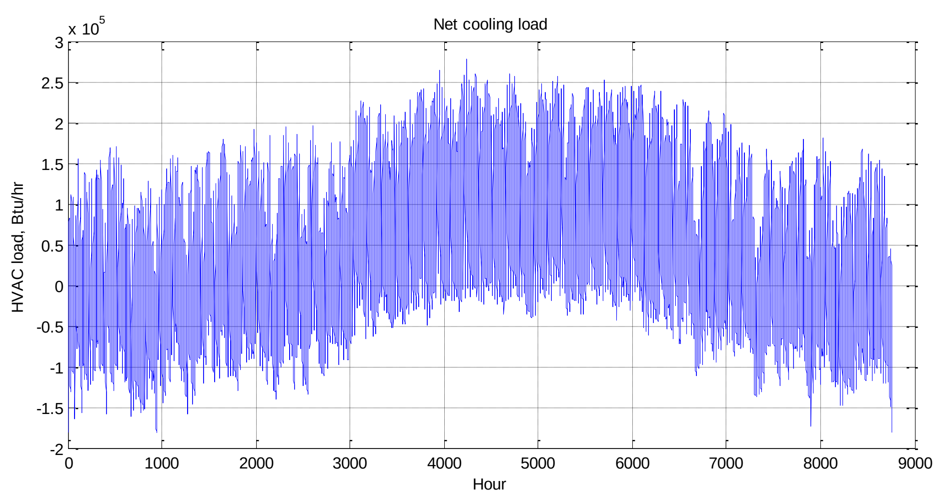

Figure 38 – Net HVAC Load

Adding all the negative values from Figure 38 gives the total Btu/year of heating required. This was found out to be 234.8 million Btu. Assuming a standard Annual Fuel

Utilization Efficiency (AFUE) of 85 % the net consumption of natural gas is 276.2 million Btu of natural gas.

Table 18 - Validation using OpenStudio

	OpenStudio®	MATLAB model
Heating (million Btu of natural gas)	563	276
Cooling (kWh of electricity consumed)	17568	12447

The variation in values is due to the fact that the MATLAB model does not take into consideration many of parameters that OpenStudio® does. These assumptions were taken so as to reduce the computation time of the model. As observed in Table 18 the results of the MATLAB model developed for this thesis are considered valid for the purpose of preliminary decisions.

Optimum Orientation

To verify the accuracy of the orientation optimization calculation the same simulation was run in OpenStudio® for different orientations and net cooling loads were estimated. Table 19 shows the net cooling load for various orientations. The trend was observed to be similar to what was simulated in the MATLAB calculations in that the minimum cooling load occurs between 0-45 degrees of orientation.

Table 19 - Cooling Loads at various orientations as simulated using OpenStudio

Surface Azimuth (degrees)	0	23	45	75	90
Cooling Load (kWh)	17568	17438	18133	18046	17964

CONCLUSION

The RTS method was integrated with NSRDB method to carry out HVAC peak load calculations for the purpose of design in the drafting phase of building design. The main goals of the plugin were to obtain HVAC loads in the shortest amount of time with minimum user input so as to integrate the simulation with the conventional workflow. Conclusions based on each of these parameters are as follows.

- **Simulation Time:** Since RTS method involves only simple algebra, the total simulation ran in approximately 30 seconds on a standard computer. The demonstration calculation showed a total time of 15 minutes to analyze the optimum orientation of the building in 5 degree increments.
- **Material Selection:** The results of the simulation were sufficiently accurate to allow for a more informed design decision in terms of materials. There is a wide selection of material properties readily available with ASHRAE that can be directly used within the simulation.
- **User input:** The model requires only the geographical coordinates of the location apart from the CAD model (already available during the drafting stage). The location coordinates are not that hard to integrate since SketchUp® has Google Maps® already built into its interface for the purpose of studying land layout.
- **Integration into the workflow:** Since the model gives nearly instantaneous results in the CAD environment directly, the model can be effectively used in the conventional workflow of the architects.

