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Master of Science Degree
in Mechanical Engineering

Master Thesis

Designing, Simulation and Analyzing Energy Consumption of HVAC System for a Public Building in the City of Turin

Advisors
Prof. Marco C. Masoero
Laura Rietto

Candidate
Seyed Mashhoud Safavisohi

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Abstract

We are living in a period in which energy plays an important role in our life. Energy isn't free and wasting it is wasting money and destroying its resources. Most types of energy can result in pollution so the more we save energy the better we save our planet. While energy efficiency optimization is becoming important for managing cost and environmental care, the way HVAC systems are used is so important because they are subjected to abusage energy more than any other sources in urban buildings.

The aim of this dissertation is to design and analyze the proper solution between three HVAC system together with simulation of their behavior during summer and winter design for a public building in Turin city. These systems are variable air volume (VAV), Fan coil system with chiller and Boiler and finally Variable Refrigerant Flow (VRF). The analysis is done by studying the performance and energy consumption of the HVAC system during summer and winter design with Design Builder which is a state of art software tool for checking building energy.

The research shows that the VRF system is the most appropriate system over the other two HVAC systems because it is calm, reliable and distributes refrigerant instead of hot and cold water in pipes to terminal units and by supplying different amount of refrigerant it provides heating and cooling at the same time. This system is logic base and by varying the amount of refrigerant based on zone load. Although their initial cost is high, but they are about 30% efficient compare to other systems and the installation is simpler with lower cost because each final unit hast only two pipes, so they don't have the complexity of chiller systems.

Acknowledgments

Foremost, I would like to express my gratitude to my advisor Prof.Masoero for giving me the opportunity to work on this interesting topic and his insightful comments and immense knowledge.

My sincere thanks also goes to Laure Rietto for her continuous support, patience and encouragements. Her guidance helped me in all the time of research and writing of this thesis.

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1 INTRODUCTION

We live in an age where energy is an absolute necessity to maintain our lifestyle and it goes beyond the basics of providing comfort and convenience. If we look back to the past we understand the reality of life without energy when nothing that you've come to be dependent on works. Energy is not free, the grown-ups in our house pay for the all the electricity we use so wasting energy is the same as wasting money and we know that's not a good idea! Wasting energy isn't good for the environment either. Most of the energy sources we depend on, like coal and natural gas can't be replaced once we use them up they're gone forever. Another problem is that most forms of energy can cause pollution so the more energy we save, the better off our pocketbooks and our earth will be.

Whilst energy efficiency optimization is becoming an increasingly important business strategy for managing costs and supporting environmental compliance, the way in which Heating Ventilation and Air Conditioning (HVAC) systems are used could be so important. Based on the information published by EUROSTAT In 2015, the households or residential sector represented 25.3% of final energy consumption or 16.8% of gross inland energy consumption in EU. Households use energy for various purposes such as space and water heating, space cooling, cooking, lighting and electrical appliances and other end-uses, which mainly cover uses of energy by households outside the dwellings themselves.

HVACs are subjected to more misuse than any other type of equipment in house sector. Poor maintenance, lack of knowledge on how to use them efficiently, overuse, and the large number of old and inefficient systems at work in the sector make HVACs a significant contributor to the country’s demand for energy.

Heating, Ventilation and Air Conditioning systems control temperature, humidity and quality of air in a building to a set of chosen or preferred conditions. To achieve this, systems need to transfer heat and moisture into and out of the air and control the level of air pollutants, either by directly removing it or by diluting it to acceptable levels. In general, the heating is needed to increase the temperature in a space to compensate for heat loss. Ventilation is needed to supply air to a space and extract polluted air from it. Cooling is needed to lower temperature in a space where heat gains are caused by the sun, activity of people and the function of equipment. Three central functions of Heating, Ventilation and Air Conditioning are interrelated to optimally provide thermal comfort, acceptable indoor air quality and ideal operating conditions within the boundaries of acceptable or reasonable costs.

HVAC systems vary widely in terms of size, functions they perform and the amount of energy they consume. Factors that influence energy usage include:

• The design, layout and operation of a building, affects how the external environment impacts on internal temperature and humidity levels

• HVAC systems will use more energy when the required indoor temperature and air quality – in extreme temperatures or in the case of operations where greater precision or more refined air quality is required

• The heat generated internally by lighting, equipment and people - all have an impact on how warm your building is, and the load on the HVAC system

• The design and efficiency of your HVAC system. Older systems tend to be less energy-efficient

• How, when and for how long your HVAC system is operated every day

• How well the HVAC system is monitored and maintained.

Based on what mentioned above, the importance of well designing and selecting the HVAC systems effects significantly on energy consumption in household section.

This thesis is about designing and analyzing a proper solution between three HVAC system together with simulation of their behavior during summer and winter design with the help of Design Builder software for a building in the city of Turin.

Design Builder is a state-of-the-art software tool for checking energy consumption, carbon emission, lighting and comfort performance of a building. Developed to simplify the process of building simulation. Design Builder allows to rapidly compare the function and performance of building designs and deliver results on time and on budget. The software provides advanced modelling tools in an easy-to-use interface. This function enables us to use the same software to develop comfortable and energy-efficient building designs from concept through to completion.

2 HVAC SYSTEMS SELECTED FOR THIS THESIS

As mentioned before three deferent HVAC systems have been selected:

- VAV or Variable Air Volume system
- VRF or Variable refrigerant flow also known as variable refrigerant volume (VRV)
- Fan coil with chiller & Boiler

Before going through details, it is good to have a brief explanation of these three systems.

2.1 VAV SYSTEMS

Variable Air Volume (VAV) is a kind of heating ventilating and air conditioning system. Despite constant air volume system, that provides a constant airflow at a variable temperature VAV systems change the airflow at a constant temperature. The advantages of VAV systems over constant-volume systems is that it provides accurate temperature control, reduced compressor damage, reduction of energy consumption by system fans, less fan noise, and additional passive dehumidification.

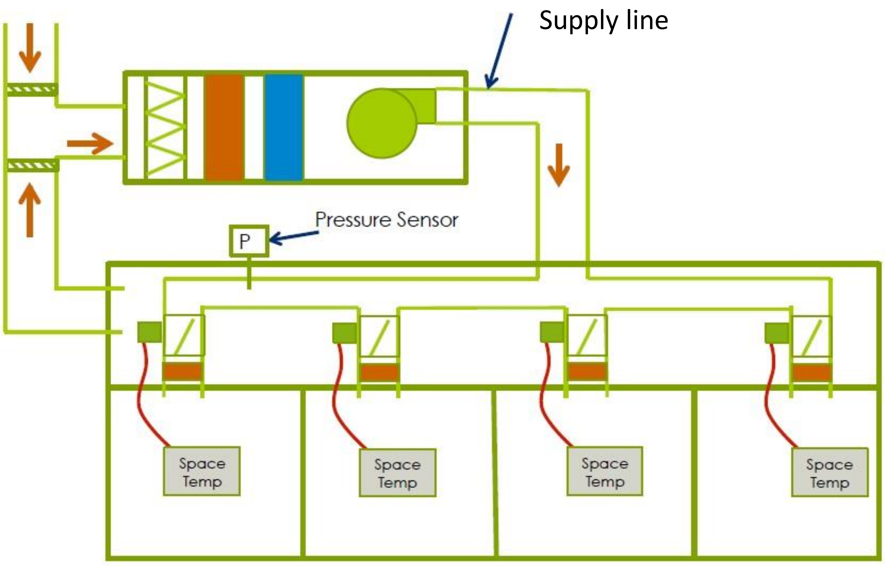


Figure 1 VAV system

The VAV system in this simulation consists of an air-cooled chiller to supply chilled water for air handling unit (AHU) coils to provide cooled air to remove heat from zones during summer days and a boiler to supply hot water for heating for coils in the AHU and the zone terminal unit to heat up zones during winter season. The air handling unit provide conditioned air to zones. The conditioned air and water distributed via loops. The schematic diagram of a basic VAV system is demonstrated figure 1.

As can be seen in the diagram of figure 1 the AHU coils can be supplied by chilled and hot water by chiller and boiler respectively. Design Builder enables us to define and change the input data for boiler, chiller, AHU, fan, pumps and other parts by navigating to their dialog boxes. Now we can see the diagram for main parts of each loop.

2.1.1 SUPPLY AND RETURN AIR LOOP

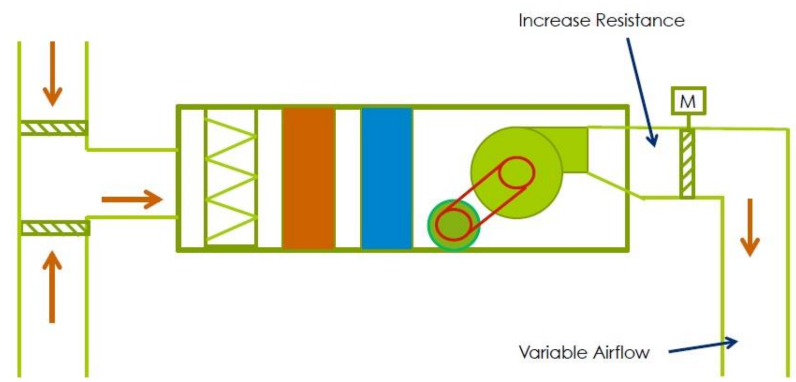


Figure 2 Air supply line

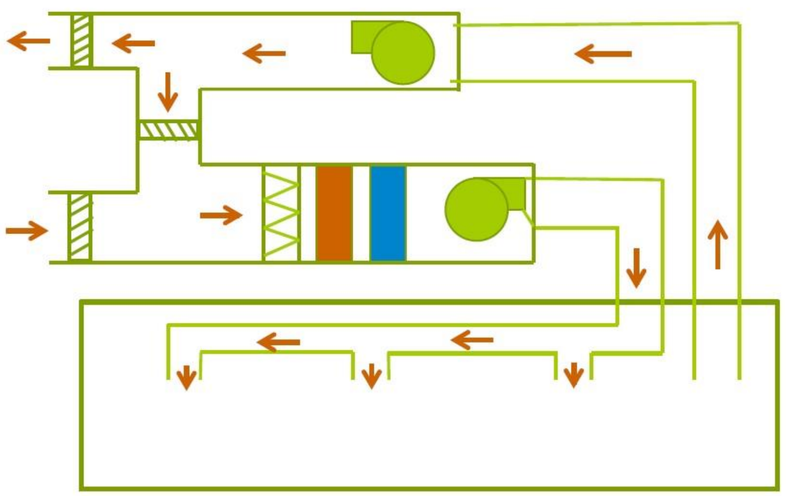


Figure 3 Air return line to AHU

The return water flow is connected to return side of the loop after the supplied energy is consumed by the coil transferring heat to satisfy the heat demand of the zone. This is true also for the return side of the chilling loop after gaining heat from the zone.

2.1.2 ZONE GROUPS

Now we can see the zone groups supplied by supply and return terminal units to transfer hot and cold air to each zone. Each zone has specific name and usage which will be described specifically later.

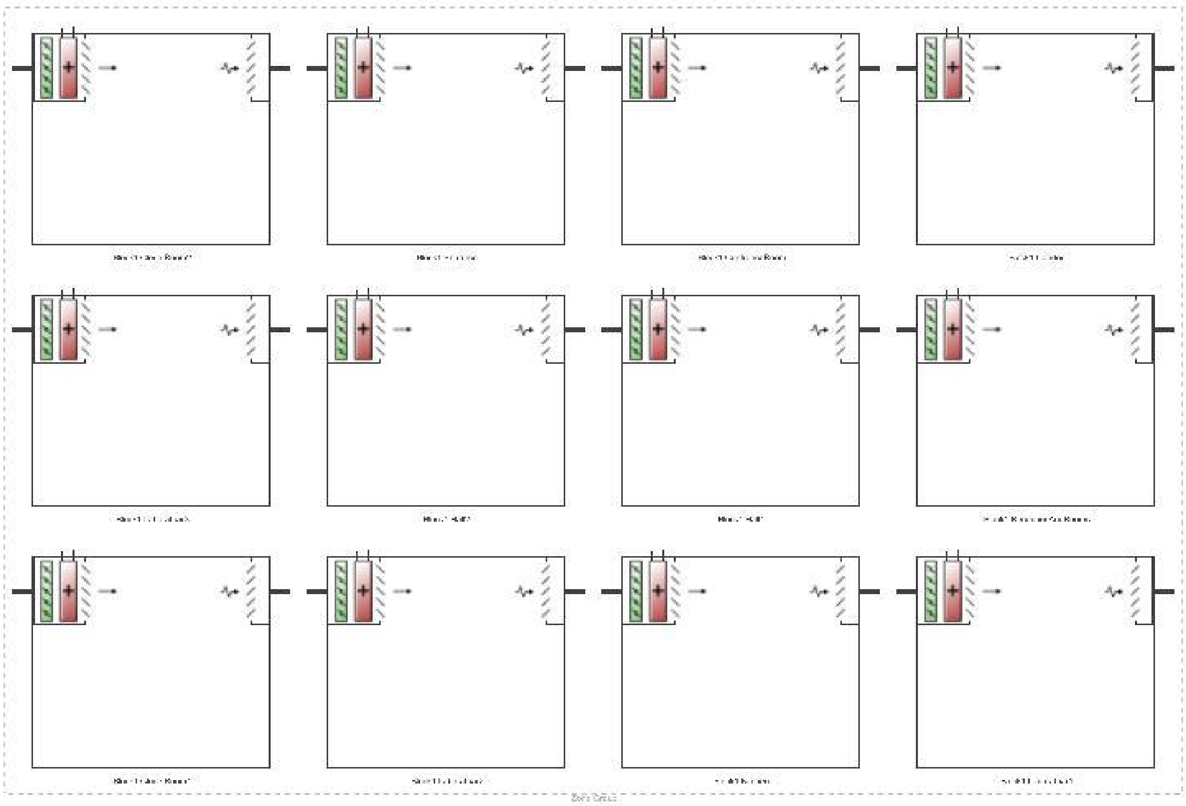


Figure 4 Zone group which supplied by VAV system

2.2 VRF systems

The term VRF stands for Variable Refrigerant Flow which was invented in 1980s by the HVAC leading company DIKIN and registered as an official trademark as VAV (Variable Refrigerant Volume). The other companies use VRF for their similar HVAC system.

2.2.1 How does VRF system work?

In this system the refrigerant is the only coolant material in the system vs chilled water system in which the refrigerant is used to cool or heat the water which is circulated through the whole system. Briefly the VRF system gets the input data from indoor comfort temperature and outside ambient temperature and based on this information the control unit of the system provides the desired comfort temperature by using optimal power consumption. The inverter compressor enables lowering power consumption during cooling and heating partial loads, so it makes this system ideal for applications with varying loads required.

VRF system are available either as heat pump system or heat recovery system when both cooling and heating are required at the same time. This system enables having several indoor units on the same refrigerant circuit also there is the ability of modular expansion specially from small to large buildings.

2.2.2 VRF system types

There are three different VRF system in the market:

Cooling only systems (less popular) – those systems are used only for cooling and the heating is not available

Heat Pump systems (most popular) – all the indoor units can either heat or cool but not at the same time.

Heat Recovery systems (less popular) – those systems are the most special ones where cooling and heating are available by each indoor unit, simultaneously.

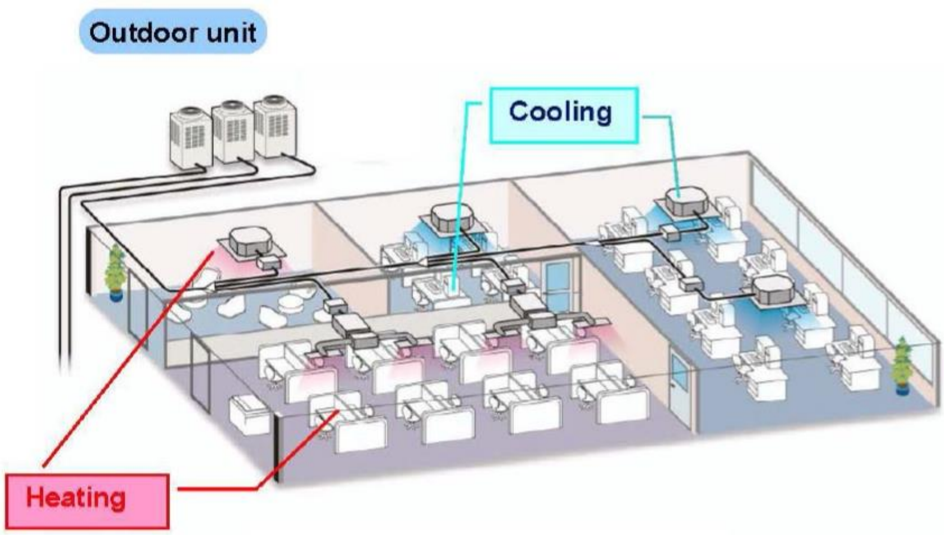


Figure 5 Simultaneous heating and cooling with VRF system

In figure 5 we have the schematic diagram of a typical VRF system.

The system consists of air loop with air handling unit to provide fresh air to each zone and the VRF system to provide variable refrigerant for zones internal units.

2.2.3 VRF UNIT

In figure 6 we can see a cut away view of VRF outdoor unit with multiple inverter

Figure 6 VRF Outdoor unit

2.3 FAN COIL AND BOILER SYSTEM

This system is a kind of HVAC system which consist of fan coil connected to air/water cooled chiller but in conjunction with central heating boiler when heating is required. The fan coil is a simple device consists of heat exchanger or coil and a fan. The fan coil unit can be controlled manually by on/off control or by use of thermostat unit. Various unit configurations are available in the market such as ceiling mounted, wall and floor mounted. This kind of system is one of the most commercial system in buildings.

2.3.1 HOW DOES A FAN COIL UNIT WORKS?

Generally, in this system the cooling unit is set up in a separated technical room or outside of the building. The chilled water (from 6 to 12 degrees Celsius) is circulated through the insulated pipes to the fan coil unit. A fan blows the air from the room over the coils thus cooling the air when the return water gains heat from the environment it passes through a cooling tower in water cooled chiller or condenser in air cooled chiller and the process repeats again.

Instead of the cold water the hot water can be circulated to the pipes through the boiler during the winter season. There are some pros and cons of this type of system which will be discussed later.

The schematic diagram of the fan coil system is demonstrated in figure 7:

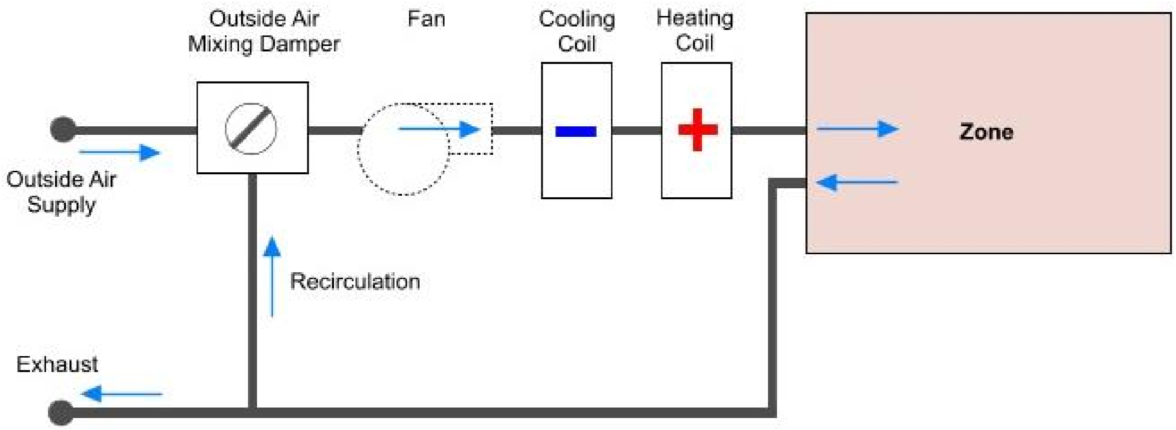


Figure 7 Fan coil system

2.3.2 CHILLED WATER LOOP

Figure 8 explains a simple chilled water loop to supply cooled air for different zone.

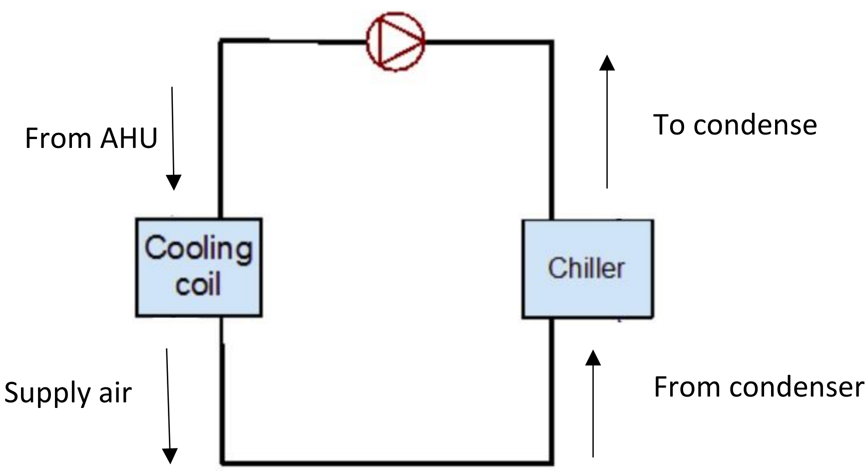
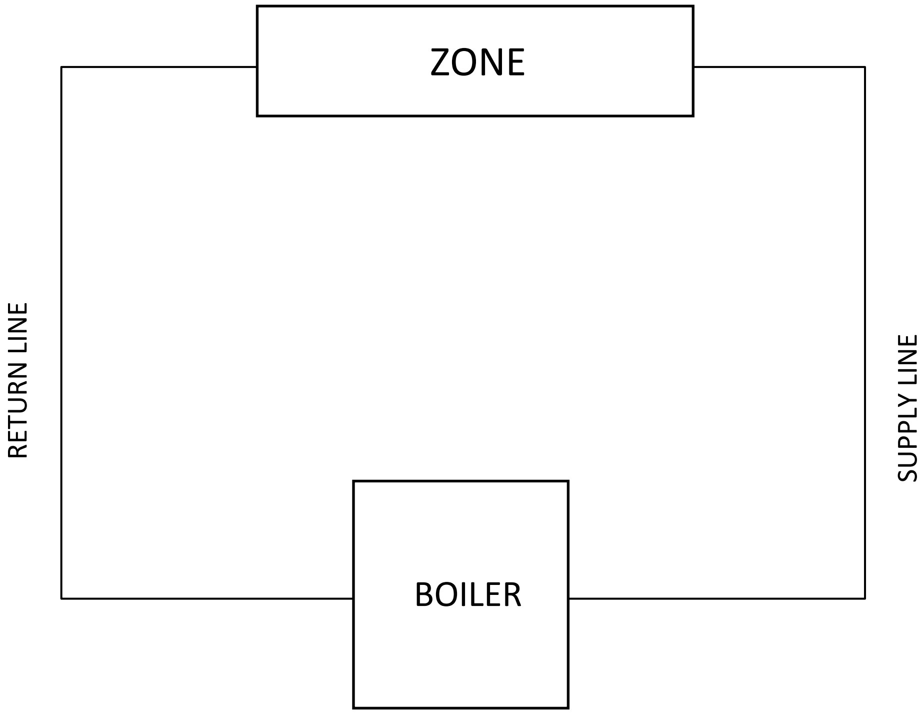


Figure 8 Chilled water loop

2.3.3 HOT WATER LOOP



The above diagram demonstrates how the hot water loop is in this system for providing hot water.

3 MODELING AND SIMULATION OF SYSTEMS

Before simulating the system in Design Builder, it is required to import the CAD model of the building to it, thus, the CAD file was built in Open studio software and then imported to Design Builder to introduce the specification of the building such as wall, roof and floor material, type of windows, lighting, zone illustration and type of each zone to determining the activity level for each zone group. In figures 9 and 10 we can see the shape of the building in deferent angels which is modeled and imported to Design Builder.

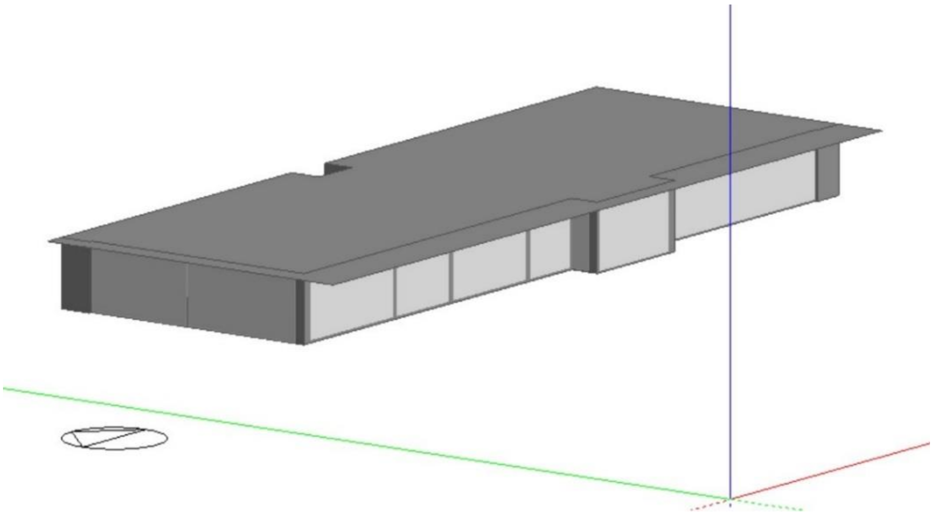


Figure 9 building view 1

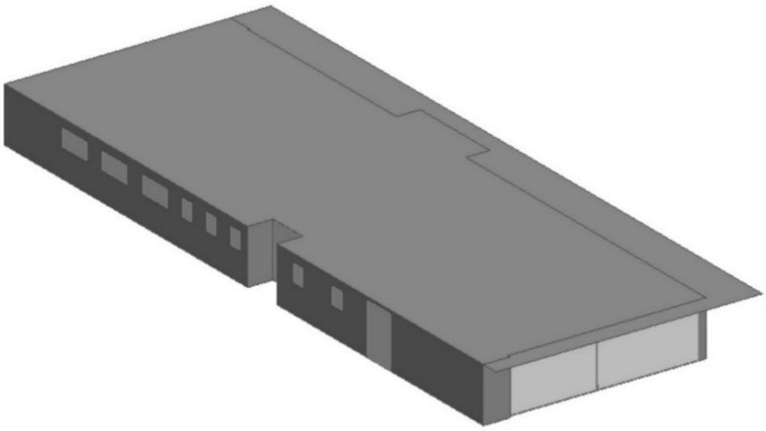


Figure 10 building view 2

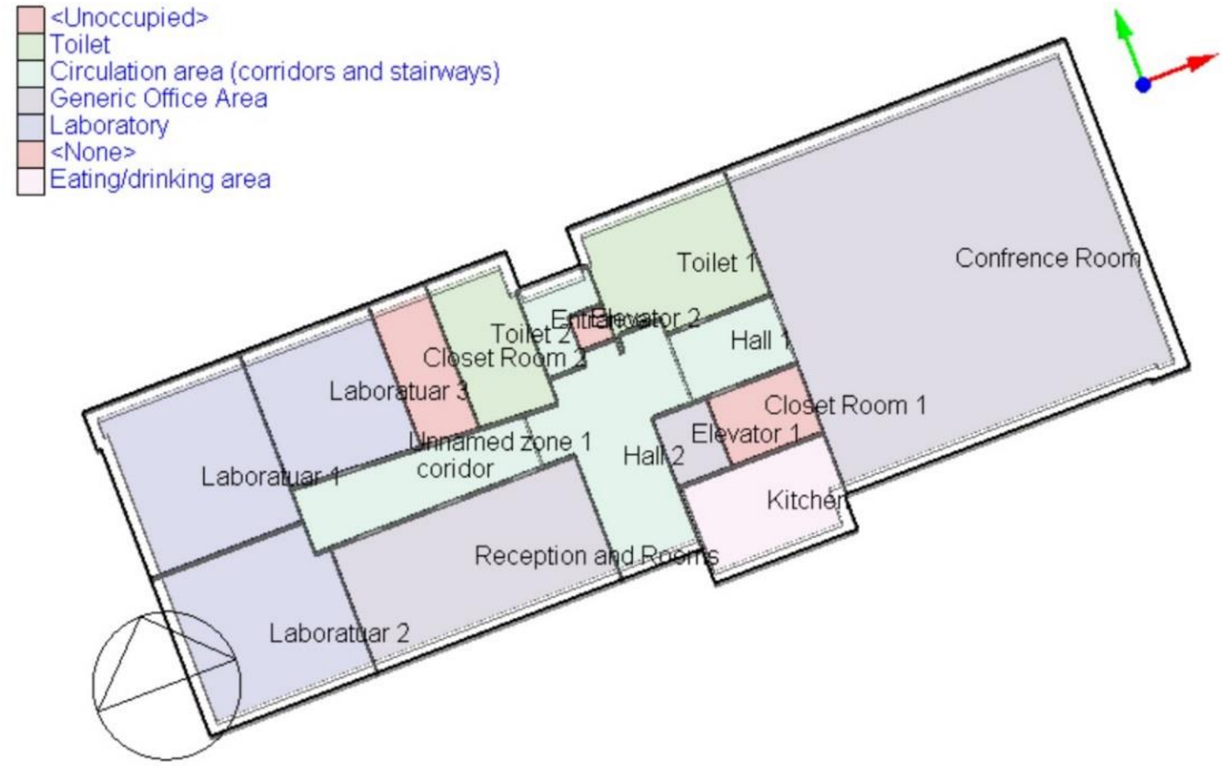


Figure 11 Building zones

Figure 12 shows the interface of Design Builder. There are different tabs such as layout, activity, construction, lighting and HVAC to input the general information of the building. At the bottom there are some other tabs which can be used for calculating the cooling and heating load of the building and simulation of the HVAC model.

