Solar House Sink Group
HVAC System Design

Final Report

12 May 2011

Bob Hayes, Will Seeber, Zhen Zhao, Zhen Kuang

ENES489P Spring 2011

Title: Design of an Intelligent HVAC System for the Solar Decathlon House
ISR Advisor: Prof. Austin, Prof. Baras, Shah-An Yang

Project Abstract
In this project we apply a systems engineering approach to design an intelligent HVAC system. Using sensors and user provided information the systems determines and adjusts the cooling load on the fly to provide the most efficient operation possible, saving energy and money. The system utilizes variable speed drives to provide just enough capacity to keep the indoor conditions of the house comfortable.

Table of Contents

Part 1. Problem Statement

Indoor conditions are critical to resident comfort and health. To achieve desired conditions, residential heating, ventilation, and air conditioning systems monitor and adjust conditions in the space. As shown in Figure 1, the energy used in space heating and cooling accounts for 54% of total residential energy use. Designing a more efficient HVAC system is an excellent opportunity to realize a reduction in residential energy use and as a result residential energy cost.

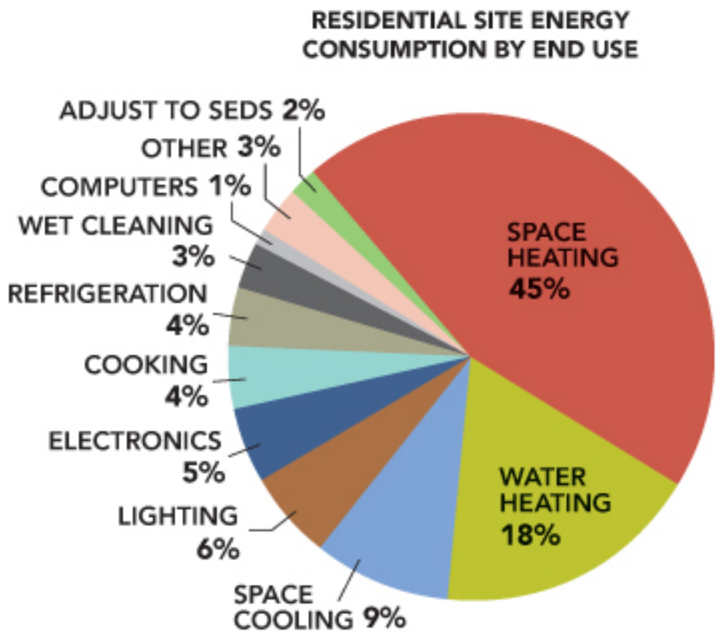


Figure 1 Residential Site Energy Consumption (Building Energy Data Book, DOE 2011)

Most HVAC systems are dumb. The user sets the desired temperature using a thermostat. The thermostat then activates the heat pump and air handler to adjust the temperature in the space until it reaches the desired temperature plus or minus a given setback. After the temperature meets the specification made by the resident, the heat pump and air handler are deactivated and the system waits until the temperature again exceeds the set point. While the there is an active feedback mechanism, knowledge of outdoor conditions, system temperature, humidity, and trends in conditions are generally not considered in determining system operating status.

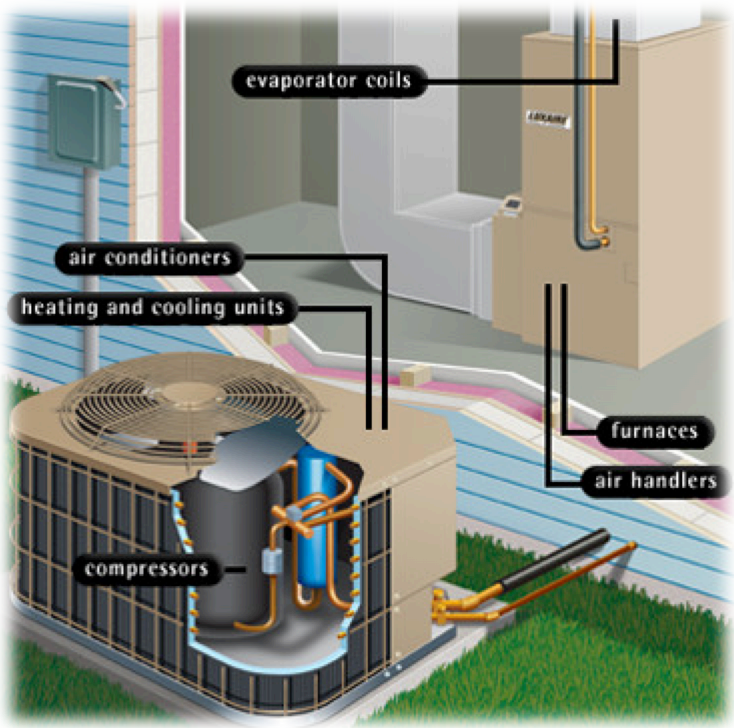


Figure 2 Typical residential heat pump Source:mustknowhow.com

A key idea in engineering for energy efficiency is to prevent Residents, HVAC contractors, HVAC manufacturers, home builders, and utility companies all benefit from more efficient HVAC systems. Reducing energy demand, reducing consumer cost, and improving user satisfaction bring benefit to all of the stakeholders.