Based on the above points it can be concluded that such a model has value for integration into a pre-construction design and architecting framework. In improving the effectiveness of building design and thereby minimizing impact that the built environment has on the climate; such a tool would benefit the society as a whole.

FUTURE WORK

Future work would be focussed on integrating other parameters of building carbon footprint due to the construction, material and end of life demolition into the plugin. This would help in having a comprehensive study of climatic impact and help reduce these sources at the initial design stage. Some of this work is already being done by the CFM team.

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APPENDIX – MATLAB M-file

```
clear;
clc;
close all;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                    Material Properties               %
%                                                      %
%This section includes options for selection of materials of walls and  %
%windows. The page numbers mentioned here are from ASHRAE fundamentals   %
%handbook 2013. Not all materials are coded into this program. For other %
%material refer the handbook.                          %
%                                                      %
%Units:                                                %
%SHGC = no units                                       %
%conduction_coefficient = Btu/h.ft2.F                  %
%IAC = no units                                        %
%time_factors = no units                               %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

window_material = input...
('Select Material\n1. Reflective Double Glazing\n2. Uncoated Double Glazing\n');

switch(window_material)
    case 1
        solar_heat_gain_coefficient      = 0.17;%ID 5l Pg 15.21
        solar_heat_gain_coefficient_diffused = 0.16;%ID 5l Pg 15.21
        window_conduction_coefficient = 0.56;%ID 9 Pg 15.8

    case 2
        solar_heat_gain_coefficient      = 0.7;%ID 5b Pg 15.20
        solar_heat_gain_coefficient_diffused = 0.6;%ID 5b Pg 15.20
        window_conduction_coefficient = 0.59;%ID 5 Pg 15.8
end

shading = input...
('Shading Type\n1. No shading\n2. Louvered Shading 45 degree angle\n');

switch(shading)
    case 1
        IAC       = 1;
        IAC_diffused  = 1;
    case 2
        IAC = 0.71; %ID 5b Louvre reflectance 0.8 Pg 15.35
        IAC_diffused = 0.76;%ID 5b Louvre reflectance 0.8 Pg 15.35
end

wall_material = input...
('Wall Type\n1. EIFS finish, R-5 insulation, sheathing, 8 in. LW CMU, gyp board\n2. Brick, sheathing, R-11 batt insulation, gyp board\n');

switch(wall_material)
    case 1
        %Wall number 10. Pg 18.24
```

```
        wall_conduction_coefficient   =  0.092;
        wall_conduction_time_factor   = ...
        [0.01; 0.02; 0.06; 0.09; 0.09; 0.09;...
         0.08; 0.07; 0.06; 0.06; 0.05; 0.05;...
         0.04; 0.04; 0.03; 0.03; 0.03; 0.02;...
         0.02; 0.02; 0.02; 0.01; 0.01; 0.00];
    case 2
        %Wall number 12. Pg 18.24
        wall_conduction_coefficient   =  0.066;
        wall_conduction_time_factor   = ...
        [0.00; 0.04; 0.13; 0.17; 0.15; 0.12;...
         0.09; 0.07; 0.05; 0.04; 0.03; 0.02;...
         0.02; 0.02; 0.02; 0.01; 0.01; 0.01;...
         0.00; 0.00; 0.00; 0.00; 0.00; 0.00];
end

construction_type = input...
('Construction Type\n1. Medium construction with carpet and 50% glass\n2. Heavy Construction with carpet and 
50% glass\n');

switch(construction_type)
    case 1
        %pg 18.28/18.29
        solar_radiation_time_factor =...
        [0.54; 0.16; 0.08; 0.04; 0.03; 0.02;...
         0.01; 0.01; 0.01; 0.01; 0.01; 0.01;...
         0.01; 0.01; 0.01; 0.01; 0.01; 0.01;...
         0.01; 0.00; 0.00; 0.00; 0.00; 0.00];
        non_solar_radiation_time_factor  = ...
        [0.49; 0.17; 0.09; 0.05; 0.03; 0.02;...
         0.02; 0.01; 0.01; 0.01; 0.01; 0.01;...