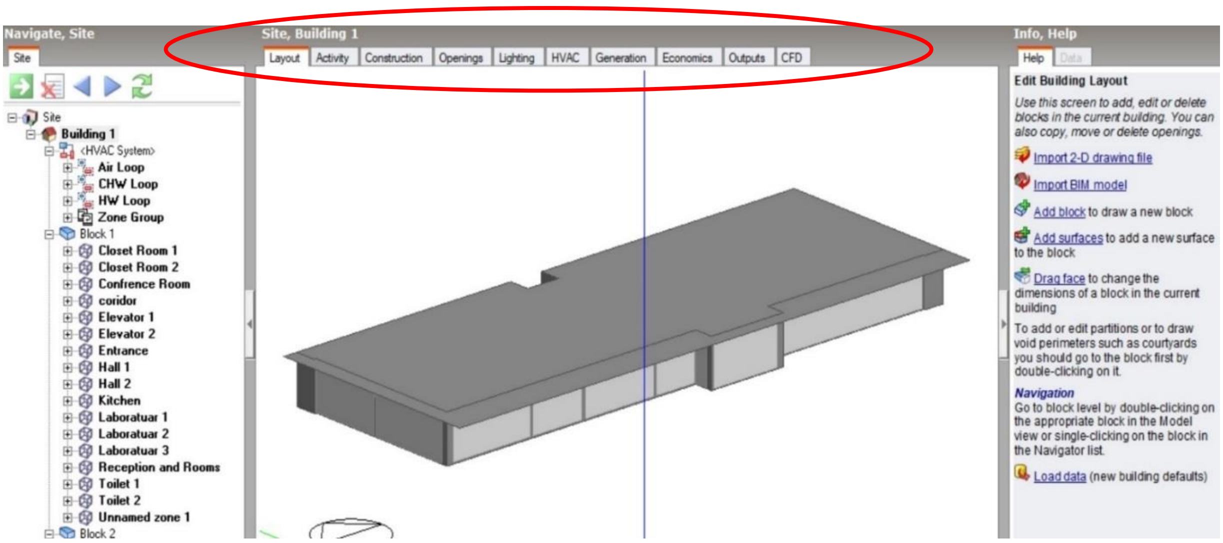


Figure 12 Design Builder interface

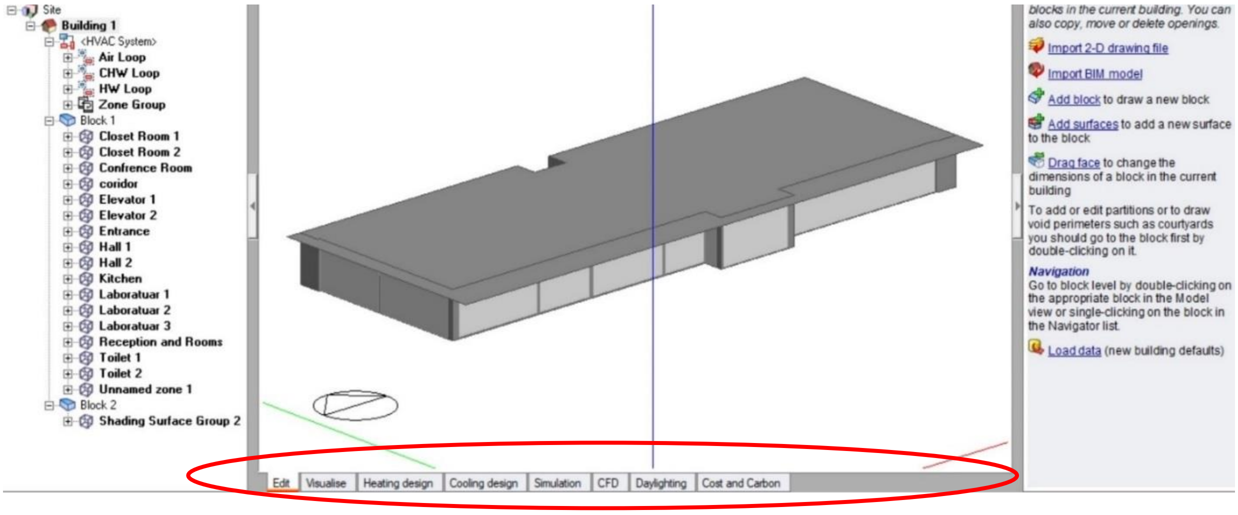


Figure 13 Design Builder building layout

In the layout tab we can see the site level of the project where we can add, delete or edit a part of the building. After importing the building to Design Builder, it is necessary to determine the location of the project to access the elevation and the most accurate weather data of the location for design and simulation calculations. For this project the Turin airport is selected which was the only choice for city of Turin. After giving the location data, it comes to importing the activity data related to zone usage. This determines most of internal heat gains which in turn impact on the building heating, cooling and ventilation requirements. The activity data cover occupant, design internal temperatures, ventilation rates, illuminants levels and equipment usage. The software contains a lot of pre-defined templates such as offices, living rooms, kitchens, toilets and circulation areas which can be selected based on the zone usage or it can be created by designer.

The activity data uses the national calculation methodology codes. The environmental control option detects the operational set points for each of the systems. The environmental control detects the operational setpoints for each system when the system is on. The default model data controls the operation of heating and mechanical cooling systems. For example, for conference room the “generic office area” is selected as the activity template and the default model data controls the heating temperature for this zone on 22(°C) and turns on the cooling system when the temperature falls below 24 (°C).

The minimum fresh air set point governs the air flow rate to the zone when mechanical ventilation to the zone is enabled. This part can be set based on fresh air per person or mechanical ventilation per area or both. Because the mechanical ventilation, heating and cooling are enabled, this tab must be defined to determine the amount of fresh air to each zone. The lighting, computer, office equipment, miscellanies, catering and process data are defined based on the appropriate template in the activity tab.

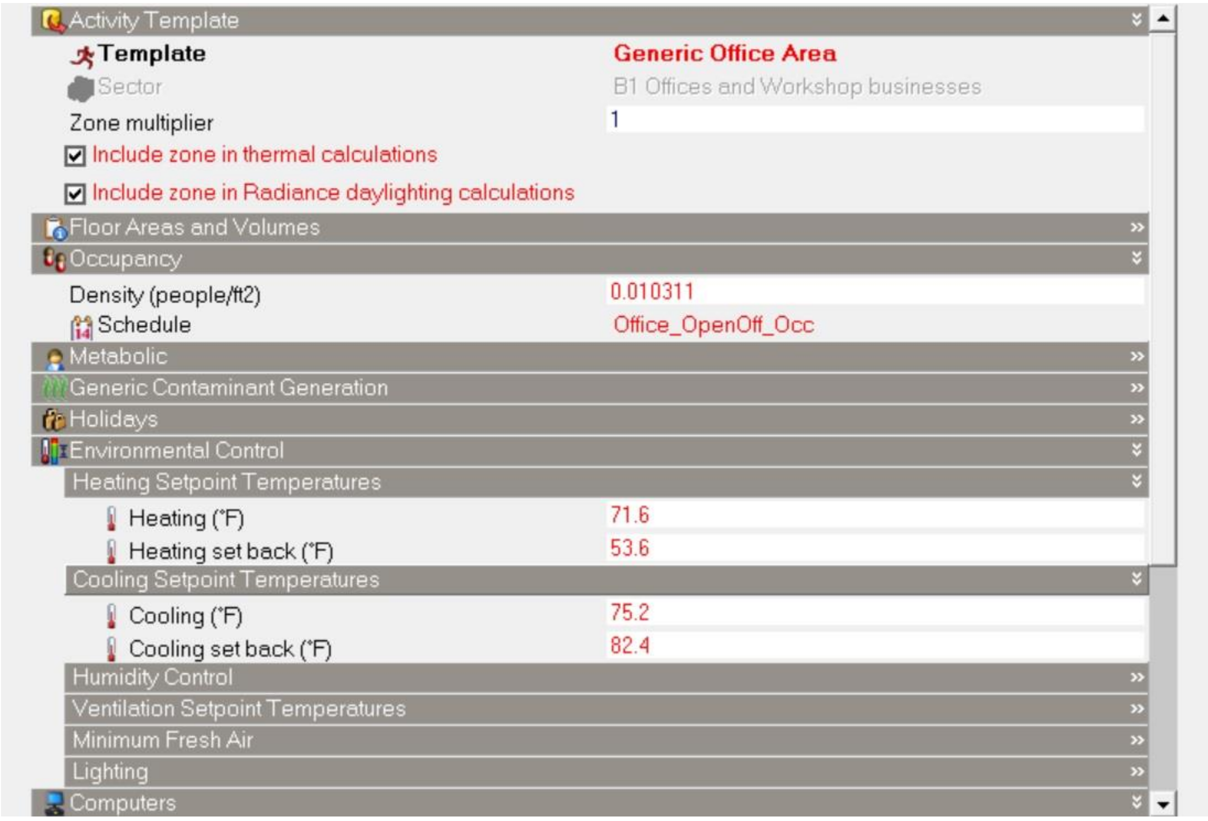


Figure 14 Activity tab

In this project we have conference room, laboratory, closet room, corridor, reception, kitchen and toilet. The activity data for all of them selected based on the appropriate template of the software. As an example, Unoccupied template is selected for closet rooms, Generic office area for conference and reception rooms, Circulation areas (corridors and stairways) for corridors and entrance part, Eating/Drinking area for kitchen, Laboratory for laboratories and finally Toilet for toilets are selected.

Another parameter which is selected automatically based on the activity template is the scheduling for each zone which determines the amount of occupancy for each workday. This data is used for the heating and cooling calculation.

3.1 CONSTRUCTION

After characterizing the activity for each zone, we go for the construction in which we specify the non-glazed building fabric properties, this dictate the thermal performance of opaque internal and external surfaces of the building and has significant impact on comfort conditions and heating and cooling loads. The construction layers consist of external walls, below grade walls, flat and pitched roof. This building doesn't have the pitched roof so only the flat roof is selected. The material for each layer is selected based on the customer need. For this building the construction consists of four layers in which the most outer layer has Cement/plaster/mortar/gypsum plaster, sand aggregate and layer two has EPS expanded polystyrene (heavyweight). The third layer consists of Cement/plaster/mortar plaster and finally concrete block (lightweight) is allocated to the inner most layer. The Design Builder is intelligent and automatically assigns constructions according to the model geometry and the activity allocated to each zone. Figure 15 shows data and the diagram of the formed layer based on selected materials.

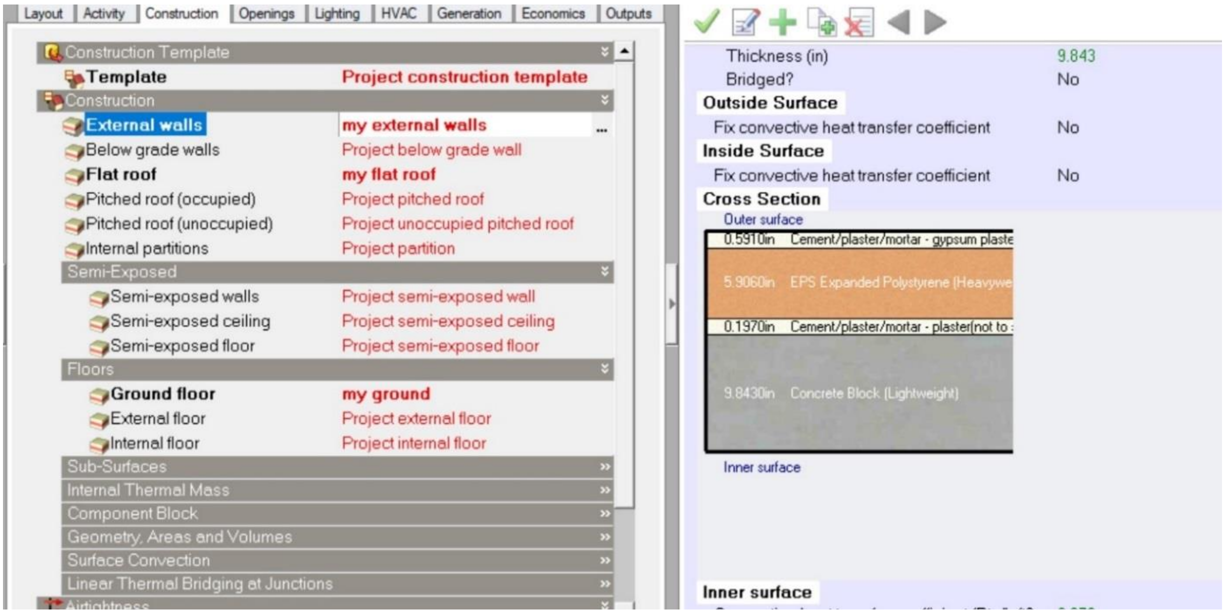


Figure 15 Construction tab

The ground floor consists of 8 layers which can be seen in figure 16. In sub-surface tab we can assign the materials for external and internal doors in which the wooden door has been selected for both.

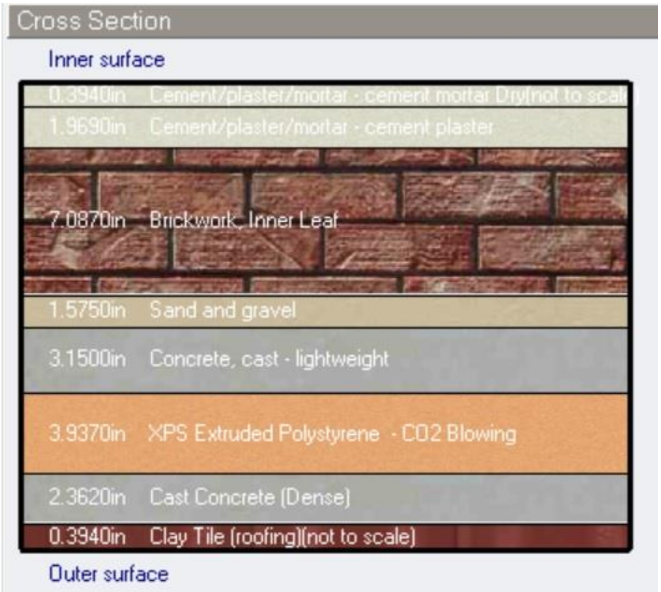


Figure 16 Ground floor layers

3.2 OPENING SURFACS

The selected windows for this building are based on the customer need just like the properties of construction and doors. The characteristics of the selected windows is demonstrated in figure 17.

Data Report (Not Editable)	
General	
My Window	
Source	
Category	Project
Region	ITALY
Definition method	
Definition method	2-Simple
Heat transfer integration mode	3-Integrated Surface Outside
Calculated Values	
Total solar transmission (SHGC)	0.340
Light transmission	0.610
U-Value (ISO 15099 / NFRC) (Btu/h-ft2-°F)	0.176
Cost	
Cost per area (GBP/ft2)	100.000

Figure 17 Opening tab

As can be seen from the generated data by Design Builder the U-Value for window is 0.176 (Btu/h-ft2-°C) which is in a appropriate range.

3.3 LIGHTING

The data entered for lighting governs the lighting performance and associated energy consumption and has significant impact on internal heat gains. The chosen template for this part is Best Practice in which contains appropriate information about the lighting. The schedule parameter is selected and starts at 7 AM to 7 PM for better controlling the lighting performance.

The energy consumption by lighting can be controlled by applying the lighting control to the model in which it reduces the lighting for zones where have natural daylight during the occupancy. The type of lighting control is Linear/off in which varies the lighting power input linearly according to available daylight illuminance, but we stay on the minimum power input when the target illuminance level in the activity tab is reached and switches off the lighting when the target illuminance level is met by daylight a lone.

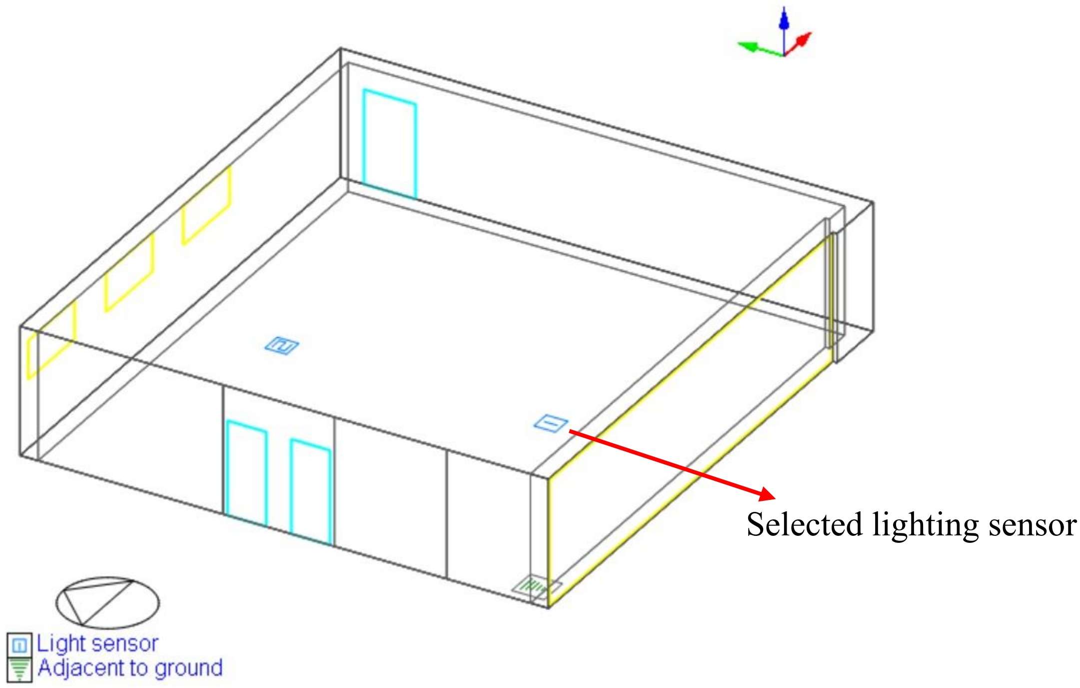


Figure 18 Lighting control system

After selecting lighting control for each zone, it is required to select sensor for each zone where the lighting should be controlled. The number of sensors is vary based on the area.

As can be seen in figure 18 two sensors are selected for the conference room where has a bigger area compared to other zones.

3.4 HVAC

Here the key parameters for heating, cooling, ventilation and domestic hot water are defined. This determines the energy consumption of HVAC system of the building. To have the correct simulation and calculation of heating and cooling load the detailed HVAV instead of simple HVAC is selected.

There are different numbers of HVAC template available to define the desired system for deferent buildings. The template selected defines which of mechanical ventilation, heating and cooling system is selected. All of three HVAC system which have been selected have this information.

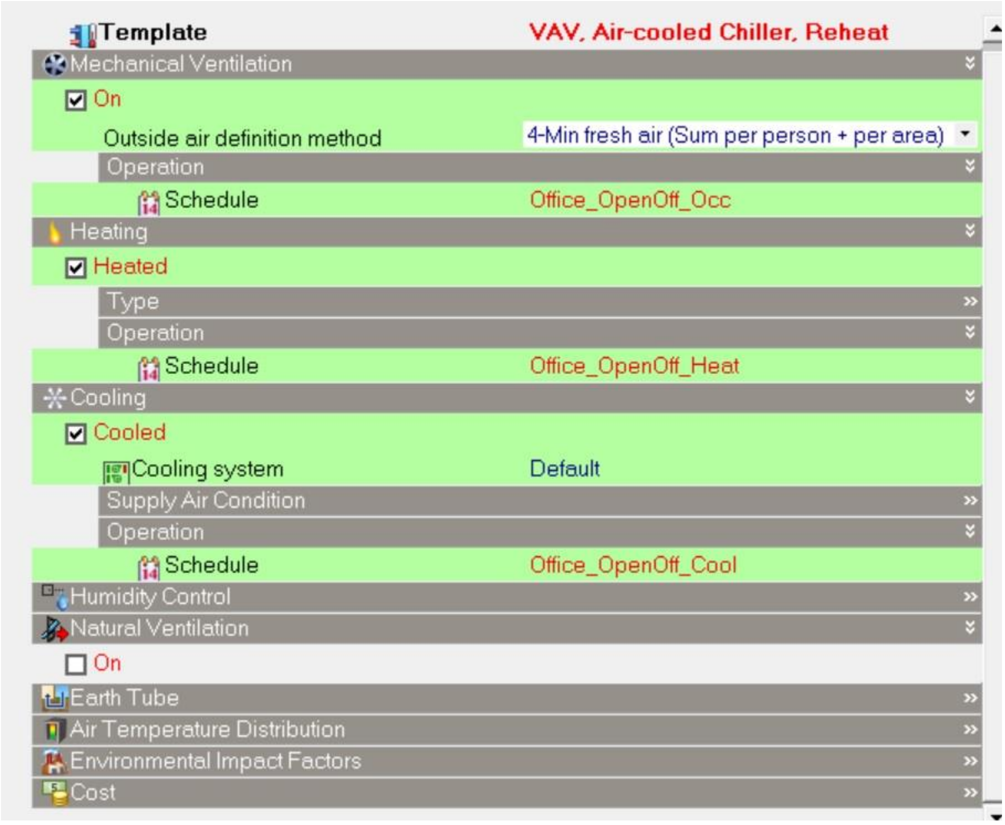


Figure 19 HVAC tab

4 HEATING DESIGN

The heating design calculation helps us to determine the size of heating plant required to meet the designed winter conditions. It is also a useful tool to analyze the building performance through the heat losses and gains for each zone in the model. It gives us information in which we can quickly check the impact of changing the insulation and other materials used in the construction to reach the optimum design solution.

Heating design calculation in Design Builder uses a constant steady state temperature set to the winter design external temperature which is taken from weather data set relative to the location of the building. Now we can take the internal gains such as lighting, equipment and occupancy and heated zones are heated constantly to achieve the heating temperature set point defined in the activity tab. Calculation dose include heat conduction and convection between zones with deferent temperatures. Before starting the calculating it is important to check to correct location of the building. The amount of wind speed is set by default based on the selected location.

The air temperature is selected as the control parameter and the calculated plant sizes is normally be lower when this option is selected as the control parameter. Here we can review the result of heating design calculation of the building

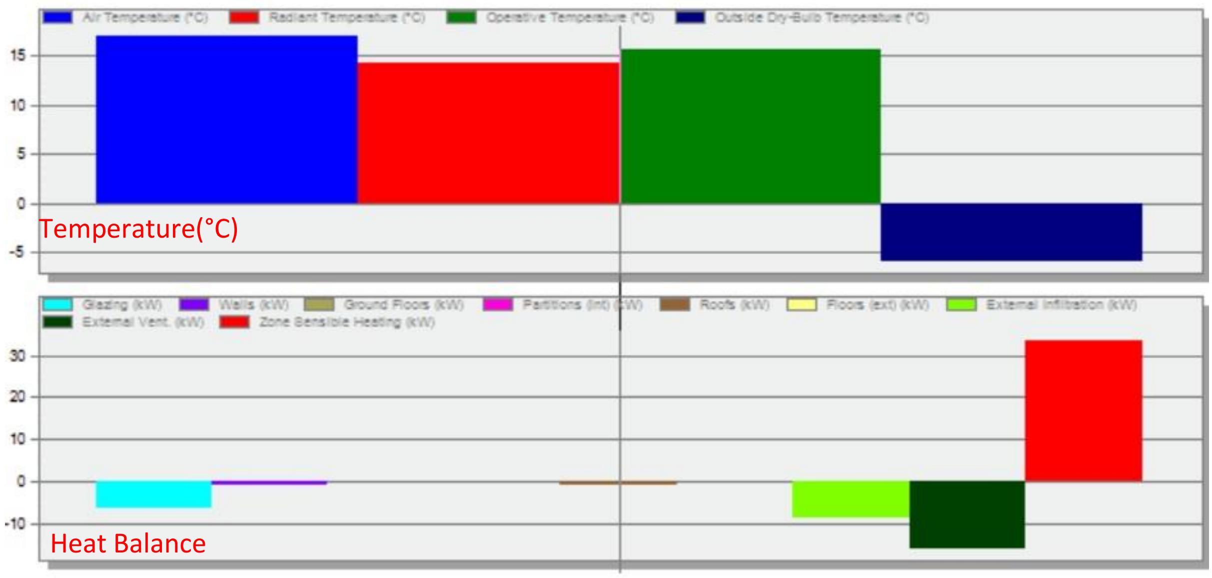


Figure 20 Heating demand by the building

Air Temperature (°C)	16.99
Radiant Temperature (°C)	14.39
Operative Temperature (°C)	15.69
Outside Dry-Bulb Temperature (°C)	-5.90
Glazing (kW)	-6.62
Walls (kW)	-0.91
Ground Floors (kW)	0.05
Partitions (int) (kW)	0.00
Roofs (kW)	-1.01
Floors (ext) (kW)	-0.12
External Infiltration (kW)	-8.65
External Vent. (kW)	-16.14
Zone Sensible Heating (kW)	33.52

Figure 21 Heating demand results

The temperatures are shown in figures 20 and 21 starting with internal air temperature which is the controlling parameter and indicating the result of radiant and operative or comfort temperature which is the combination of air and radiant temperatures and it is a measure of average perceived temperature in each zone.

Figure 21 shows the results in number, the comfort temperature is about two degrees below the zone set point because the air temperature was set as the control parameter. External design winter temperature is -5.9°C. the heat balance graph provides a breakdown of the heat gains and losses in kilowatt for the whole building. To the left we have the heat losses for each fabric component such as glazing -6.62 kw and walls -0.88 kw, the other losses can be read from the table. To the far right we can see the total heat input of 33.52 kw require from the heating plant to meet the heat losses at design conditions.

The ventilation load represented as external vent which is -16.14 kw and this is set to minimum fresh air per person so it is dictated by occupancy density and specified minimum fresh air rate. Finally, the total heating design capacity for building to meet the heat losses in winter condition is 41.9 kw.

5 COOLING DESIGN

In this part we study the cooling design calculation which helps us to determine the size of the cooling system require to meet the design summer conditions. It could be also a useful tool to analyze the building performance to understand the source of the most significant heat gains which contribute to cooling loads.

Like heating design calculation, the cooling design calculation in Design Builder uses periodic steady state external temperatures calculated maximum and minimum design summer weather conditions. The simulation calculates half hourly temperatures and heat flows for each zone and determines the cooling capacities required to maintain any cooling temperature set points in each zone.

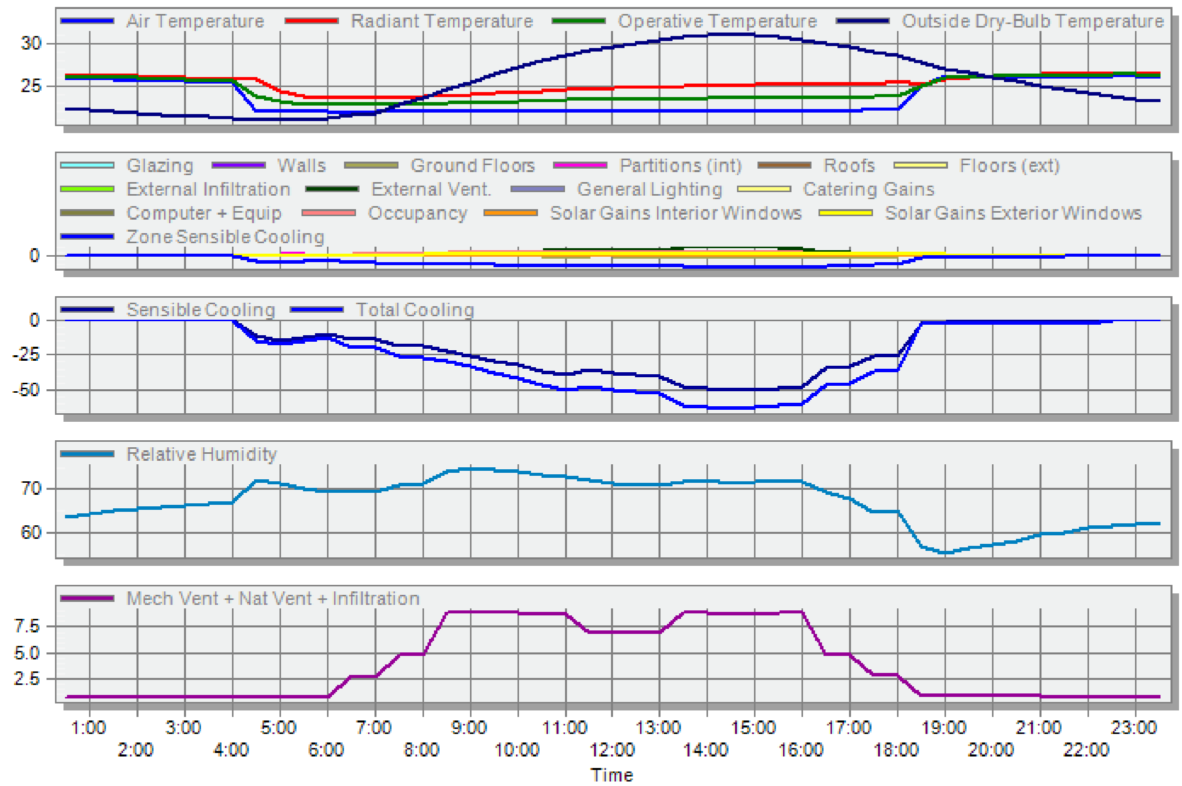


Figure 22 Building cooling design 1

The calculation assumes the still ambient air condition and includes solar gain through windows, schedule natural ventilation, internal gains from occupants, lights and any other equipment and consideration of heat conduction and convection between zone temperatures. Just like the heating design the location of the building must be checked before starting the simulation. Also, the type of temperature control is air temperature to have accurate system control. The design margin is set to 1.15 by default which means the plant sizing is based on calculated cooling load plus 15% to care the effect of any additional cooling capacity required when the cooling system is switched off for extended periods such as overnight or during the weekend. It effectively reduced the pre-cooling time required to achieve the comfort set points at design summer conditions. The design margin can be increased or decreased if required. The graph in figure 22 gives us the simulation results of the cooling calculation and we can review the calculation results.

On the top of the chart we have external temperature and internal air, operative and radiant temperatures. The second graph shows the heat balance and cooling load results are shown on the third one. The relative humidity and ventilation details are shown in fourth and fifth graph respectively.

When we look at the first graph regarding the comfort data we can see how the air temperature is close to 22°C and follows a constant trend during the occupancy, that is why the air temperature was set as the control parameter. As discussed before the comfort temperature is about 2°C higher than the air temperature due to higher radiant temperatures. We can see that the operative temperature is the combination of air and radiant temperature and is an average sensed temperature in each zone. The peak external design summer temperature is about 31°C occurs around 14:30 pm. The relative humidity is not a control parameter but can be seen it drops when cooling and ventilation systems start condition the building and then stays stable during occupancy.

