Analyzing Thermal Mass Property of Concrete using Design Requirements, Thermal Properties and Energy Modelling Simulations

by

Akhil Tripuraneni
Bachelor of Technology, Lovely Professional University, 2017

A Report Submitted in Partial Fulfillment of
the Requirements for the Degree of

MASTER OF ENGINEERING

In the Department of Mechanical Engineering

Supervisory Committee

Analyzing Thermal Mass Property of Concrete using Design Requirements, Thermal Properties and Energy Modelling Simulations

by

Akhil Tripuraneni
Bachelor of Technology, Lovely Professional University, 2017

Supervisory Committee

Dr. Rishi Gupta, Department of Civil Engineering
Supervisor

Dr. Caterina Valeo, Department of Mechanical Engineering
Supervisor

Abstract

Thermal mass is the ability of the substance to absorb and retain heat and release heat when needed. Thermal mass, when properly designed, provides an effective solution to reduce the heating and cooling loads in buildings and results in cost savings for consumers. However if thermal mass is not properly designed, it can lead to negative consequences such as overheating and discomfort for occupants. This study focuses on the thermal mass, its design and the thermal properties that should be used in buildings.

Energy modelling is the process of building computer models using certain software’s and then simulating them to check how the model behaves in terms of energy consumption. This process involves assigning all the components of the house, the HVAC, etc., and then simulating it with the weather conditions of the area in which the building is to be constructed. This enables researchers to know what kind of material combinations are working and what properties of materials lead to energy savings before constructing a building on site. This is a common process prior to the construction of buildings around the world. The current study involves the use of Energy Plus software to investigate potential energy savings when thermal mass (concrete) strategies are used in low-rise residential buildings in British Columbia.

In the current study, a low rise building that represents a typical low rise building in British Columbia has been modelled. Then some of the components in the baseline model were replaced with the thermal mass strategies, which included replacing wooden floor with concrete floor, replacing interior drywall of external wall with concrete wall, modifying the U- value of windows, and providing shadings. Replacing the components of building with thermal mass strategies led to a decrease in heating and cooling load by 11.3% and 15.7% annually. Furthermore, thermal mass strategies resulted in an annual reduction in electric consumption by approximately 880 Kwh, resulting in a savings of approximately 98 dollars per year.

.

Table of Contents

List of Tables

List of Figures

Acknowledgements

I would like to express my sincere gratitude to my supervisors Dr. Rishi Gupta and Dr. Caterina Valeo for providing me the opportunity to study at the University of Victoria and for their supervision and support throughout my master's program. I am grateful to Dr. Rishi Gupta for his kind advice on my research topic.

I would like to express my gratitude to all professors who provided guidance and support during my studies. At last special gratitude to all the staff at the administrative office and the library. Their help made all the difference in my day-to-day operations at UVIC. I would like to thank my UVIC co-students, with whom it has been a joy to learn and grow together in the last two years.

Chapter 1. Design Requirements and properties affecting thermal mass of Concrete

1.1 Introduction

The building sector is responsible for a significant amount of electrical energy consumption in North American countries. Due to the increase in population and the need to maintain comfortable indoor conditions, demand for electricity is rising significantly. According to a study by the Canadian government [1], it was determined that the heating and cooling requirements of buildings accounts for almost two thirds of the electrical energy consumption. There is an immediate need to reduce this energy consumption in order to reduce CO_2 emissions and increase cost savings.

The use of thermal mass is one effective way to minimize heating and cooling loads in houses, particularly in areas where there are significant regular fluctuations in temperature (Diurnal range more than 7 ^{o}C [2]). It retains heat throughout the day, making the temperature inside the house colder and reducing the cooling loads. At night, when the temperature inside the house is cold, the thermal mass releases the heat accumulated in the house and keeps the house warm, reducing the heating loads.

Thermal mass is a material's ability to absorb and retain heat and, when needed, release this heat. Heavy structural components such as concrete slabs and walls can be used as thermal mass due to their high heat absorption capacity. These components can absorb the heat during the day and inhabited times and release heat at night. The heat transfer between thermal mass and the atmosphere is based on three mechanisms [3]:

- Radiation: From the sun, or some other higher-temperature surfaces
- Convection: By air passage past the thermal mass surface
- Conduction: In contact with the mass by any solid materials

In Heating: In buildings, materials with higher mass such as concrete, brick can be used for thermal mass purposes. During the day, when the sun rays directly fall on the concrete floor through windows and when the temperature of the air adjacent to the thermal mass is higher than its temperature, the heat will flow into the mass due to the temperature difference. As the thermal mass absorbs all the thermal energy during the day, its temperature will be higher than the temperature of adjacent air. At this time, the heat will flow from the thermal mass to the air inside the room and warms up the place during night [2].

In Cooling: In summers, thermal mass can be used to cool temperatures inside the house in the following manner. During the day, thermal mass absorbs and stores excess heat in the house, reducing refrigeration and energy consumption. And during the night, the ventilation air passes through the thermal mass. Since the mass has stored energy during the day, its temperature is higher than the temperature of the air. Thus, the heat is transferred from the thermal mass to the air, and the heat is transferred to the outside, thus providing thermal comfort inside the house [2]. This process is extremely useful in warmer climates. Also, during the summers, proper care should be taken to avoid overheating the house by the sun. This involves using overhangs and blinds / shades to restrict sunlight to the room (mainly on the south side).

1.2 Design Requirements for Thermal Mass of Concrete

Thermal mass is the material's ability to absorb and store heat during the day and release heat at night to provide thermal comfort. Properly and carefully designed thermal mass can have maximum efficiency and will lead to reduced power consumption and increased energy savings. Some of the important design aspects are explained below.

1.2.1 Location

It is beneficial to have thermal mass inside the house. The reason for this is that if thermal mass is located on the outer wall, it is exposed to outer air and the heat in the mass is transferred to outer air, which is not intended. Consider winter heating as an example, if the masonry wall is placed on the outside, it will absorb and store heat during the day. But during the night, as the masonry wall is exposed to colder outside temperatures, because of the temperature gradient, the heat stored in the mass will be transferred to outside air, which we do not want to happen (we want the heat absorbed to be used in the house to warm up the place). It is therefore always beneficial to have thermal mass inside the house with proper insulation [4].

1.2.2 Orientation

The most crucial aspect to maximize the efficiency of thermal mass is the orientation. It should be oriented in such a way that it receives maximum sunlight. South orientation is considered as the most appropriate one because of the movement of the earth [5]. Figure 1 shows sun movement in summer and winter. Thermal mass located in the south direction will get maximum sunlight and therefore can absorb the radiant heat and store it.

In winters, the sunlight is incident at an angle of 17 - 40 degrees on earth (South side). And in winters we want the thermal mass to absorb as much heat as possible and release it at night to reduce energy consumption. Therefore, the rooms that are used the most should be on the south side of the house and in a way that they allow maximum sunlight to fall on the thermal mass (through glazing). Therefore, well insulated and a good area of glazing should be installed on the south side rooms to allow maximum light to pass through [5]. Other rooms that are least used can be located on the north side of the house as they do not require the benefit of thermal mass constantly. Also, to maximize the benefit of thermal mass and to avoid thermal leakages, proper insulation should be installed at the concrete floor and at walls.

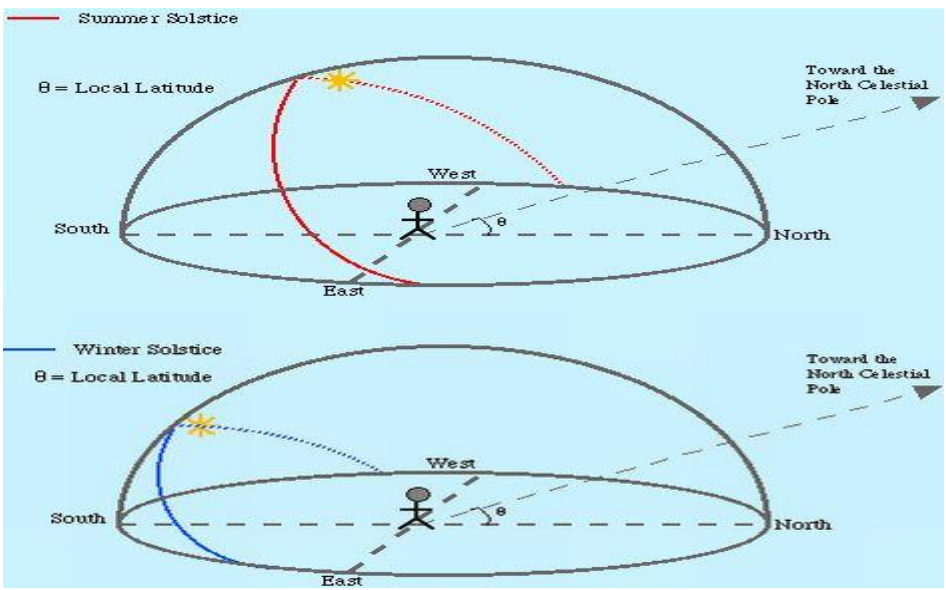


Figure 1: Position of Sun in summers and winters [6]

In summers, the sunlight is incident at an angle of 40 - 64 degrees on earth (South side). And during this time, the sunlight that is incident on thermal mass should be minimized to avoid overheating and to get maximum benefit. Therefore, on the Southside of the house, overhangs are usually installed in such a way that they block the sunlight from entering into the house during summers [5]. But in winters, these overhangs will allow the rays to pass through which is intended. Windows should be installed in such a way that they allow ventilation during summer nights (The ventilated air passes through the thermal mass and cools it down)

1.2.3 Glazing/Windows

For maximum benefit, the basic requirement is to install large windows on south facing and relatively small windows on the north facing. Some factors like performance of glazing in insulation, area of thermal mass must be considered while sizing the windows. Windows/Glazing should also not be too large because the quantity of heat leak from the glazing increases and it also increases the risk of overheating in summer.

U-value and solar heat gain co-efficient are two important things to consider regarding glazing. Well insulated triple or double pane glazing with a U-value of 1.6 $W/m^2.K$ or even better should be used in order to minimize heat loss during winters.

1.2.4 Ventilation

Another important aspect in the design of thermal mass is ventilation. It plays a very crucial role in summers. During the day thermal mass absorbs the heat and stores it, and during the night with proper ventilation, the cold air from outside passes through the thermal mass and heat gets exchanged due to temperature gradient. If there is no proper ventilation, there is no way the thermal mass can exchange its heat and this will lead to overheating of the house and thermal discomfort and increases cooling loads. Also windows should be designed in such a way that they allow good ventilation for proper cooling of thermal mass during nights.

1.2.5 Shadings

Shading is another important aspect in the design of thermal mass. Especially in summers, shading should be used to not let the sunlight from entering into the house and overheating it. Different types of shading can be used. The most commonly used shadings are overhangs and blinds. Overhangs are used especially to restrict the summer sunlight (40 - 64 degree Sun) into the house on the south side. But for other sides of the house other coverings like blinds should be used. Blinds are also used to restrict the sunlight into the house in summers, but blinds can also be used in winter to cover the glazing so that they do not allow the heat loss from the house into the outer environment.

1.2.6 Insulation

There are a few scenarios in which the heat absorbed by the thermal mass can leak into surrounding environments. During the winters, the temperature of the ground is much lower than that of the concrete floor. (The temperature of the concrete floor is higher as it absorbs thermal energy from the sun). In this case, the heat stored from the floor to the ground is lost due to temperature differences. This causes a considerable amount of heat loss. In order to counteract this problem, the contact area of the concrete floor and the ground should be well insulated (mainly the southern edge as it stores a large amount of heat). This reduces the heat loss to the ground and therefore the thermal mass can function effectively as intended.