         0.01; 0.01; 0.01; 0.01; 0.01; 0.01;...
         0.01; 0.01; 0.00; 0.00; 0.00; 0.00];
    case 2
        solar_radiation_time_factor =...
        [0.49; 0.12; 0.06; 0.04; 0.03; 0.02;...
         0.02; 0.02; 0.02; 0.02; 0.02; 0.02;...
         0.01; 0.01; 0.01; 0.01; 0.01; 0.01;...
         0.01; 0.01; 0.01; 0.01; 0.01; 0.01];
        non_solar_radiation_time_factor  =...
        [0.38; 0.09; 0.06; 0.04; 0.04; 0.03;...
         0.03; 0.03; 0.03; 0.03; 0.02; 0.02;...
         0.02; 0.02; 0.02; 0.02; 0.02; 0.02;...
         0.02; 0.02; 0.01; 0.01; 0.01; 0.01];
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                                                                       %
%                              CAD properties                           %
%                                                                       %
%This section pulls data from the CAD file. All areas are in sq.ft. The %
%floor area is obtained by multiplying the number of floors with building %
%dimensions. This demonstration only considers a rectangular building with%
%standard orientations. The calculation may be applied to any surface   %
%orientation.                                                           %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
floor_count = input('Enter the number of floors:\n');
length = input('Enter the length of the building(side facing plan north)\n');
breadth = input('Enter the breadth of the building(side facing plan east)\n');
slab_height = input('Enter slab height\n');
window_ratio = input('Enter ratio of window area to total surface area\n');
total_area = repmat(floor_count*[length*slab_height 0 breadth*slab_height 0],1,2);
wall_area = (1-window_ratio)*total_area;
window_area = window_ratio*total_area;
floor_area = floor_count*length*breadth;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                                                                   %
%                  Operation Schedules                              %
%                                                                   %
%This section sets the operation schedule of the building. The lighting   %
%and equipment wattage are calculated using a per sq.ft. power density  %
%relation as expalined in the dissertation. The schedule is set by using 1%
%for on and 0 for off. Partial loads are not considered. All units in         %
%watts.                                                             %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

lighting_watts = 1.11*floor_area;
lighting_schedule = [0;0;0;0;0;0;1;1;1;1;1;1;1;1;1;1;1;1;0;0;0;0;0;0];

equipment_watts = 1*floor_area;
equipment_schedule = [0;0;0;0;0;0;1;1;1;1;1;1;1;1;1;1;1;1;0;0;0;0;0;0];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                                                                        %
%            NSRDB Data & Solar calculation                              %
%                                                                        %
%This section pulls data from the NSRDB databse and calculates the hourly %
%instantaneous solar radiation. The database has units in SI form and are      %
%converted to english units.                                             %
%                                                                        %
%Units:                                                                  %
%irradiance = Btu/h.ft^2 (SI units - W/m^2)                              %
%temperature = fahrenheit                                                %
%all angles = degrees                                                    %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

location = input...
('Location\n1. Denver Intl" Airport\n2. JFK Intl" Airport\n');

switch(location)
   case 1
       [values,strings] = xlsread('725650TY.csv');
   case 2
       [values,strings] = xlsread('744860TY.csv');
end

direct_irradiance = 0.317.*values(3:8762,8);%W/m^2 to Btu/h.ft^2