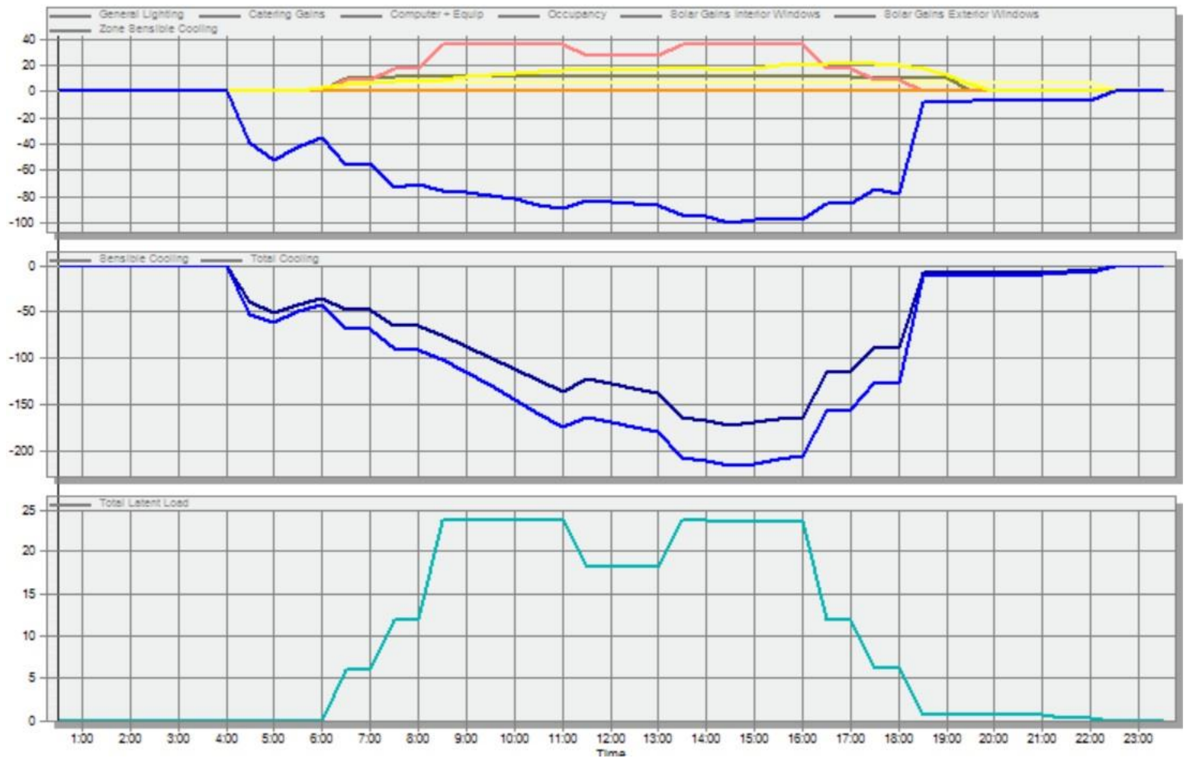


Figure 23 Cooling design 2

In the bottom graph of figure 22 there is total fresh air delivery rate. We can see the infiltration level at around 0.7 air changes per hour. The mechanical ventilation rate changes with the occupancy level according to activity and HVAC tab settings. Internal gains, sensible cooling and latent cooling are shown here respectively.

The first chart represents the heat balance for building in which considers solar gains, equipment, occupancy and zone sensible cooling which increases by increasing the occupancy during the workday. As can be seen from the above chart the latent heat gains follows the occupancy schedules. finally based on the cooling calculation for design summer days the amount of cooling load for building is 36.45 kw so any HVAC system should be able to remove this amount of heat gain from the building.

6 SETTING UP SIMULATIONS

The likely performance of the HVAC system of a building can be modeled by running simulations. Real weather data is used in simulation to produce detailed information which can be used to assess aspects such as the energy, thermal and comfort performance of the system.

Simulation includes solar gains through glazing and consideration of heat conduction and convection between zones of deferent temperatures. It is important not to consider any HVAC system for a zone which is not requiring to be considered in simulation and should be switched off.

Before running and analyzing the results of simulation and performance of building HVAC system it is good to explain the selected HVAC system in Design Builder for this project. As explained before there are three deferent heating ventilation and air conditioning system considered for this project.

The first system which that we are going to study is VAV system. It is important to notice that all three systems are modeled in Design Builder as detailed HVAC because the simple HVAC doesn't give the accurate performance of the HVAC system.

6.1 VAV system

As mentioned before the Variable Air Volume which has been modeled in Design Builder is consist of air cooled chiller, Boiler and Air Handling Unit. The schematic diagram of the system is demonstrated in figure 24. The chiller is air cooled chiller to supply chilled water for air handling unit coils.

The boiler as explained before is to supply the heat water for air handling unit and internal unit coil. There is also a return line for chiller and boiler to make the return water to be chilled and hot for another loop. The air handling unit is to condition the supply air for each zone. There is also a set point manager for chiller and boiler output water to check if the output water is met the target temperature or not.

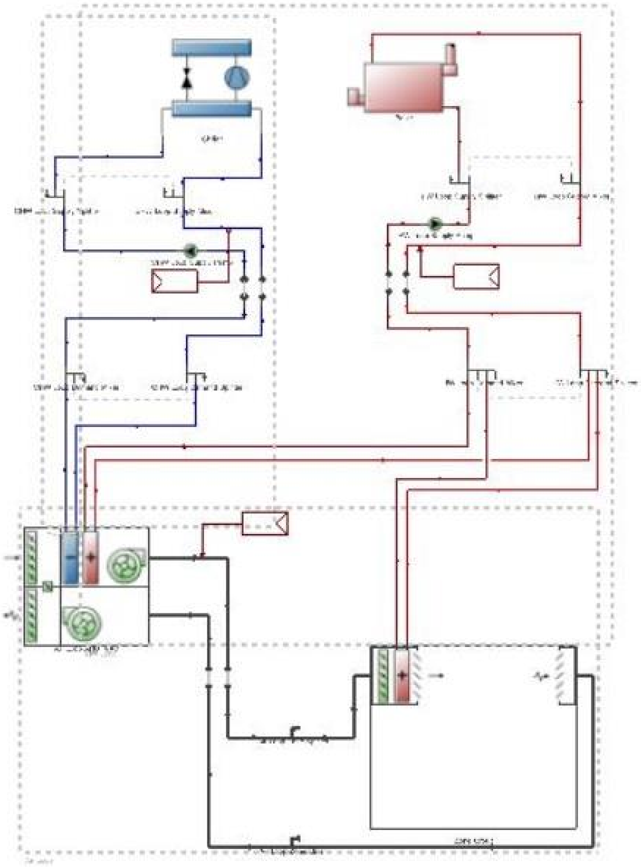


Figure 24 VAV loop modeled in Design Builder

6.2 Air handling unit

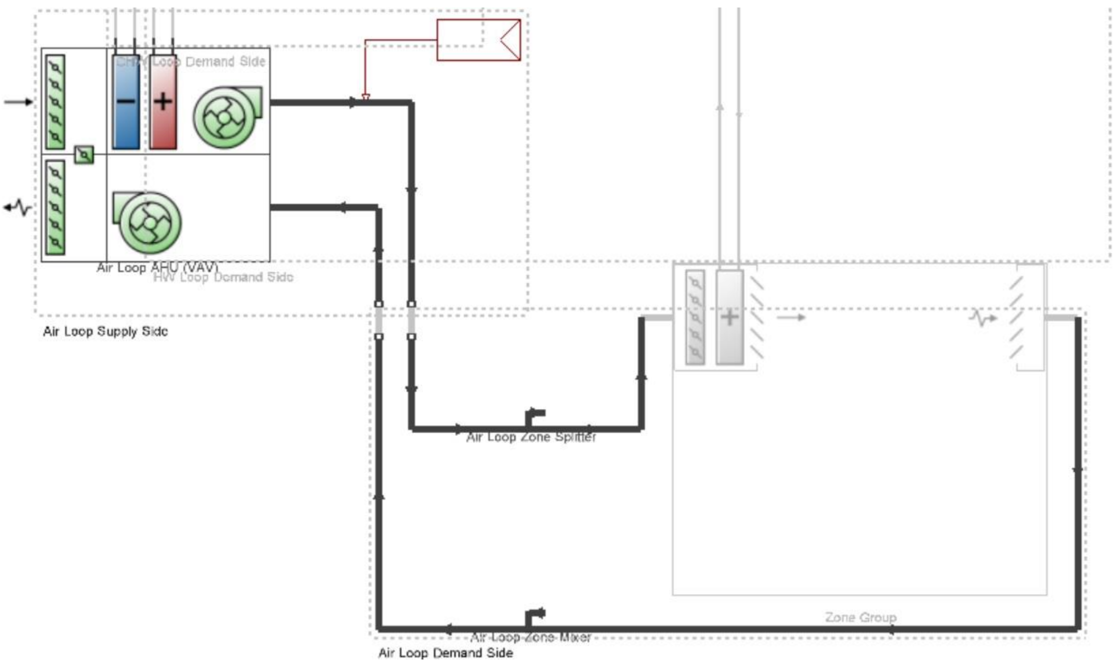


Figure 25 Air handling unit (AHU)

6.3 Hot water loop and chilled water loop

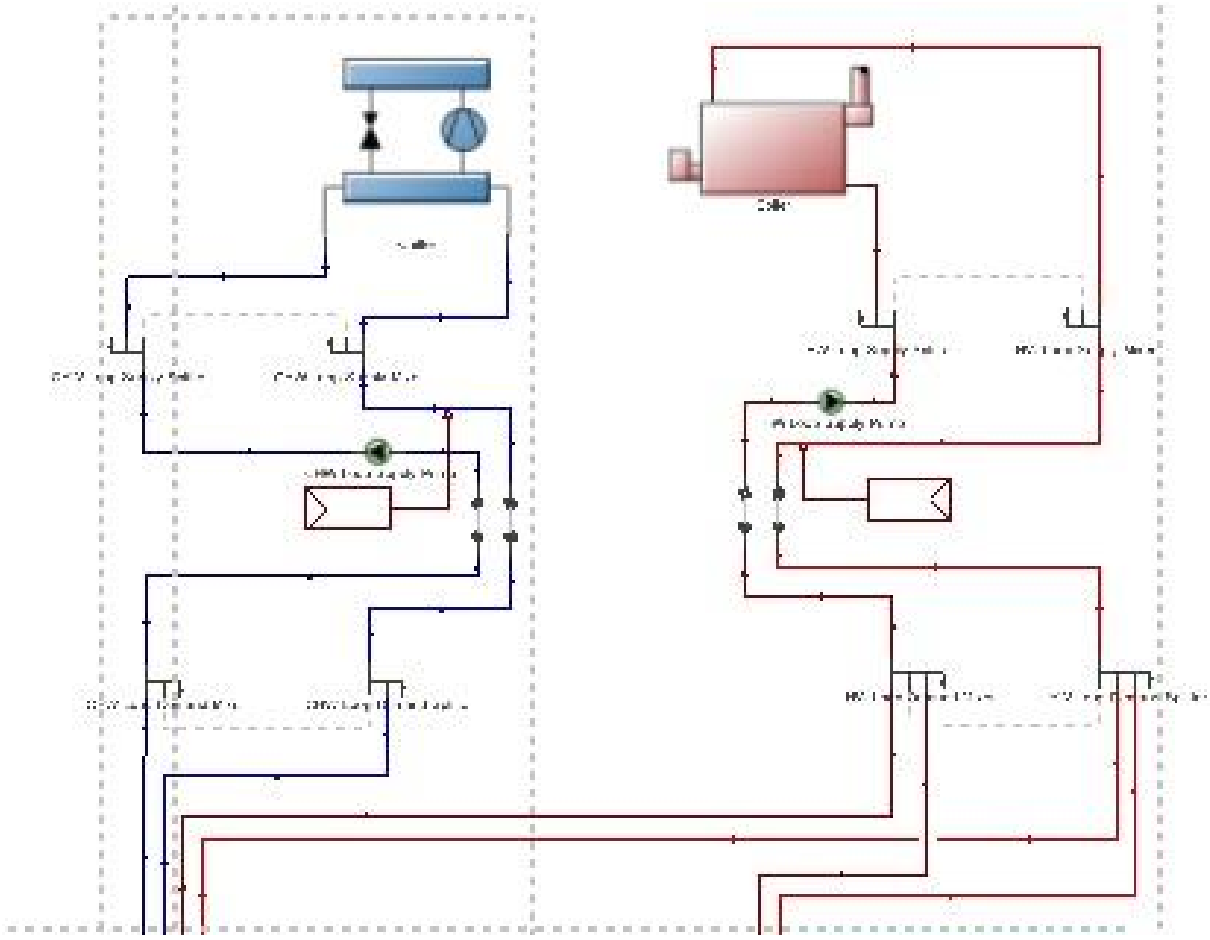


Figure 26 Hot water and chilled water loop

6.4 Simulation with VAV system

Now we can analyze the simulation of the building performance by considering the VAV system as its primary heating ventilation and air conditioning system. At first, we study the simulation for heating during the winter design week and then the cooling during the summer design week.

6.4.1 Heating design simulation

As mentioned before, the heating design can help us to select the proper heating system to satisfy the design winter condition. It also helps us to analyze the building performance during the winter design period. For calculating the heating system, the winter design week is selected in Design Builder which considers winter coldest temperature in site location based on weather data. This period is between 6th of Jan. to 12th of Jan. Here we can see the results of heating calculation.

Table 1 Building area

	Area (m²)
Total building area	529.77
Net conditioned area	386.48
Unconditioned area	143.29

Table 1 shows the net values for building used for conditioning and not conditioned zoned where are unoccupied during the occupancy. Also, we can see the amount of end uses heating and electricity for VAV system to satisfy the winter design condition. we can see the boiler nominal capacity as well with its nominal efficiency.

Table 2 Heating end uses

	Electricity (KW)	Natural gas (KW)
Heating	1.11	1713.21
Cooling	298.09	0.00
Interior lighting	100.85	0.00
Interior equipment	276.01	0.00
Fans	135.42	0.00
pumps	8.76	0.00
Total	820.23	1713.21

Table 3 Boiler characteristics

	Type	Nominal capacity(W)	Nominal efficiency(W/W)
Boiler	Hot water boiler	35965.34	0.89

Figure 27 shows the simulation results for fuel consumption, air temperature and comfort, heat balance, system loads and total fresh air during winter design week respectively which we can study them.

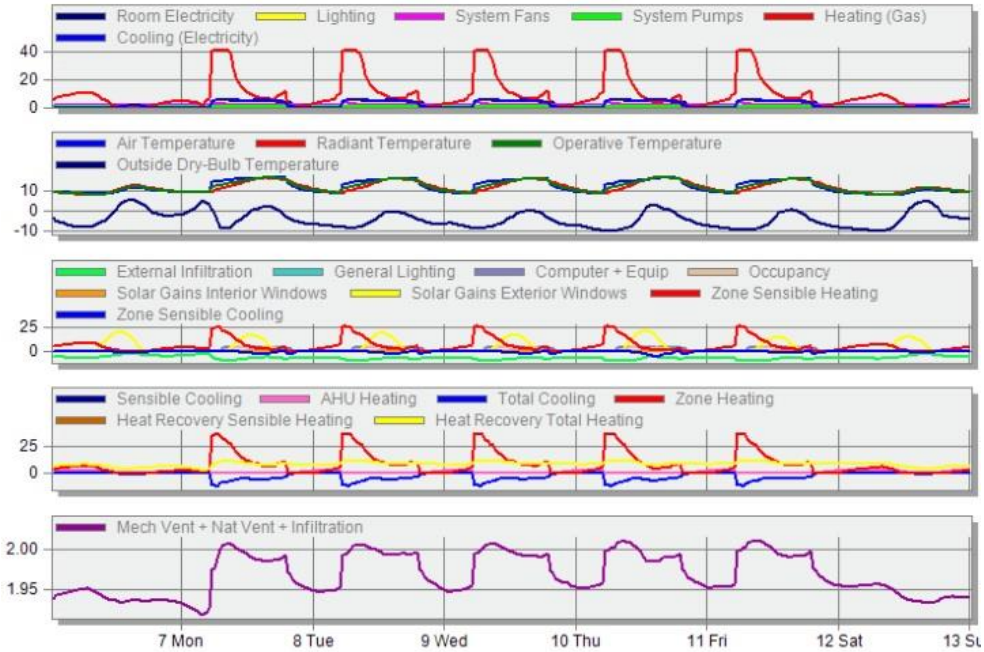


Figure 27 Simulation results at building level for VAV system

6.4.1.1 Fuel breakdown

At building level, we can see the fuel breakdown. The fuel consumption associated to heating system is shown in red, this shows the heating system operating in the early hours to maintain set back temperature in the building and peaking to reach the set point temperature just prior to occupation.

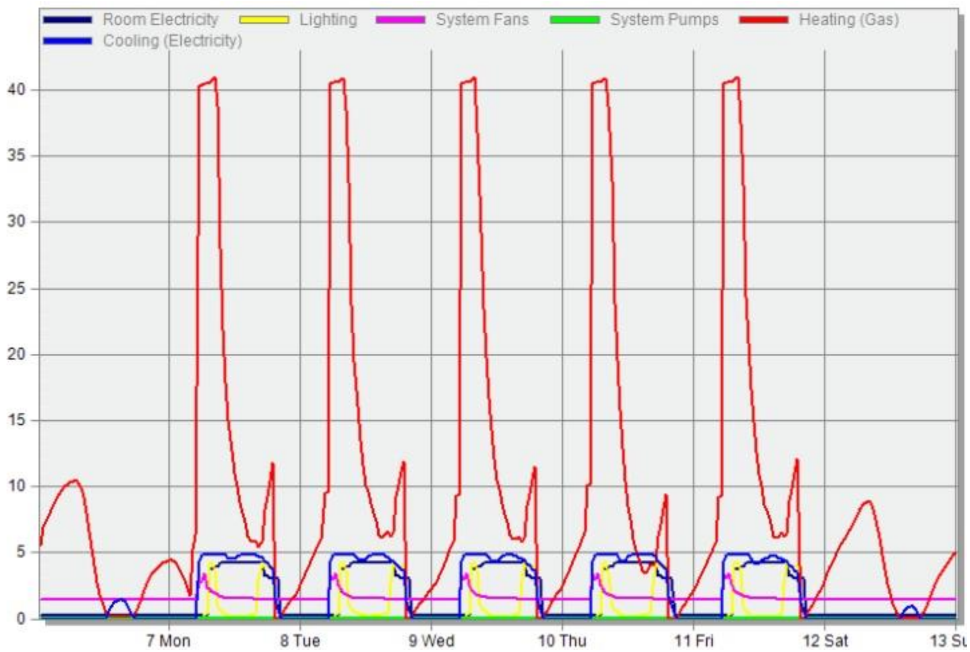


Figure 28 Fuel breakdown at building level

Every peak in the graph prior to occupation occurs between 5 AM to 7 AM then the load on heating system drops through the day because the thermal mass warms up and the heat gains to the space from other sources increase. If we look at the blue lines, we can see the behavior of electricity consumption for each zone during the occupancy and it has a flat trend during the working day and drops in weekend period which is due to zone control system selected for each zone to control the lighting which results in reduction of energy consumption of the building.

6.4.1.2 Total fresh air

Figure 29 demonstrates the fresh air change during the week. Here the air change rate is relatively low. The variance in infiltration appears to be significant but if we check the Y axis we can see the variation is small, although the infiltration rate is set to constant value it is based on reference temperature so dose change with variation in the inside temperature and the air density.

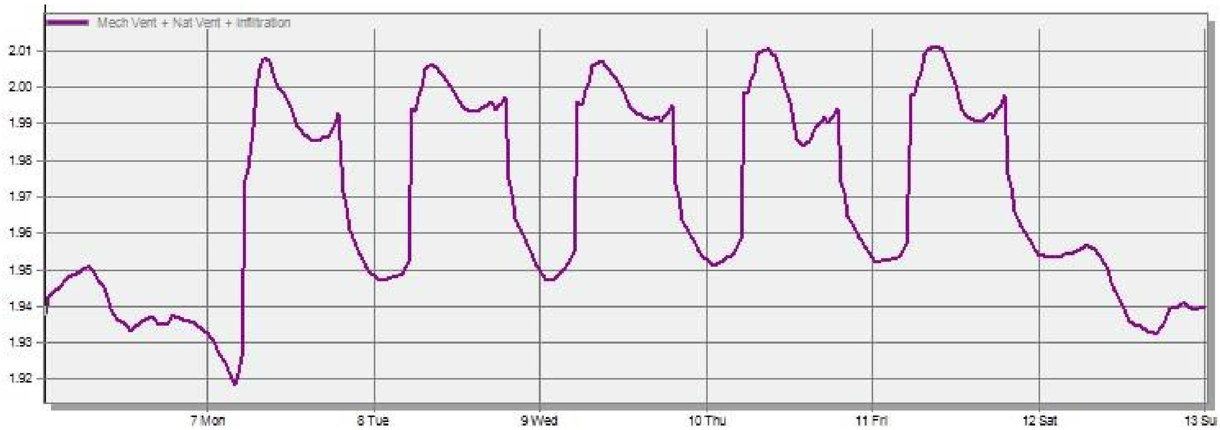


Figure 29 Mechanical and natural ventilation

6.4.1.3 Heat balance

Figure 30 illustrates the heat balance performance of the building in kilo watt during the winter design week. The red pattern shows the zone sensible heating required to compensate the zone sensible cooling. The graph shows there is a peak at the beginning of the workday just prior the occupancy to keep the set point of the heating system and it drops significantly during the day by increasing heat from other sources in zones and there is a slight increase of the heating system in the afternoon by increasing the zone sensible cooling. The trend repeats for the other day. The green line shows the general lighting performance which drops ideally during the full occupancy and that's because of the lighting control system which turns off the light by increasing the sun light.

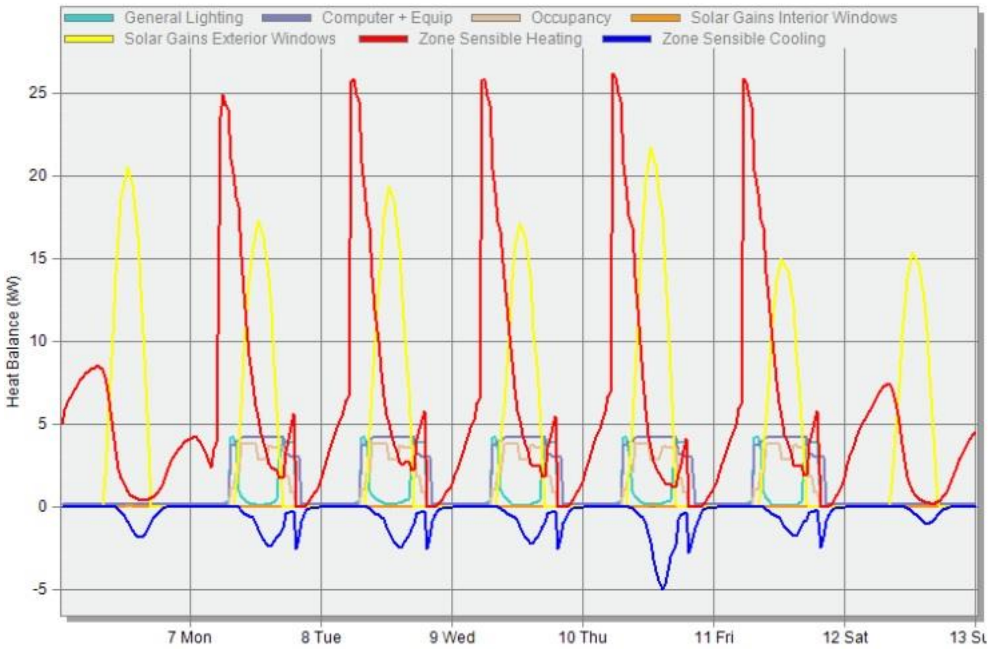


Figure 30 Heat balance at building level

6.4.1.4 CO2 production

CO2 production of the HVAC system during the winter deign week is demonstrated in figure 31 and has the same trend as the heat balance of the building. The CO2 production increases at around 7:30 AM prior the occupancy which means the heating system is working to meet the set point temperature which was determined in the activity tab and by decreasing the heating system performance during the day the amount of CO2 production decreases as well.

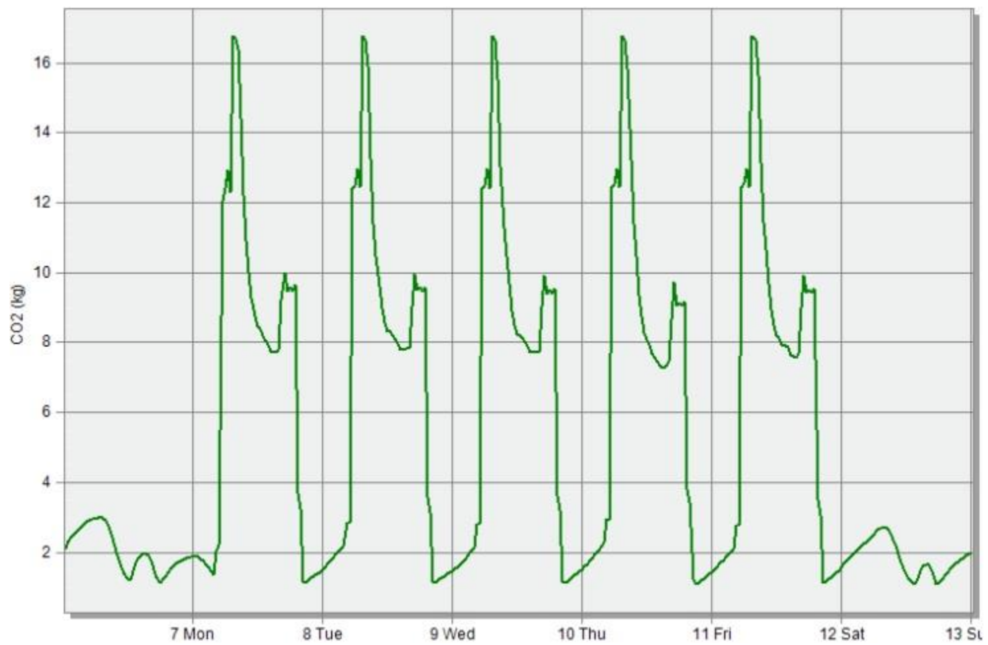


Figure 31 Co2 production at building level

6.4.1.5 System loads

The HVAC load during the winter design week is shown in figure 32 and illustrates the amount of load applied on heating system to offset the total cooling which is 37 KW before the full occupancy for each working day to prepare the heating set point and 7 KW in the afternoon.

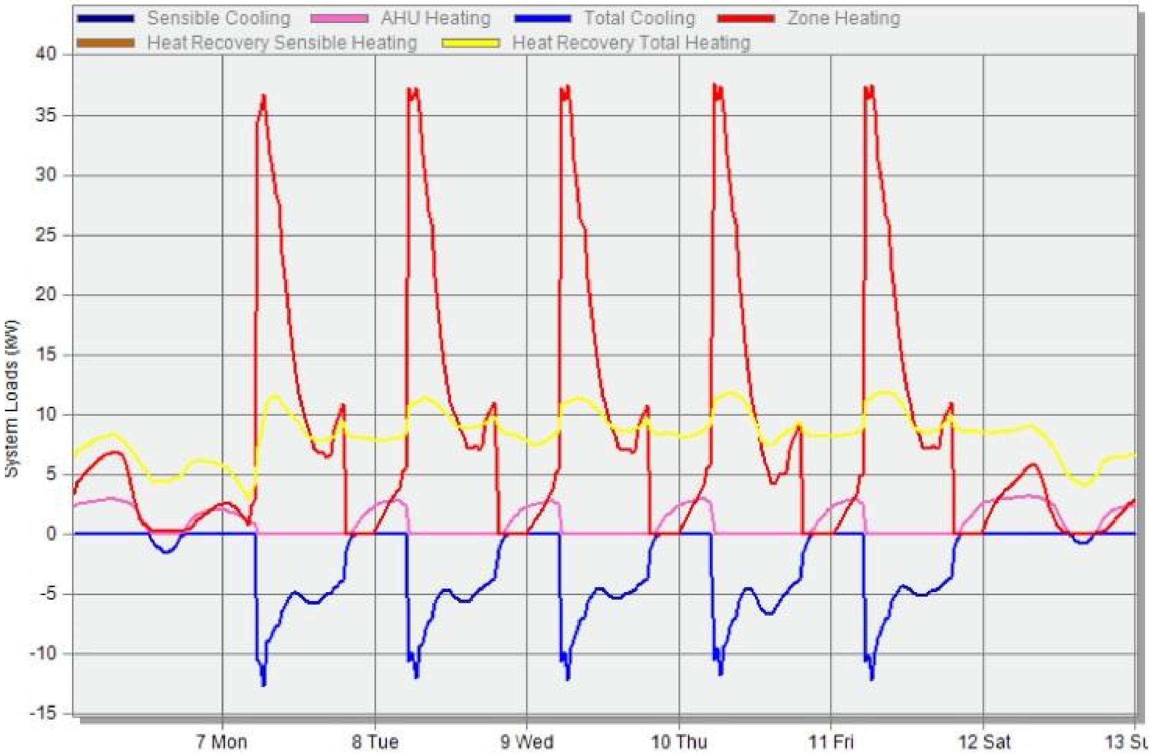


Figure 32 Heating load on system

6.4.1.6 Conference room comfort situation

To see better performance of the heating system to make sure the set point and set back temperatures are applied well we can go to each zone to see if it is applied or not. As an example, the conference room is selected which has the largest area in the building.

As can be seen from the chart in figure 33 the air temperature never drops below 22°C because the air temperature is the control parameter and it doesn't fall below 12°C which guarantees the performance of the system and satisfying the comfort situation for the occupants.