The scenario is also similar in the masonry walls. If the outer layer of the wall is not insulated, there is a high chance that it can act as a thermal bridge, leading to a loss of heat. Therefore, the outer layer of the masonry wall should be insulated to minimize heat loss and maximize savings and energy consumption.

1.3 Properties Affecting Thermal Mass of Concrete

1.3.1 Density

Density can be defined as the quantity of matter in a given volume of space. Or in other words it is defined as mass per volume. It is measured in kg/m^3. Density is one of the most important parameters affecting the performance of the thermal mass. Ideal thermal mass material should be of high density [2]. The reason is that, as the density increases, the amount of air trapped inside the material will be less and therefore the thermal conductivity will be good. If the density is low, the amount of trapped air inside the material will be high, leading to thermal resistance. Table 1 below shows the densities of different materials used in construction.

Table 1: Typical values of Thermal Properties of Construction Materials [7, 8, 9, 10]

Material	Density (Kg/m^3)	Volumetric Heat Capacity (MJ/m^3K)	Thermal Conductivity (W/m.k)	Thermal Diffusivity (m^2/s)
Air	1.204	0.0012	0.024	0.2×10^{-7}
Wood	550	0.231	0.13	1.5×10^{-7}
Water	1000	4.18	0.6	1.42×10^{-7}
Dry Sand	1522	1.337	0.25	2.7×10^{-6}
Gypsum	1602	1.746	0.17	-
Brick	2301	2.018	0.690	5.2×10^{-7}
Concrete	2371	2.086	0.8-2	7.5×10^{-7}
Limestone	2611	2.193	1.2-3.1	-
Granite	2691	2.125	1.7-3.1	1.6×10^{-6}

As shown in table 1, Concrete has a high density in comparison to other commonly used construction materials like gypsum, brick. Therefore it is most widely used as a thermal mass material.

1.3.2 Heat Capacity

Heat capacity is defined as the amount of heat that should be supplied to a given amount of mass to change its temperature by unit degree. It is measured in J/K. Ideal thermal mass material should have a high heat capacity, because it can store more amount of heat without much change in its temperature [8]. Volumetric heat capacity (MJ/m^3K) is used as a common metric to determine a thermal mass system, because the overall quantity of heat energy stored is proportional to the material density or size. Table 1 above shows the heat capacities of different materials used in construction.

There should be a good combination of heat capacity and density for the thermal mass material [8]. As can be seen from Table 1 the air heat capacity is very high, but the air density is very low. Concrete is almost 2000 times dense than air, so concrete can store more heat than air. Instead of air, water has a decent density and a very high heat capacity. This is why water is used as thermal mass in tanks and pipes in some passive house designs. But these are not used as much as concrete, because water has a tendency to leak easily. The construction is therefore not really simple compared to concrete, and therefore concrete is preferred over water for thermal mass material. Out of all materials used in construction, concrete is the most widely used material and is often cost-effective relative to granite. It is therefore most widely used in thermal mass applications [2].

1.3.3 Thermal conductivity

It can be described as a measure of a material's capability to transfer and conduct heat. It is measured in W/m.k. The thermal conductivity should be moderate (good) for an ideal thermal mass material [2]. If the thermal conductivity is too high, the heat stored in thermal mass will be released back into the environment before it can be used at night when it is most needed. If the thermal conductivity is too low, the thermal mass material will take a lot of time to absorb the heat and there is a high chance that the useful material will escape before it is absorbed. Thermal conductivity should therefore be optimal. The table below shows the thermal conductivity of various building materials. As it can be seen from the table 1, the thermal conductivity of concrete varies between 0.8 and 2. It can be changed accordingly by varying the w/c ratio and a moderate conductivity can be achieved.

1.3.4 Thermal diffusivity

It is defined as the rate at which transfers per unit volume of material. It is measured in m^2/s. Thermal diffusivity of a given thermal mass material should be low. If the diffusivity is high, the material will allow for rapid heat transfer without sufficient heat storage [2]. For example, the thermal diffusivity of the material adjacent to the air should be low in order to prevent the transfer of heat to the air. The table 1 above shows the thermal diffusivities of some common materials. As it can be seen from the table the thermal diffusivity of concrete is low compared to other materials. Therefore it reduces the amount of heat flow to other materials and this enhances heat storage and releases the heat at required time.

1.3.5 Time lag

Time lag can be described as the time by which peak temperature can be delayed up to certain hours. Or In other words can be described as the difference in time from absorption of heat to re-releasing it. Time lag is an important consideration when choosing a thermal mass material because the material should be able to store the absorbed heat for a certain amount of time before releasing it, in order to reduce the peak temperature inside the house [2].

1.4 Project Objectives and Layout

The objective of the project is to determine whether thermal mass has any effect on energy savings in standard low-rise residential buildings in British Columbia (Canada).

After this introductory chapter, Chapter 2 includes modeling a low-rise residential building, simulating it, and performing optimizations with thermal mass strategies to see if there are any energy savings in British Columbia using Energy Plus software.

Chapter 3 refers to the conclusions and includes information on potential money and electrical energy savings

Chapter 2: Energy Modelling Simulations to analyze thermal mass property of concrete and investigating potential energy savings in a Low Rise Residential Building in BC region.

As discussed in Chapter 2, thermal mass of concrete, when properly designed, will result in reduced electrical consumption and increased energy savings. Energy savings of up to 60% can be achieved through efficient design strategies [11]. Previous studies by some researchers looked at the impact of thermal mass of concrete on high-rise residential and office space in Ontario and the BC regions.

Janusz Alexander performed energy simulation on a high-rise residential building in Ontario in the 1960s using Energy Plus software [12]. In the study, Janusz retrofitted the components of the high-rise residential building of the 1960s with new components and thermal mass strategies of concrete and observed savings of up to $34,000 annually.

Tasnuva Ahmed carried out energy simulations using Energy plus software on CCHT (Canadian Center for Housing Technology) and Row Houses in the Ottawa and Toronto Region [13]. Total energy consumption reductions of 8.5% and 5.8% were observed in CCHT houses and row houses, respectively.

Another study conducted by the CAC (Cement Association of Canada) on two buildings in the UBC (University of British Columbia) campus showed that 59% of energy savings can be achieved by using proper heating and cooling technology using thermal mass of concrete [11].

However, there is no significant information available on how much energy can be saved in the BC for a standard low-rise residential house by using thermal mass property of concrete, especially when the heating source is electricity. In the current study, simulations using Energy Plus energy modelling software were performed on a low-rise residential building and the energy savings that could be achieved were investigated.

Methodology:

The methodology involves modelling a low-rise residential building in Sketch up. And then use the Energy Plus modelling software to simulate the model. The flow chart below shows the steps involved in the process.

- Step 1
  - Modelling a standard Low rise residential building in Sketch up
- Step 2
  - Using Open Studio plug-in and assigning all the inputs (Weather files, Materials, Thermal property Values, Thermal zones, construction sets, HVAC)
- Step 3
  - Performing simulations on baseline model for Vancouver climate and noting down the simulation results
- Step 4
  - Start Optimizing the model by replacing some components of the current baseline model with thermal mass strategies and performing individual simulations
- Step 5
  - Simulating the entire model by replacing the all the materials in investigation with thermal mass materials
- Step 6
  - Comparing the results from simulation and summarize on the potential savings

The simulation tool used in the study was Energy Plus. It was developed by the U.S. Department of Energy and is one of the most established energy modelling software available. It calculates the heating and cooling consumption of buildings by taking into account all indoor and outdoor parameters, including geographical location, temperature, solar intensity, wind speed, etc. All of these parameters were input into the simulation using the EPW file.

2.1 Step 1: Modelling a low rise residential building in sketch up

In the first step, a building representing a typical low-rise building in Vancouver was modelled using Sketch up. It has an open studio plug-in that allows building geometry sketches to be used by Energy Plus software. The model geometry is shown in Figure 2. The building consists of two floors with an area of 310 m^2, a higher window-to-wall ratio on the south side and a total of 3 thermal zones ventilated by the Electric Furnace and the Air Conditioner. The occupancy density was set at 5 for 310 m^2.

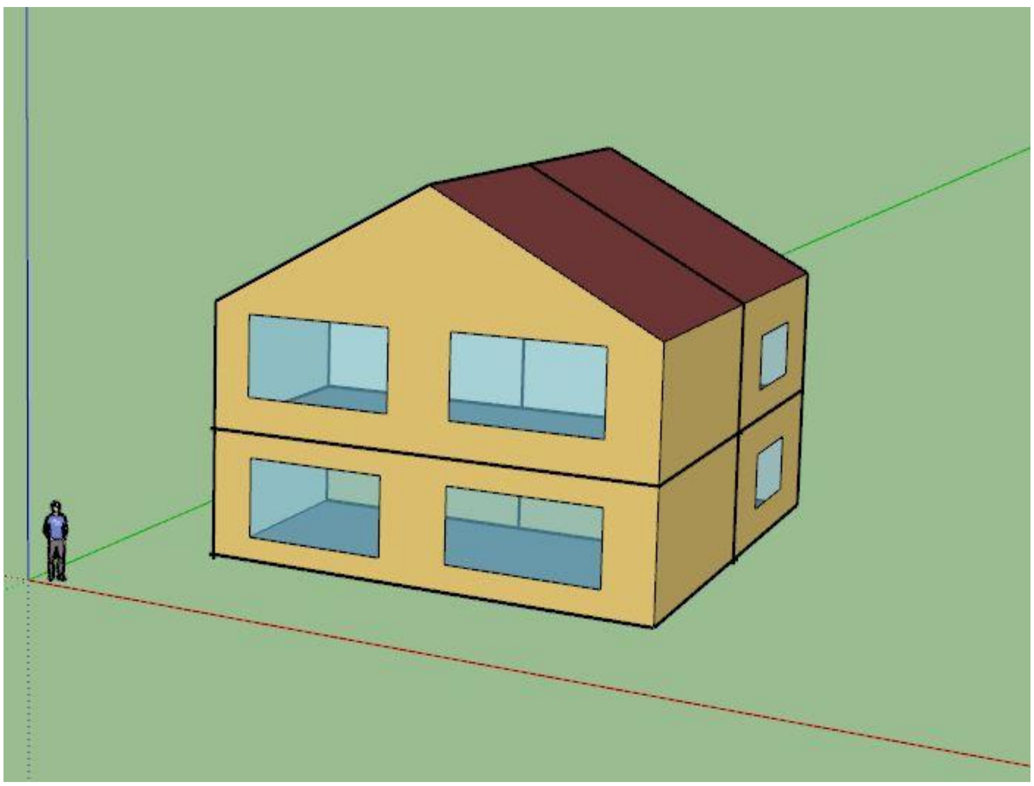


Figure 2: Sketch Up Model representing a Low Rise Building in British Columbia

2.2 Step 2: Assigning Inputs to the model

In the first step, a model that represents a typical low rise building in British Columbia has been designed using Sketch. Now, in the second step, using the Open Studio Plug-in, inputs such as Weather Files, Schedules, Materials, Thermal Property Values, Thermal Zones, Construction Sets, HVAC have been assigned to the model. The steps below explain how the inputs were assigned to the model.

2.2.1 Weather Files:

As the current study focuses on determining potential energy savings in the BC region, Vancouver has been selected for simulation. Weather files for the Vancouver region were downloaded from the Energy plus website and assigned to the Open Studio software as shown in Figure 3. Once the weather file is input into the Open Studio, the temperature, humidity, wind pressure, and solar intensity of the Vancouver region are automatically taken into account during the simulation process.