diffused_irradiance = 0.317.*values(3:8762,11);%W/m^2 to Btu/h.ft^2
dry_bulb_temp  = (1.8.*values(3:8762,32))+32;%centigrade to fahrenheit
inside_temperature = 75;
```

```
%Pulling data from database
serial_number = values(1,1);
city = strings(1,2);
state = strings(1,3);
time_zone  = values(1,4);
latitude = values(1,5);
longitude = values(1,6);

%Infiltration Air Heat Gain

infiltration_air_heat = floor_area*slab_height*(inside_temperature-dry_bulb_temp);

%Calculating Declination for each day of year
equation_time = zeros(1,365);%in minutes
declination = zeros(1,365);
for n=1:365
N = 2*pi*((n-1)/365);% n = day of year
equation_time(n) = 229.18*(0.000075+0.001868*cos(N)-0.032077*sin(N)-...
              0.014615*cos(2*N)-0.04089*sin(2*N));
declination(n)=57.296*(0.006918-0.399912*cos(N)+0.070257*sin(N)-...
            0.006758*cos(2*N)+0.000907*sin(2*N)-0.002697*cos(3*N)+...
            0.001480*sin(3*N));
end
clear N n;

local_standard_time = 1:1:24;%Taken every hour.
local_standard_meridian = 15*time_zone;
apparent_solar_time = zeros(24,365);%Calculated for 365 days at each hour
hour_angle = zeros(24,365);%Calculated for 365 days at each hour
altitude_angle = zeros(24,365);%Calculated for 365 days at each hour
solar_azimuth = zeros(24,365);%Calculated for 365 days at each hour
for h=1:24
  for n=1:365
    apparent_solar_time(h,n) = local_standard_time(h)+...
                    (equation_time(n)/60)+...
                    ((longitude-local_standard_meridian)/15);
    hour_angle(h,n) = 15*(apparent_solar_time(h,n)-12);
    altitude_angle(h,n) = asind(cosd(latitude)*cosd(declination(n))*...
                    cosd(hour_angle(h,n))+sind(latitude)...
                    *sind(declination(n)));
    if hour_angle(h,n)<0
      solar_azimuth(h,n) = -1*acosd(  (sind(altitude_angle(h,n))*...
                  sind(latitude)-sind(declination(n))) /...
                  (cosd(altitude_angle(h,n))*cosd(latitude)));
    else
      solar_azimuth(h,n) = acosd(  (sind(altitude_angle(h,n))*...
                  sind(latitude)-sind(declination(n))) /...
                  (cosd(altitude_angle(h,n))*cosd(latitude)));
    end
  end
end
clear h n;

rotation = input('Rotation of building anticlockwise in degrees:\n');
orientation = rotation+[180,-135,-90,-45,0,45,90,135];
sigma = 90;%Wall inclination with horizontal
```

```
surface_azimuth = zeros(24,8,365);%Surface azimuth
incident_angle = zeros(24,8,365);%Incident angle
cos_incident_angle = zeros(24,8,365);
diffusion_factor = zeros(24,8,365);

for d=1:365
    for h=1:24
      for n=1:8
          surface_azimuth(h,n,d) = solar_azimuth(h,d)-orientation(n);
          incident_angle(h,n,d) = acosd(cosd(altitude_angle(h,d))*...
                                cosd(surface_azimuth(h,n))*...
                                sind(sigma)+...
                                sind(altitude_angle(h,d))*...
                                cosd(sigma));
          cos_incident_angle(h,n,d) = cosd(incident_angle(h,n,d));
          if cos_incident_angle(h,n,d)<=0
              cos_incident_angle(h,n,d)=0;
              %No solar gain for negative cos(theta) values. Represents
              %night time
          end
          diffusion_factor(h,n,d) = max(0.45,...
                                0.55+...
                                0.437*cosd(incident_angle(h,n,d))+...
                                0.313*cosd(incident_angle(h,n,d))*...
                                cosd(incident_angle(h,n,d)));
      end
    end
end
clear h n d;

%Arranging the 24*8*365 matrix into 8760*8 matrix
for i = 1:365
    if i == 1
        cos_theta_arranged = cos_incident_angle(:, :, i);
        diffusion_multiplier_arranged = diffusion_factor(:, :, i);
    else
        cos_theta_arranged = [cos_theta_arranged;cos_incident_angle(:,:,i)];
        diffusion_multiplier_arranged = [diffusion_multiplier_arranged;...
                                diffusion_factor(:, :, i)];