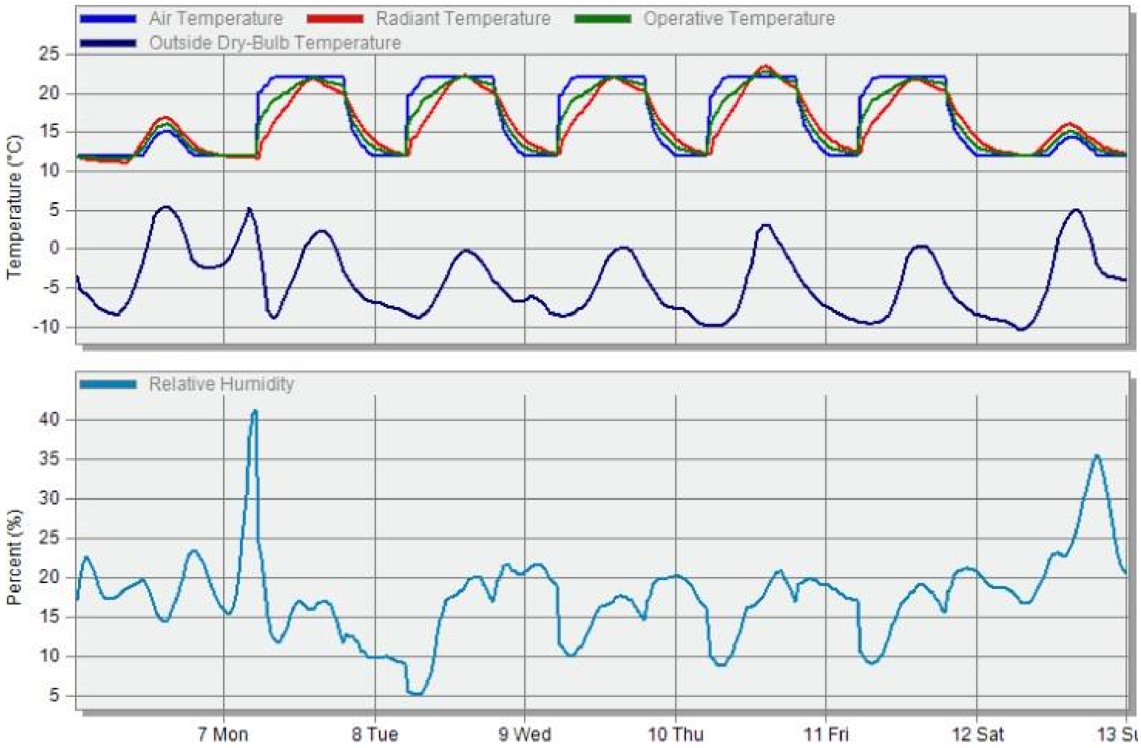


Figure 33 conference room comfort situation

6.4.2 Cooling design simulation

After analyzing the results of the heating design, we can look at the data reported regarding cooling design simulation which helps us to select the proper cooling system to satisfy the heating load applied on the building during the hot days. For calculating the cooling system, the summer design week is selected in Design Builder which is between 3rd of Aug to 9th of Aug.

Table 4 Building area

	Area (m²)
Total building area	529.77
Net conditioned area	386.48
Unconditioned area	143.29

The table 4 shows the net values for building used for conditioned and not conditioned zone which are unoccupied during the occupancy. Also, we can see the amount of end uses cooling and electricity for VAV system to satisfy summer design condition in table 6. The chilled water flow rate for chiller and chiller capacity are represented in the table 5.

Table 5 Chiller characteristics

	Type	Chilled water flow rate (m^3/s)	Design size reference capacity (w)
chiller	Air cooled chiller	0.002117	48865.42

Table 6 Cooling end uses

	Electricity (KW)	Natural gas (KW)
Heating	0.03	45.53
Cooling	886.96	0.00
Interior lighting	10.22	0.00
Interior equipment	276.01	0.00
Fans	129.63	0.00
pumps	10.9	0.00
Total	1313.74	45.53

Figure 34 explains the simulation results for fuel consumption, air temperature and comfort, heat balance, system loads and total fresh air during summer design week respectively which we can study them.

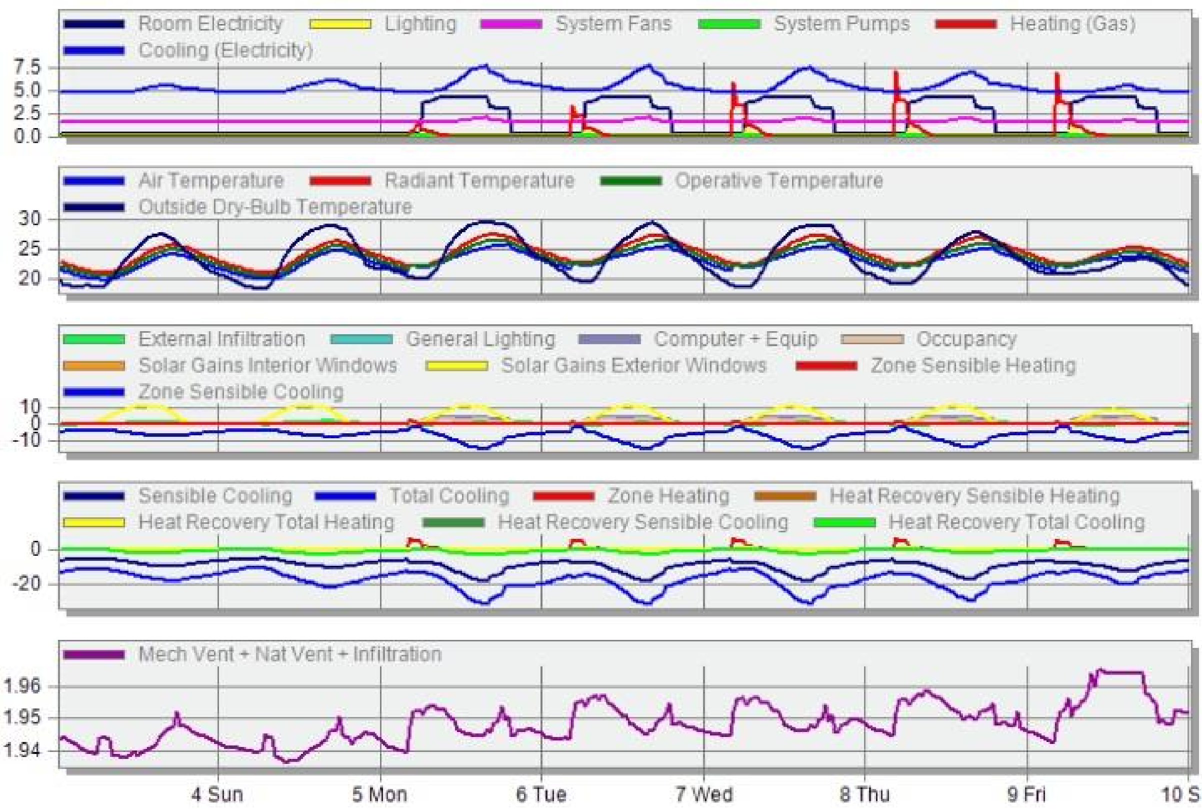


Figure 34 Cooling deign at building level with VAV system

6.4.2.1 Fuel breakdown

The graph below carries information regarding the fuel breakdown of the VAV system during cooling season. Figure 35 demonstrates that the chiller starts working in the morning before the full occupancy to satisfy the set point and there is a peak in the afternoon, thus, the system experiences more fuel consumption at this time compare to other time of the day. The room electricity consumption has a flat trend during full occupancy due to scheduling for each equipment.

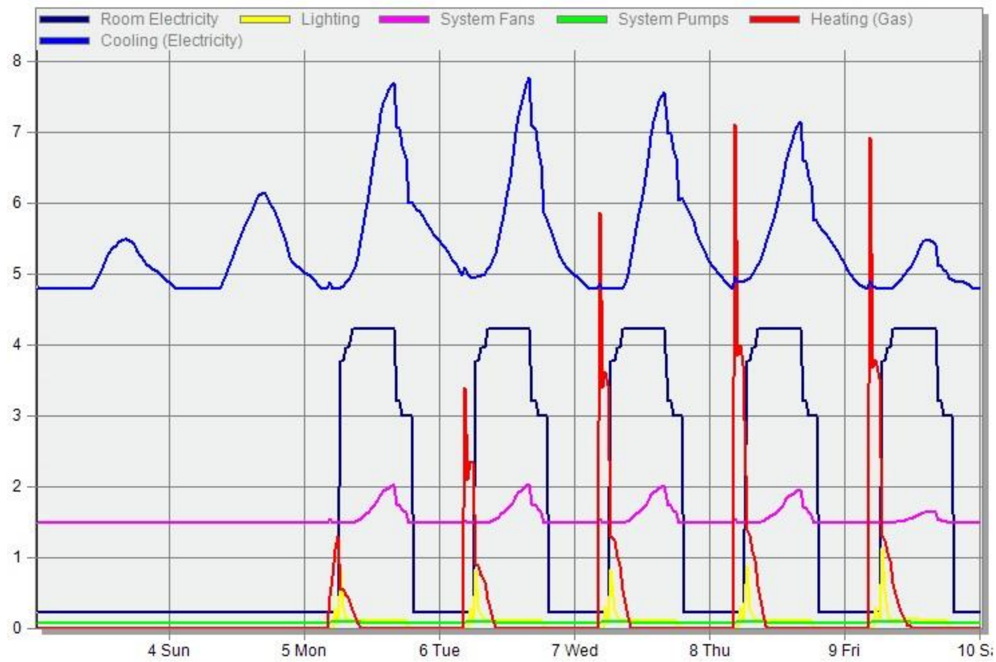


Figure 35 fuel breakdown at building level

Fuel consumption associated to lighting has a small portion due to lighting control for each zone.

6.4.2.2 Heat balance

Figure 36 shows the amount of cooling required for each day to offset the heat gain during the day. There is a peak at the beginning of the day before the occupancy to satisfy the cooling set point to guarantee the comfort situation and by the end of the day by decreasing the ambient heat gain there is a reduction in cooling system performance. The computer and equipment, solar gain through exterior and interior windows and occupancy level are demonstrated as well.

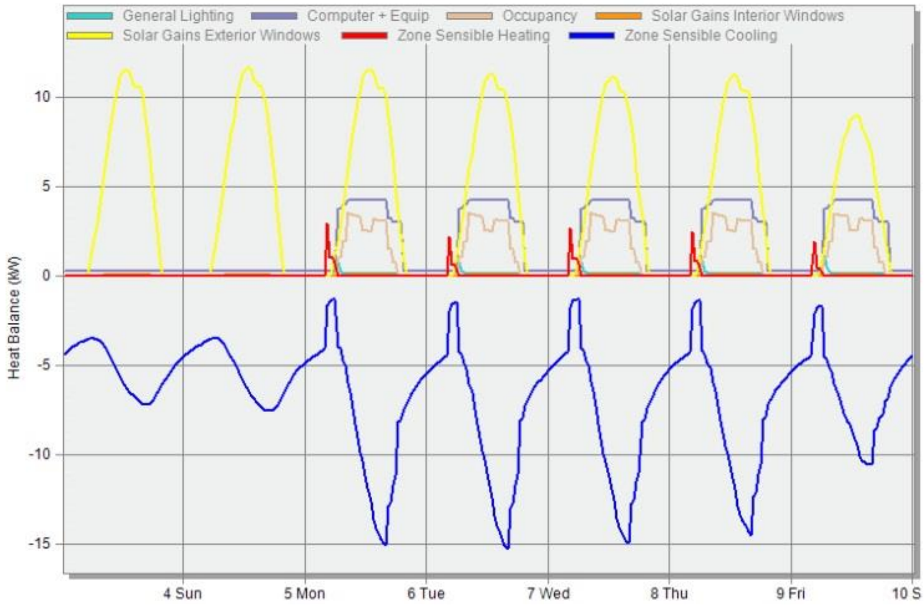


Figure 36 heat balance at building level

6.4.2.3 System load

The peak load generally happens in the afternoon when the heat gain through building envelop increases and we have heat flux from exterior walls and external openings to zones. The total cooling load applied on cooling system to remove heat from the building is shown on the graph below and the peak load on system occurs 4 pm.

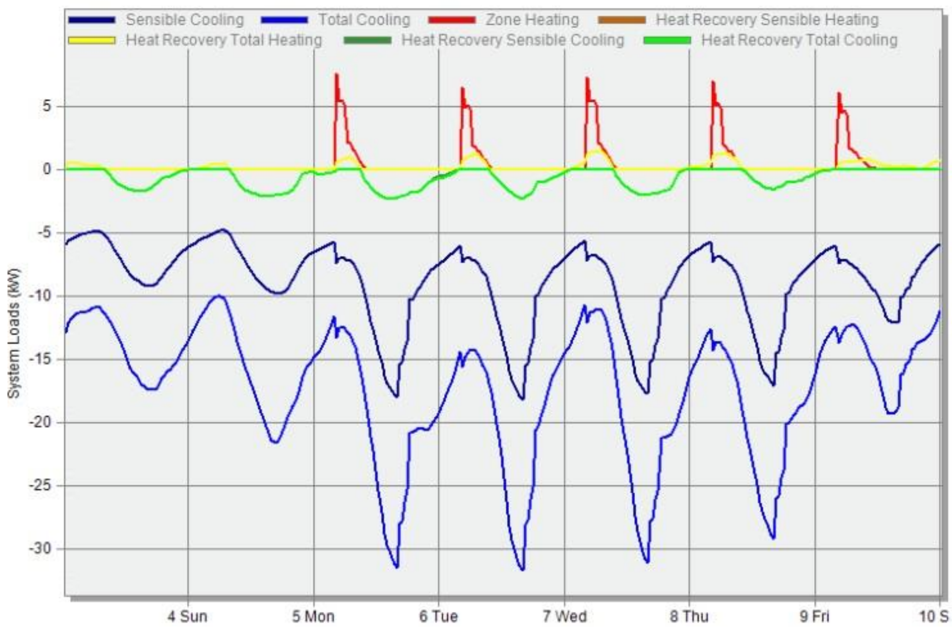


Figure 37 cooling load on VAV system

6.4.2.4 Conference room cooling comfort

By going to conference room as an example, we will be sure if the set point and set back temperature are satisfied by the cooling system. By looking at the figure 38 there is a rise in air temperature before the occupancy to satisfy the set point temperature which was set to 24°C during full occupancy. The setback temperature never exceeds above 28°C which is the setback temperature determined in the activity level.

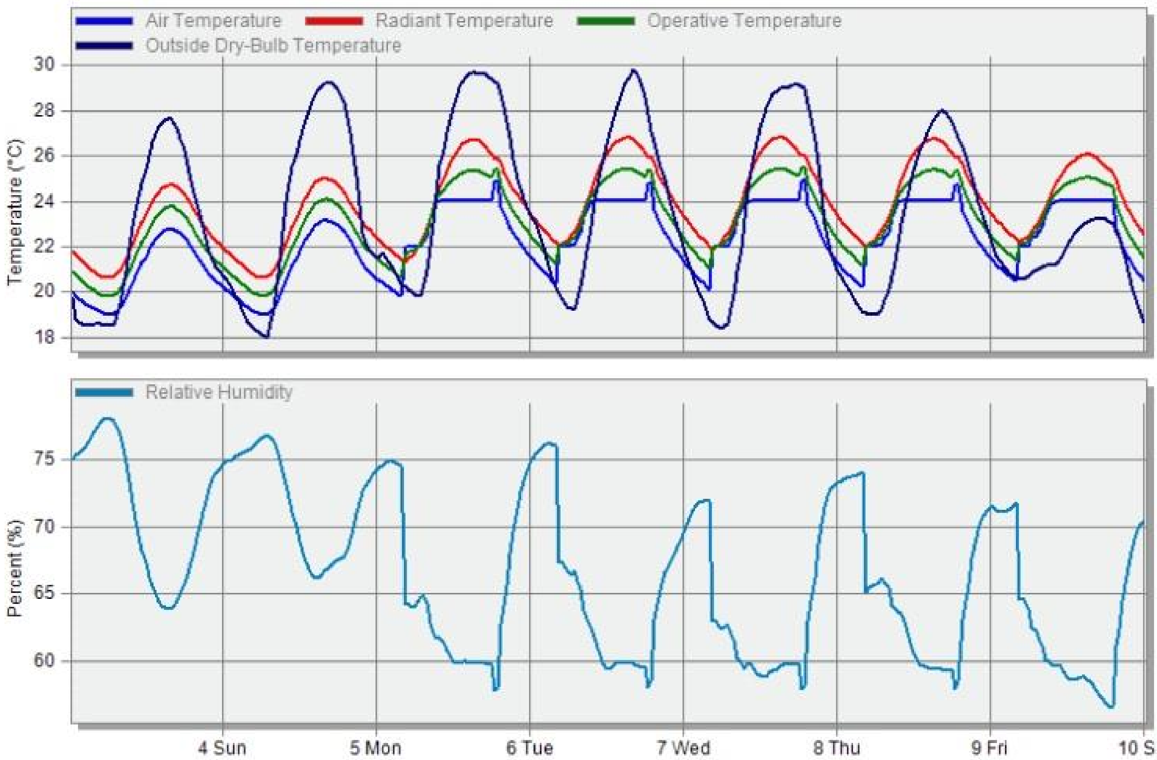


Figure 38 conference room cooling comfort with VAV

6.4.2.5 Conference room heat balance for cooling design

The graph in figure 39 explains the amount of zone sensible cooling required for conference room during summer design week. The peak in trend happens around 3 PM when there is full occupancy , so, the cooling system uses most energy to remove heat from the zone. the yellow line shows the solar gains through exterior windows which has the same behavior for each working day. The computer and equipment graph work properly based on the determined schedule in the activity tab for each zone.

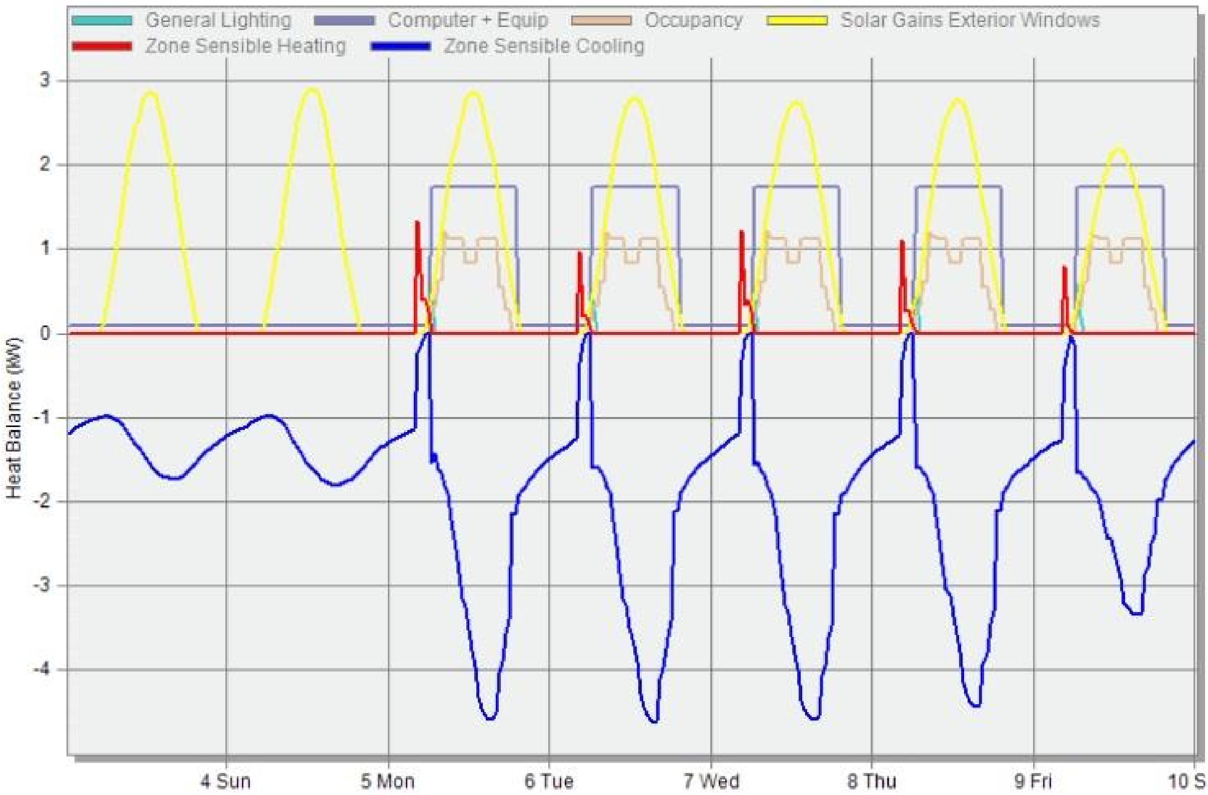


Figure 39 Conference room heat balance with VAV

7 Fan coil unit system

As explained before this system is one of the most used HVAC system for deferent constructions. The system consists of a chiller to provide chilled water, boiler to provide hot water during the cold season and fan coil units which are used as terminal unit. There is deferent type of fan coils. They can be mounted on ceiling, wall or put on the floor.

The fan coil system for this thesis is consist of an air-cooled chiller which provides chilled water for internal fan coil unit and a boiler which supplies hot water for coils of indoor fan coil unit. The indoor fan coil units are located on the floor. There is a set point manager for chiller and boiler output line to check if the temperature of output water is equal to what is determined. There are also splitter and mixer even for chilled water and hot water loop.

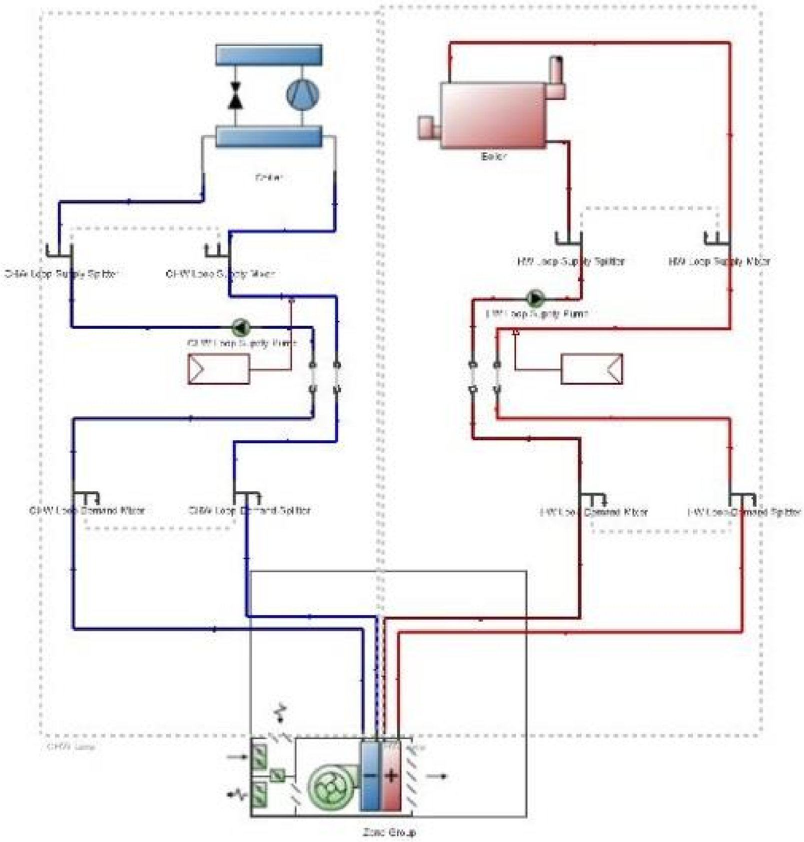


Figure 40 Fan coil system

There are two pumps, one for chilled water loop and one for hot water loop to return the water to chiller and boiler to compensate the lost energy. Figure 40 shows the system layout.

7.1 Zone group

In figure 41 we can see the zone group supplied by fan coil system. In each zone a fan coil unit is located for heating and cooling.

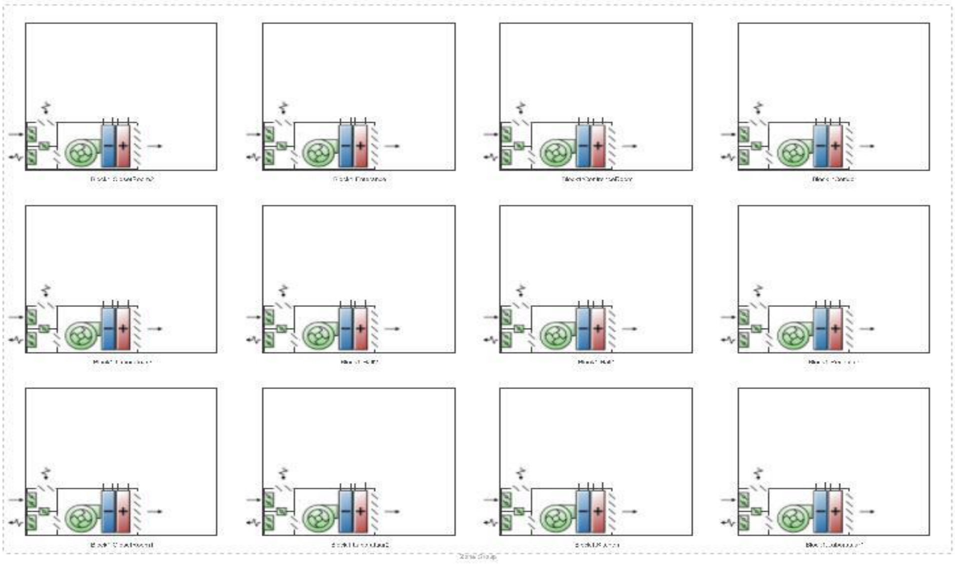


Figure 41 zone groups

7.2 Simulation results for fan coil system

We analyze the simulation of the building performance by considering the fan coil system as its primary heating ventilation and air conditioning system. At first, we study the simulation results for heating during the winter design week and then the cooling results during the summer design week.

7.2.1 Heating design simulation

The heating calculation helps us to select the proper heating system to satisfy the design winter condition. It also helps us to analyze the building performance during the winter design period. For calculating the heating system, the winter design week is selected in

Design Builder which considers winter coldest temperature in site location based on weather data. This period is between 6th of Jan – 12th of Jan.

Table 7 Building area

	Area (m²)
Total building area	529.77
Net conditioned area	386.48
Unconditioned area	143.29

The table 7 shows the net values for building used for conditioning and not conditioned zones where are unoccupied during the occupancy. Also, we can see the amount of end uses heating and electricity for fan coil system to satisfy the winter design condition. we can see the boiler information as well.

Table 8 Boiler characteristics

	Type	Nominal capacity(W)	Nominal efficiency(W/W)
Boiler	Hot water boiler	33466.7	0.89

In figure 42 we can see the results of heating calculation. The graph shows the result for fuel breakdown, comfort level, heat balance, load on HVAC system and infiltration at building level. The amount of electricity which has been used in each room can be seen for each working day in heat balance part of the graph which is the first graph.

The section regarding comfort demonstrates the comfort situation at building level which gives the mean value at building level. As can be seen from the comfort section the set point and set back temperatures are satisfied by the system, therefore, we can claim that the system is working well and can meet the temperatures which have been already set in activity tab.

The reason is that the air temperature is the control parameter, thus, the system starts working prior the occupancy. That is why there is a rise in the morning before occupying the building. The green line is operative temperature which explains the comfort situation at building level for each working day. The red line demonstrates the radiant temperature due to radiant gain of the building. Outside dry bulb behavior during winter design situation is represented as well in comfort section of the graph and shows the fluctuation of the outside temperature during winter design. The other parts of the simulation are explained in the following sections.

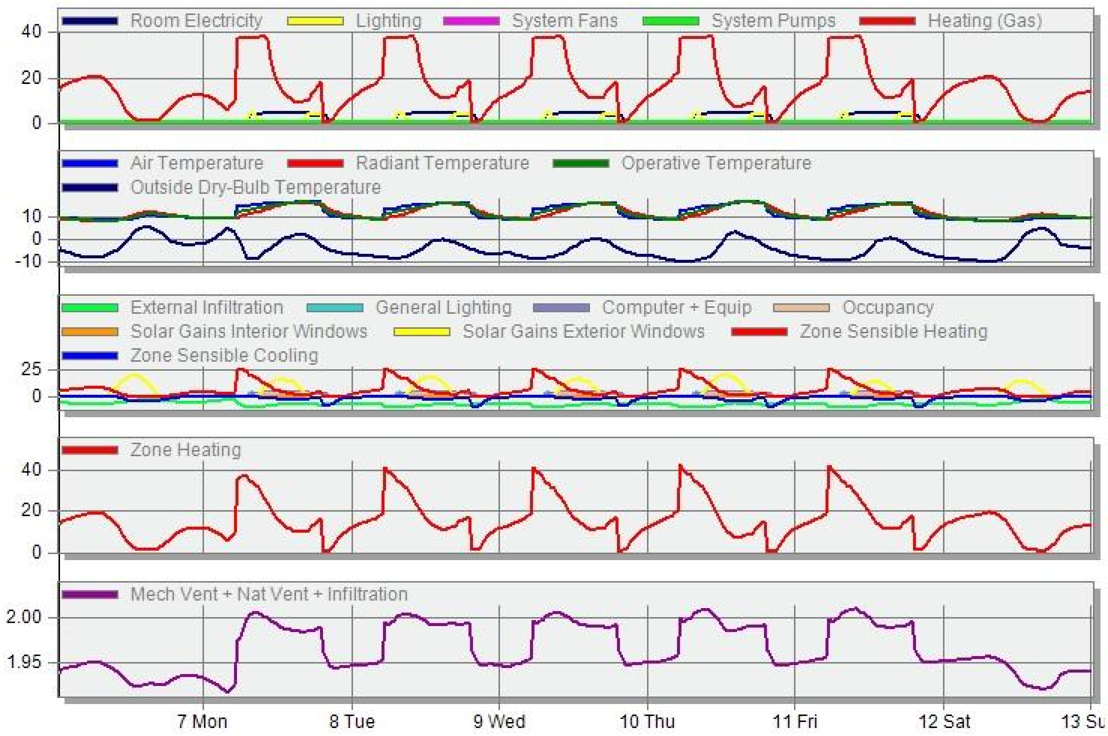


Figure 42 Heating design simulation at building level with fan coil system

Table 9 Heating end uses for fan coil system

	Electricity (KW)	Natural gas (KW)
Heating	1.88	2722.05
Cooling	0.00	0.00
Interior lighting	100.85	0.00
Interior equipment	276.01	0.00
Fans	55.52	0.00
pumps	3.81	0.00
Total	438.07	2722.05

7.2.2 Fuel breakdown

we can see the fuel breakdown at building level. The fuel consumption associated to heating system is shown in red, this shows the heating system operating in the early hours to maintain set back temperature in the building and peaking to reach the set point temperature just prior to occupation then the load on heating system drops through the day because the thermal mass warms up and the heat gains to the space from other sources increase. If we look at the blue lines, we can see the behavior of electricity consumption for each zone during the occupancy and it has a flat trend during the working day and drops in weekend period which is due to zone control system selected for each zone to control the lighting which results in reduction of energy consumption of the building.

Figure 43 Fuel breakdown at building level with fan coil system

7.2.3 Heat balance

The figure 44 shows the heat balance performance of the building in kilo watt during the winter design week. The red pattern shows the zone sensible heating required to compensate the zone sensible cooling. The graph shows there is a peak at the beginning of the workday just prior the occupancy to keep the set point of the heating system and it drops significantly during the day by increasing heat from other sources and there is a slight increase of the heating system in the afternoon by increasing the zone sensible cooling. The green line shows the general lighting performance which drops ideally during the full occupancy and that’s because of the lighting control system which turns off the light by increasing the sun light.

The zone sensible cooling trend shows the amount of cooling which should be removed from the building. The results demonstrate that this amount is in maximum during the night, but the heating system is not working because the building is not occupied in that moment.