By reducing system cycling, reducing system size, and providing just enough capacity to meet the residents requirements, large energy savings can be realized. In this project, we utilize a systems engineering approach to design an intelligent HVAC system. The system is labeled intelligent because it leverages knowledge of indoor and outdoor conditions, as well as the status of each component in the system.

Part 2. Use Case Development

The goal of an HVAC system is to maintain comfortable indoor conditions. Residents would like this to be accomplished as quietly and using as little money as possible. Total cost is the sum of system operation costs and capital costs. And since electricity is the largest operational expense in HVAC systems, the corollary to inexpensive operation is operation that requires less energy.

We have identified five primary fragments of functionality to describe an HVAC system. As shown in Figure 3, these five use cases are: temperature control, indoor air quality control, humidity control, system maintenance, and system installation.

The four actors shown in Figure 3 are residents, technicians, outdoor conditions, and indoor conditions. Residents set the temperature and maintain or control maintenance of the system. Technicians are trained professionals certified to install and maintain HVAC systems. Outdoor conditions is an abstraction for ambient outdoor temperature, air quality, humidity, and insolation. Outdoor conditions determine the heating load, are used to control indoor air quality, and determine in part the amount of humidification or dehumidification required by the system. Similarly, indoor conditions is an abstraction for ambient indoor temperature, humidity, air quality, and indoor heat loads.

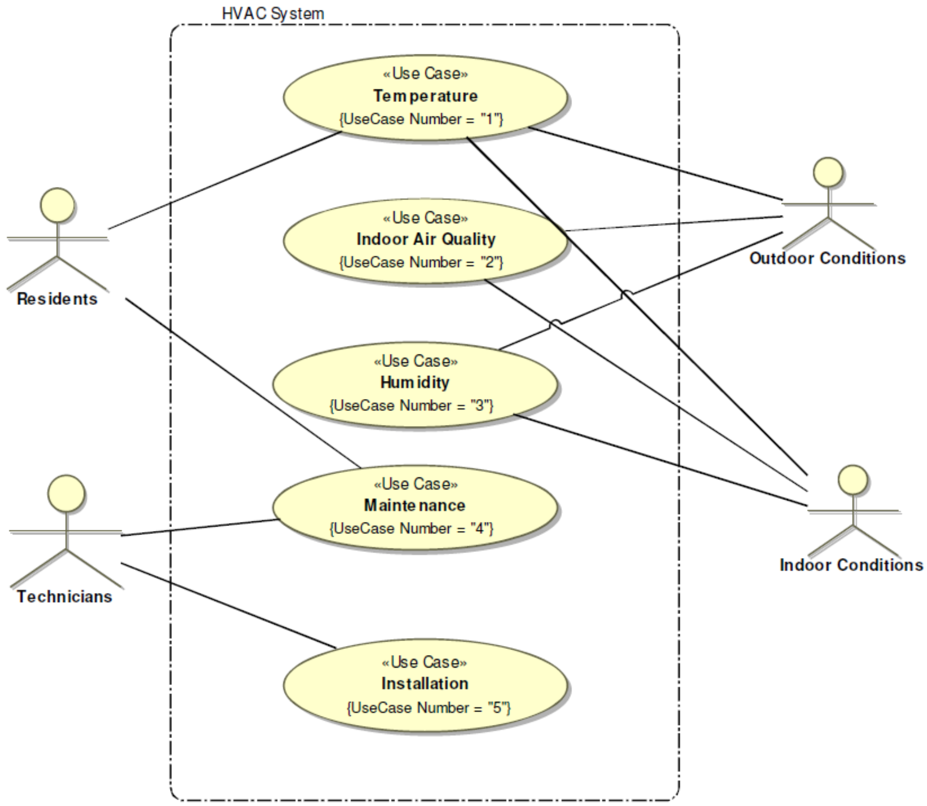


Figure 3 Use Case Diagram

Part 3. Textual Scenarios and System Behavior

Use Case 1: Indoor Air Temperature

Primary Actors: Residents, Indoor Conditions, Outdoor Conditions
Description: System maintains indoor air temperature at user-defined temperature setting
Pre-conditions: System is on and the resident has selected desired indoor air temperature via control user interface
Flow of Events:

1. Control subsystem measures indoor air temperature
2. Control subsystem collects outdoor air temperature and indoor condition stats
3. Control subsystem calculates difference between desired and actual indoor air temperatures
4. Control subsystem adjusts load on compressor, evaporator, and condenser drives accordingly.
5. Events 1 through 4 repeat

Post-conditions: System is on and indoor air temperature is within prescribed range of user-desired temperature