    end
end
clear i;

for i = 1:365
    if i == 1
        sin_altitude_angle = sind(altitude_angle(:, i));
    else
        sin_altitude_angle = [sin_altitude_angle; sind(altitude_angle(:, i))];
    end
end
clear i;

%Calculate net direct, diffused and reflected irradiance.
net_direct_irradiance = [direct_irradiance.*cos_theta_arranged(:,1),...
                    direct_irradiance.*cos_theta_arranged(:,2),...
                    direct_irradiance.*cos_theta_arranged(:,3),...
```

```
                        direct_irradiance.*cos_theta_arranged(:,4),...
                        direct_irradiance.*cos_theta_arranged(:,5),...
                        direct_irradiance.*cos_theta_arranged(:,6),...
                        direct_irradiance.*cos_theta_arranged(:,7),...
                        direct_irradiance.*cos_theta_arranged(:,8)];

net_diffused_irradiance =...
[diffused_irradiance.*diffusion_multiplier_arranged(:,1),...
 diffused_irradiance.*diffusion_multiplier_arranged(:,2),...
 diffused_irradiance.*diffusion_multiplier_arranged(:,3),...
 diffused_irradiance.*diffusion_multiplier_arranged(:,4),...
 diffused_irradiance.*diffusion_multiplier_arranged(:,5),...
 diffused_irradiance.*diffusion_multiplier_arranged(:,6),...
 diffused_irradiance.*diffusion_multiplier_arranged(:,7),...
 diffused_irradiance.*diffusion_multiplier_arranged(:,8)];

%Ground reflectance of 0.2 and vertical wall
net_reflected_irradiance = 0.1*((direct_irradiance.*sin_altitude_angle)...
                              +diffused_irradiance);

En = [net_reflected_irradiance+net_diffused_irradiance(:,1),...
      net_reflected_irradiance+net_diffused_irradiance(:,2),...
      net_reflected_irradiance+net_diffused_irradiance(:,3),...
      net_reflected_irradiance+net_diffused_irradiance(:,4),...
      net_reflected_irradiance+net_diffused_irradiance(:,5),...
      net_reflected_irradiance+net_diffused_irradiance(:,6),...
      net_reflected_irradiance+net_diffused_irradiance(:,7),...
      net_reflected_irradiance+net_diffused_irradiance(:,8)];

EN =...
[net_reflected_irradiance+net_direct_irradiance(:,1)+net_diffused_irradiance(:,1),...
 net_reflected_irradiance+net_direct_irradiance(:,2)+net_diffused_irradiance(:,2),...
 net_reflected_irradiance+net_direct_irradiance(:,3)+net_diffused_irradiance(:,3),...
 net_reflected_irradiance+net_direct_irradiance(:,4)+net_diffused_irradiance(:,4),...
 net_reflected_irradiance+net_direct_irradiance(:,5)+net_diffused_irradiance(:,5),...
 net_reflected_irradiance+net_direct_irradiance(:,6)+net_diffused_irradiance(:,6),...
 net_reflected_irradiance+net_direct_irradiance(:,7)+net_diffused_irradiance(:,7),...
 net_reflected_irradiance+net_direct_irradiance(:,8)+net_diffused_irradiance(:,8)];

%Obtaining Sol-Air temperature
sol_air_temp = zeros(8760,8);
for i=1:1:8
        sol_air_temp(:,i) = 0.15.*EN(:,i)+dry_bulb_temp;
end
clear i;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                                                                       %
%                              Lighting Load                            %
%                                                                       %
%This section evaluates the cooling load due to lighting. A convection  %
%fraction of 0.43 is considered using page 18.6 of the handbook.The factor %
%3.41 converts watts to Btu/h. The lighting schedule has to be repeated %
%for 365 days of the year. Breaks due to holidays or down time are      %
%neglected. Non solar RTS values are applied to lighting instantaneous  %
%heat gains. A convesion factor of 3.41 is taken to convert watts to the %
```

```
%total cooling load due to the lighting.                                  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

heat_gain_profile_lighting = repmat(3.41*lighting_watts.*...
                              lighting_schedule,365,1);
convective_heat_gain_lighting = 0.43*heat_gain_profile_lighting;