The solar gain through windows represented in this part. It has almost the same behavior for each working day.

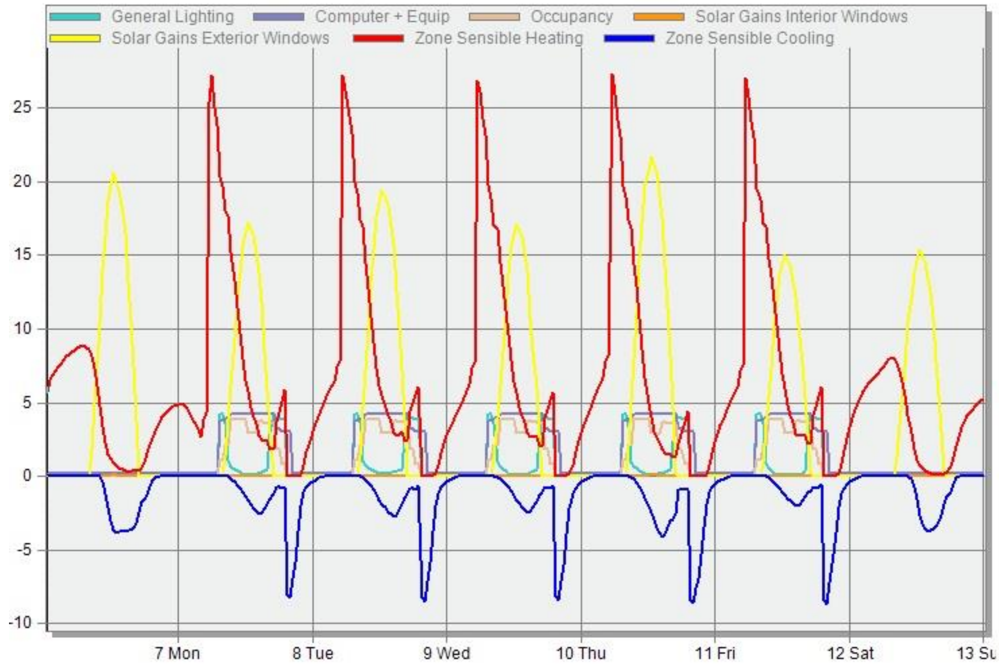


Figure 44 Heat balance at building level with fan coil system

7.2.4 Total fresh air

Figure 45 shows the fresh air change during the week. Here the air change rate is relatively low. The variance in infiltration appears to be significant but if we check the Y axis we can see the variation is small, although the infiltration rate is set to constant value it is based on reference temperature so dose change with variation in the inside temperature and the air density.

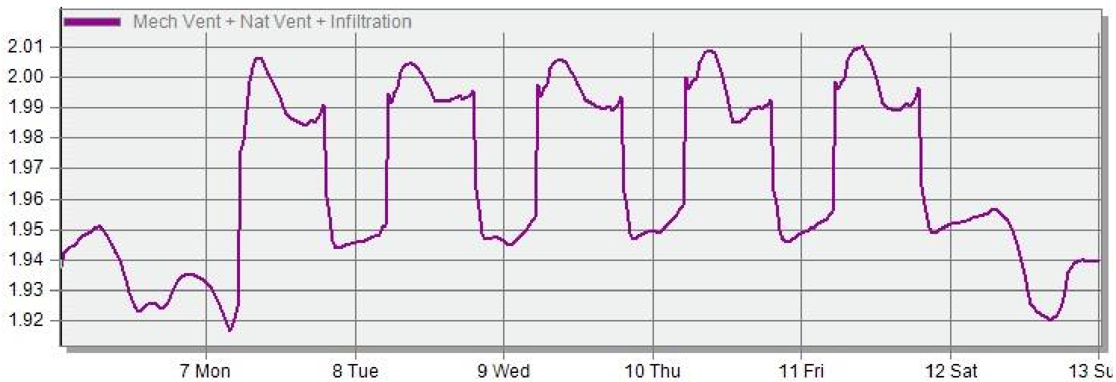


Figure 45 Mechanical and natural ventilation at building level

7.2.5 CO2 production

The CO2 production of the HVAC system during the winter deign week is demonstrated in figure 46 and has almost the same trend as the heat balance of the building. The CO2 production increases at around 7:30 AM prior the occupancy which means the heating system is working to meet the set point temperature which was determined in the activity tab and by decreasing the heating system performance during the day the amount of CO2 production decreases as well. Decreasing the outside dry bulb temperature causes a slight increase in the heating system performance which leads to increase of CO2 production.

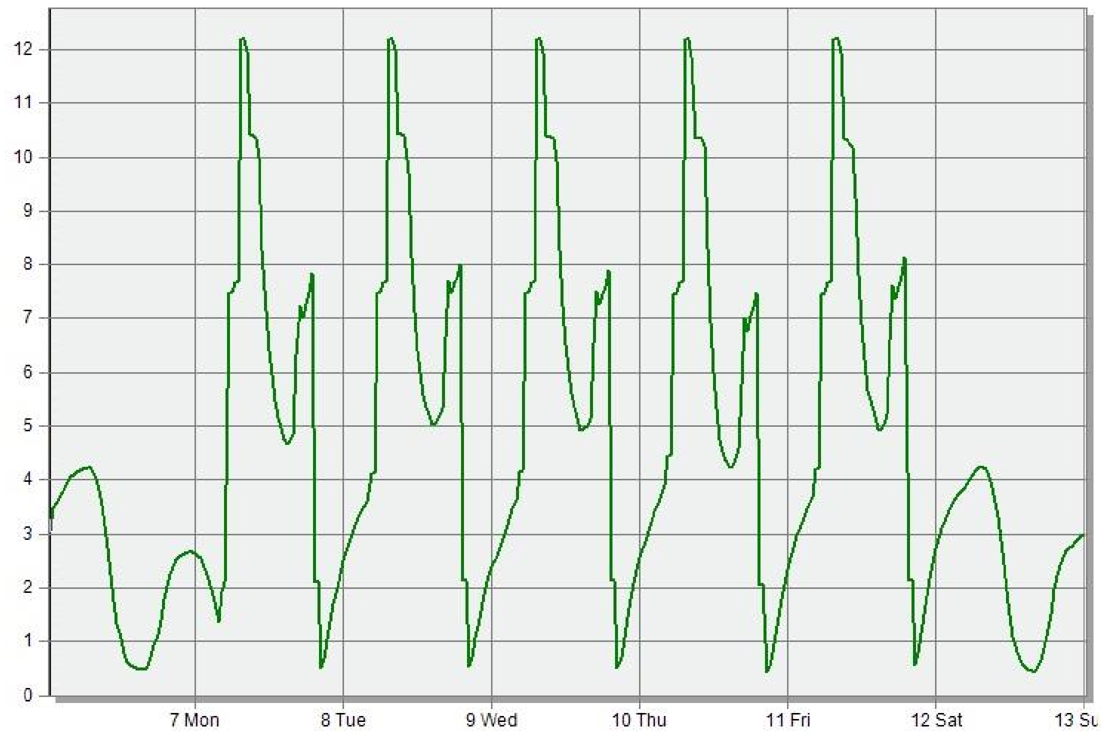


Figure 46 Amount of CO2 production at building level with fan coil system

7.2.6 System loads

The HVAC load during the winter design week is shown in figure 47 and illustrates the amount of load applied on heating system to offset the cooling load for each working day. The graph shows there is an increase in thermal load on heating system in the early hours before the occupancy.

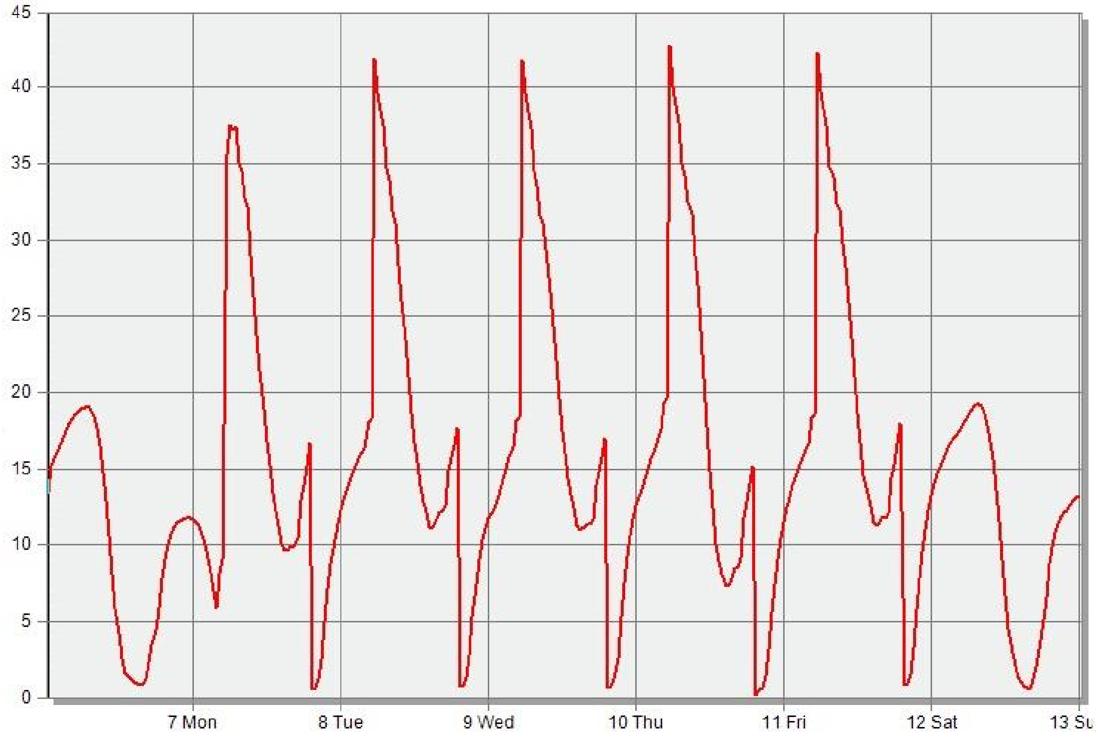


Figure 47 Heating load applied on system

7.2.7 Conference room comfort situation

To see better performance of the heating system to make sure the set point and set back temperatures are applied well we can go to each zone to see if it is applied or not. As an example, the conference room is selected which has the largest area in the building.

As can be seen from the chart in figure 48 the air temperature never drops below 22°C because the air temperature is the control parameter and it doesn't fall below 12°C which guarantees the performance of the system and satisfying the comfort situation for the occupants. The second graph in figure 48 illustrates the relative humidity behavior during the week.

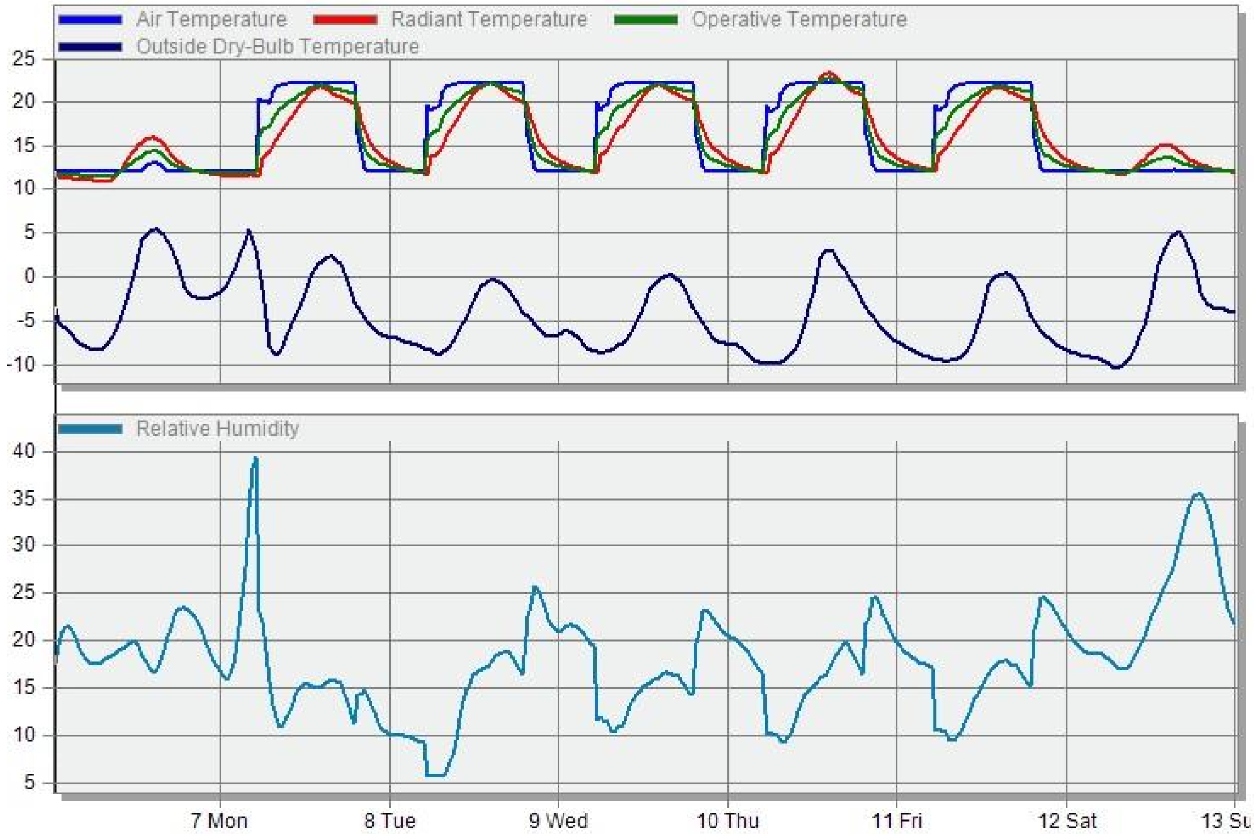


Figure 48 Conference room comfort situation with fan coil system

7.3 Cooling design simulation

After observing the results of the heating design simulation, we can look at the data reported regarding cooling design simulation which can help us to select the relevant cooling system to satisfy the cooling load applied on the building during the hot days. For calculating the cooling system, the summer design week is selected in Design Builder which is between 3rd and 9th of August.

The net conditioned area and unconditioned area for the building is just like the heating design. we can see the amount of end uses cooling and electricity for fan coil system to satisfy summer design condition. Also, the chilled water flow rate for chiller and chiller capacity are represented in table 10.

Table 10 Chiller characteristics

	Type	Chilled water flow rate (m^3/s)	Design size reference capacity (w)
chiller	Air cooled chiller	0.001661	38345.22

Table 11 Cooling end uses with fan coil system

	Electricity (KW)	Natural gas (KW)
Heating	0.00	0.00
Cooling	308.77	0.00
Interior lighting	10.22	0.00
Interior equipment	276.01	0.00
Fans	55.52	0.00
pumps	3.55	0.00
Total	654.07	0.00

Figure 49 shows the results of cooling simulation for fuel consumption, air temperature and comfort, heat balance, system loads and total fresh air during summer design week respectively which we can study them.

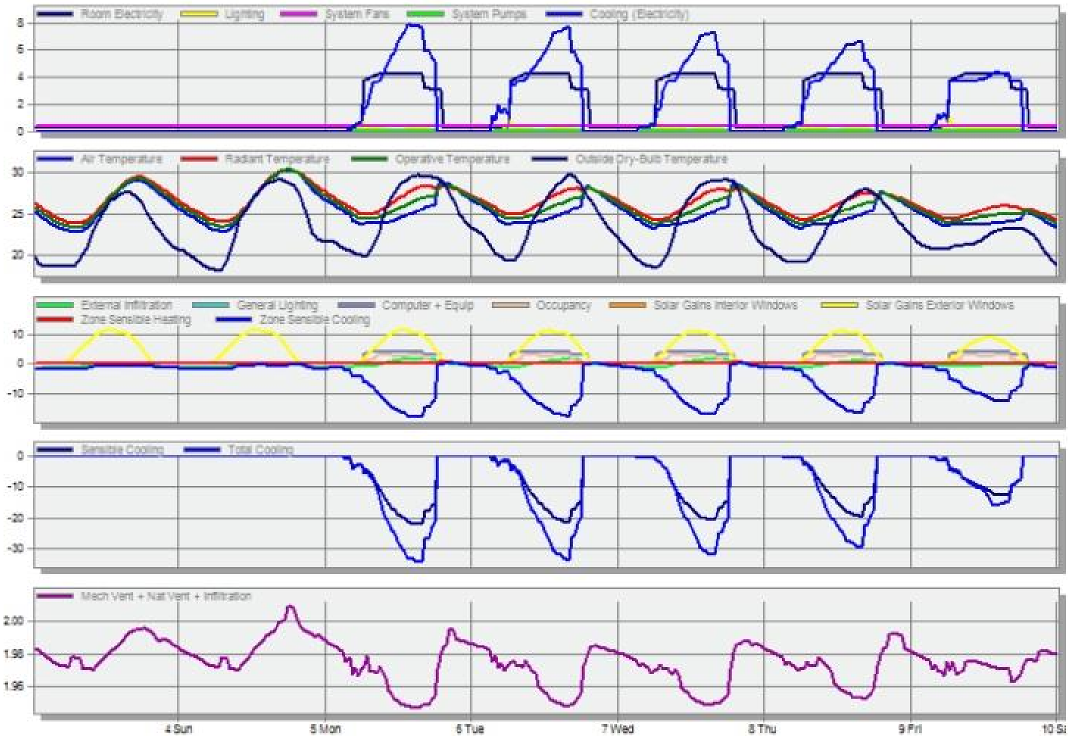


Figure 49 Cooling design simulation at building level with fan coil system

7.3.1 Heat balance

Figure 50 demonstrates the amount of cooling required for each day to offset the heat gain during the day. There is a peak at the beginning of the day before the occupancy to satisfy the cooling set point to guarantee the comfort situation. In the end of the day by decreasing the ambient heat gain there is a reduction in cooling system performance. The computer and equipment, solar gain through exterior and interior windows and occupancy level are demonstrated as well.

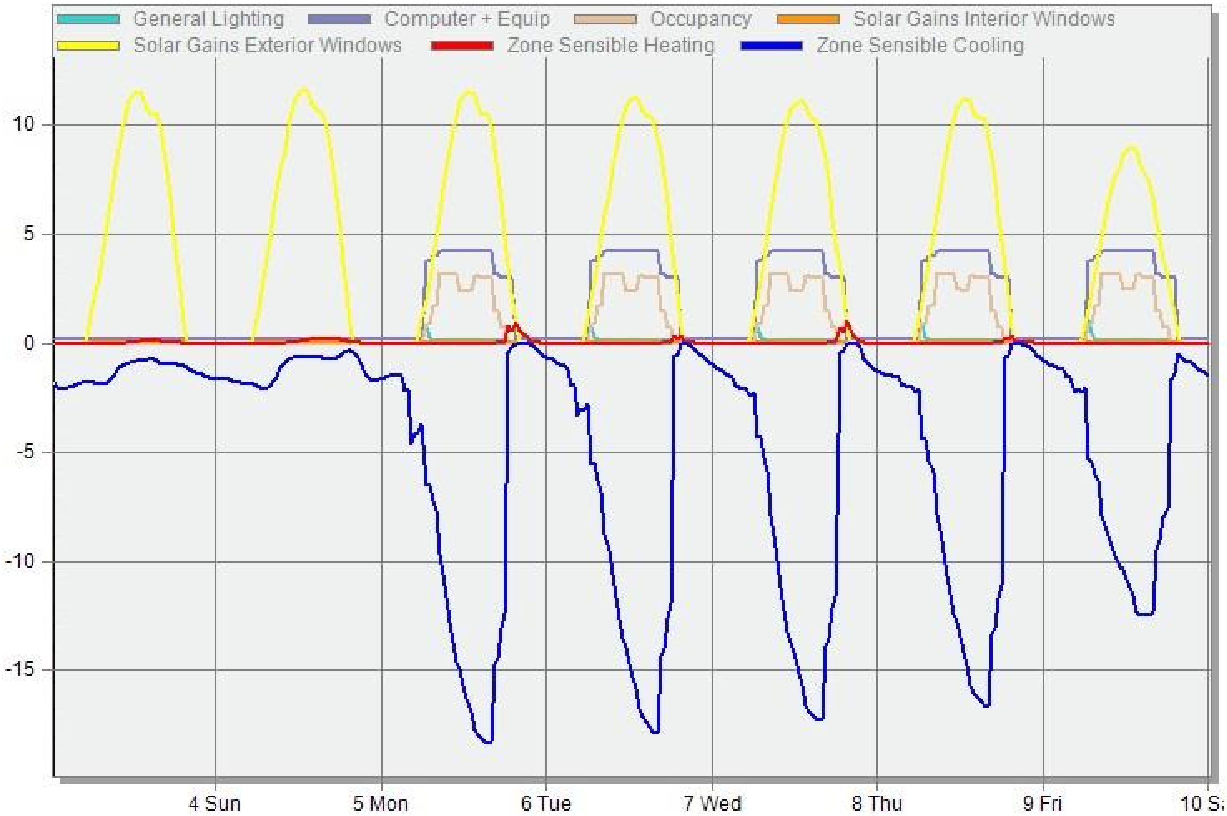


Figure 50 Heat balance at building level with fan coil system

7.3.2 Fuel breakdown

In figure 51 we can see the fuel breakdown at building level. The fuel consumption associated to cooling system is shown in blue, this shows the cooling system operating in the early hours to maintain set back temperature in the building and peaking to reach the set point temperature just prior to occupation then the load on cooling system drops through the day by decreasing the outside dry bulb temperature. we can see also the behavior of electricity consumption for each zone during the occupancy and it has a flat trend during the working day and drops in weekend period which is due to zone control system selected for each zone to control the lighting which results in reduction of energy consumption of the building.

Fan coil unit system

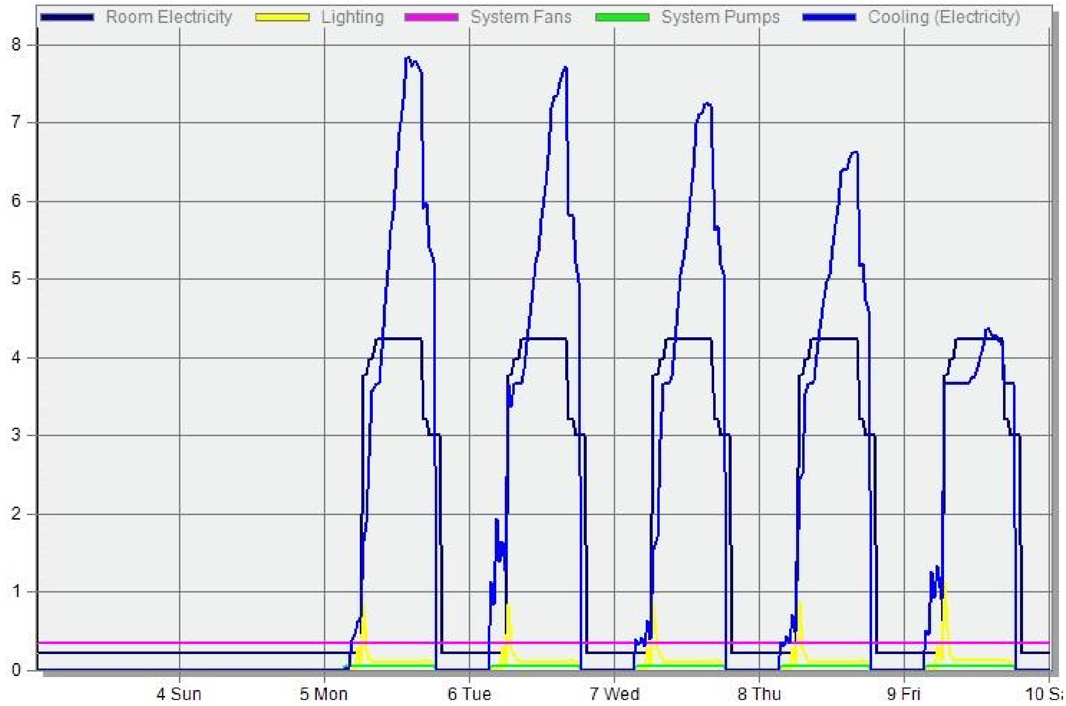


Figure 51 Fuel breakdown at building level with fan coil system

7.3.3 CO2 production

The graph in figure 52 shows the trend of CO2 production based on performance of HVAC system for cooling design.

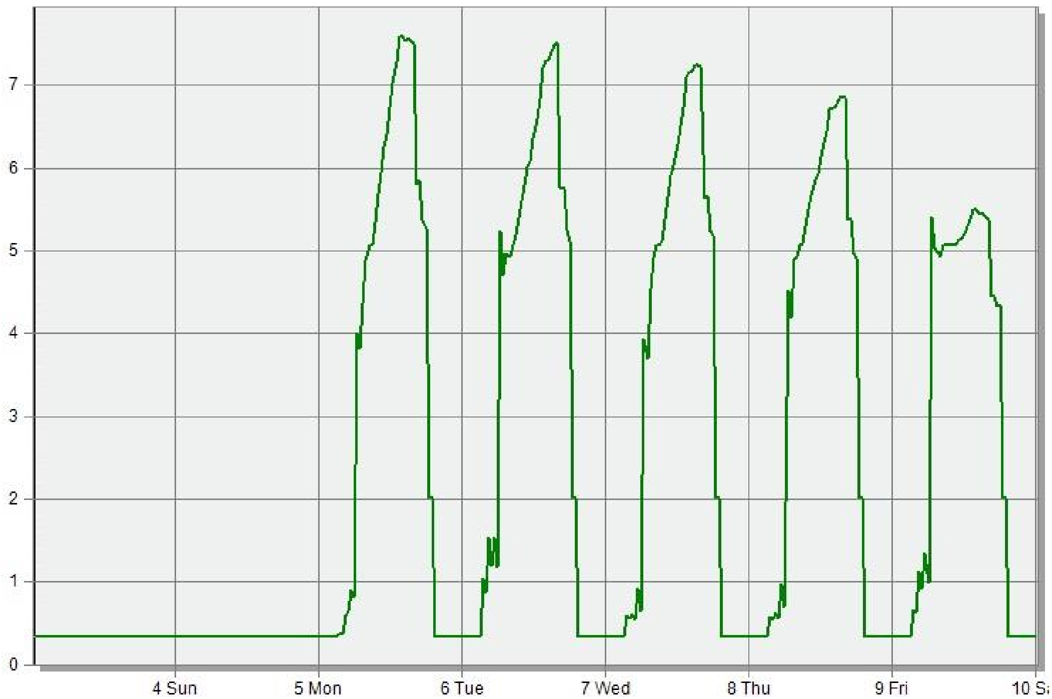


Figure 52 CO2 production at building level with fan coil system

7.3.4 System load

The graph in figure 53 demonstrates that the peak load generally happens in the afternoon around 3 PM when the heat gain through building envelop increases and we have heat flux from exterior walls and external openings to zones.

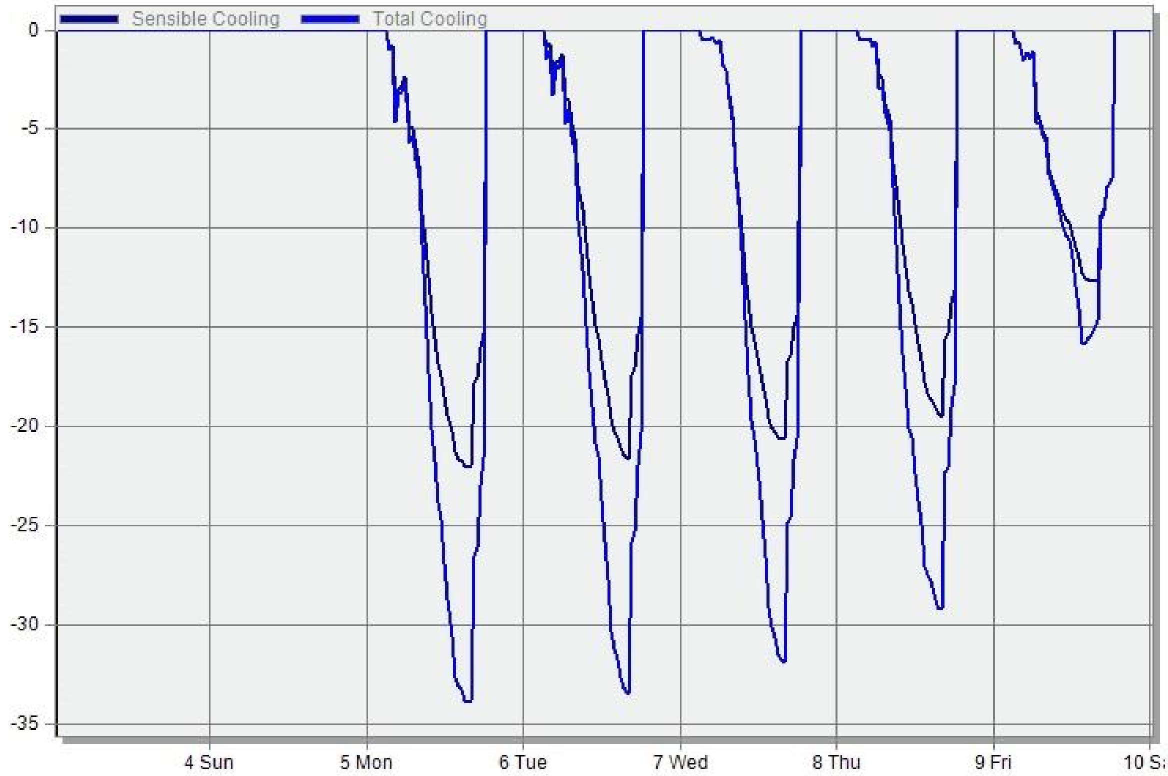


Figure 53 Cooling load on system

7.3.5 Conference room cooling comfort

To make sure if the cooling system works well and if the set point and set back temperatures are satisfied by the system we can go to a specific zone to verify that. As an example, we check the conference room. By looking at the figure 54 we can see that during the occupancy the air temperature which is the control parameter is set on 24°C between 6:30 AM to 5 PM. There is an increase in air temperature in the afternoon by decreasing the outside dry bulb. The second graph shows the relative humidity during the week.