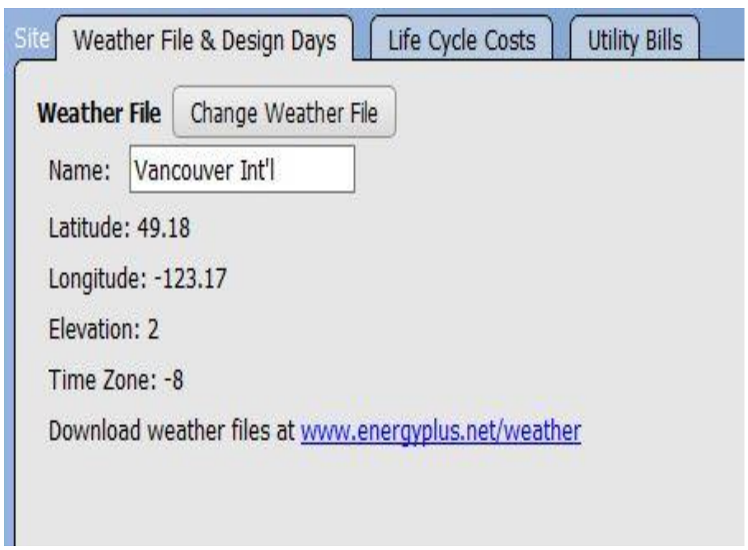


Figure 3: Assigning Weather File into Simulation

2.2.2 Schedules:

After the weather file is selected, the next step in the simulation is to input the schedule. Schedules typically represents at what time there is lot of people occupancy, activity or electricity demand in house. Based on these timings it calculates the HVAC heating and cooling loads in the simulation. It was assumed that there are family of 5 people in the house. During 12: 00 Am to 6:00 Am as everyone is in the house, and the house is completely occupied. From 7:00 Am people get ready for their day and leave to work one by one and the occupancy decreases. Everyone comes back to home by 9:00 Pm in the night and again the house is fully occupied. Likewise with the same assumption, schedule sets for activity, heating and cooling equipment were created and input into the simulation.

2.2.3 Construction sets:

Construction sets are those in which the materials, components and their properties are defined. Materials and properties that have been entered into the Open Studio plug-in are shown in Table 2. Details of the material assembly must be defined for each component. Consider, for example, a component such as an exterior wall. It has seven materials as defined in Table 2. Thus, in order to create a component, properties of all 7 materials are individually defined and then assembled as a single complete component. The materials defined for exterior wall can be seen in figure 5. In the same manner, components such as exterior wall, floor, roof, interior wall etc. have been defined. The construction sets defined for this simulation can be seen in figure 6. And the properties of the materials that are input can be seen in table 2. Most of the construction details and values in the tables below have been taken from the approved set of values from BCBC (British Columbia Builders Code) [14], NBC (National Building Code of Canada) [15], and some others have been taken from the internationally used IES modelling software [16].

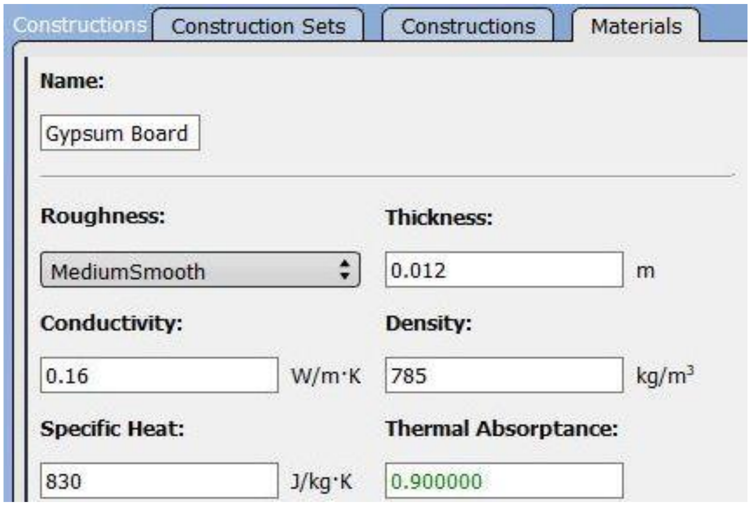


Figure 4: Creating individual layers in the Simulation

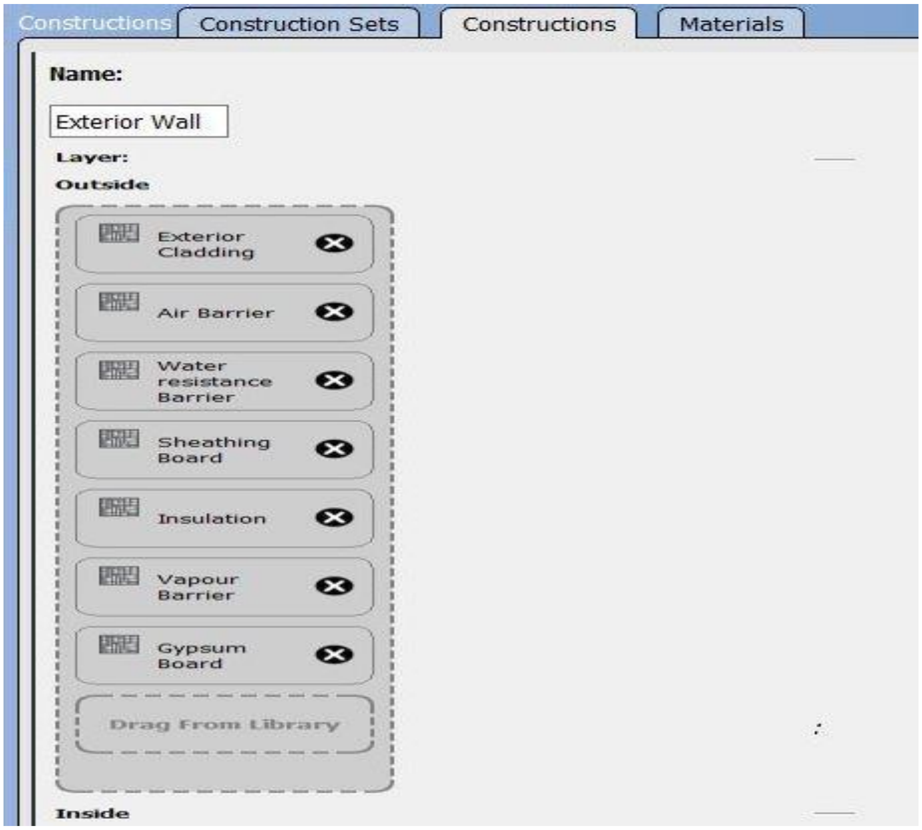


Figure 5: Creating Components in the Simulation

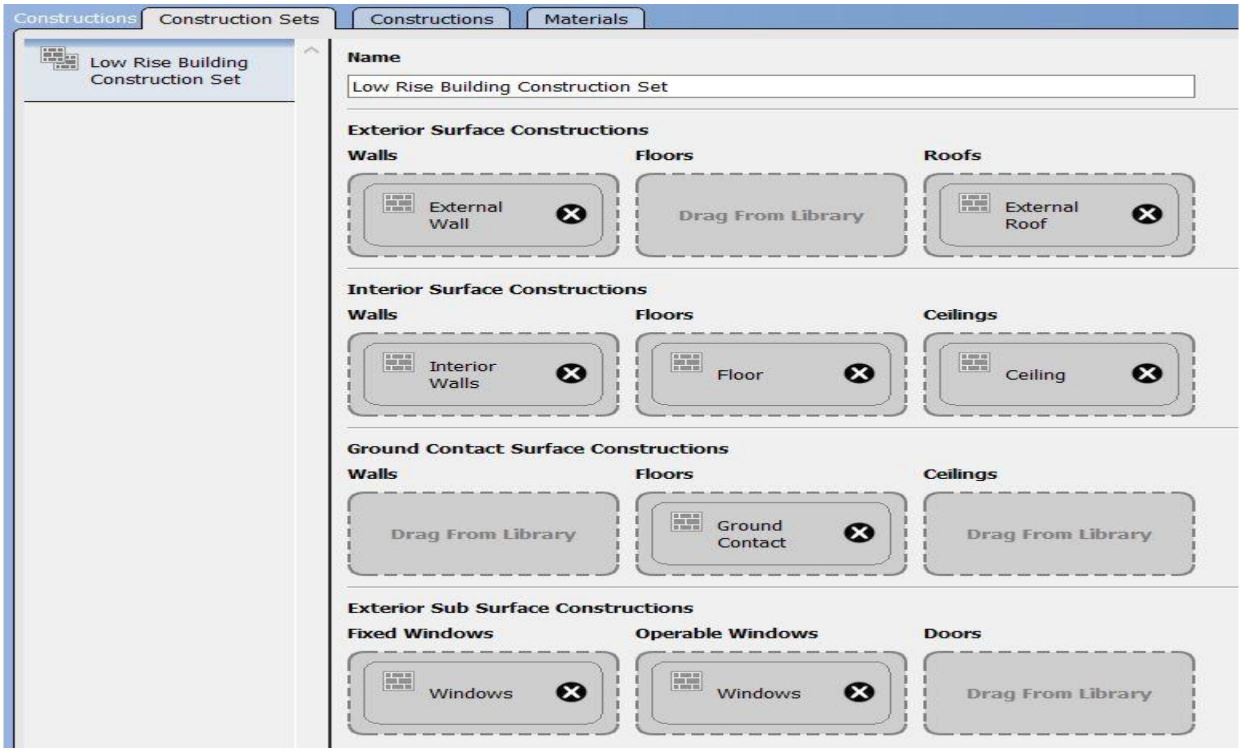


Figure 6: Construction sets defined in the Simulation

Table 2: Thermal Properties of the materials and components input into the simulation

Components	Assembly Details	Thickness (m)	Density (Kg/m^3)	Conductivity (W/m.k)	Specific Heat (J/kg.k)	R-Value	R-Value	U-Value
Exterior Wall	Exterior cladding	0.022	600	0.13	940	0.50	18.1	
	Air Barrier	0.00023	90	0.08	632	0.12		
	Water Barrier	0.00022	130	0.09	712	0.15		
	Sheathing Board	0.011	697	0.19	1460	1.32		
	Mineral Wool Insulation	0.089	10	0.043	837	15.4		
	Vapor Barrier	0.00015	110	0.075	592	0.2		
	Gypsum Board	0.012	785	0.16	830	0.45		
Roof	Asphalt Shingle	0.0047	1110	0.4	1000	0.44	30.4	
	Eave Protection	0.0001	127	0.08	650	0.15		
	Sheathing	0.0025	697	0.19	1460	1.32		
	Fiber Glass Batt Insulation in Joist Cavity	0.084	12	0.042	700	28		
	Ceiling Air Barrier	0.00023	90	0.08	738	0.12		
	Gypsum Board	0.012	785	0.16	830	0.45		
Interior Walls	Gypsum Board	0.019	800	0.16	1090	0.45		

	Air Space	0.0010		0.024				
	Gypsum Board	0.019	800	0.16	10900.	0.45		
Interior Floor	Hardwood Layer	0.028	721	0.15	1255	0.7	17	
	Softwood Layer	0.019	513	0.11	1381	1.4		
	Supportin g layer (Floor Joists)	0.095	700	0.15	1420	0.62		
	Insulation	0.089	10	0.043	837	15.4		
Interior Ceiling	Gypsum Board	0.019	800	0.16	1090	0.45		
Ground Contact Concrete	Concrete	0.10	2240	1.3	836	0.5		
Windows	Windows	0.025	2579	1.1	792	-	-	2.8

2.2.4 HVAC and Thermal Zones:

HVAC is a very important component of the house, providing heating in winters, cooling in summers and providing thermal comfort to all occupants inside the house. The electrical furnace was used in the current simulation for heating. Figure 7 shows the electrical furnace assembly and its connection to the zones. On the supply side, there is a heating coil, a fan and a set point manager, while on the demand side there are three thermal zones. Heating parameters have been set as shown in Figure 8. The temperature in the thermal zone 1 representing the living room was set at 20 ^{o}C and the temperature in the thermal zones 2 and 3 representing the bedrooms was set at 22 ^{o}C. The Air Humidity ratio was set to 40%.