radiative_heat_gain_lighting = zeros(8760,1);

 for j=1:8760
        if j<24
           index = [j:-1:1 8760:-1:(8760-(23-j))];
           radiative_heat_gain_lighting(j,1) = ...
           0.57*sum(non_solar_radiation_time_factor.*...
                   heat_gain_profile_lighting(index,1));
        else
           index = j:-1:(j-23);
           radiative_heat_gain_lighting(j,1) = ...
           0.57*sum(non_solar_radiation_time_factor.*...
                   heat_gain_profile_lighting(index,1));
        end
 end
 clear j;

 cooling_load_lighting = convective_heat_gain_lighting +...
                    radiative_heat_gain_lighting;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                                                                    %
%                     Equipment Load                                 %
%                                                                    %
%The same procedure as the lighting section applies to this section as  %
%well.                                                               %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

heat_gain_profile_equipment = repmat(3.41*equipment_watts.*...
                               equipment_schedule,365,1);
convective_heat_gain_equipment = 0.43*heat_gain_profile_equipment;

radiative_heat_gain_equipment = zeros(8760,1);

 for j=1:8760
        if j<24
           index = [j:-1:1 8760:-1:(8760-(23-j))];
           radiative_heat_gain_equipment(j,1) =...
           0.57*sum(non_solar_radiation_time_factor.*...
                   heat_gain_profile_equipment(index,1));
        else
           index = j:-1:(j-23);
           radiative_heat_gain_equipment(j,1) =...
           0.57*sum(non_solar_radiation_time_factor.*...
                   heat_gain_profile_equipment(index,1));
        end
 end
 clear j;
```

```
cooling_load_equipment = convective_heat_gain_equipment +...
                    radiative_heat_gain_equipment;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                                                                               %
%                           Wall Cooling Load                       %
%                                                                              %
%This section evaluates the cooling load due to the walls. A convective   %
%fraction of 0.54 was used as per page 18.22 of the handbook. The         %
%convective portion is multiplied with the conduction time series factors %
%whereas the radiative prition is multiplied with the solar RTS factors.    %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


heat_gain_profile_wall=wall_conduction_coefficient*...
                  repmat(wall_area,8760,1).*...
                  (sol_air_temp-inside_temperature);


conductive_heat_gain_wall = zeros(8760,8);
radiative_heat_gain_wall = zeros(8760,8);
 for i=1:1:8
    for j=1:8760
       if j<24
          index = [j:-1:1 8760:-1:(8760-(23-j))];
          conductive_heat_gain_wall(j,i) =...
          0.54*sum(wall_conduction_time_factor.*...
                 heat_gain_profile_wall(index,i));
          radiative_heat_gain_wall(j,i) =...
          0.46*sum(non_solar_radiation_time_factor.*...
                 heat_gain_profile_wall(index,i));
       else
          index = j:-1:(j-23);
          conductive_heat_gain_wall(j,i) =...
          0.54*sum(wall_conduction_time_factor.*...
                 heat_gain_profile_wall(index,i));
          radiative_heat_gain_wall(j,i) =...
          0.46*sum(non_solar_radiation_time_factor.*...
                 heat_gain_profile_wall(index,i));
       end
    end
 end
 clear i j;

 cooling_load_wall = conductive_heat_gain_wall + radiative_heat_gain_wall;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                                                                                 %
%                          Window Heating Load                           %