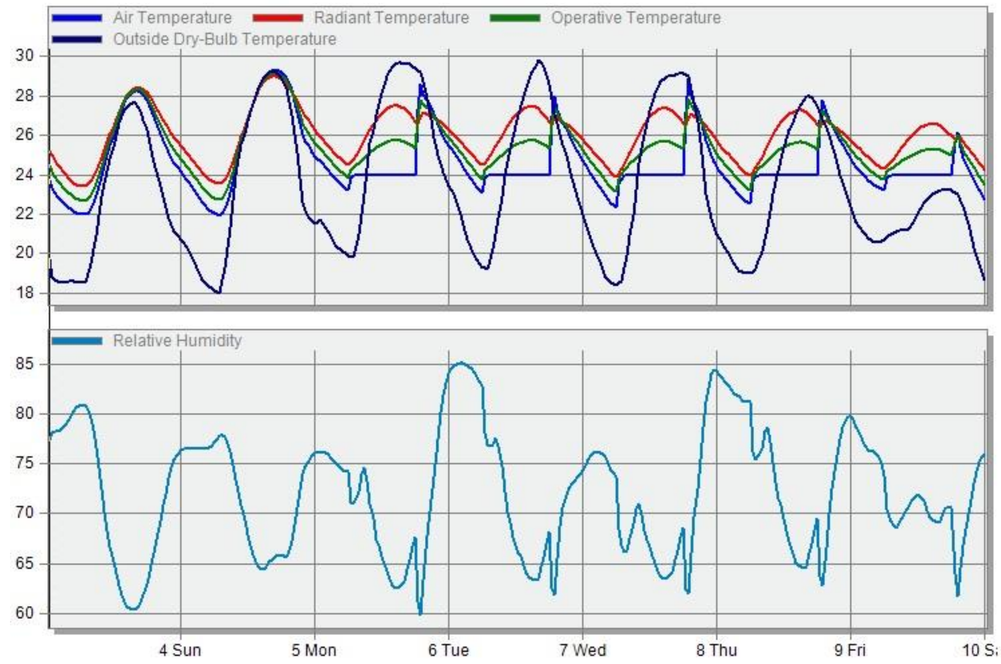


Figure 54 Conference room comfort situation with fan coil system

7.3.6 Conference room heat balance for cooling

The graph in figure 55 shows the amount of zone sensible cooling required for conference room during summer design week. The peak load for this zone occurs mostly between 2:30 PM to 3:30 PM.

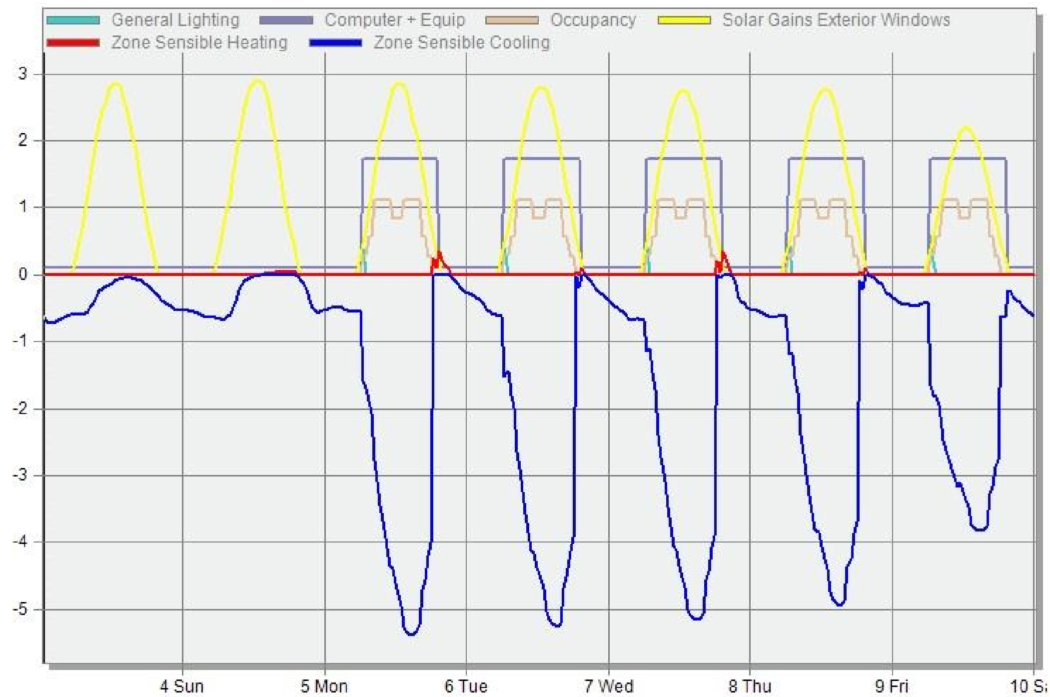


Figure 55 Conference room heat balance with fan coil system

8 Simulation results for VRF system

As explained before in VRF system the refrigerant is the coolant material. The VRF system gets the input data from indoor comfort temperature and outside ambient temperature and based on this data the control unit of the system provides the desired comfort temperature by using optimal power consumption.

The inverter compressor enables lowering power consumption during cooling and heating partial loads, so it makes this system ideal for applications with varying loads required. Here we can see the schematic diagram of the VRF system applied in this project.

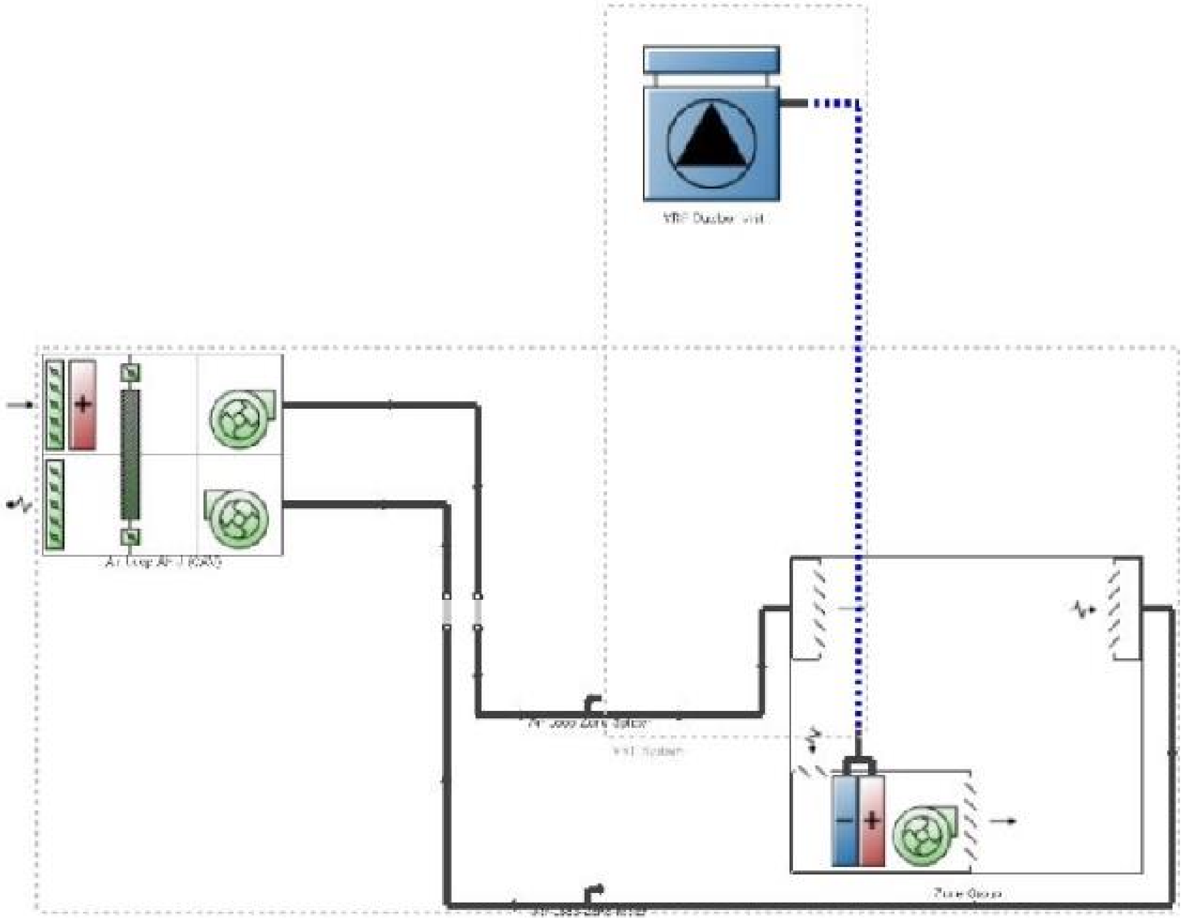


Figure 56 VRF system loop

8.1 VRF outdoor unit

Figure 57 shows the VRF outdoor unit which can be mounted outside of the building to provide the refrigerant for cooling and heating to internal unit.

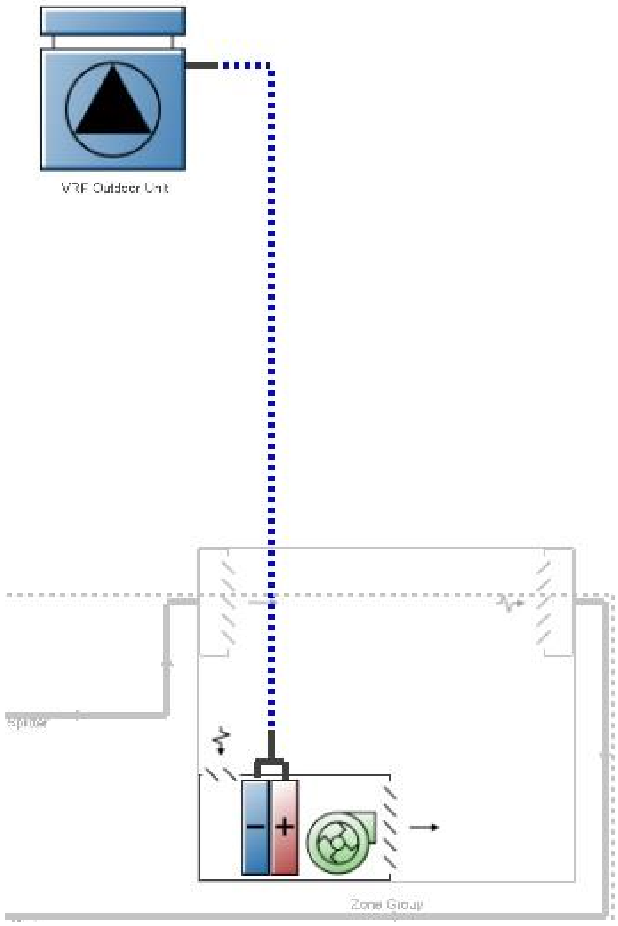


Figure 57 VRF outdoor unit

8.2 AHU unit

The air handling unit provides fresh air to condition the zone. Figure 58 shows the schematic diagram of AHU for this VRF system and illustrates how the supply air provided for each zone. The extracted fan sucks air to air handling unit and condition it again.

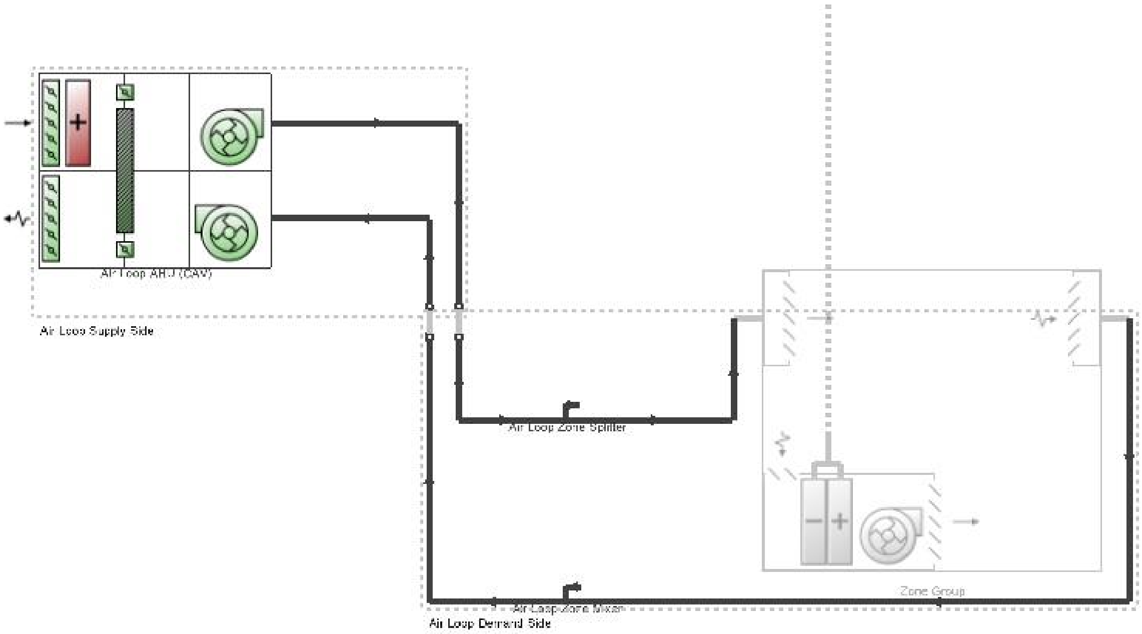


Figure 58 f Air Handling Unit in VRF system

8.3 Zone group

The figure 59 shows the zone group which is being cooled and heated by VRF system.

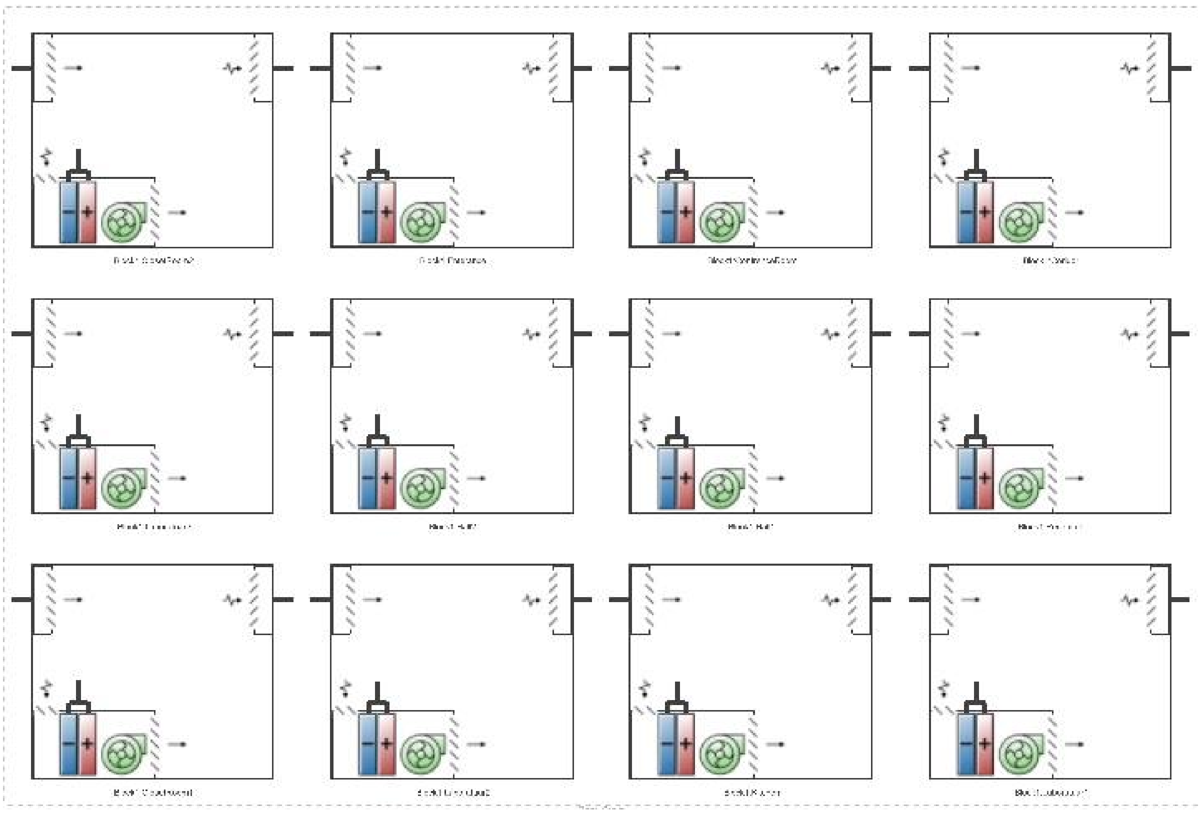


Figure 59 Zone group in VRF system

8.4 Heating design simulation

The heating design simulation gives us proper information of heating ventilating and cooling system performance in which we are be able to understand if the system works well or not. The results consist of information regarding system fuel consumption during winter and summer season, occupants comfort, system load, heat balance and infiltration. The tables below give un information about the building area and net area which is conditioned and not conditioned.

Also, we can see the amount of end uses heating and electricity for VRF system to satisfy the winter design condition.

Table 12 Heating end uses with VRF system

	Electricity (KW)	Natural gas (KW)
Heating	1207.25	0.00
Cooling	5.52	0.00
Interior lighting	100.85	0.00
Interior equipment	276.01	0.00
Fans	55.52	0.00
pumps	3.81	0.00
Total	438.07	0.00

The information regarding design size total cooling and heating capacity of outdoor VRF unit displays below

Table 13 VRF outdoor unit characteristics

VRF outdoor unit	Quantity (W)
Design size rated total cooling capacity	38290.43
Design size rated total heating capacity	38290.43
Design size defrost heater capacity	38290.43
Design size condenser air flow rate	4.37
Pump rated power consumption	163.35

The graph in figure 60 shows the result for fuel breakdown, comfort level, heat balance, load on HVAC system and infiltration at building level for VRF system for this project.

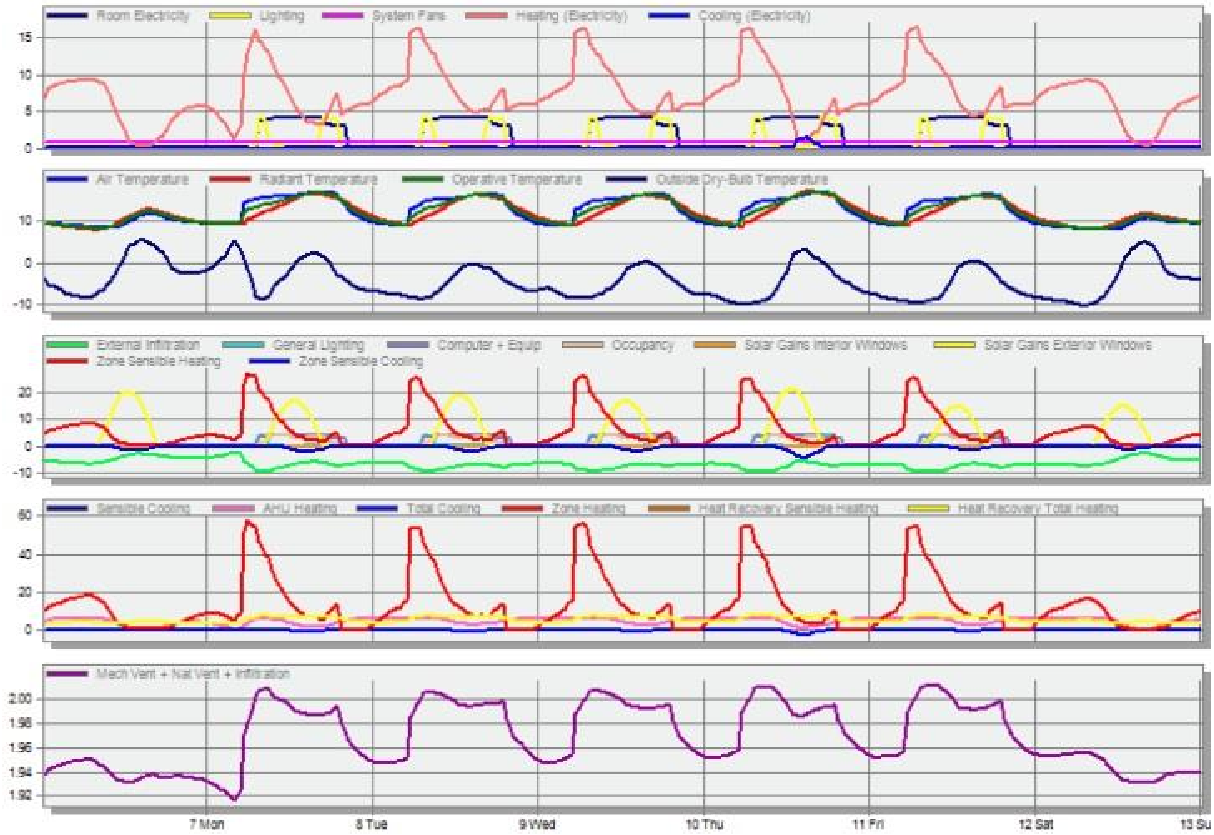


Figure 60 Heating design simulation at building level with VRF system

8.4.1 Fuel breakdown

we can see the fuel breakdown result at building level. The fuel consumption associated to heating system is shown in red, this shows the heating system operating in the early hours to maintain set back temperature in building and peaking to reach the set point temperature just prior to occupation then the load on heating system drops through the day because the thermal mass warms up and the heat gains to the space from other sources increase.

If we look at the blue lines in figure 61, we can see the behavior of electricity consumption for each zone during the occupancy and it has a flat trend during the working day and drops in weekend period which is due to zone control system selected for each zone to control the lighting which results in reduction of energy consumption of the building.

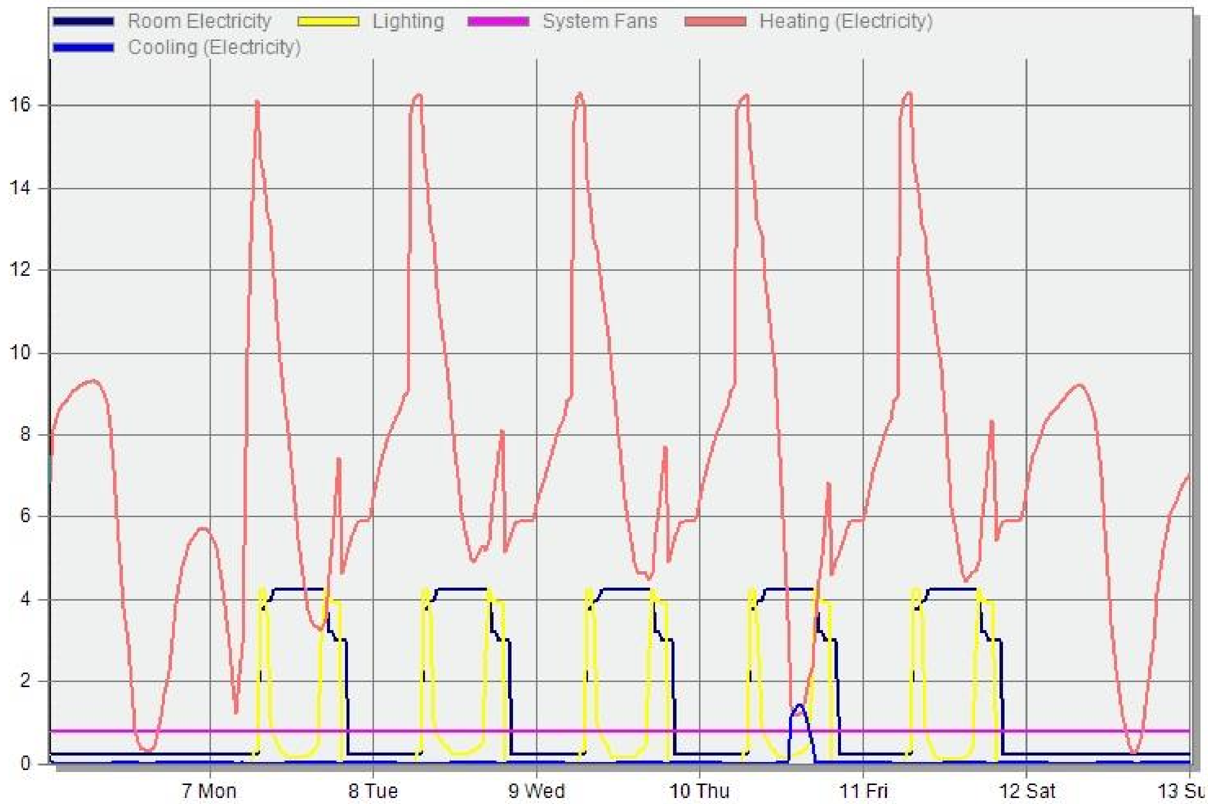


Figure 61 Fuel breakdown at building level with VRF system

8.4.2 Heat balance

The graph in figure 62 shows the heat balance performance of the building in kilo watt during the winter design week. The red pattern shows the zone sensible heating required to compensate the zone sensible cooling. The graph shows there is a peak at the beginning of the workday just prior the occupancy to keep the set point of the heating system and it drops significantly during the day by increasing heat from other sources and there is a slight increase of the heating system in the afternoon by increasing the zone sensible cooling.

The green line shows the general lighting performance which drops ideally during the full occupancy and that's because of the lighting control system which turns off the light by increasing the sun light. The computer and equipment graph experience a constant behavior for each working day because they are modeled with scheduling which gives the best performance of the equipment.

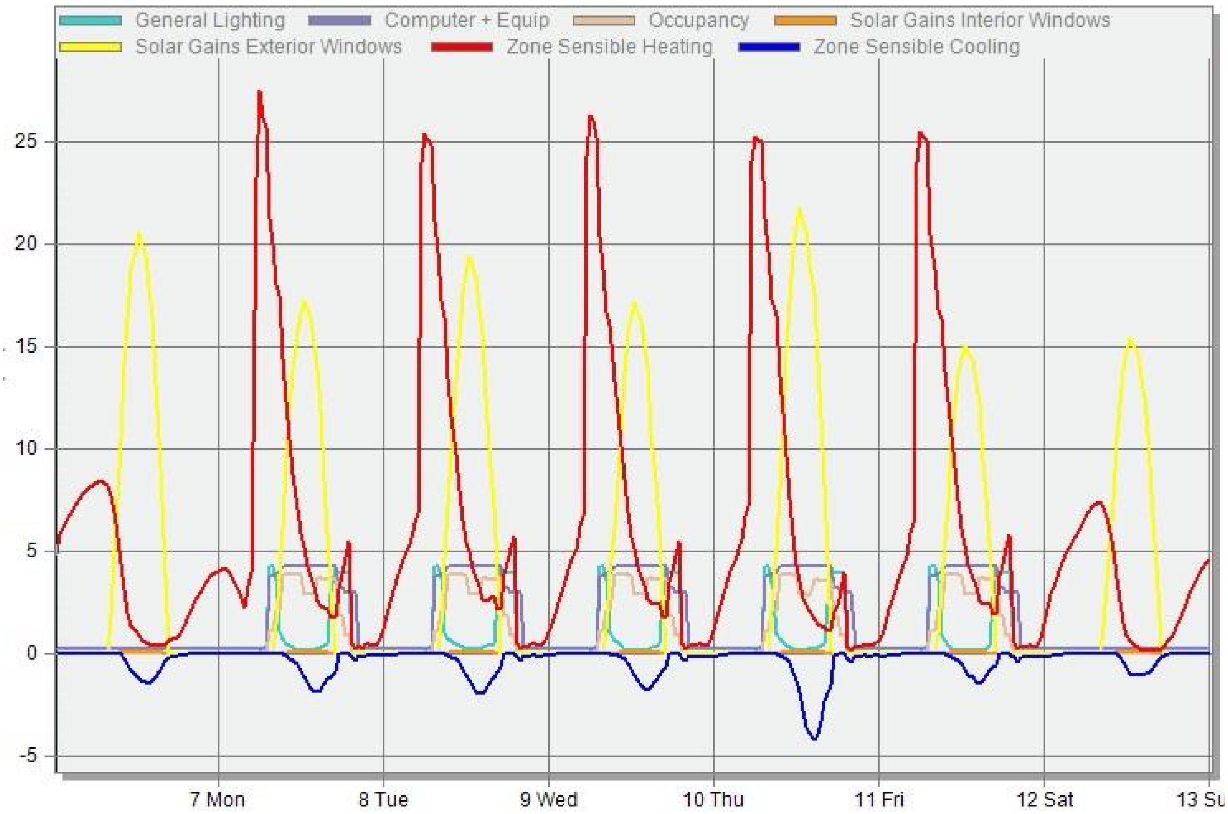


Figure 62 Heat balance at building level with VRF system

8.4.3 Total fresh air

Figure 63 explains the fresh air variation during the week. Here the air change rate is relatively low. The variance in infiltration appears to be significant but if we check the Y axis we can see the variation is small, although the infiltration rate is set to constant value it is based on reference temperature so dose change with variation in the inside temperature and the air density.

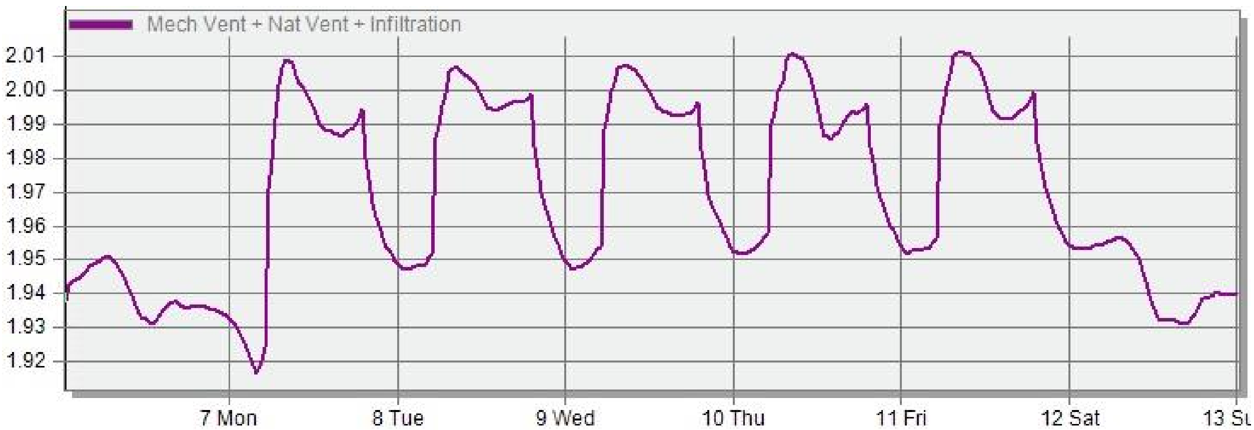


Figure 63 Mechanical and natural ventilation

8.4.4 CO2 production

The CO2 production of the HVAC system during the winter deign week is demonstrated in figure 64 and has almost the same trend as the heat balance of the building. The CO2 production increases at around 7:30 AM prior the occupancy which means the heating system is working to meet the set point temperature which was determined in the activity tab and by decreasing the heating system performance during the day the amount of CO2 production decreases as well. Decreasing the outside dry bulb temperature causes a slight increase in the heating system performance which leads to increase of CO2 production.