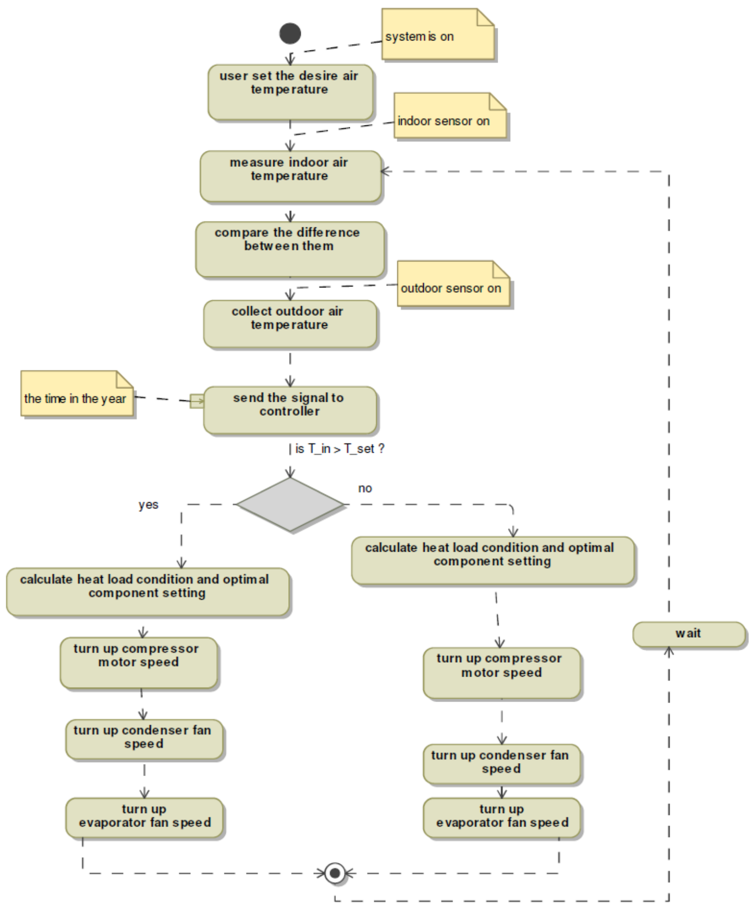


Figure 4 Activity diagram for temperature

Use Case 2: Indoor Humidity Level

Primary Actors: Outdoor Conditions
Description: System maintains indoor humidity level within predetermined range programmed into Control Subsystem
Pre-conditions: System is ON
Flow of Events:

1. Control subsystem measures indoor humidity level
2. Control subsystem measures outdoor humidity level
3. Control subsystem calculates difference between current indoor humidity level and programmed desired humidity level
4. Control subsystem adjusts evaporator, and energy recovery subsystems accordingly
5. Events 1 through 4 repeat

Post-conditions: System is ON and indoor humidity level is within prescribed range according to Control subsystem

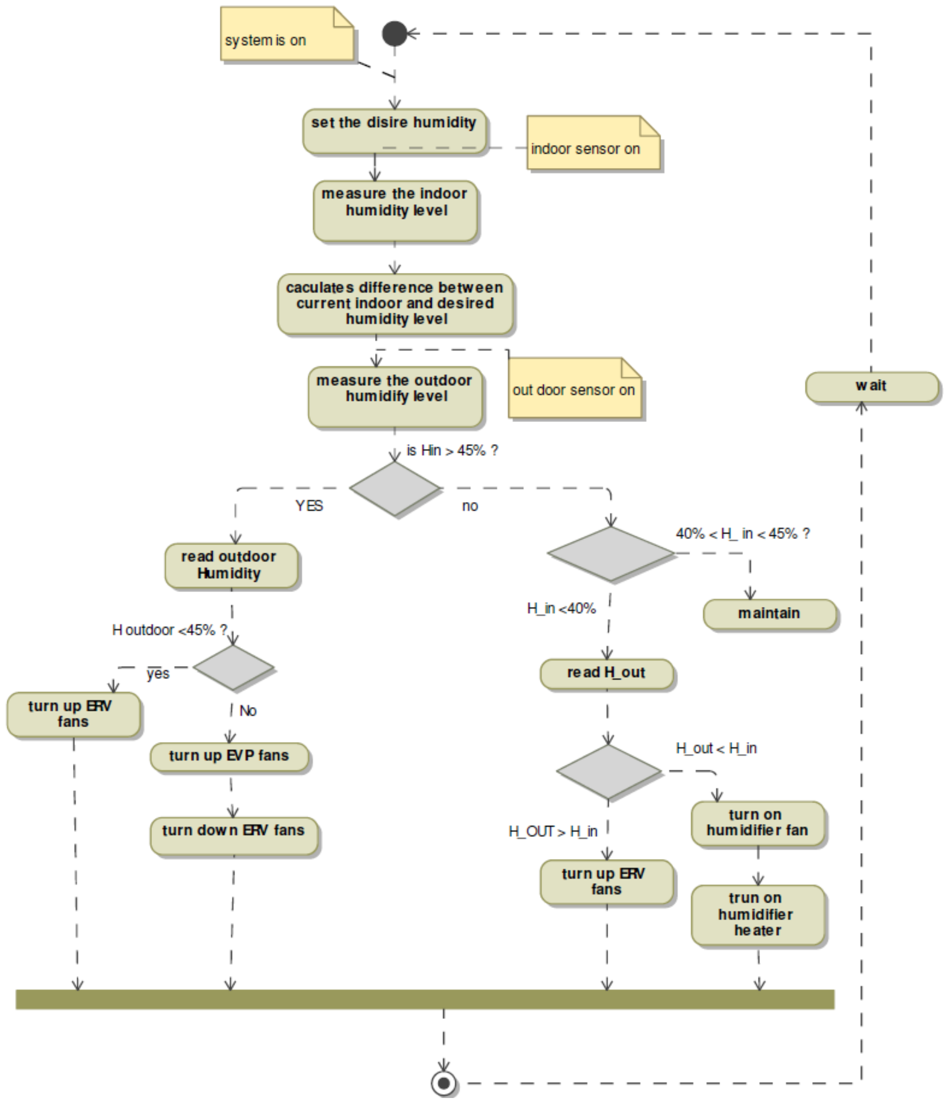


Figure 5 Indoor Humidity level humidity diagram

Use Case 3: Indoor Air Quality

Primary Actors: Outdoor Conditions
Description: System maintains air quality within predetermined range programmed into Control Subsystem
Pre-conditions: System is ON
Flow of Events:

1. Control subsystem measures indoor levels of CO2, VOCs, and particulates
2. Control subsystem measures outdoor levels of C02, VOCs, and particulates
3. Control subsystem calculates difference between current indoor air quality and programmed desired air quality
4. Control subsystem adjusts ERV subsystem accordingly

Post-conditions: System is ON and indoor air quality is within prescribed range according to Control subsystem

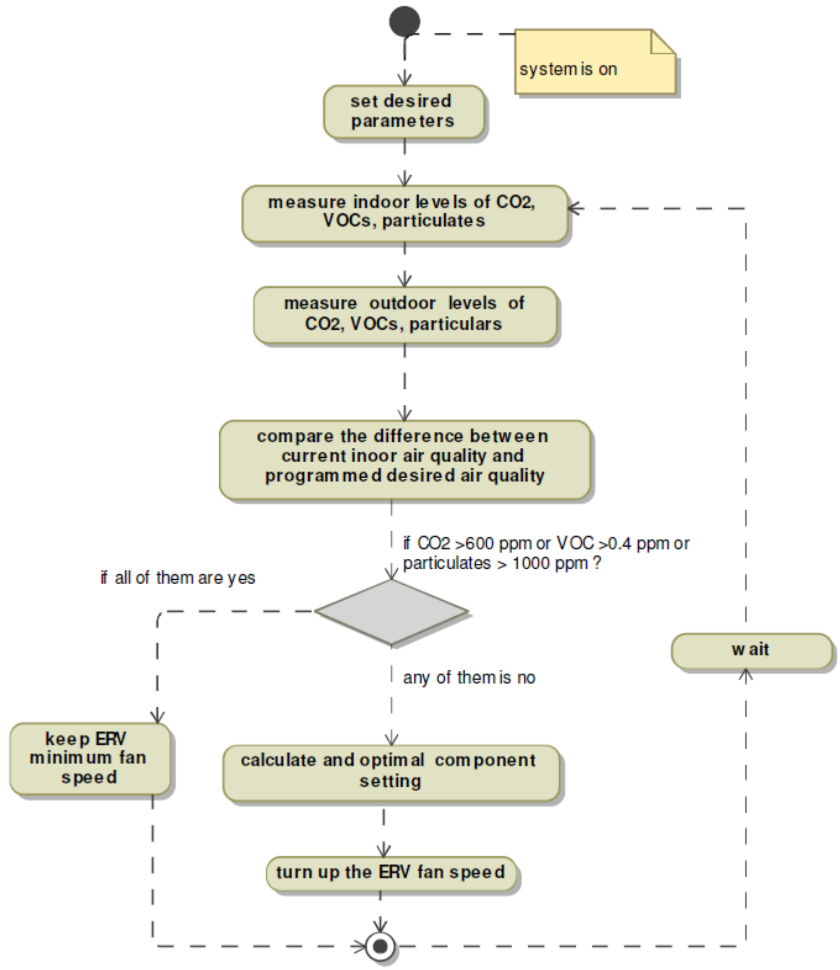


Figure 6 Activity diagram for indoor air quality

Use Case 4: Maintenance

Primary Actors: User, Technicians

Description: System notifies user when maintenance is required due to Control subsystem finding operational parameter out of spec

Pre-conditions: System is ON and maintenance is required

Flow of Events:

1. Control subsystem measures air filter pressure differential, condenser fan pressure differential, evaporator fan pressure differential, condenser fan motor oil level, evaporator fan motor oil level, evaporator coil pressure differential, evaporator drain pressure, and refrigerant level
2. Control subsystem notifies user via user-control subsystem interface of which operational parameter is out of spec and what maintenance is required
3. Technician performs required maintenance