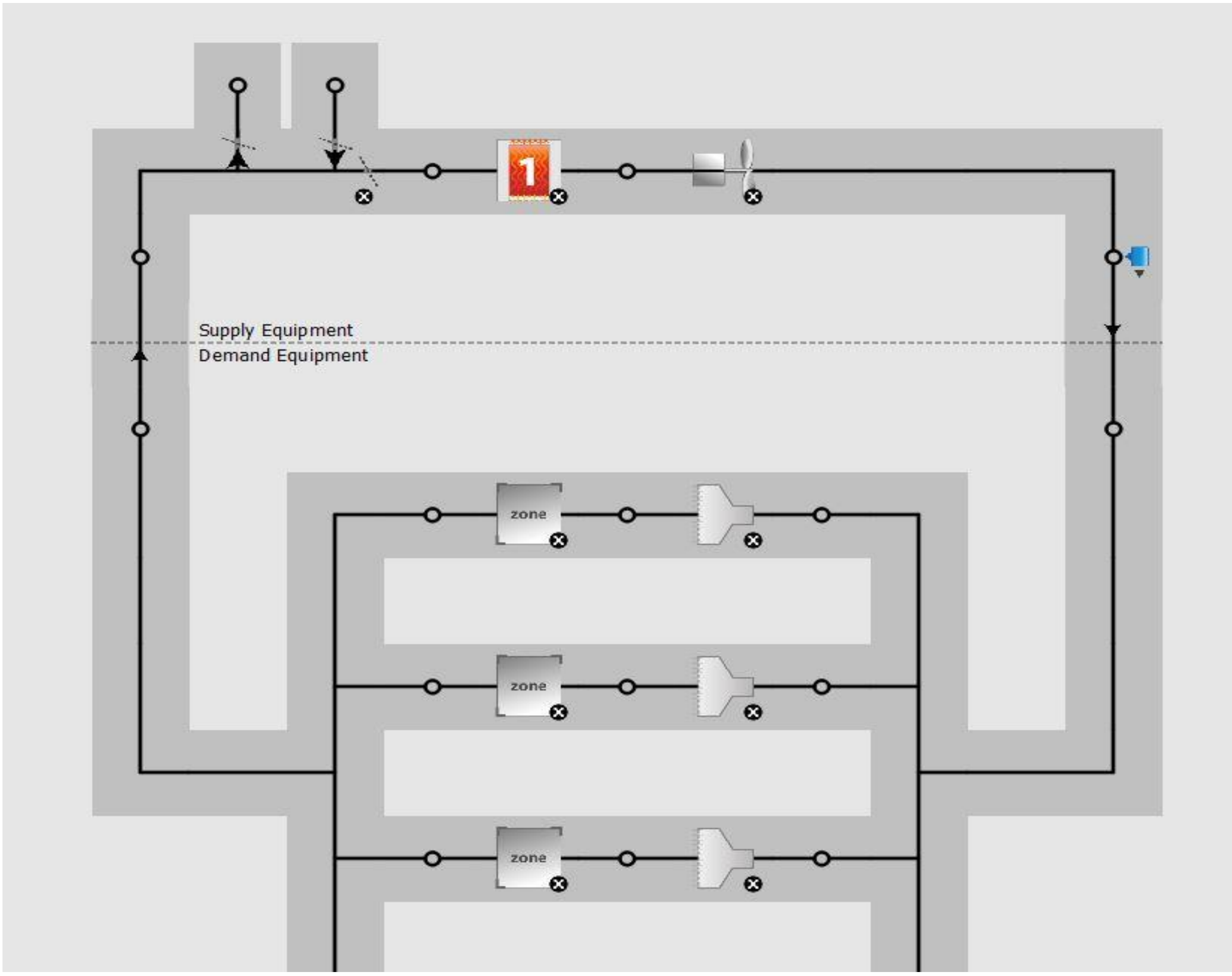
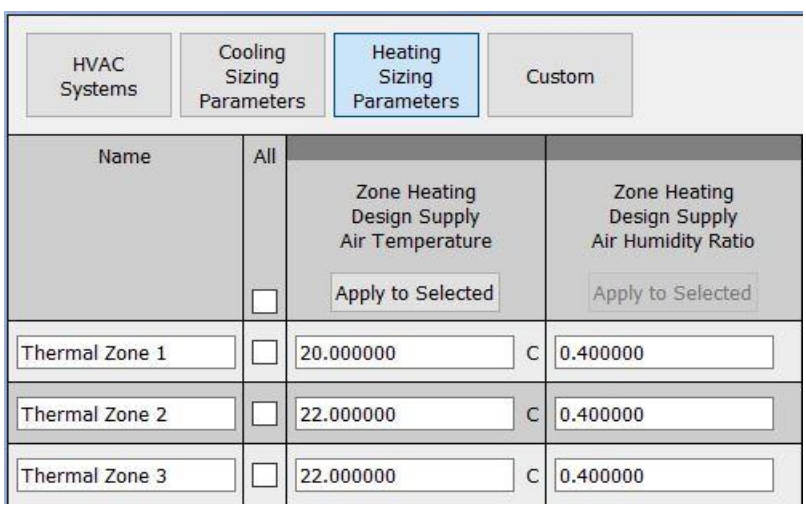


Figure 7: Heating Equipment and its connections to zones (Electric Furnace)



Name	All	Zone Heating Design Supply Air Temperature Apply to Selected		Zone Heating Design Supply Air Humidity Ratio Apply to Selected
Thermal Zone 1		20.000000	C	0.400000
Thermal Zone 2		22.000000	C	0.400000
Thermal Zone 3		22.000000	C	0.400000

Figure 8: Heating Parameters

VAV Air conditioner was used to cool the house in the summers. Figure 9 shows the assembly of the VAV and its connections to zones. On the supply side, there is a cooling coil, a heating coil, a fan and a set point manager, while on the demand side there are three thermal zones. Cooling parameters have been set as shown in Figure 10. The temperature of the air conditioning in all three thermal zones was set at 20 °C and the ratio of air humidity was set at 50%.

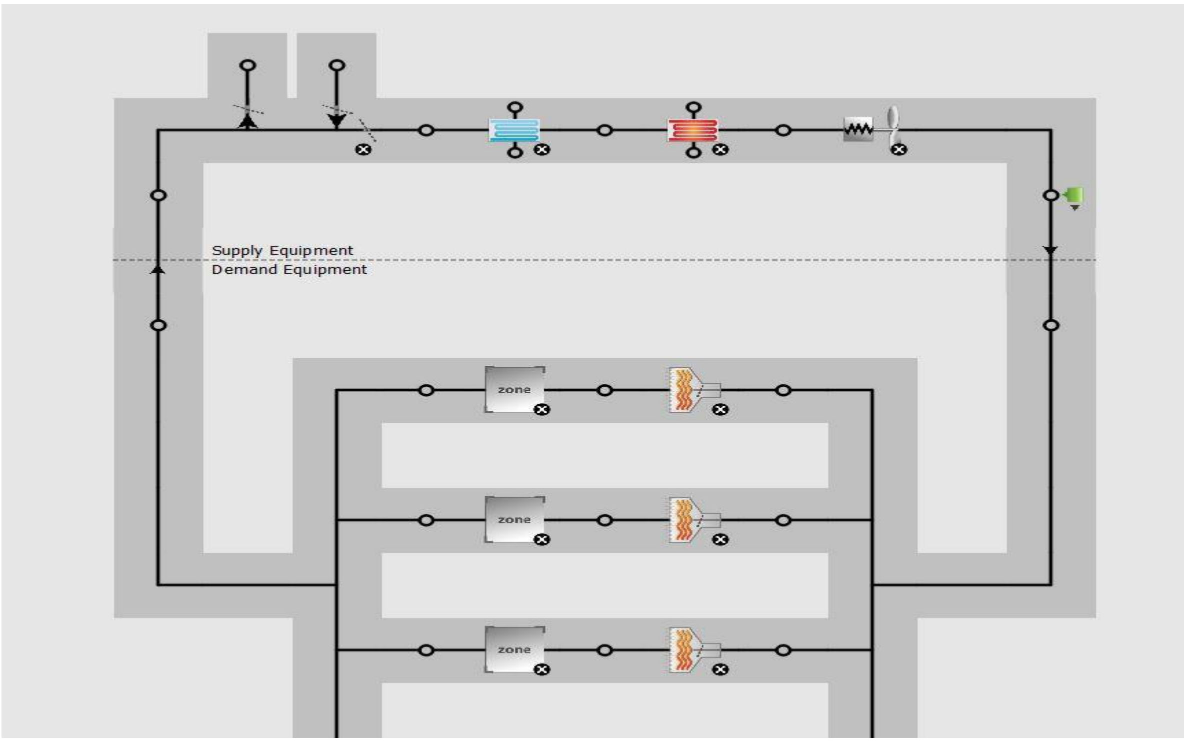
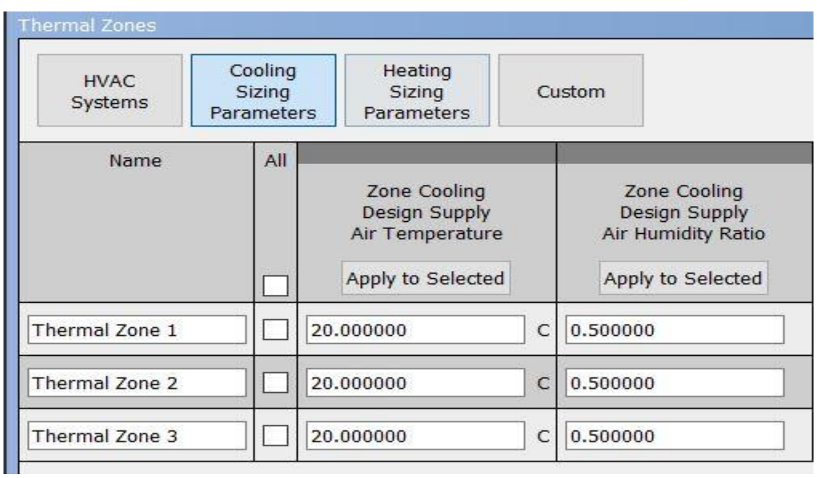


Figure 9: Cooling Equipment and its connections to zones (VAV Air Conditioner)



Thermal Zones

HVAC Systems | Cooling Sizing Parameters | Heating Sizing Parameters | Custom

Name	All	Zone Cooling Design Supply Air Temperature (Apply to Selected)		Zone Cooling Design Supply Air Humidity Ratio (Apply to Selected)
Thermal Zone 1	☐	20.000000	C	0.500000
Thermal Zone 2	☐	20.000000	C	0.500000
Thermal Zone 3	☐	20.000000	C	0.500000

Figure 10: Cooling Parameters

2.3 Step 3: Baseline Model Simulation

After all the materials, properties, HVAC's were set, the model was simulated. The results of the model are shown in the table below. One of the common metrics to define electric consumption is Kilo Watt Hour (Kwh). Since, electricity is the source of heating and cooling in the current study, all the results in the simulations are converted into Kilo watt hours (Kwh) from Giga Joules (GJ).