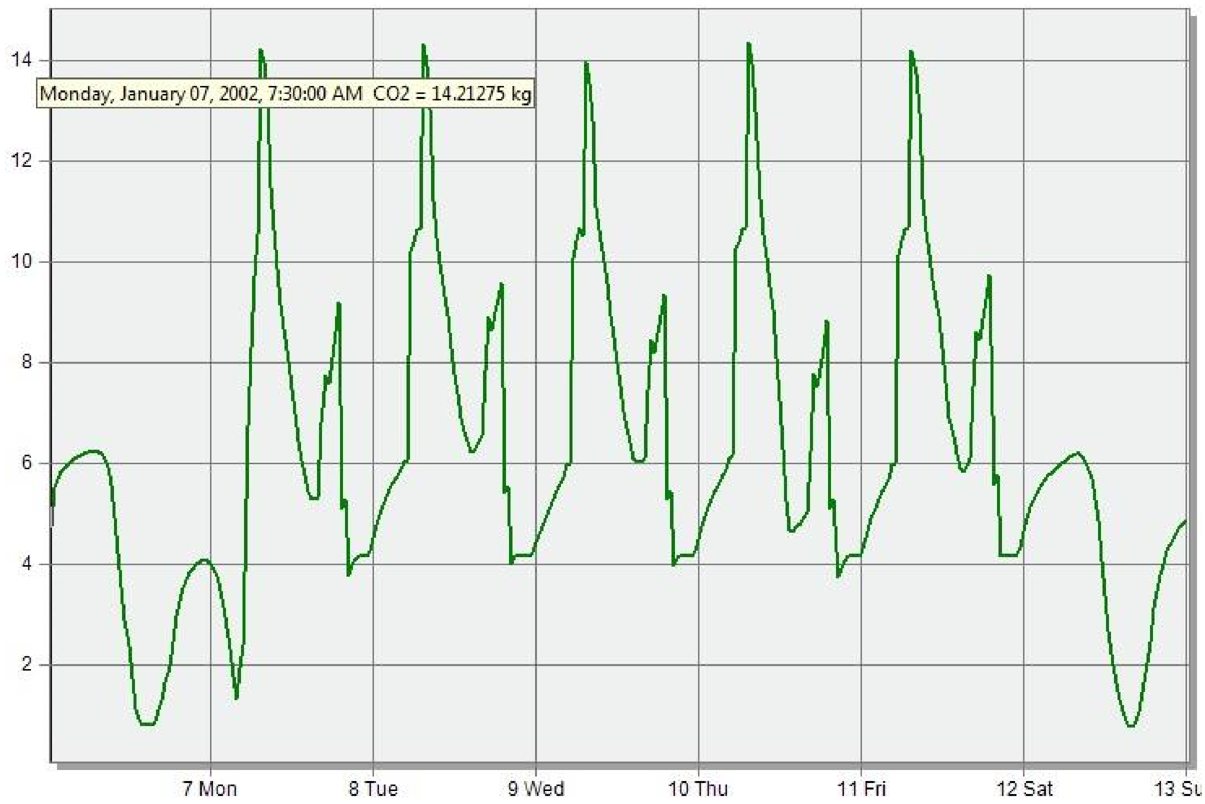


Figure 64 CO2 production at building level with VRF system

8.4.5 System load

The system load during the winter design week is shown in figure 65 and illustrates the amount of load applied on heating system to offset the cooling load for each working day. The graph shows there is an increase in thermal load on heating system in the early hours before the occupancy.

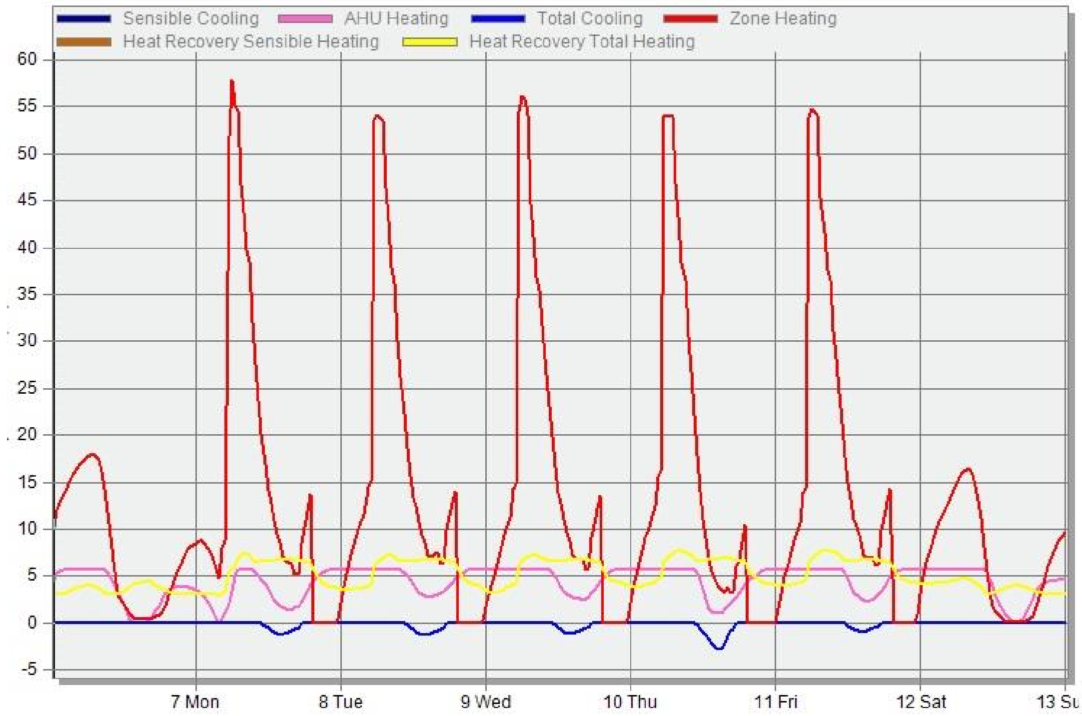


Figure 65 Heating load on system

8.4.6 Conference room comfort situation

To see the performance of the heating system to make sure if the set point and set back temperatures are applied well we can go to each zone to see if it is applied or not. As an example, the conference room is selected which has the largest area in the building.

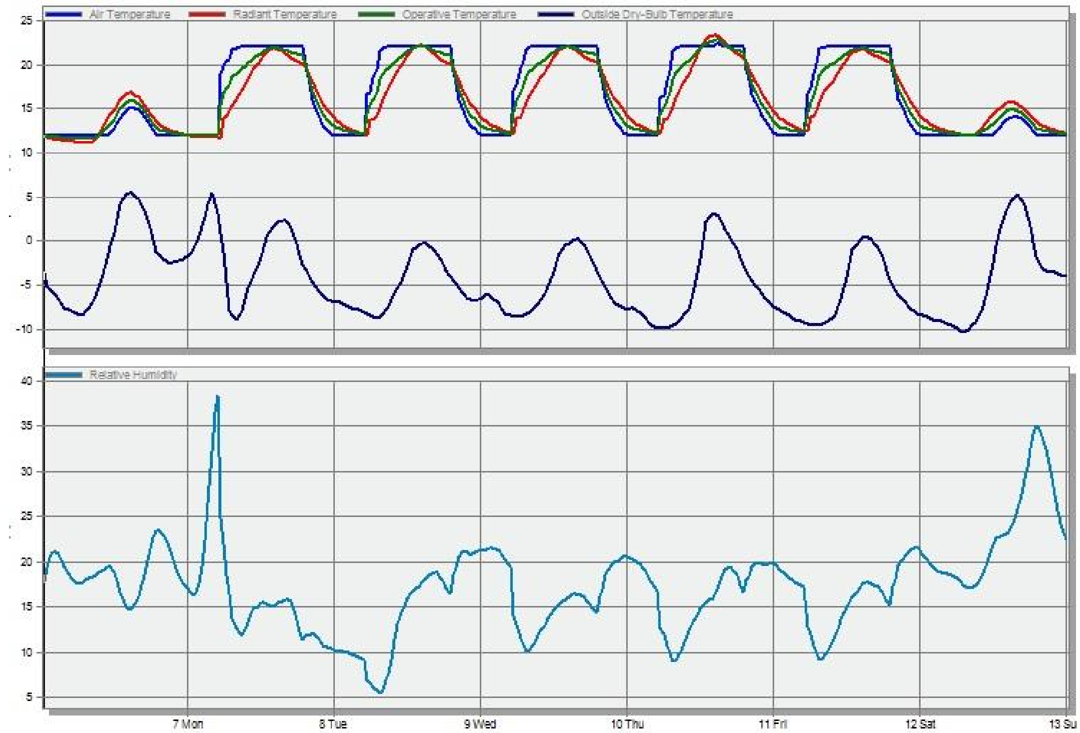


Figure 66 Conference room comfort situation in heating mode

The chart in figure 67 carries the simulation data regarding air temperature distribution in conference room, comfort level of occupants, outdoor air temperature and radiant temperature. As can be seen from the chart the air temperature never drops below 22°C because the air temperature is the control parameter and it doesn't fall below 12°C which guarantees the performance of the system and satisfying the comfort situation for the occupants. The second graph shows the relative humidity behavior during the week.

8.4.7 Conference room heat balance

The graph below shows that the heating system works with high capacity prior the occupancy and it drops by increasing heat emitted from other sources in zone. However, the heating system experiences another peak in the afternoon due to reducing the outdoor temperature. The yellow lines show the solar gain through windows. If we look at the general internal lighting, we can see the effect of using lighting control in zone as it reduces the electricity consumption by increasing the outside light.

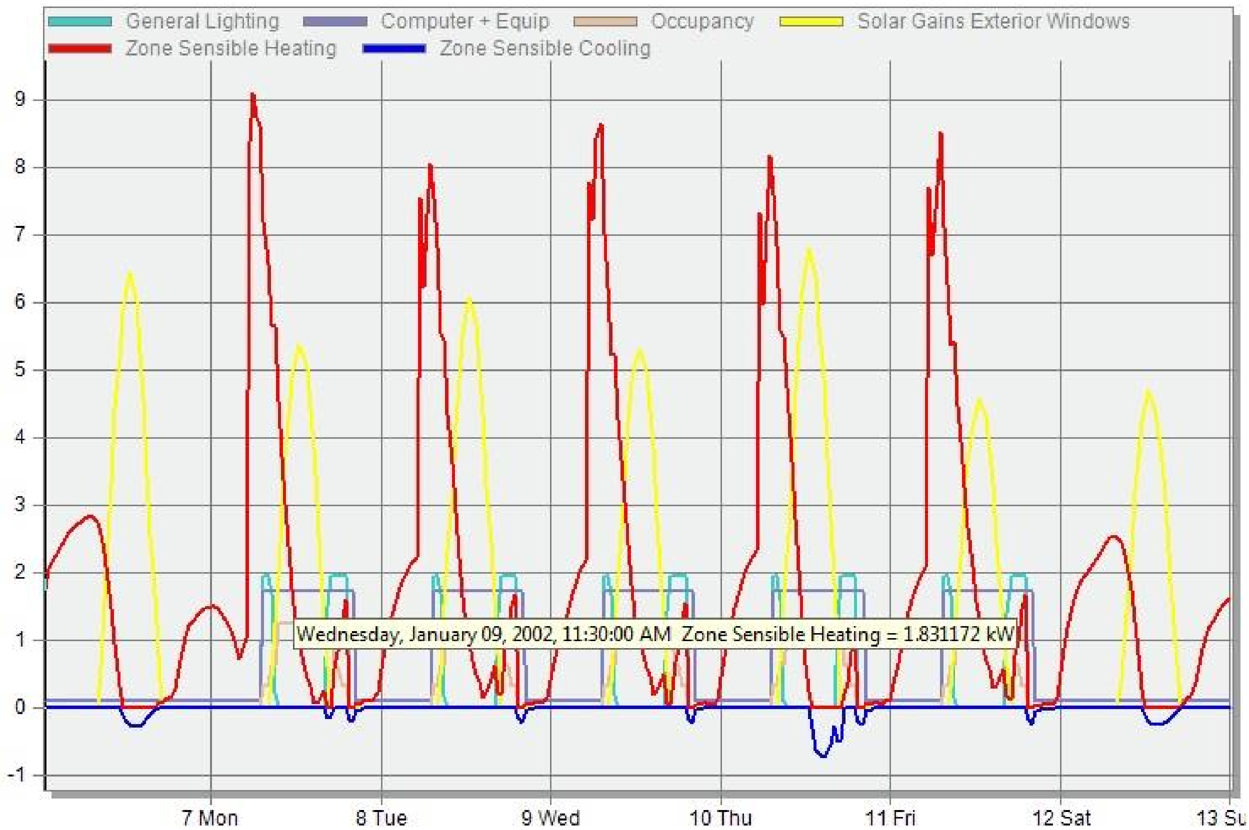


Figure 67 Conference room heat balance on heating mode

8.5 Cooling design simulation

After observing the results of the heating design simulation, we can look at the data reported about cooling design simulation which can help us to select the relevant cooling system to satisfy the cooling load applied on the building during the hot days and to see if the system works properly or not. For that purpose, the summer design week is selected in Design Builder which is between 3rd of Aug to 9th of Aug. The net conditioned area and unconditioned area for the building is just like the heating design. we can see the amount of end uses cooling and electricity for VRF system to satisfy summer design condition.

8.5.1 Heat balance

The chart in figure 69 shows the amount of cooling required for each day to offset the heat gain during the day. There is a peak at the beginning of each day before full occupancy to satisfy the cooling set point to guarantee the comfort situation. By end of the day by decreasing the ambient heat gain there is a reduction in cooling system performance. The computer and equipment, solar gain through exterior and interior windows and occupancy level are demonstrated as well.

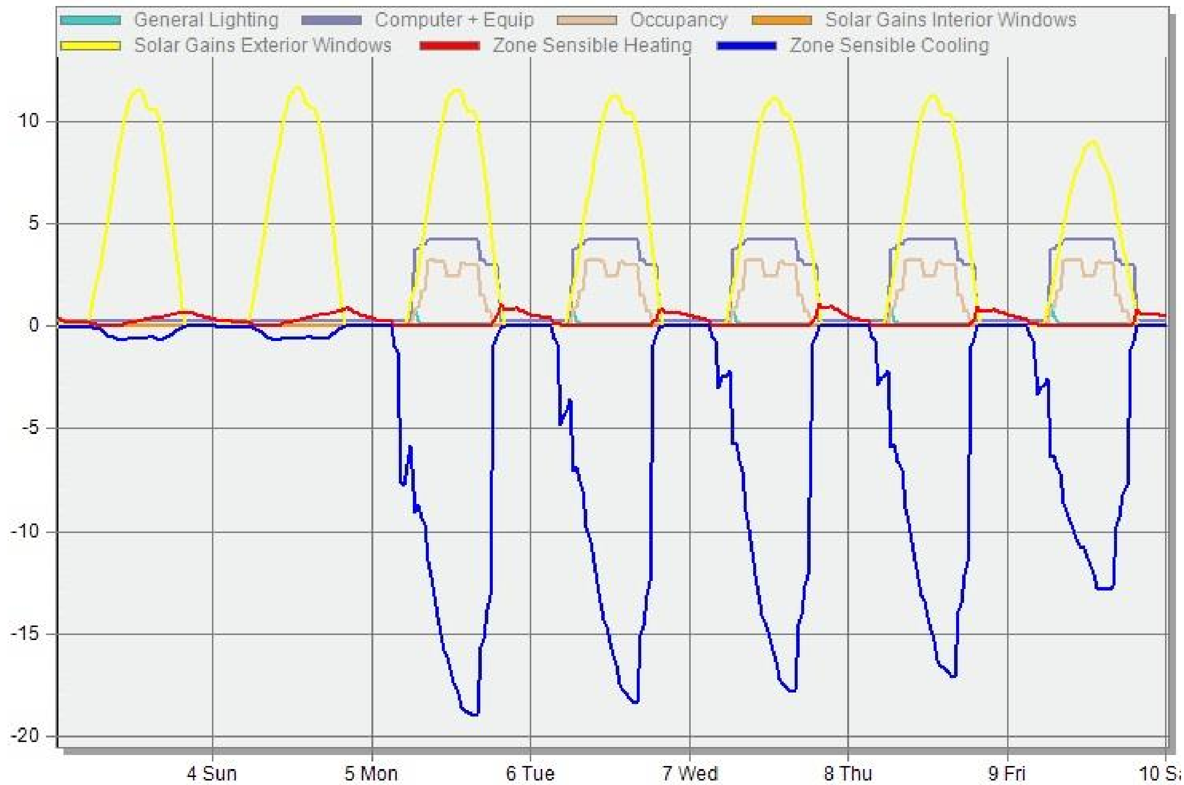


Figure 68 Heat balance at building level with VRF system

8.5.2 Fuel breakdown

we can see the fuel breakdown at building level. The fuel consumption associated to cooling system is shown in blue, this shows the cooling system operating in the early hours to maintain set back temperature in the building and peaking to reach the set point temperature just prior to occupation then the load on cooling system drops through the day by decreasing the outside dry bulb temperature. we can see also the behavior of electricity consumption during the occupancy and it has a flat trend during the working day and drops in weekend period which is due to zone control system selected for each zone to control the lighting which results in reduction of energy consumption of the building.

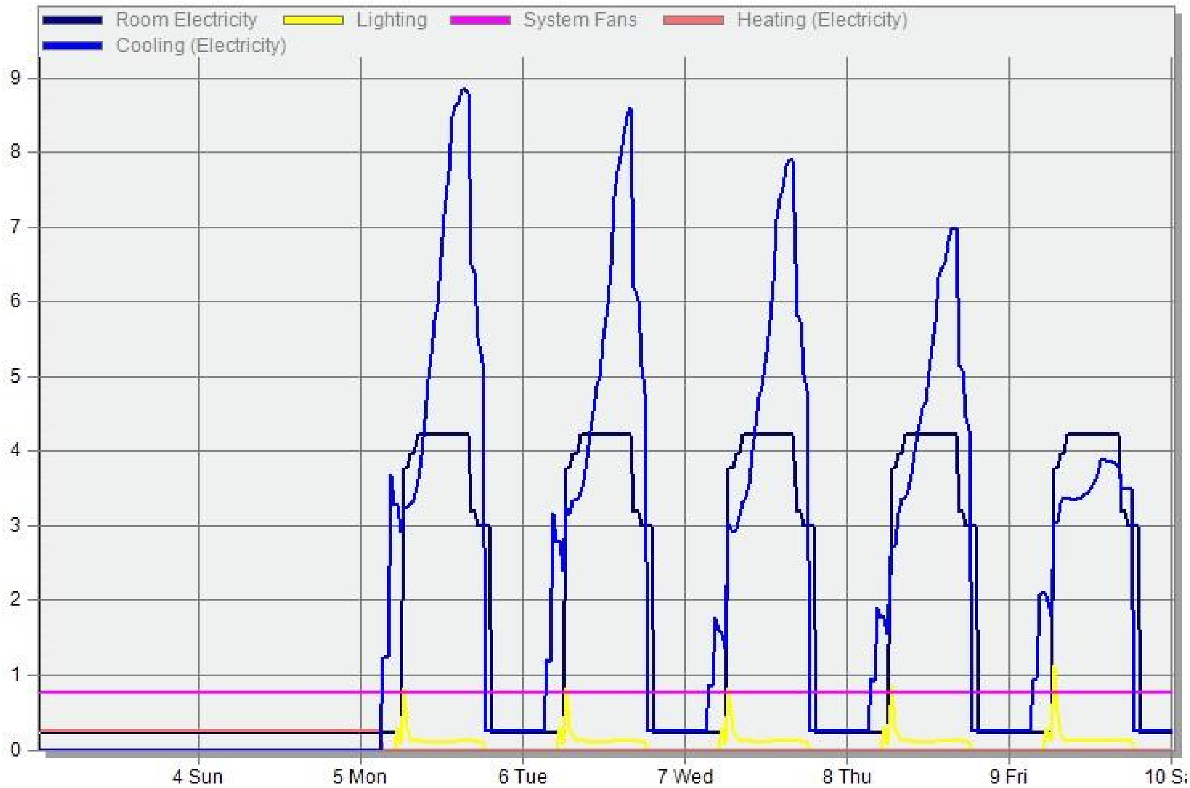


Figure 69 d Fuel breakdown at building level with VRF system

8.5.3 CO2 production

Figure 70 explains the trend of CO_2 production based on performance of HVAC system for cooling design. The graph has the same trend as fuel breakdown at building level which means the system works with high load to meet the set point before the full occupancy and CO_2 production decreases by reducing the outside temperature.

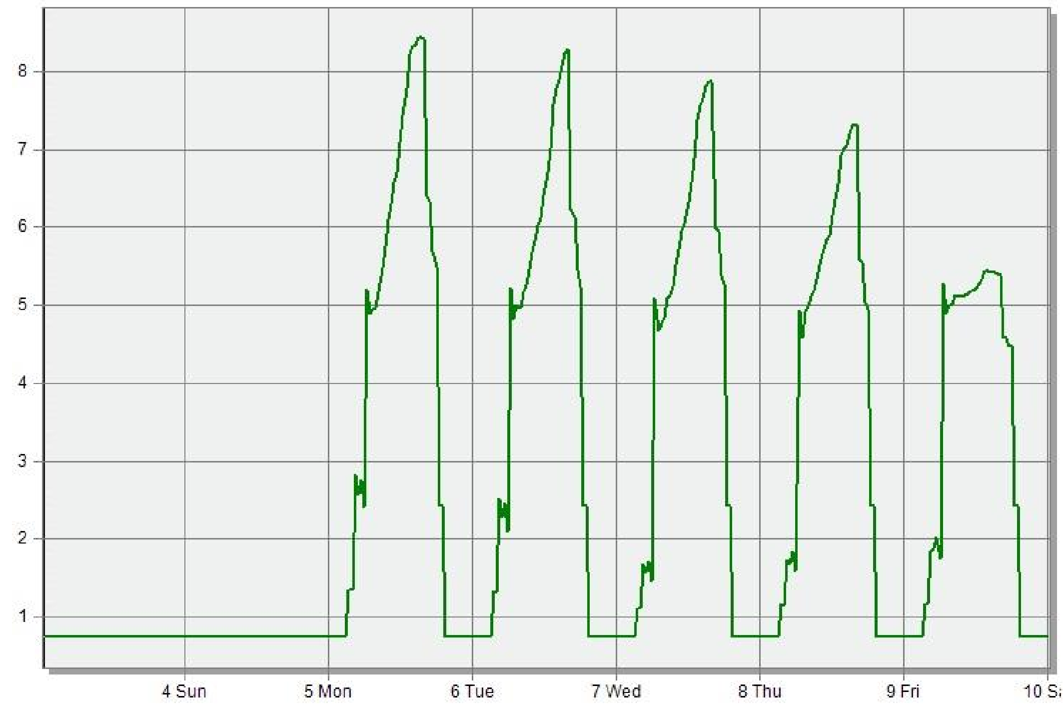


Figure 70 CO2 production at building level with VRF

8.5.4 System load

the graph in figure 71 illustrates the amount of load applied on VRF system during summer design week for defined days.

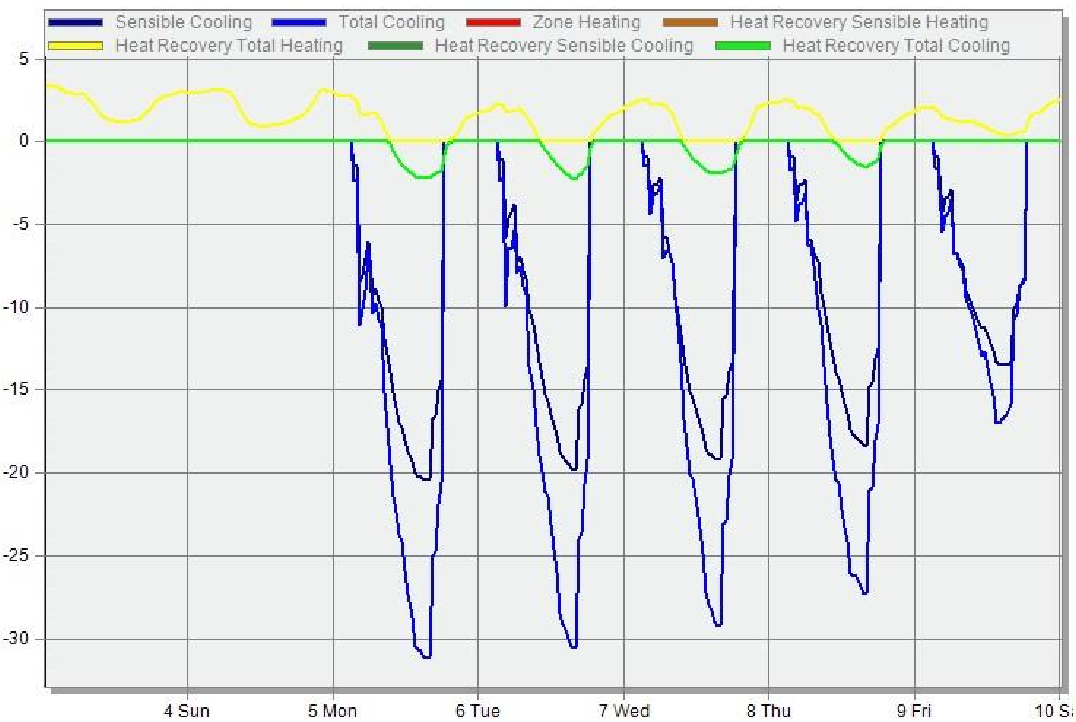


Figure 71 Cooling load at building level with VRF system

8.5.5 Conference room comfort situation

To make sure if the cooling system works well and if the set point and set back temperatures are satisfied by the system we can go to a specific zone to verify that. Just like the heating design we check the conference room. By looking at the graph we can see that during the occupancy the air temperature which is the control parameter is set on 24°C between 4:30 AM to 6 PM. There is an increase in air temperature in the afternoon by decreasing the outside dry bulb. The second graph in figure 72 shows the relative humidity during the week.

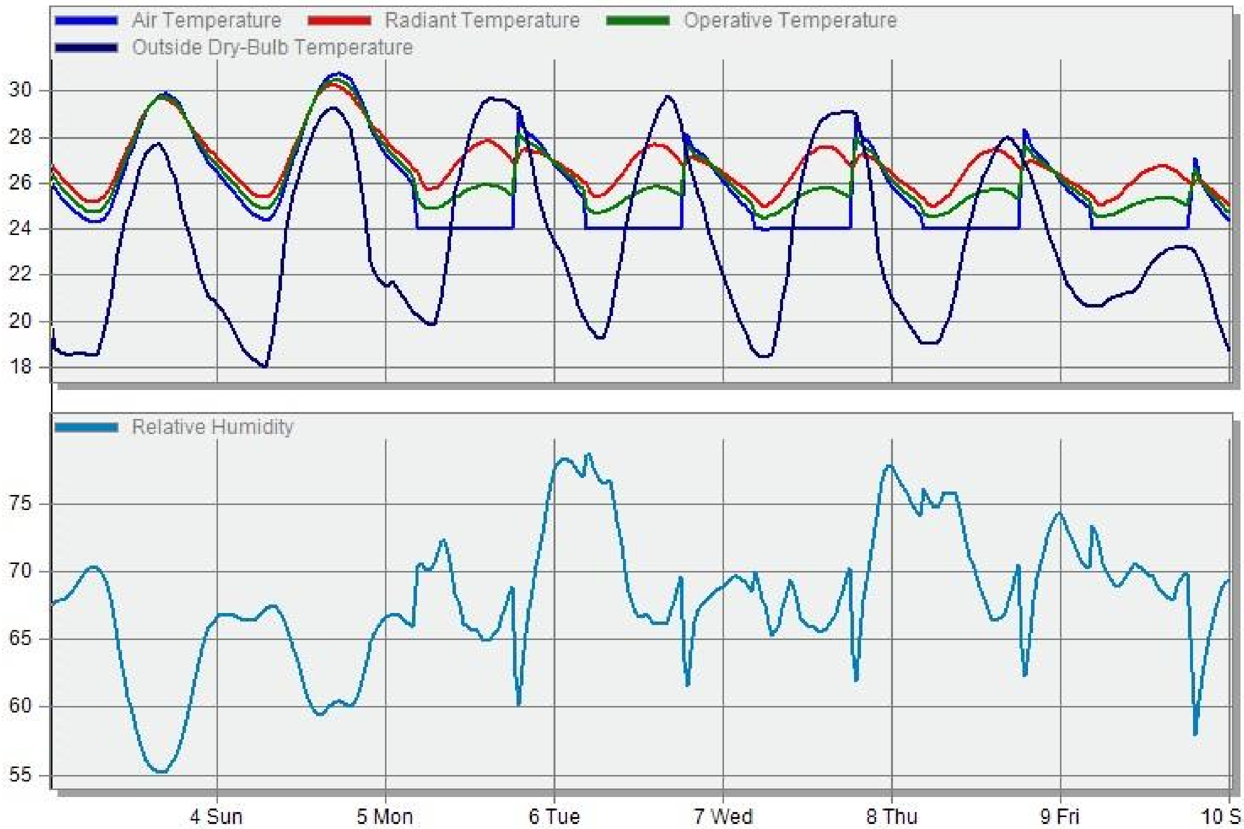


Figure 72 Conference room comfort situation with VRF system

8.5.6 Conference room heat balance

The graph in figure 73 shows the amount of zone sensible cooling required for conference room during summer design week. The peak load for this zone occurs mostly between 2:30 PM to 3 PM.