Post-conditions: System is ON and maintenance is no longer required

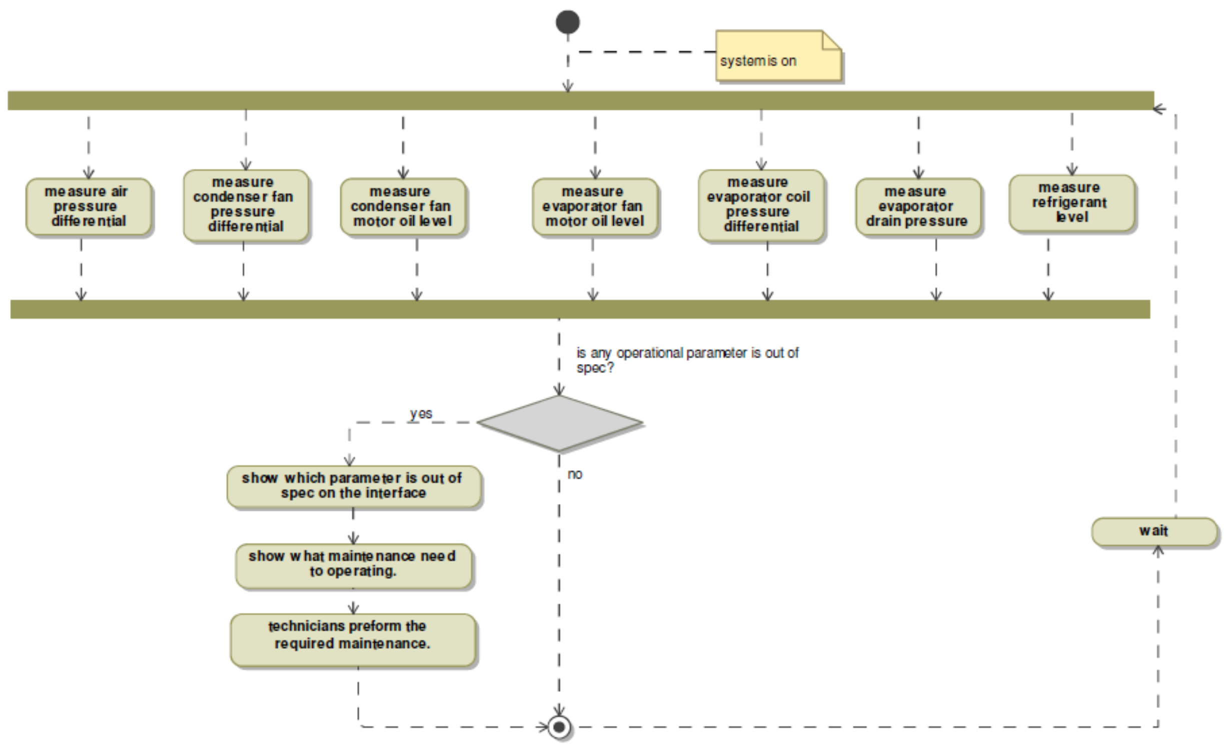


Figure 7 Activity diagram for maintenance

Use Case 5: Installation

Primary Actors: Technicians
Description: Certified technicians install system in house
Pre-conditions: Home is without HVAC
Flow of Events:

1. Technician selects indoor unit location based on guidelines
2. Technician selects outdoor unit location based on guidelines
3. Technician calculates piping length and elevation
4. Technician mounts installation plates
5. Technician drills wall holes for refrigerant line pipes and ERV
6. Technician flares all necessary pipes
7. Technician connects indoor refrigerant piping
8. Technician installs ERV
9. Technician connects ERV ducting to indoor units
10. Technician connect outdoor unit piping
11. Technician connects cabling between indoor and outdoor units
12. Technician connects power cabling to outdoor unit
13. Technician installs drainage piping
14. Technician checks drainage
15. Technician charges and air purges refrigerant lines
16. Technician powers system ON via user-control subsystem interface
17. Technician inputs building parameters through user-control subsystem interface
18. Technician tests system