Table 3: Results of Baseline Model

Annual Heating Load (Kwh)	Annual Cooling Load (Kwh)
7103.34	594.49

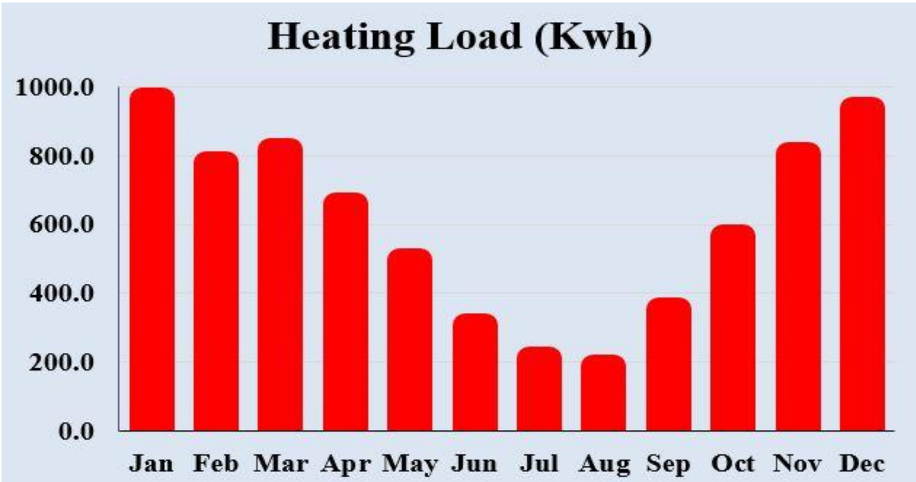


Figure 11: Baseline Model Heating Load Monthly Distribution

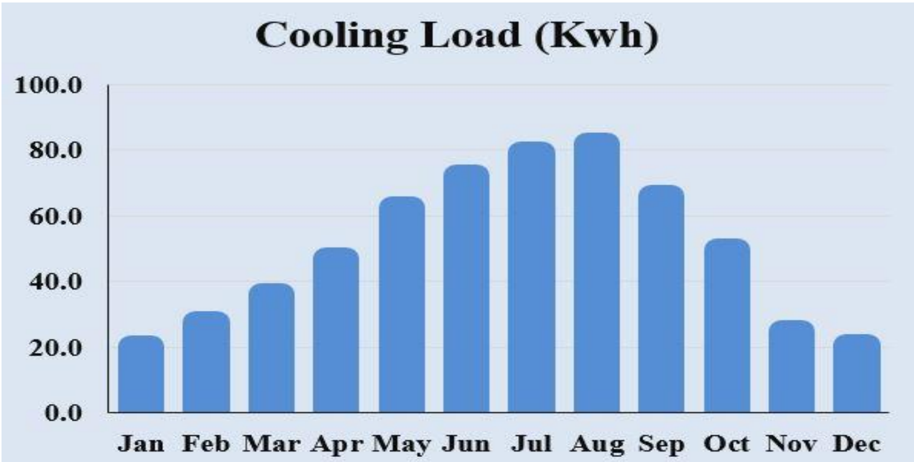


Figure 12: Baseline Model Cooling Load Monthly Distribution

As can be seen from Table 3, the heating load at the house is 7103.34 Kwh and the cooling load is 594.49 Kwh. It can be seen from the monthly distribution in Figure 11 that the heating load is high in the winter months and low in the summer months. It can be seen from Figure 12 that the cooling load is high in the summer months and low in the winter months. The highest heating load was observed in January and the highest cooling load was observed in August.

2.4 Step 4: Optimizing the baseline model

In the previous steps a baseline model was built and simulated. Now in this step, the strategy is to replace some of the components in the baseline model with thermal mass strategies. Therefore some components of the baseline model will be replaced individually and will be tested to check if there are any potential energy savings. Four optimizations will be performed as follows

1) Modifying the wooden floor in the baseline model with Concrete floor
2) Modifying the drywall in external wall assembly with concrete wall
3) Modifying the U value of windows from the baseline model
4) Providing Overhangs on top of the windows in baseline model

2.4.1 Optimization 1: Modifying the wooden floor in the baseline model with concrete floor

In the baseline model, the floor assembly is made of wood and represents a typical floor in most of the houses in BC. As, discussed in previous sections , slabs built with concrete can store heat during the day and release it in later part of night providing potential savings on heating bills. In order to check if there are any potential savings in simulation, the wooden floor assembly has been replaced with concrete slab assembly. Table 4, shows the change in assembly components of the floor.

Table 4: Materials and Properties of the Floor assembly in optimization 1.

Components	Details	Thickness (m)	Density (Kg/m^3)	Conductivity (W/m.k)	Specific Heat (J/kg.k)	R- Value
Interior Floor Assembly	Tiles	0.010	2100	1.10	837	0.45
	Concrete slab	0.030	2371	1.4	957	0.5

After the floor assembly was modified, the optimized model was simulated. The inputs for the simulation were the same as in table 2. The only change was the concrete floor assembly in table 4, replaces the wooden floor assembly in table 2.

Simulation Results:

Table 5: Results of Optimization 1

Annual Heating Load (Kwh)			Annual Cooling Load (Kwh)		
Baseline Model	Optimization 1	% Difference	Baseline Model	Optimization 1	% Difference
7103.34	6644.97	6.45	594.49	525.02	8.1

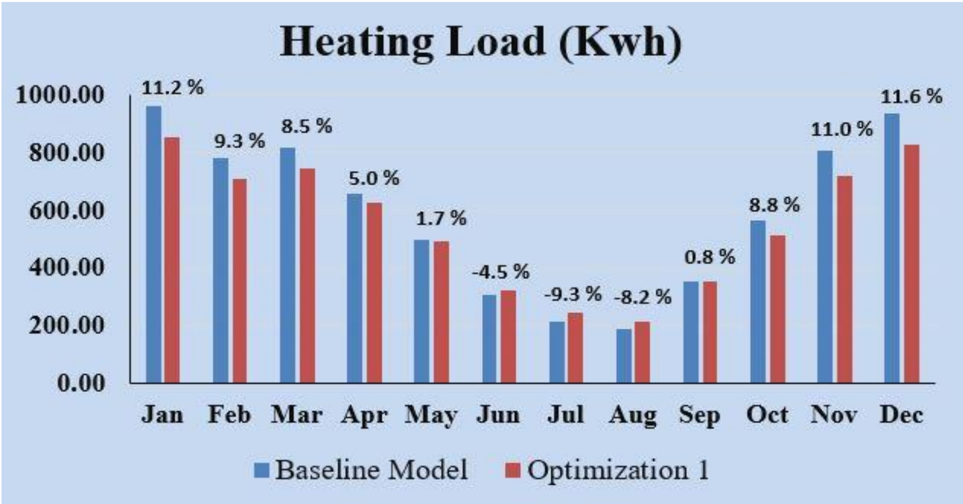


Figure 13: Heating Load Comparison between baseline model and optimization 1

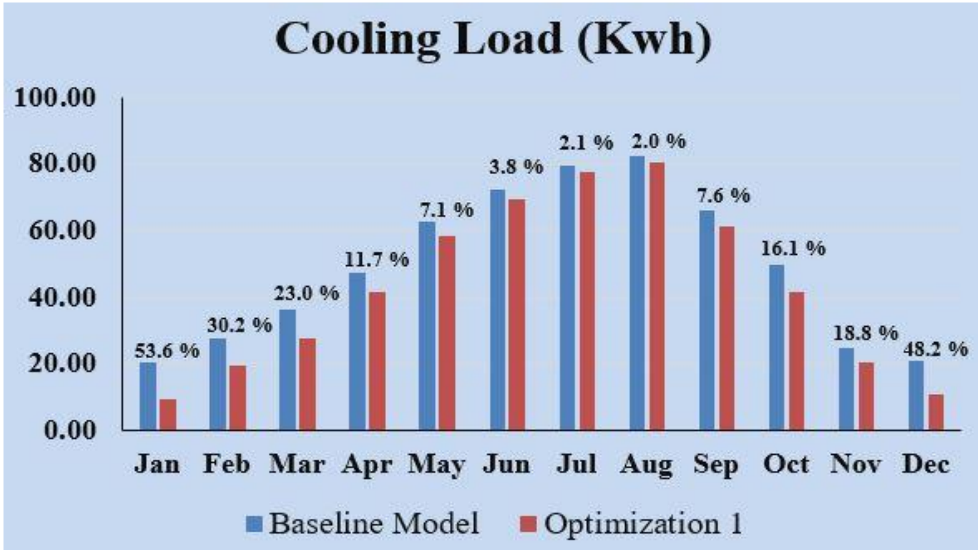


Figure 14: Cooling Load Comparison between baseline model and optimization 1

Table 5 shows that replacing the wooden floor with a concrete floor has reduced the annual heating and cooling load by 6.45% and 8.1%, respectively. This is because the concrete used in the current study has a high density and moderate thermal conductivity compared to wood. Therefore concrete when used as thermal mass in floor has the potential to absorb sunlight during the day and then releases absorbed heat into the house, thus reducing the load on HVAC and having a potential impact on savings.

2.4.2 Optimization 2: Modifying exterior wall assembly with concrete wall assembly

In the baseline model, the interior side of wall assembly is drywall and represents a typical wall assembly in most of the houses in BC. As, discussed in previous sections , wall assemblies when built with concrete can store heat during the day and release it in later part of night providing potential savings on heating bill. In order to check, it there are any potential savings, the dry wall in the exterior wall assembly has been with concrete wall. Table 6, shows the change in assembly components of the wall.

Table 6: Materials and Properties of the Floor assembly in optimization 2.

Components	Assembly Details	Thickness (m)	Density (Kg/m^3)	Conductivity (W/m.k)	Specific Heat (J/kg.k)	R- Value
Exterior Wall	Exterior cladding	0.022	600	0.13	940	0.50
	Air Barrier	0.00023	90	0.08	632	0.12
	Water Barrier	0.00022	130	0.09	712	0.15
	Sheathing Board	0.011	697	0.19	1460	1.32
	Mineral Wool Insulation	0.089	10	0.043	837	15.4
	Vapor Barrier	0.00015	110	0.075	592	0.2
	Concrete wall	0.022	2240	1.3	830	0.55

After the wall assembly was modified, the optimized model was simulated. The inputs for the simulation were the same as in table 2. The only change was the Exterior wall assembly in table 6, replaces the Exterior wall assembly in table 2.

Simulation Results:

Table 7: Results of Optimization 2

Annual Heating Load (Kwh)			Annual Cooling Load (Kwh)		
Baseline Model	Optimization 2	% Difference	Baseline Model	Optimization 2	% Difference
7103.34	6997.78	1.48	594.49	588.93	0.93