%                                                                                  %
%This section evaluates the cooling load due to windows. The direct          %
%radiation through windows is added to the cooling load after multiplying %
%with the solar RTS values. But the diffused and conduction gains are       %
%added, split into convective and radiative fractions. This radiative          %
%portion is processed using non solar RTS values.                                %
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

heat_gain_profile_window_direct = IAC*solar_heat_gain_coefficient*...
                              (repmat(window_area,8760,1).*...
                               net_direct_irradiance);
heat_gain_profile_window_diffused= IAC_diffused*...
                               solar_heat_gain_coefficient_diffused*...
                               (repmat(window_area,8760,1).*En);
heat_gain_profile_window_conduction =...
                     window_conduction_coefficient*...
                     repmat((dry_bulb_temp-inside_temperature),1,8).*...
                     repmat(window_area,8760,1);

radiative_heat_gain_window = zeros(8760,8);
diffused_heat_gain_window = zeros(8760,8);
for i=1:1:8
    for j=1:8760
        if j<24
            index = [j:-1:1 8760:-1:(8760-(23-j))];
            radiative_heat_gain_window(j,i) =...
                          sum(solar_radiation_time_factor.*...
                              heat_gain_profile_window_direct(index,i));
            diffused_heat_gain_window(j,i) = 0.46*...
                     sum(non_solar_radiation_time_factor.*...
                         (heat_gain_profile_window_diffused(index,i)+...
                         heat_gain_profile_window_conduction(index,i)));
        else
            index = j:-1:(j-23);
            radiative_heat_gain_window(j,i) =...
                          sum(solar_radiation_time_factor.*...
                              heat_gain_profile_window_direct(index,i));
            diffused_heat_gain_window(j,i) = 0.46*...
                     sum(non_solar_radiation_time_factor.*...
                         (heat_gain_profile_window_diffused(index,i)+...
                         heat_gain_profile_window_conduction(index,i)));
        end
    end
end

diffused_conduction_heat_gain_window = diffused_heat_gain_window+0.54*...
                                   heat_gain_profile_window_conduction;

cooling_load_window = diffused_conduction_heat_gain_window +...
                    radiative_heat_gain_window;

%%%%%%%%%%%%%%%%%%%%%%%%%
%                                    %
%           Output Files              %
%                                    %
%%%%%%%%%%%%%%%%%%%%%%%%%

figure
plot(cooling_load_equipment)
title('Equipment Cooling Load')
xlabel('Hour')
ylabel('Btu/hr')
```

```
grid on

figure
plot(cooling_load_lighting)
title('Lighting Cooling Load')
xlabel('Hour')
ylabel('Btu/hr')
grid on

figure
plot(cooling_load_wall)
title('Wall Cooling Load')
xlabel('Hour')
ylabel('Btu/hr')
legend('N','NE','E','SE','S','SW','W','NW')
grid on

figure
plot(cooling_load_window)
title('Window Cooling Load')
xlabel('Hour')
ylabel('Btu/hr')
legend('N','NE','E','SE','S','SW','W','NW')
grid on

peak_lighting = max(cooling_load_lighting);
peak_equipment = max(cooling_load_equipment);
[peak_wall, peak_wall_index] = max(cooling_load_wall);
sum(peak_wall);
[peak_window, peak_window_index] = max(cooling_load_window);
sum(peak_window);

hvac_load = cooling_load_lighting+cooling_load_equipment+...
        sum(cooling_load_wall,2)+sum(cooling_load_window,2);

heating_load = (100*sum(hvac_load(hvac_load<0)))/(-1000000*85);
cooling_load = max(hvac_load)*628/14000;

disp(['The net natural gas consumption using an 85% efficient equipment is ',num2str(heating_load),' million Btu of natural gas'])
disp(['The net electricity consumption due to cooling using a 14 SEER equipment is ',num2str(cooling_load),' kWh'])
```