Post-conditions: Home has working HVAC

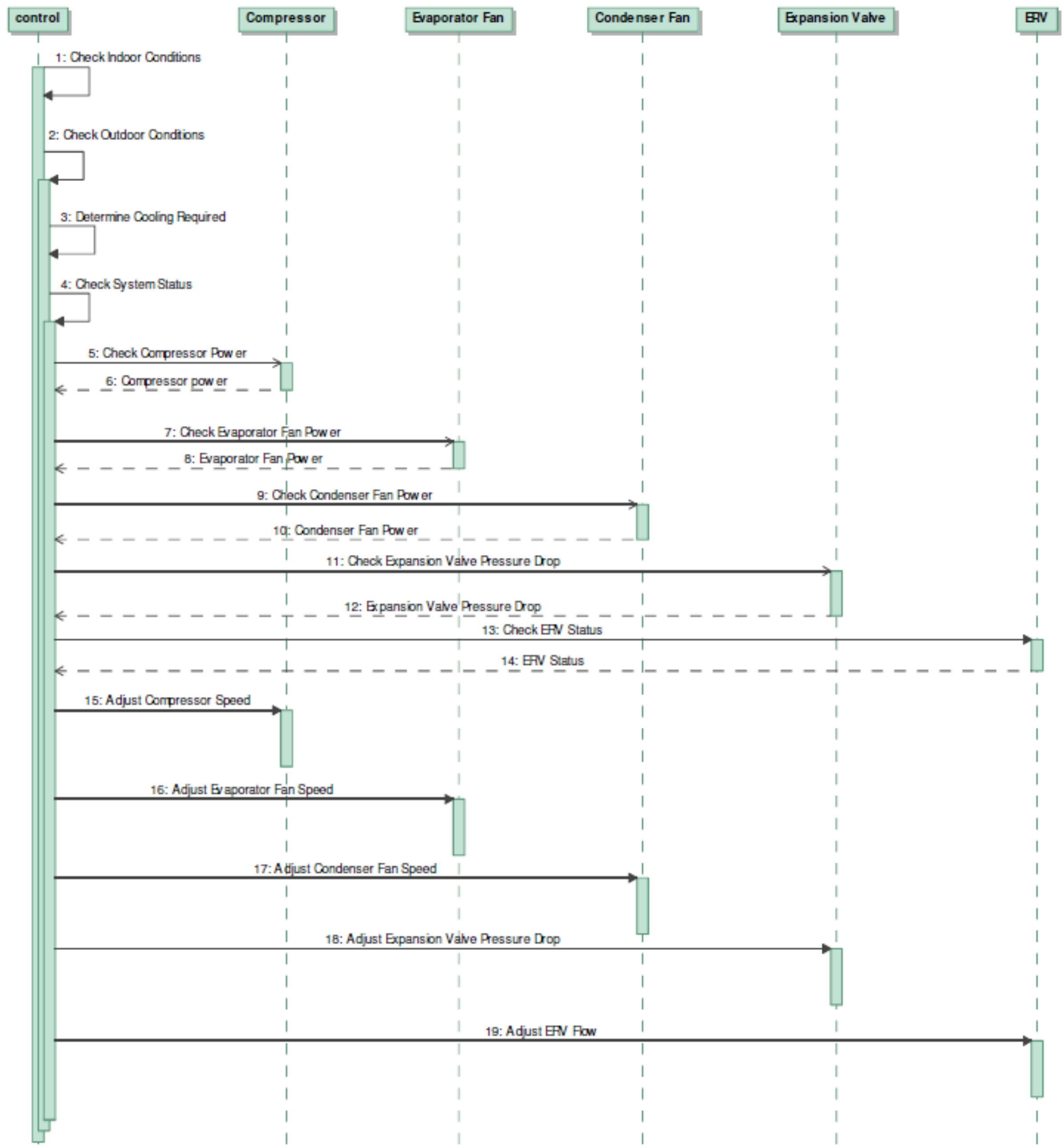


Figure 8 Sequence diagram for HVAC system

Part 4. Simplified Models of System Structure

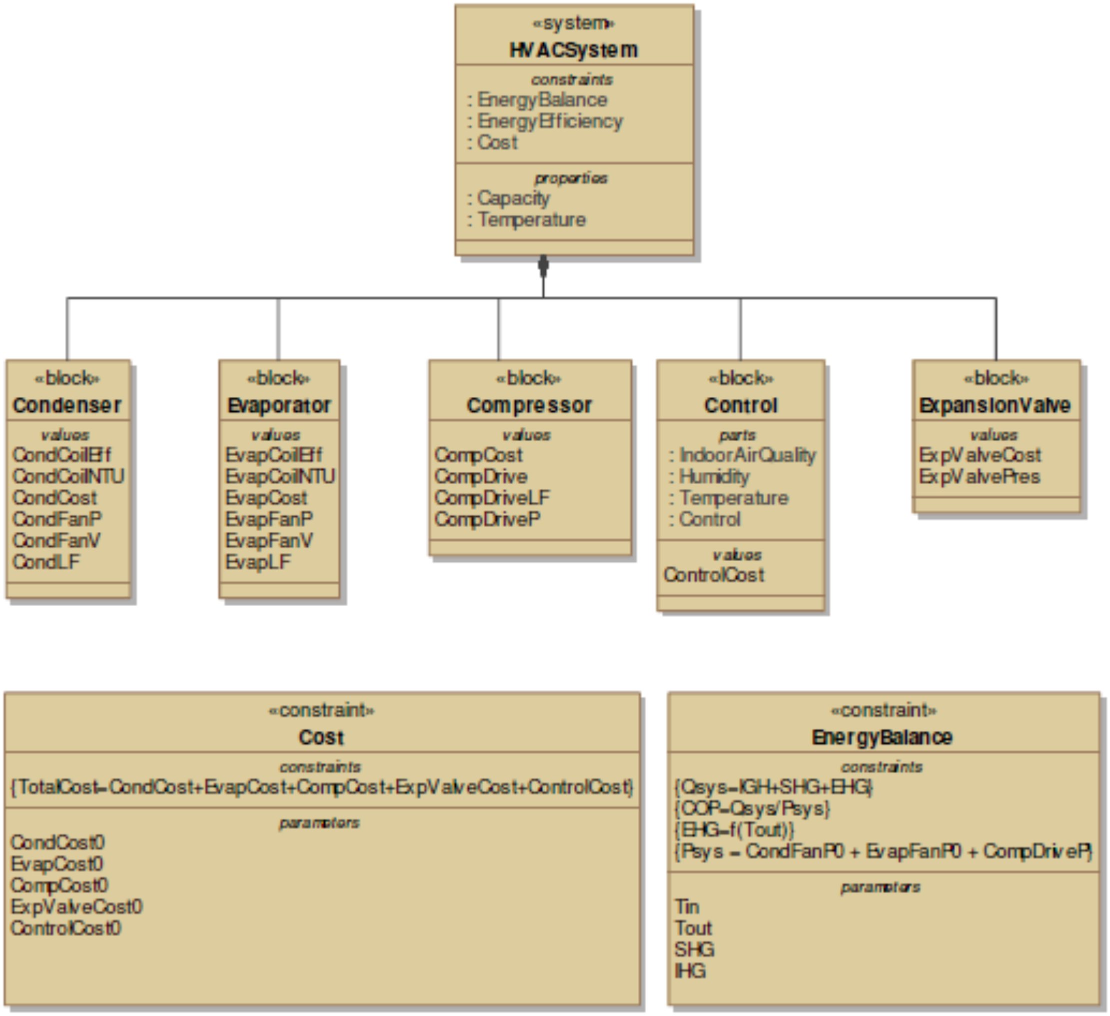


Figure 9 Block Definition Diagram

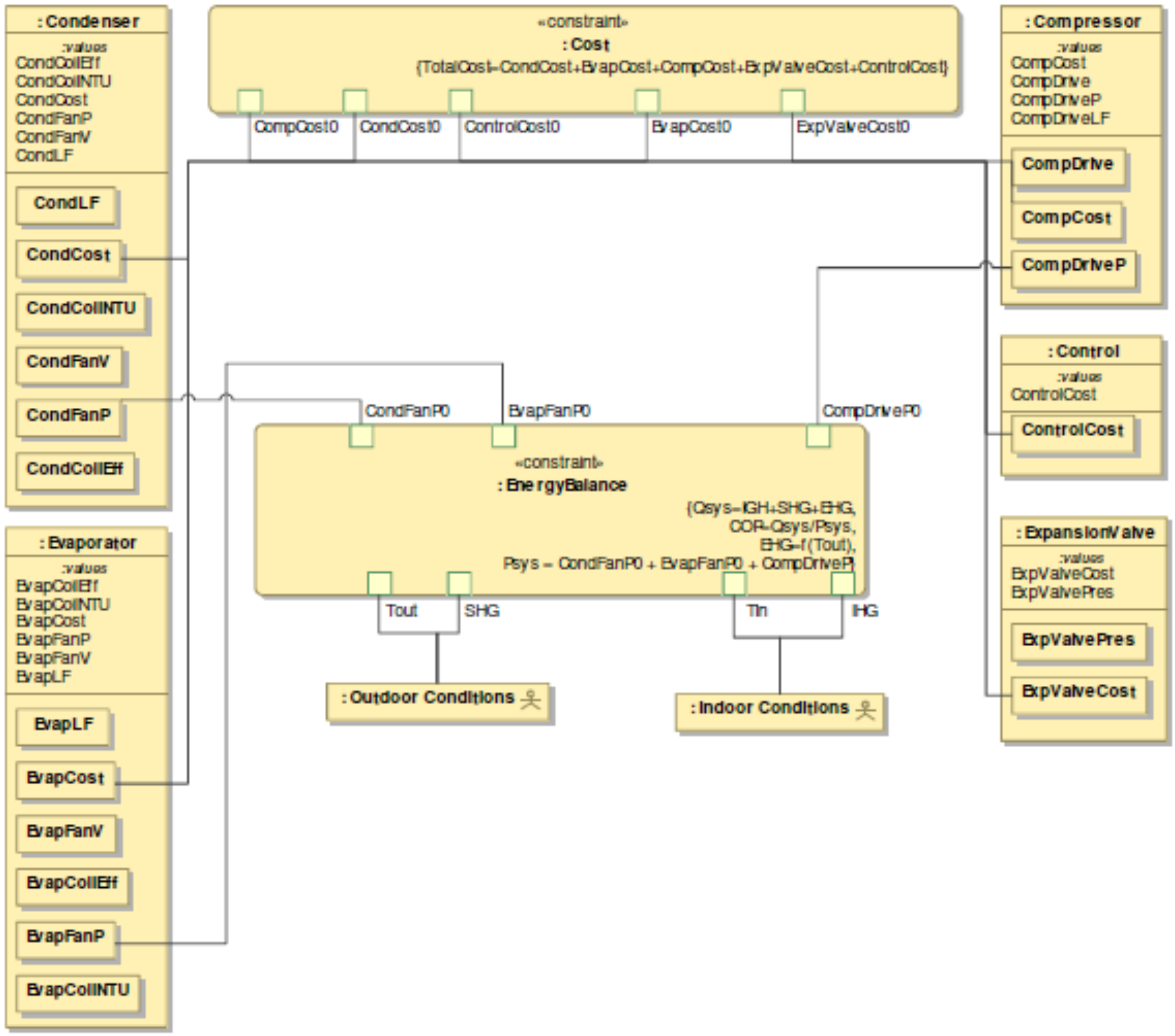


Figure 10 Parametric diagram showing cost constraint and energy balance constraint

Components

Condenser –The condenser is located outside of the house. Heat is pumped from inside the house and dispersed by the condenser. The condenser is a refrigerant to air heat exchanger. Outside air with a lower temperature than the refrigerant is blown over the condenser. Inside the condenser, the refrigerant is cooled and changes phases from vapor to liquid.

CondCoilEff	Condenser coil effectiveness
CondCoilNTU	Condenser coil number of transfer units
CondCost	Condenser cost
CondFanP	Condenser fan power
CondFanV	Condenser fan volumetric flowrate
CondLF	Condenser fan drive load factor

Evaporator – The evaporator is located inside the house. Warm air is blown over the evaporator, cooled, and then released into the conditioned space. The evaporator is a refrigerant to air heat exchanger. Inside the evaporator the refrigerant is heated and changes phase from a liquid-vapor mix to a vapor only. Water vapor condenses on the evaporator and is drained out of the house to reduce the relative humidity. This process also achieves latent cooling, because wet air has a much greater specific heat than dry air.

EvapCoilEff	Evaporator coil effectiveness
EvapCoilNTU	Evaporator coil number of transfer units
EvapCost	Evaporator cost
EvapFanP	Evaporator fan power
EvapFanV	Evaporator volumetric flowrate
EvapLF	Evaporator fan drive load factor

Compressor – The compressor is located outside of the house. The compressor pumps refrigerant from the lower pressure of the evaporator to the higher pressure in the condenser.