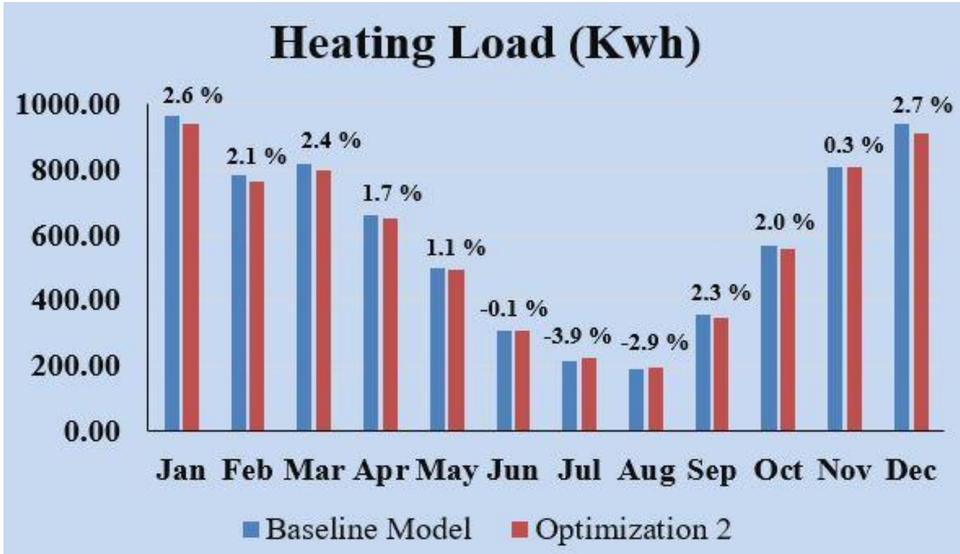


Figure 15: Heating Load Comparison between baseline model and optimization 2

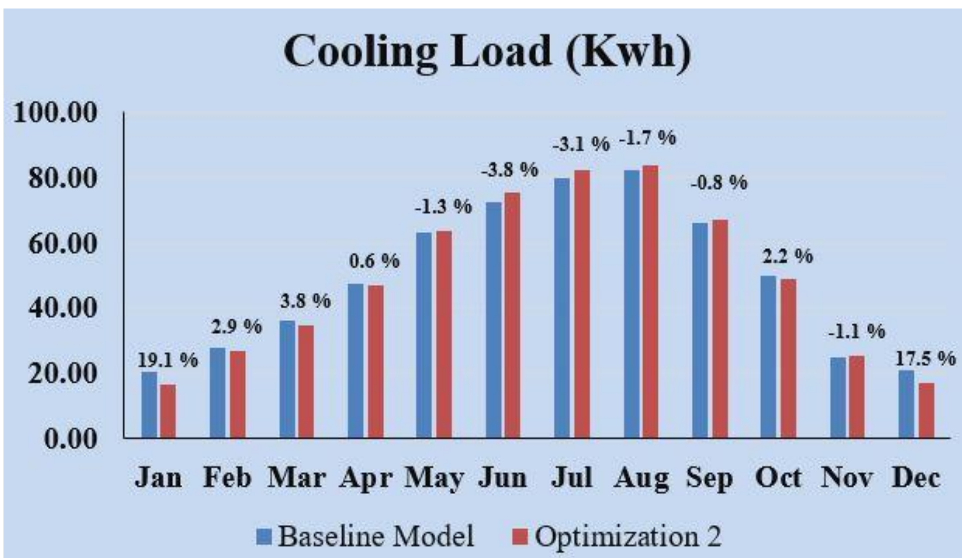


Figure 16: Cooling Load Comparison between baseline model and optimization 2

It can be seen from the table 7 that replacing the dry wall of exterior wall assembly with concrete wall has reduced the heating load by 1.4% and cooling load by 0.9% annually. The energy savings are not very high. This can be explained in the following way, the sunlight coming through the windows do not fall on the wall directly. Only the rays that are reflected from surfaces like floor fall on the walls. Floors usually absorb most of the incident sunlight and only reflect when its storing capacity is full. Therefore there is not much sufficient heat for the walls to store and emit heat, thus resulting in potentially less savings.

2.4.3 Optimization 3: Modifying the U value of Windows

Glazing plays a very important role in maintaining the temperature inside the house, particularly during the heating season. Researchers estimate that 25-30% of the heat lost from the house is through windows [17]. Windows that usually have a high U value are not very efficient in stopping the heat from passing through them. U-value also known as the thermal transmittance is the rate of heat transfer through a material. The lower the U-value, the better its insulating capacity. The windows in the baseline model are higher in U-value. Now, in the current optimization, the U value of the windows has been modified and simulation has been performed to check if there is any potential energy savings.

Table 8: Properties of the Windows in optimization 3.

Component	Thickness (m)	Density (Kg/m^3)	Conductivity (W/m.k)	Specific Heat (J/kg.k)	U - Value	Solar Heat Gain Co-efficient
Windows	0.025	2579	1.1	792	1.4	0.55

After the U-value of windows was modified, the optimized model was simulated. The inputs for the simulation were the same as in table 2. The only change was the Windows in table 8, replaces the Windows in table 2.

Simulation Results:

Table 9: Results of Optimization 3

Annual Heating Load (Kwh)			Annual Cooling Load (Kwh)		
Baseline Model	Optimization 3	% Difference	Baseline Model	Optimization 3	% Difference
7103.3	6583.8	7.31	594.49	546.15	9.81

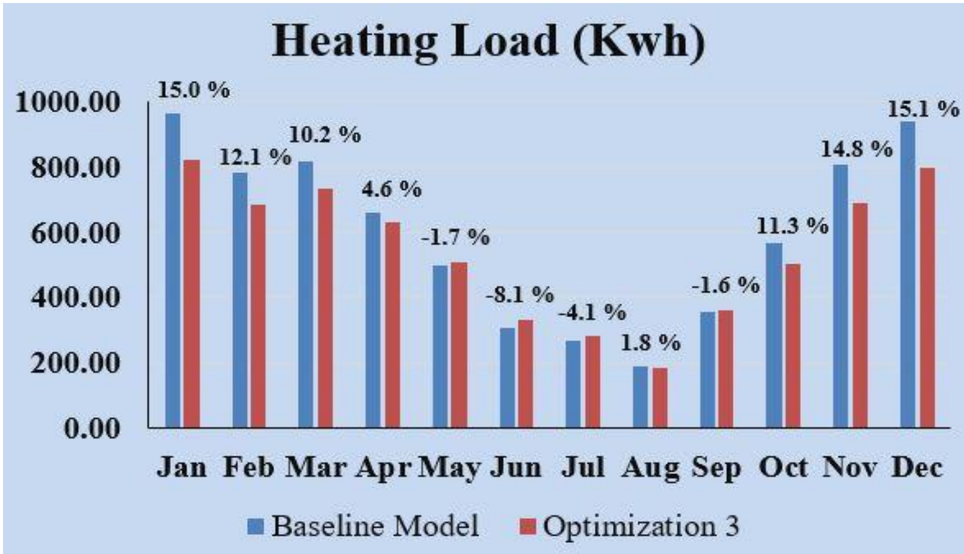


Figure 17: Heating Load Comparison between baseline model and optimization 3

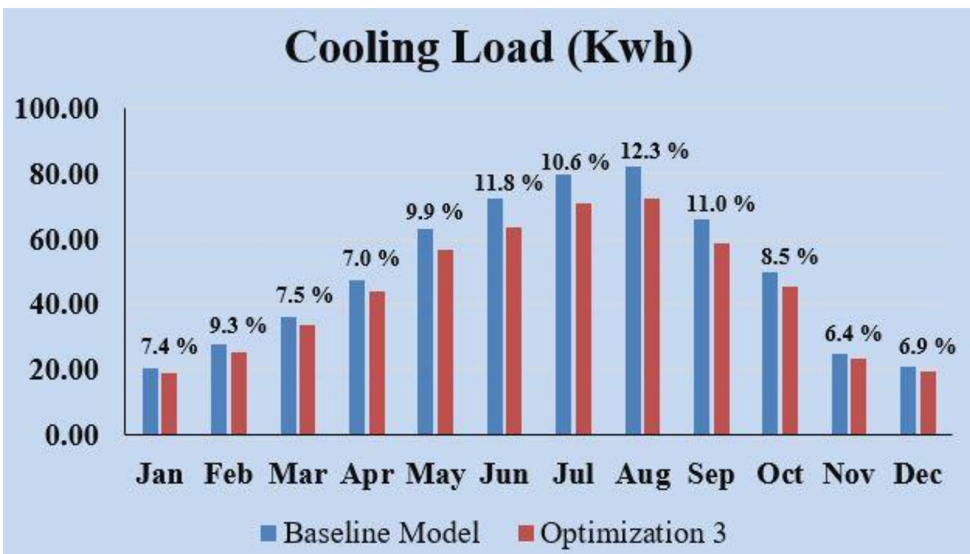


Figure 18: Cooling Load Comparison between baseline model and optimization 3

It can be seen from the table 9 that as the U value of the windows decreased heating and cooling load decreased by 7.31% and 9.81% annually. This is because, in winters, windows with a lower U-Value do not allow the heat inside the building to pass through them easily, resulting in a reduction in the heating load. It does not allow heat from the outer atmosphere to enter the house during the summers, thereby reducing the cooling requirements of HVAC and resulting in less energy consumption.

2.4.4 Optimization 4: Providing Over hangs on top of windows

Shadings is one of the most important aspects of thermal mass design, especially in summer. Because if there's no overhanging in the summer, the sunlight enters the house through the windows and warms up the place. This results in an increase in the cooling requirement for HVAC. It is therefore very important to provide shades at the top of the glazing.

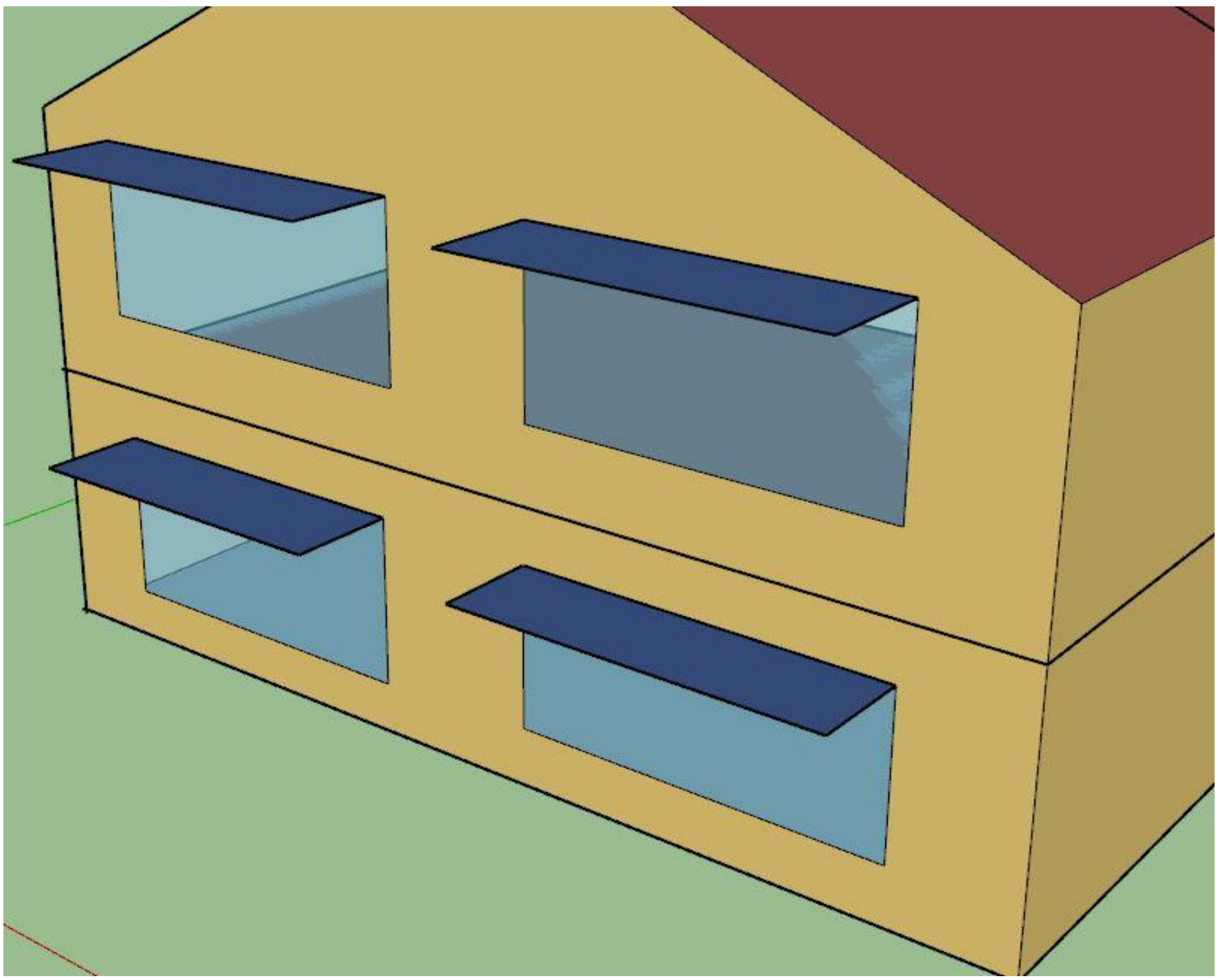


Figure 19: Overhangs on top of the glazing on south side of the house

No overhangs were installed in the baseline model. In the current optimization process, overhangs were installed at the top of the windows on the south side of the house. The reason for the installation of overhangs on the south side is that, as a result of the rotation of the earth, the sun's ray's fall directly on the south side of the house. Therefore, overhangs were added by a projection factor of 0.6. The model with overhangs installed is shown in Figure 19 above. After installing the overhangs, the optimized model was simulated. The inputs for the simulation were the same as in table 2. The only change was the addition of overhangs.