Simulation results for VRF system

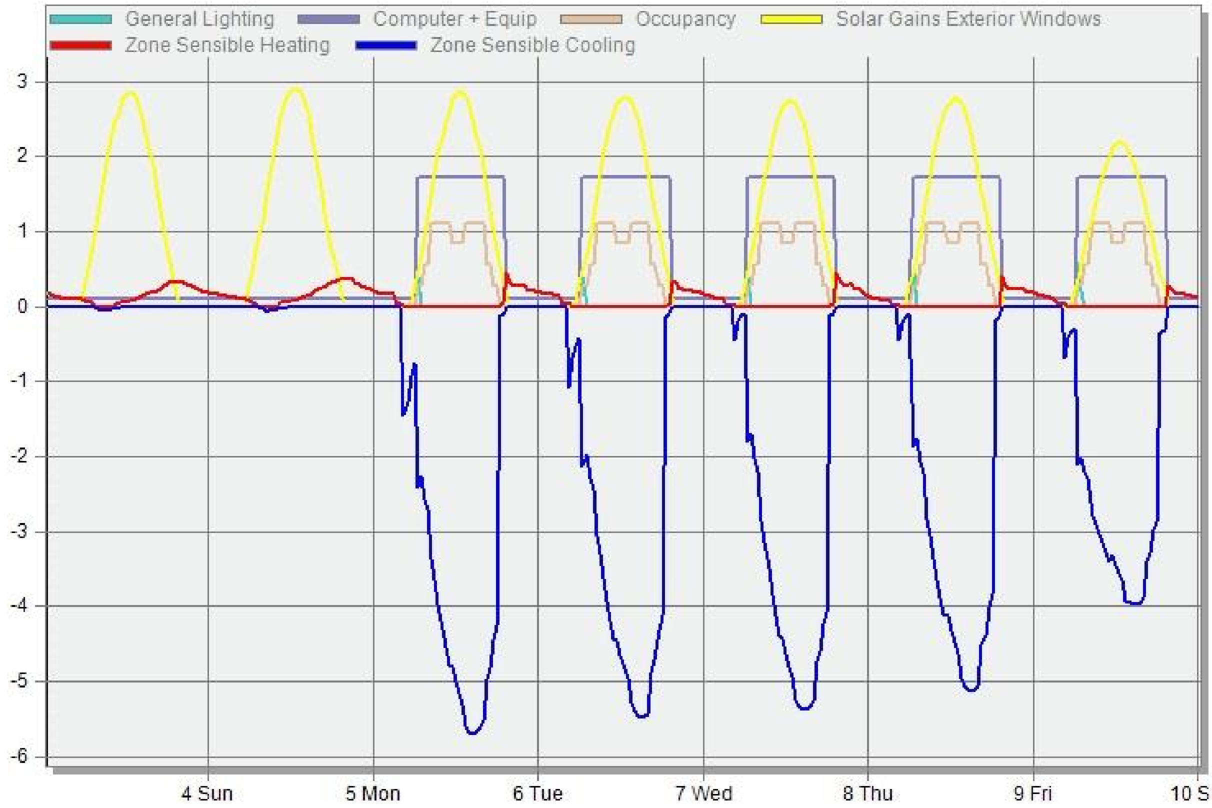


Figure 73 Conference room heat balance with VRF system

Simulation results for VRF system

9 Comparing the simulation results for heating

After obtaining the simulation results by Design Builder we can analyze which system meets our purposes by considering the amount of primary energy which has been used by each system and considering other parameters such as efficiency of the system and fuel breakdown which demonstrates the amount of fuel consumption regarding heating system.

Tables 14, 15 and 16 show the information about total end uses energy for VRF, VAV and fan coil system respectively. The total end uses amount is the sum of mainly interior and exterior lighting, interior and exterior equipment, fans and pumps.

Table 14 VRF heating end uses

	Electricity [kWh]	Natural Gas [kWh]	Additional Fuel [kWh]	District Cooling [kWh]	District Heating [kWh]	Water [m3]
Heating	1207.25	0	0	0	0	0
Cooling	5.52	0	0	0	0	0
Interior Lighting	100.85	0	0	0	0	0
Exterior Lighting	0	0	0	0	0	0
Interior Equipment	276.01	0	0	0	0	0
Exterior Equipment	0	0	0	0	0	0
Fans	128.52	0	0	0	0	0
Pumps	0	0	0	0	0	0
Heat Rejection	0	0	0	0	0	0
Humidification	0	0	0	0	0	0
Heat Recovery	0	0	0	0	0	0
Water Systems	0	0	0	0	0	0
Refrigeration	0	0	0	0	0	0
Generators	0	0	0	0	0	0
Total End Uses	1718.15	0	0	0	0	

Comparing the simulation results for heating

Table 15 VAV heating end uses

	Electricity [kWh]	Natural Gas [kWh]	Additional Fuel [kWh]	District Cooling [kWh]	District Heating [kWh]	Water [m3]
Heating	1.11	1713.21	0	0	0	0
Cooling	298.09	0	0	0	0	0
Interior Lighting	100.85	0	0	0	0	0
Exterior Lighting	0	0	0	0	0	0
Interior Equipment	276.01	0	0	0	0	0
Exterior Equipment	0	0	0	0	0	0
Fans	135.42	0	0	0	0	0
Pumps	8.76	0	0	0	0	0
Heat Rejection	0	0	0	0	0	0
Humidification	0	0	0	0	0	0
Heat Recovery	0	0	0	0	0	0
Water Systems	0	0	0	0	0	0
Refrigeration	0	0	0	0	0	0
Generators	0	0	0	0	0	0
Total End Uses	820.23	1713.21	0	0	0	

Table 16 Fan coil heating end uses

fan coil heating	Electricity [kWh]	Natural Gas [kWh]	Additional Fuel [kWh]	District Cooling [kWh]	District Heating [kWh]	Water [m3]
Heating	1.88	2722.05	0	0	0	0
Cooling	0	0	0	0	0	0
Interior Lighting	100.85	0	0	0	0	0
Exterior Lighting	0	0	0	0	0	0
Interior Equipment	276.01	0	0	0	0	0
Exterior Equipment	0	0	0	0	0	0
Fans	55.52	0	0	0	0	0
Pumps	3.81	0	0	0	0	0
Heat Rejection	0	0	0	0	0	0
Humidification	0	0	0	0	0	0
Heat Recovery	0	0	0	0	0	0
Water Systems	0	0	0	0	0	0
Refrigeration	0	0	0	0	0	0
Generators	0	0	0	0	0	0
Total End Uses	438.07	2722.05	0	0	0	0

To calculate the amount of used primary energy we should convert the total electricity and natural gas end uses to primary energy by using the source conversion factor. The source conversion factor for electricity in Italy is 2.17 and for gas is 1.5. The table 17 shows the amount of final primary energy for each system.

Table 17 Primary energy demand for heating at building level

Type of system	Primary energy[kwh]
VRF	3728.3
VAV	7349.714
Fan coil	5033.687

As can be seen from the information which is covered by the above table, the variable refrigerant flow uses less amount of energy associated to heating compare to variable air volume and fan coil system. In addition to primary energy, we can compare the fuel breakdown result for each system.

The graphs 74, 75 and 76 show the result for fuel breakdown for VRF, VAV and fan coil system respectively.

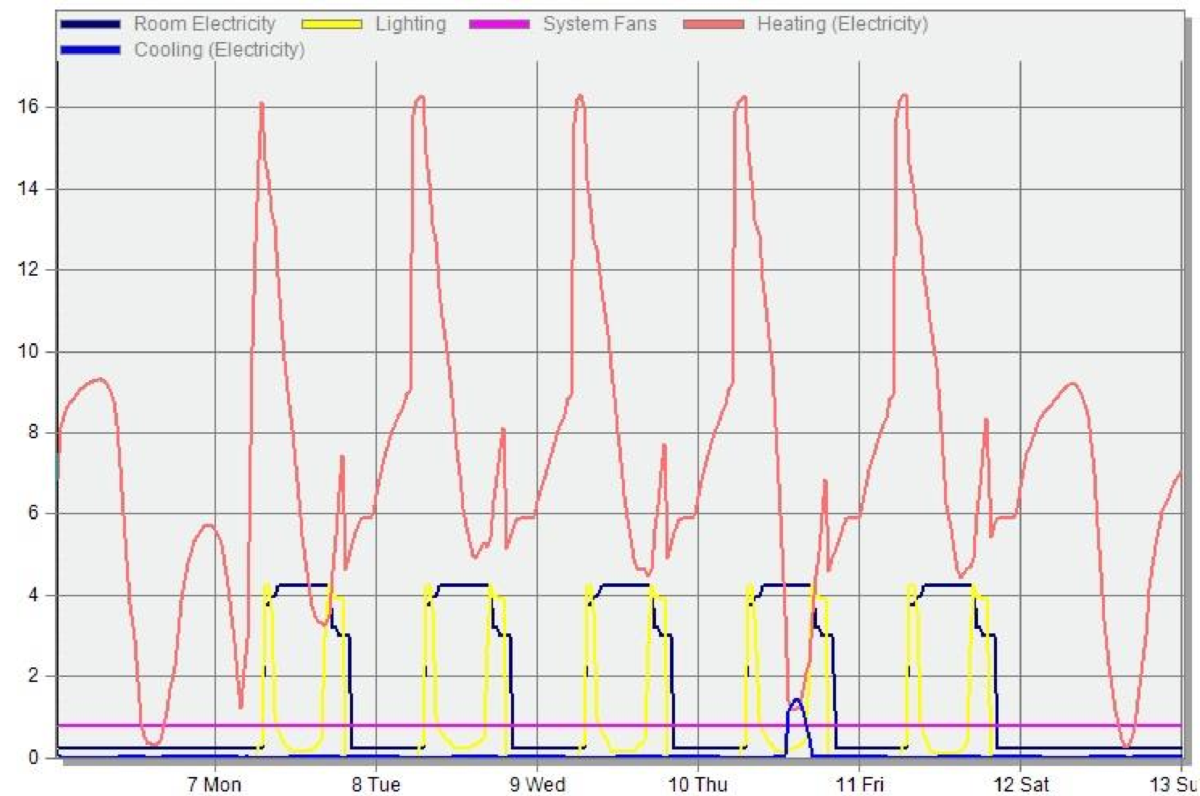


Figure 74 VRF fuel breakdown in heating mode

Comparing the simulation results for heating

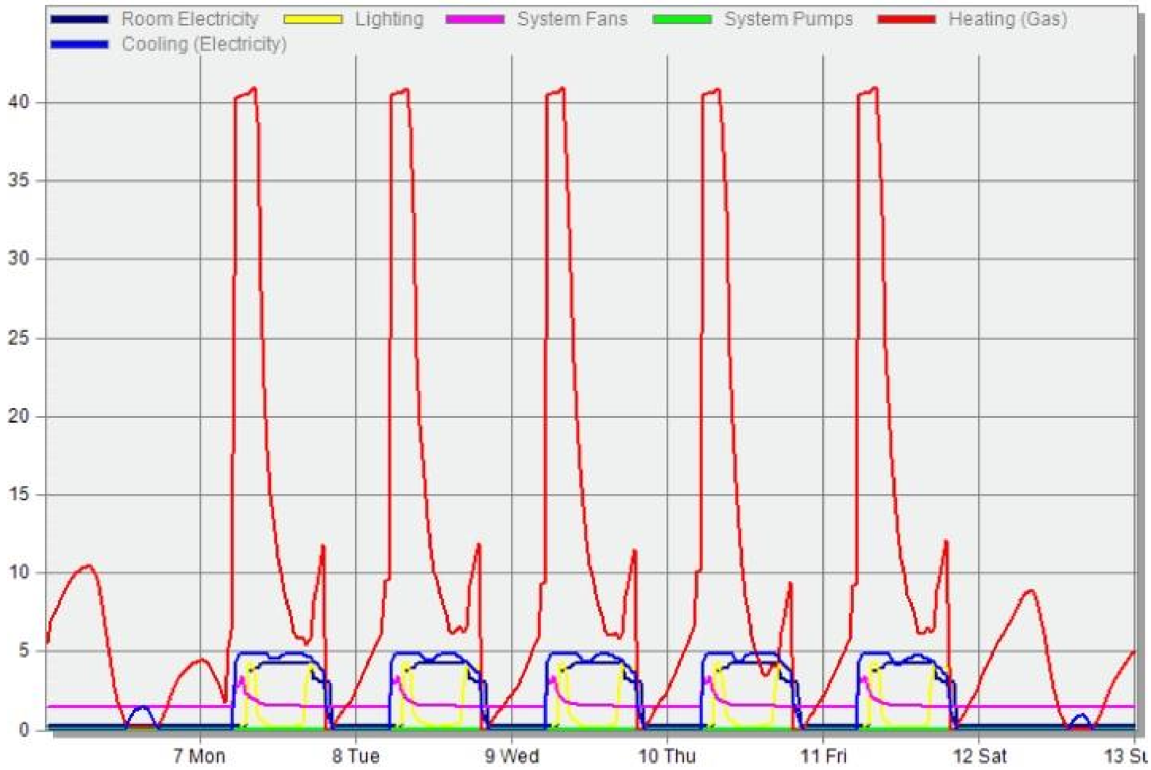


Figure 75 VAV fuel breakdown in heating mode

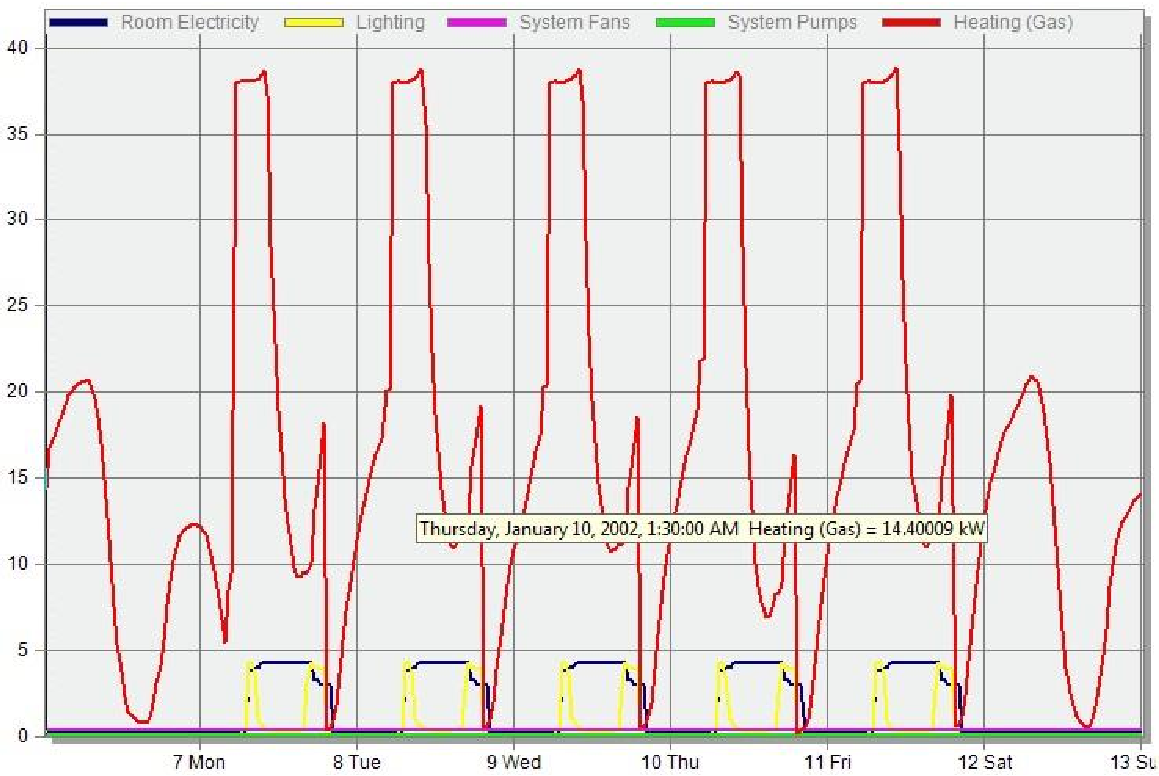


Figure 76 Fan coil fuel breakdown in heating mode

By looking at the above graphs, the amount of fuel consumption associated to heating design for VRF system is lower than VAV and fan coil system. The amount of fuel consumption prior the occupancy which is the highest value is 16 kw and this value for VAV and fan coil system is 41 kw and 38 kw respectively. Both result show that the VRF system has better performance in terms of fuel consumption which means it can save more energy compare to other conventional systems.

Comparing the simulation results for heating

10 Comparing the simulation results for cooling

The procedure to analyze the results for cooling design is just like what we did for heating design. The tables 18, 19 and 20 represent the amount of end uses energy in kw for VRF, VAV and fan coil system respectively.

Table 18 VRF cooling end uses

	Electricity [kWh]	Natural Gas [kWh]	Additional Fuel [kWh]	District Cooling [kWh]	District Heating [kWh]	Water [m3]
Heating	12.24	0	0	0	0	0
Cooling	337.97	0	0	0	0	0
Interior Lighting	10.22	0	0	0	0	0
Exterior Lighting	0	0	0	0	0	0
Interior Equipment	276.01	0	0	0	0	0
Exterior Equipment	0	0	0	0	0	0
Fans	128.52	0	0	0	0	0
Pumps	0	0	0	0	0	0
Heat Rejection	0	0	0	0	0	0
Humidification	0	0	0	0	0	0
Heat Recovery	0	0	0	0	0	0
Water Systems	0	0	0	0	0	0
Refrigeration	0	0	0	0	0	0
Generators	0	0	0	0	0	0
Total End Uses	764.96	0	0	0	0	0

Comparing the simulation results for cooling

Table 19 VAV cooling end uses

	Electricity [kWh]	Natural Gas [kWh]	Additional Fuel [kWh]	District Cooling [kWh]	District Heating [kWh]	Water [m3]
Heating	0.03	45.53	0	0	0	0
Cooling	886.96	0	0	0	0	0
Interior Lighting	10.22	0	0	0	0	0
Exterior Lighting	0	0	0	0	0	0
Interior Equipment	276.01	0	0	0	0	0
Exterior Equipment	0	0	0	0	0	0
Fans	129.63	0	0	0	0	0
Pumps	10.9	0	0	0	0	0
Heat Rejection	0	0	0	0	0	0
Humidification	0	0	0	0	0	0
Heat Recovery	0	0	0	0	0	0
Water Systems	0	0	0	0	0	0
Refrigeration	0	0	0	0	0	0
Generators	0	0	0	0	0	0
Total End Uses	1313.74	45.53	0	0	0	0

Table 20 Fan coil cooling end uses

	Electricity [kWh]	Natural Gas [kWh]	Additional Fuel [kWh]	District Cooling [kWh]	District Heating [kWh]	Water [m3]
Heating	0	0	0	0	0	0
Cooling	308.77	0	0	0	0	0
Interior Lighting	10.22	0	0	0	0	0
Exterior Lighting	0	0	0	0	0	0
Interior Equipment	276.01	0	0	0	0	0
Exterior Equipment	0	0	0	0	0	0
Fans	55.52	0	0	0	0	0
Pumps	3.55	0	0	0	0	0
Heat Rejection	0	0	0	0	0	0
Humidification	0	0	0	0	0	0
Heat Recovery	0	0	0	0	0	0
Water Systems	0	0	0	0	0	0
Refrigeration	0	0	0	0	0	0
Generators	0	0	0	0	0	0
Total End Uses	654.07	0	0	0	0	0

To calculate the amount of used primary energy we follow the same procedure which we used for heating design

Table 21 Primary energy end uses for cooling at building level

Type of system	Primary energy[kw]
VRF	1659.963
VAV	2919.1
Fan coil	1419.332

The above results in table 21 show that the fan coil system uses less amount of energy compare to VRF and VAV system. We can also consider the fuel breakdown for each system for cooling design. Figures 77, 78 and 79 show that the fan coil system uses almost less amount of electricity for air cooled chiller to cool down the building but in general because of the advantages of VRF system compare to conventional systems would be a better choice as a primary HVAC system for this project.

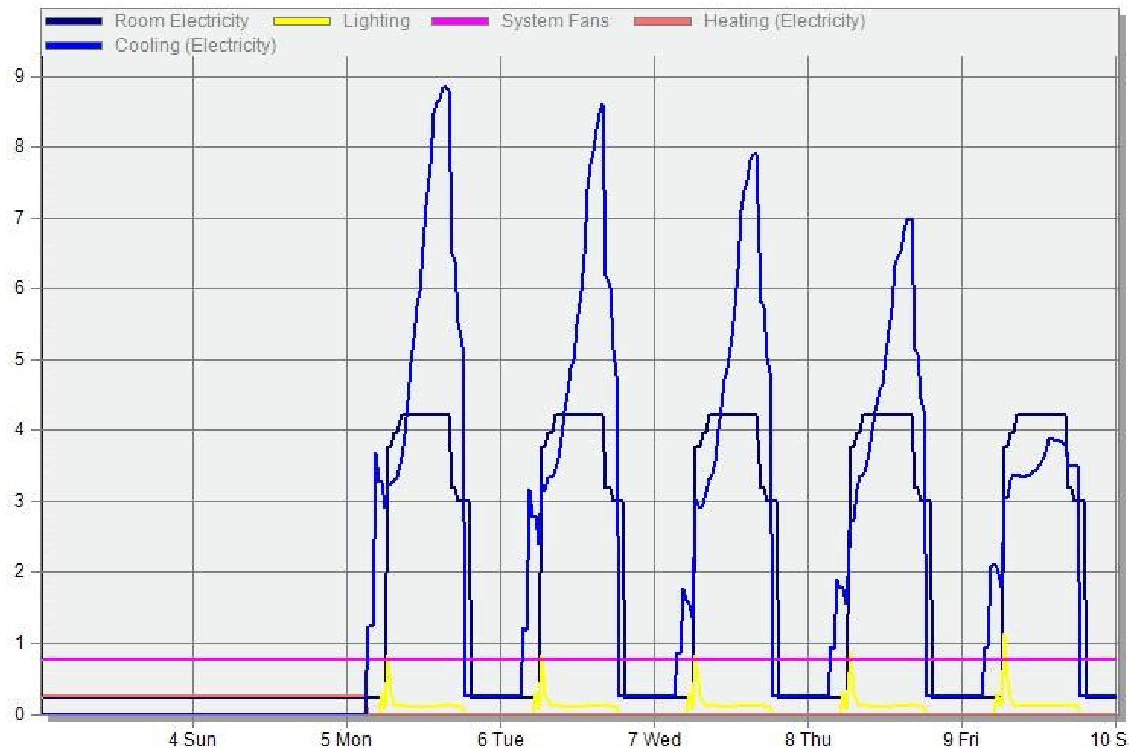


Figure 77 VRF fuel breakdown for cooling at building level

Comparing the simulation results for cooling

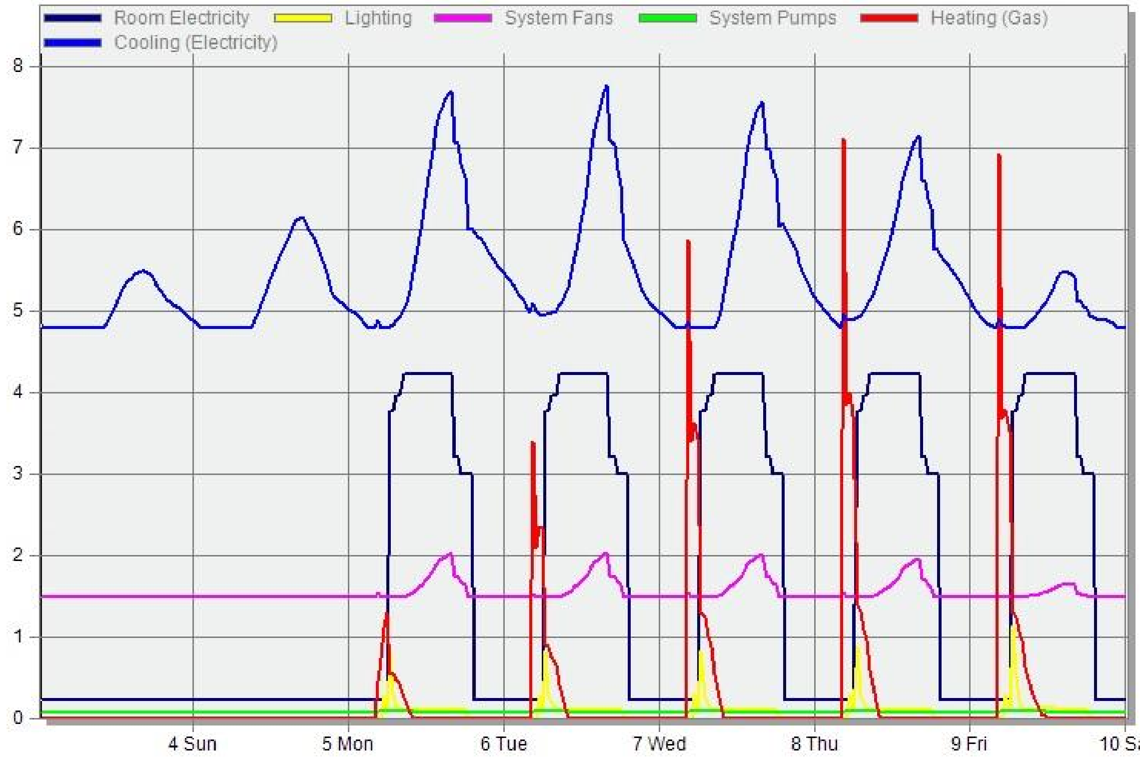


Figure 78 VAV breakdown for cooling at building level

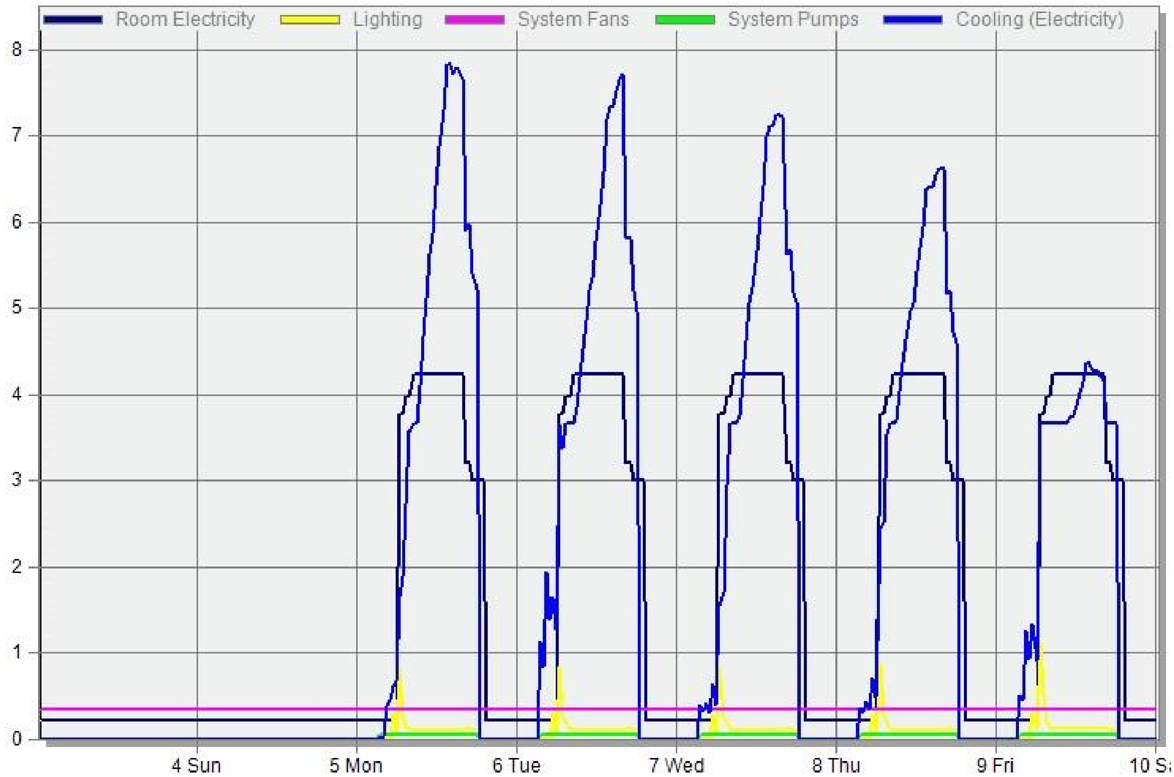


Figure 79 Fan coil breakdown for cooling at building level

11 Conclusion

A comparative analysis between VRF, VAV and fan coil system is presented. This dissertation investigates which HVAC system is suitable for conditioning the selected building. The analysis shows that the advantages of VRF systems over VAV or chiller and fan coil system, make this system more suitable choice than the other two systems. These advantages are as follows

11.1 Simultaneous heating and cooling

The major benefit of variable refrigerant flow system over the conventional systems is to provide heating and cooling simultaneously for each zone by transferring the excess heat from a zone that requires cooling to the other zone that needs heating. The VRF system enables heat recovery applied between heating and cooling requiring zones. This feature of VRF system doesn't swing the space temperature which means it avoids space over cooling or heating which we may experience with conventional HVAC systems.

For instance, the VAV with reheat system provides high variability in internal zones. During the cooling season, the system provides cooled air for zones with lower temperature than they require. Thus, reheating the air is required to meet the set point temperature which results in more energy consumption.

The compressors of VRF systems use variable refrigerant flow and controlled by variable speed, therefore, they are more efficient compare to conventional compressors with the same size. Although, the compressors are more efficient, but the complexity of the system makes the compressors more expensive than conventional compressors.

11.2 Effective cost of installation

Despite traditional HVAC systems which require ductwork or very large pipe line they are simple to install and this feature makes them a cost alternative to conventional system. Generally, the outdoor unit has light weight and requires small place to install so they can be put on roof or outside of each zone which means saving on total construction cost can be achieved since no central plant is required for installing them. As far as we know the chiller and boiler system require a specific place to put them which increases the cost of construction and wasting more space. The chiller and boiler system require large pipe line, more pumps and other instruments to run the system effectively, therefore, installation of them is more difficult and takes a lot of time. Whereas, simple pipe line of VRF outdoor unit to indoor terminal unit makes the installation of VRF system much faster than conventional systems.

11.3 Comfort

The technology of VRF system enables providing heating and cooling individually for large number of zones in a single building which provides more choice for each zone. The system can meet quickly the load of each zone by continuously adjusting the amount of refrigerant, thus, minimizes the temperature change for each zone.

11.4 Design flexibility

Multiple type and size of indoor unit of VRF system provides design flexibility to meet any taste and fit to any application. Also, if in any case the new construction should be added to the existing building, the modular capability of VRF system allows complementary outdoor and indoor unit combined to the existing unit without any problem.

11.5 Quiet

VRF system works significantly at lower noise level compare to traditional HVAC system. Due to partial work of outdoor unit the noise level has been reduced 5dB. This function is an advantage of VRF system which allows to use them in buildings which require minimum noise such as hospital, library, research labs, libraries and others.

11.6 Reliability and less maintenance

Due to controlling each zone separately, the VRF system can work continuously even if there is a failure in an indoor unit which increase the level of reliability. Despite traditional HVAC systems which have duct to transfer air or other applications such as pumps, splitter, mixer, cooling tower and boiler which require annual maintenance cost, the simplicity of VRF system reduces its maintenance cost. The maintenance of VRF system consists of only cleaning coils and changing filters.

Based on economic analysis, the VRF system can be highly recommended for buildings which use large amount of energy such as hospitals. Based on simulation which has been done in this dissertation it is evident that VRF system could be recommended for other buildings such as residential and commercial buildings in most climate zones except for very cold zones which considerable heating required. In this case, systems which work with natural gas would be preferred.

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