Simulation Results:

Table 10: Results of Optimization 4

Annual Heating Load (Kwh)			Annual Cooling Load (Kwh)		
Baseline Model	**Optimization 4**	**% Difference**	**Baseline Model**	**Optimization 4**	**% Difference**
7103.3	7158.9	-0.7	594.49	565.6	6.5

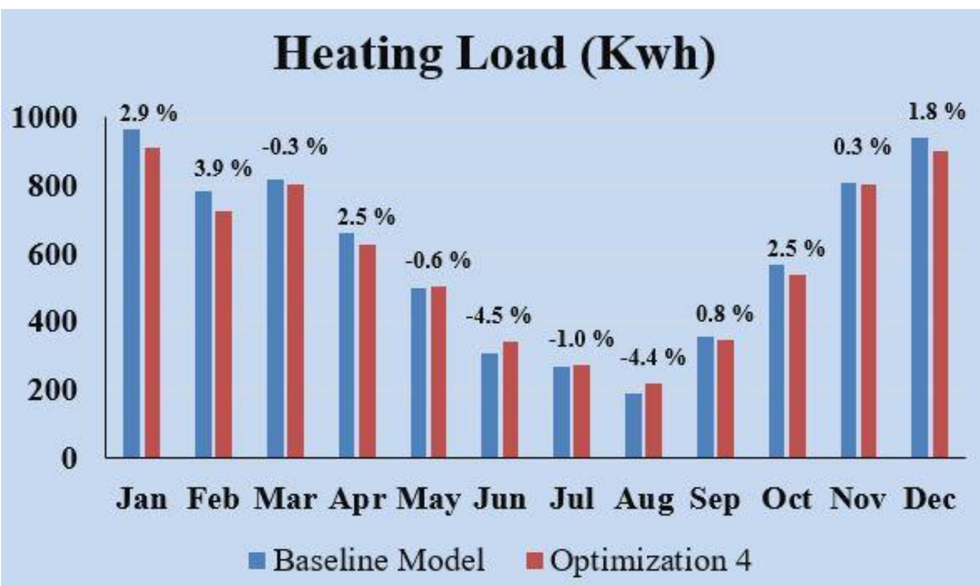


Figure 20: Heating Load Comparison between baseline model and optimization 4

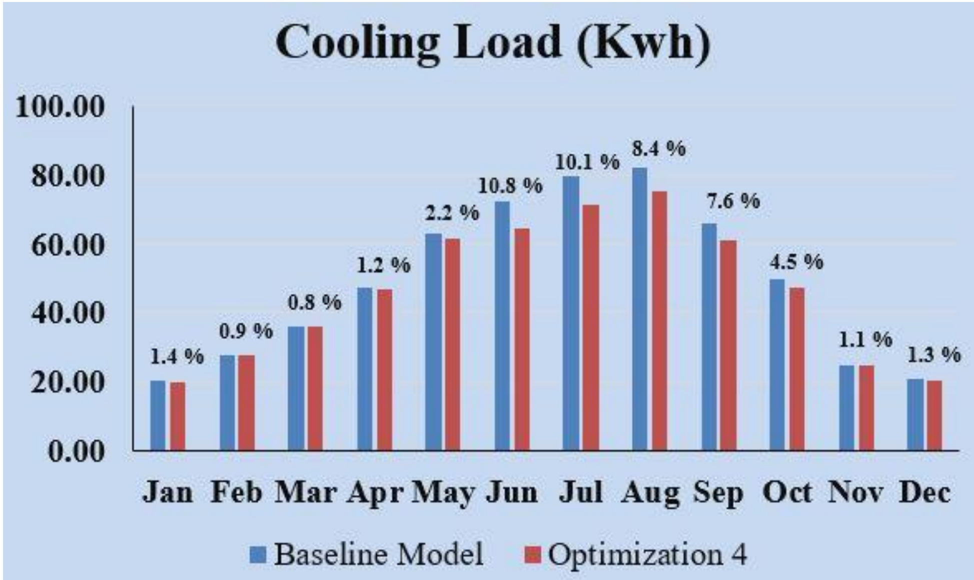


Figure 21: Cooling Load Comparison between baseline model and optimization 4

It can be seen from the table 10, that overhangs increased the heating load by an amount of 0.7%. However, the 0.7% change can be considered ignorable because during the optimizations it was assumed that any percentage change in the range of -1 to +1 is insignificant/ignorable. On the other hand, Overhangs showed significant impact on cooling load, especially during summers by decreasing the cooling load by 6.5%. This is because, in summers overhangs protects the interior space from sunshine and avoids overheating of the space, thus reducing the cooling load on HVAC systems. The overhangs should be built in such a way that it stops the summer sun shine and allows the winter sun. This way, it can allow the winter sun to fall on thermal mass such as concrete and provides heating in winters.

2.5 Step 5: Complete Optimization

In the first 4 optimizations, components such as concrete slab, concrete wall, low U-value windows, and overhangs were installed and tested individually. But in the current optimization, all the 4 of them are combined and are simulated and tested in single simulation. This optimization represents complete design requirement of thermal mass of concrete.

Simulation Results:

Table 11: Results of Complete Optimization

Heating Load (Kwh)			Cooling Load (Kwh)		
Baseline Model	**Complete Optimization**	**% Difference**	**Baseline Model**	**Complete Optimization**	**% Difference**
7103.3	6314.8	11.31	594.49	504.2	15.7

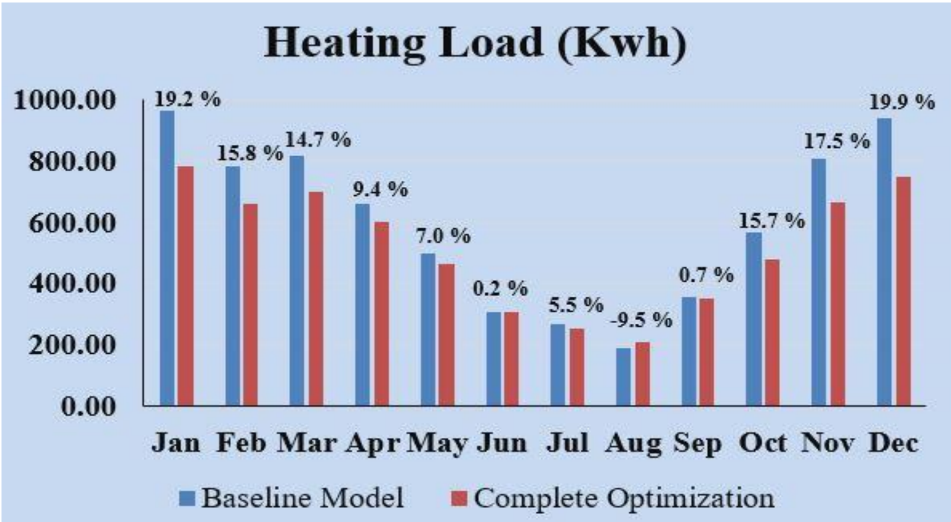


Figure 22: Heating Load Comparison between baseline model and complete optimization

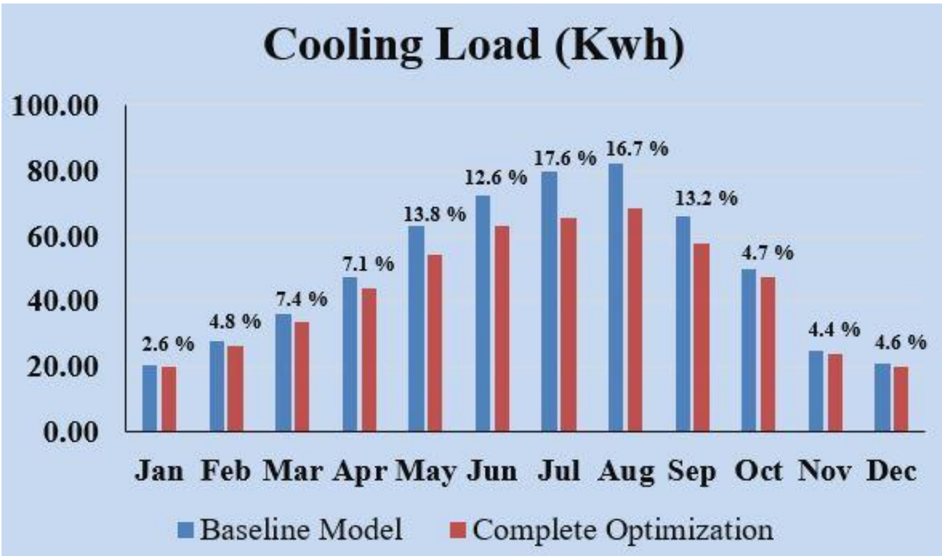


Figure 23: Cooling Load Comparison between baseline model and complete optimization

Heating Consumption: It can be seen from table 11 that complete optimization led to an annual decrease of 11.3% in energy consumption. This is because all the thermal mass strategies have been put in place. As the summer sun shines on the concrete slab, the concrete slab absorbs the heat and stores it until the night. It releases the heat stored in it at night, thus increasing energy savings. And the lower U-value windows played their part by not allowing the heat inside the house to escape, thus reducing energy consumption.

Cooling Consumption: It can be seen from table 11 that complete optimization resulted in 15.7% less cooling consumption per year. This is because the overhangs placed at the top of the windows do not allow the sun's rays to fall on the concrete slab, thus reducing the cooling consumption. Also in summers, U-pane windows do not allow heat from outside to enter the house, thereby reducing energy consumption.

2.6 Step 6: Comparing all the optimizations and summarizing on potential savings

In the previous steps, individual optimizations and complete optimizations were performed and the results were presented. In the current step, all the results were compared. Figures 29 and 30, shows the comparison between the models in terms of heating and cooling load.

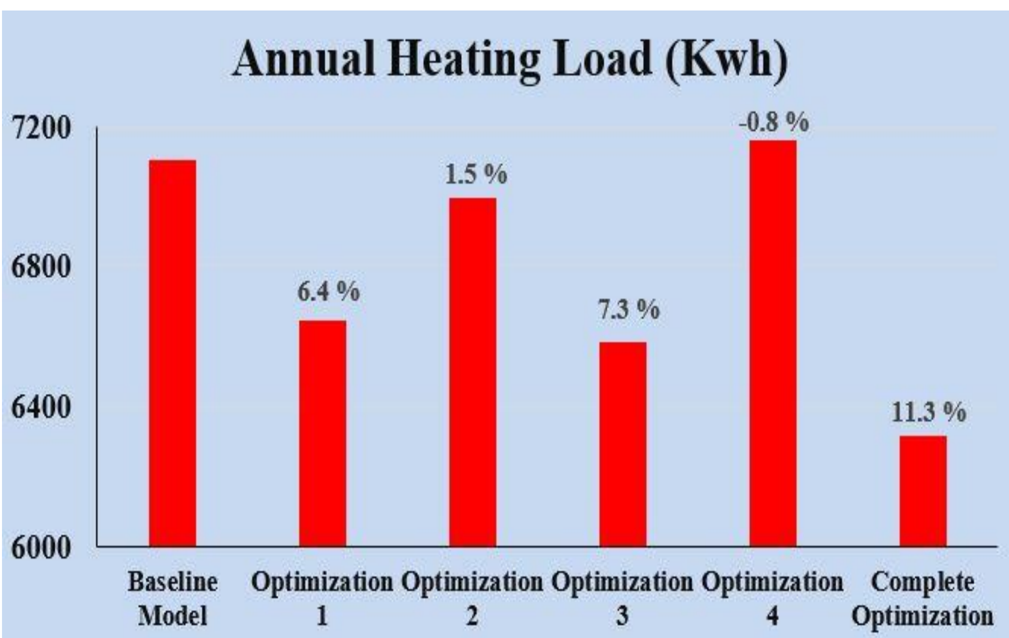


Figure 24: Comparison between optimizations based on Annual Heating Load

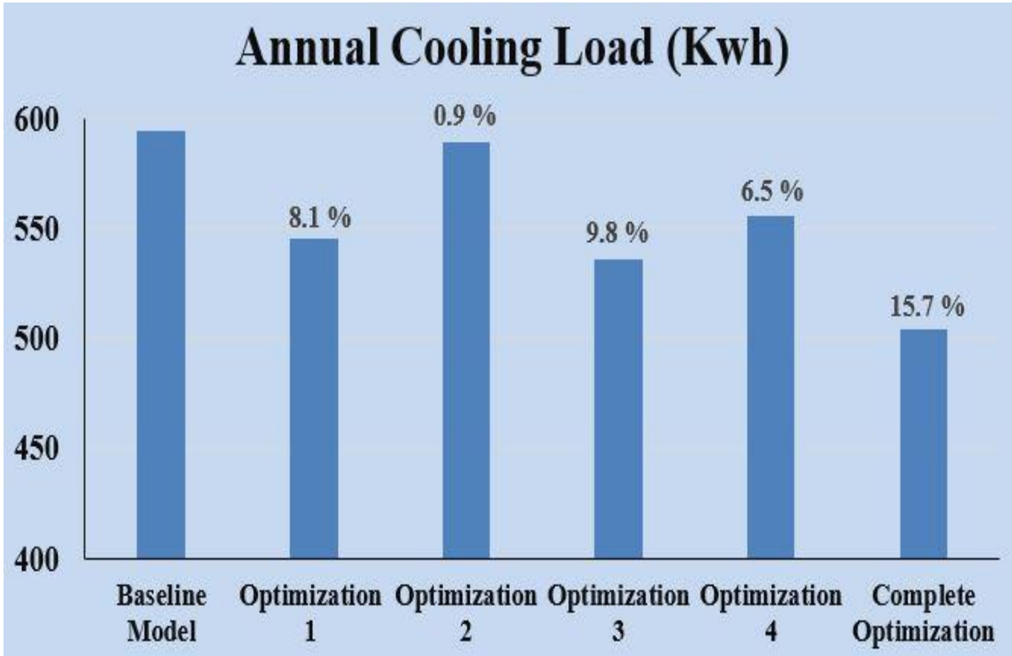


Figure 25: Comparison between optimizations based on Annual Cooling Load

Figures 24 and 25 show that the performance of complete optimizations is better compared to individual optimizations in terms of heating and cooling load. This means that the complete design set of thermal mass of concrete works better than the individual elements. The fully optimized model led to savings of 789 Kwh per year in heating consumption, which is 11.3% lower than the baseline model. And the fully optimized model led to savings of 90 Kwh per year on cooling consumption, which is 15.7% lower than the baseline model. Details on potential savings on money in a year are discussed below.

Potential Savings on Money Annually:

As per prices in BC hydro website [18], every kWh costs approximately 11 cents. Therefore multiplying the annual heating and cooling consumption with prices gives the results below as shown in table 12 below.

Table 12: Potential Energy and Money Savings in a year

	Annual Energy Consumption		**BC Hydro rate per Kwh ($)**	**Annual Cost ($)**	
	Heating (Kwh)	Cooling (Kwh)		Heating	Cooling
Baseline Model	7103.3	594.4	0.11	781.3	65.3
Complete Optimization	6314.2	504.3	0.11	694.5	54.3
Potential savings on consumption and billing	789.09	90.1		87.3	10.0

As can be seen from the calculations in Table 12, a total of $87.3 can be saved on a heating bill and a total of $10 can be saved on a cooling bill. So in the year, there is a total savings of $97.3 on heating and cooling bills. As per BC building statistics and building report, every year approximately 11000-12000 low rise residential building homes are built every year [19]. If thermal mass strategies are applied to the newly built houses, approximately 10500 Mwh can be saved in terms of electrical energy annually.

The savings in terms of money are not very high, but it should be noted that the simulation was carried out on a low-rise residential building. But if these thermal mass strategies are applied to multi-story office or residential buildings, the savings will be in thousands of dollars. This simulation can be a good demonstration just to understand how thermal mass can result in savings.

Chapter 3: Conclusion

Thermal mass, when properly designed, is one effective way to reduce energy consumption and increase cost savings. Proper care must be taken when designing thermal mass, otherwise it will lead to negative consequences such as overheating, heat loss, etc. To make the best use of thermal mass, it should be located on the south side of the house, as this part of the house receives a maximum amount of sunlight during the day. In winters, in order to allow the maximum amount of sunlight to fall on the thermal mass, glazing should be used on the south side of the house, as this allows for maximum sunlight. However in summers, in order to avoid overheating, roofs and overhangs should be used to prevent sunlight from falling on thermal mass. And proper ventilation should be provided, so that the cold outside air can pass through the hot thermal mass and cool it down during the night.

Materials used for thermal mass should have high specific heat capacity, high density, moderate conductivity and low diffusivity. Concrete, when properly designed, can have all these properties and can be used as a thermal mass inside the house as slabs and walls. It is very beneficial to have thermal mass inside the house, because if it is outside the heat stored will be lost to the outside environment.

Simulations performed on a low-rise residential building have shown that thermal mass of concrete can result in high energy savings when appropriate design strategies are used. The heating consumption decreased by 11.3% and the cooling consumption decreased by 15.7% when concrete is used as thermal mass on floor and walls and by providing efficient windows and proper shadings. Annual Money savings of $97.3 have been noted. Although Money savings are not high in terms of cooling load, but they are much better when there is a decrease in heating load. Similar designs, when incorporated into multistory buildings, can result in savings of thousands of dollars and can also reduce energy consumption by a good amount.

Future Work:

The building simulated in this study is a standalone, low-rise building. No factors such as outside environments, such as nearby trees or shadows, are taken into account. In order to obtain even more accurate results, it is recommended that simulations be carried out taking into account all of these factors. Also, in the current simulation, all heating and cooling systems are considered to be constant. In the future simulations it is recommended to check how different heating and mechanical systems work with respect to thermal mass of concrete.

References

[1] N. R. Canada, “Energy Efficiency Trends in Canada 1990 to 2013,” *www.nrcan.gc.ca*, Sep. 20, 2016. [Online]. Available:https://www.nrcan.gc.ca/energy/publications/19030. [Accessed: 10-Jul-2020].

[2] C. Reardon, “Thermal mass | YourHome,” *Yourhome.gov.au*, 2012. [Online]. Available: https://www.yourhome.gov.au/passive-design/thermal-mass#:~:text=Thermal%20mass%20is%20most%20appropriate. [Accessed: 11-Jul-2020].

[3] K. W. Childs, G. E. Courville, and E. L. Bales, “Thermal mass assessment: an explanation of the mechanisms by which building mass influences heating and cooling energy requirements,” *Thermal mass assessment: an explanation of the mechanisms by which building mass influences heating and cooling energy requirements (Technical Report) | OSTI.GOV*, 01-Sep-1983. [Online]. Available: https://www.osti.gov/servlets/purl/5788833. [Accessed: 23-Jul-2020].

[4] I. and E. Ministry of Business, “Using thermal mass for heating and cooling - Smarter Homes Practical advice on smarter home essentials,” *Smarter Homes*, 29-Jul-2020. [Online]. Available: https://www.smarterhomes.org.nz/smart-guides/design/thermal-mass-for-heating-and-cooling/#:~:text=Thermal mass should be placed,the house is generally best. [Accessed: 30-Aug-2020].

[5] “Thermal Mass for Housing,” *www.concretecentre.com*. [Online]. Available: https://www.concretecentre.com/Publications-Software/Publications/Thermal-Mass-for-Housing.aspx. [Accessed: 13-Jul-2020].

[6] Goodpal, “How the Sun Moves Through the Sky,” *Solar Power for Ordinary People*, Mar. 08, 2013. [Online]. Available: https://livingonsolarpower.wordpress.com/2013/03/08/how-the-sun-moves-through-the-sky/. [Accessed: 15-Jul-2020].

[7] J. Hanania, “Thermal mass - Energy Education,” *energyeducation.ca*, Sep. 03, 2015. [Online].Available: https://energyeducation.ca/encyclopedia/Thermal_mass#:~:text=The%20total%20amount%20of%20energy. [Accessed: 19-Jul-2020].

[8] W. Edwards, “An Explanation of Thermal Mass | Build Green Canada,” *www.buildgreen.ca*, Sep. 08, 2008. [Online]. Available: http://www.buildgreen.ca/2008/09/an-explanation-of-thermal-mass/. [Accessed: 03-Aug-2020].

[9] S. ILOMETS, K. KUUSK, L. PAAP, E. ARUMÄGI, and T. KALAMEES, “IMPACT OF LINEAR THERMAL BRIDGES ON THERMAL TRANSMITTANCE OF RENOVATED APARTMENT BUILDINGS,” *JOURNAL OF CIVIL ENGINEERING AND MANAGEMENT*, vol. 23, no. 1, pp. 96–104, Jun. 2016, doi: 10.3846/13923730.2014.976259.

[10] “Thermal Diffusivity,” *Nuclear Power*. [Online]. Available: https://www.nuclear-power.net/nuclear-engineering/heat-transfer/thermal-conduction/heat-conduction-equation/thermal-diffusivity/. [Accessed: 04-Aug-2020].

[11] *Concretebc.ca*. [Online]. Available: http://www.concretebc.ca/wp-content/uploads/2017/09/ENERGY-EFFICIENT-CONCRETE-BUILDINGS.pdf. [Accessed: 23-Jan-2021].

[12] A. Janusz, “Reducing Greenhouse Gas Emissions and Energy Costs in Canadian Buildings using Thermal Mass,” *TSpace*, 01-Nov-2019. [Online]. Available: https://tspace.library.utoronto.ca/handle/1807/98100. [Accessed: 25-Jan-2021].

[13] “Investigating the impact of thermal mass towards energy efficient housing in Canada,” *Ryerson.ca*. [Online]. Available: https://digital.library.ryerson.ca/islandora/object/RULA%3A1549. [Accessed: 23-Jan-2021].

[14] BCBC, “British Columbia Codes,” *BC Codes*. [Online]. Available: https://www.bccodes.ca/index.html. [Accessed: 02-Feb-2021].

[15] N. R. C. Canada, “National Building Code of Canada 2015,” *National Research Council Canada*, 30-May-2019. [Online]. Available: https://nrc.canada.ca/en/certifications-evaluations-standards/codes-canada/codes-canada-publications/national-building-code-canada-2015. [Accessed: 03-Feb-2021].

[16] “Table 6 thermal conductivity, specific heat capacity and density,” *Iesve.com*. [Online]. Available: https://help.iesve.com/ve2018/table_6_thermal_conductivity__specific_heat_capacity_and_density.htm. [Accessed: 03-Feb-2021].

[17] “Update or Replace Windows,” *Energy.gov*. [Online]. Available: https://www.energy.gov/energysaver/design/windows-doors-and-skylights/update-or-replace-windows#:~:text=Heat gain and heat loss,heating and cooling energy use. [Accessed: 07-Feb-2021].

[18] B. C. Hydro, “Residential Rates,” *BC Hydro - Power smart*. [Online]. Available: https://app.bchydro.com/accounts-billing/rates-energy-use/electricity-rates/residential-rates.html. [Accessed: 17-Feb-2021].

[19] “BC Residential Building Statistics & Trends Report,” 2018.