CompCost	Compressor cost
CompDrive	Type of compressor drive {VFD, single speed}
CompDriveLF	Compressor drive load factor
CompDriveP	Compressor drive power

Control – In a typical residential building, the primary control for an HVAC system is a thermostat. In the system we design, the control system measures many more variables and takes into account the house's design conditions. The control system measures indoor and outdoor temperature, indoor and outdoor relative humidity, and indoor and outdoor air quality. In addition, the control system measures component values including: condenser temperature, evaporator temperature, compressor power, condenser fan power, and evaporator fan power.

Expansion Valve – The expansion valve controls the pressure difference between the evaporator and the condenser. The expansion valve pressure drop can be varied electromechanically

Constraints

Cost – The cost constraint is very straightforward. Requirement 2 System Cost indicates that the system must cost less than comparable systems on the market. The cost constraint block considers the upfront cost of the system as the sum of the cost for each component. In order to provide a more useful and a more intuitive cost model, the costs are expressed as the percent increase over a non-VFD alternative. In other words, instead of using absolute cost, the costs are estimates of the premium for a more efficient component.

Energy Balance – As per the system requirements, the system must provide enough cooling to keep the house's indoor conditions comfortable for residents. The energy balance constraint block uses the component power use, the house's heat gain, and system capacity to determine COP. The system adjusts its cooling capacity based on the house's heat gain (a function of indoor temperature, insolation, and occupancy) and the status of the systems components.

Part 5. Requirements Engineering

Level 1 Requirements

1. System must maintain highly comfortable and healthy indoor air conditions
2. System must be energy efficient
3. System cost must be competitive with higher efficiency systems on the market today

Level 2 Requirements

ID	Name	Text
1	**Indoor Conditions**	System must maintain comfortable and healthy indoor air conditions.
1.1	User Interaction	System must allow user to set desired temperature
1.1.1	Wireless User Interface	System must have wireless user interface
1.1.2	iPad2 Interface	System must be compatible with iPad2 control application
1.2	Humidity	System must maintain indoor air humidity between 40 and 50% relative humidity
1.3	Indoor Air Quality	System must maintain healthy indoor air quality
1.3.1	CO2	CO2 concentration must be less than 600 ppm
1.3.2	VOC	VOC concentration must be less than 0.4 ppm
1.3.3	PM	Particulate Matter concentration must be less than 1000 ppm
1.3.4	Ventilation	ERV must allow ventilation rate between 15 cfm and 200 cfm
1.4	Cooling Capacity	System must have a cooling capacity of at least 5.275 kW
1.5	Sound Pollution	System must not generate too much noise
1.6	Temperature	System must maintain indoor conditions to within 2 degrees Celsius of the set temperature
2	**Energy Efficiency**	System must be energy efficient
2.1	SEER	SEER Rating must be greater than 25
3	Cost	Installed system cost must not exceed $6000
3.1	Installation Cost	System installation cost must be comparable to commercially available high efficiency HVAC systems
3.2	Operating	System's operating cost must be comparable to commercially available high efficiency HVAC systems
4	**Maintenance**	System must be able to be maintained
4.1	User Notification	System must notify user when maintenance is required
4.1.1	System Monitoring	System must monitor component status
4.1.2	Compatibility	System sensors must use 6 pin mini din connectors
4.2	Common Maintenance	System must be maintainable by certified technicians

5	**Installation**	System must be installable by certified technicians

Level 3 Requirements for system sensing

ID	Name	Text
SS1	Filter Static Pressure	System must measure the pressure drop across the air filter
SS2	Condenser Fan Pressure	System must measure the pressure drop across the condenser fan
SS3	Evaporator Fan Pressure	System must measure the pressure drop across the evaporator fan
SS4	Evaporator Coil Pressure	System must measure the pressure drop across the evaporator heat exchanger
SS5	Refrigerant Level	System must measure the amount of refrigerant in the system
SS6	Condenser Temperature	System must measure the condenser temperature
SS7	Outdoor Conditions	System must measure outdoor air conditions
SS7.1	Outdoor Temperature	System must measure outdoor temperature
SS7.2	Outdoor Relative Humidity	System must measure outdoor relative humidity
SS8	Indoor Conditions	System must measure indoor air conditions
SS8.1	Indoor Temperature	System must measure indoor temperature
SS8.2	Indoor Relative Humidity	System must measure indoor relative humidity
SS8.3	Indoor PM	System must measure indoor particulate matter concentration
SS8.4	Indoor VOC	System must measure indoor volatile organic compound concentration
SS8.5	Indoor CO2	System must measure indoor carbon dioxide concentration
SS9	Evaporator Temperature	System must measure the evaporator temperature

Level 3 Requirements for user interface

ID	Name	Text
UI1	Maintenance	User interface must display system add reason for repair
UI2	Set point	User should be able to control their set points.
UI3	Wireless operation	User interface must operate wirelessly
UI4	Power	User interface must display system power consumption
UI5	iPad2 compatibility	User interface must operate with iPad2 compatibility
UI6	On/Off	User interface must allow the user to be able to turn system on and off.

Requirements Traceability to Use Cases

Use cases	Req. ID	structure/ behavioral	description
indoor air temperature	1	behavioral	system must maintain a good indoor air temperature
	1.6	behavioral	indoor temperature must maintain within 2 degrees Celsius of the set temperature
indoor humidity level	1	behavioral	system must maintain indoor humidity level less than 45%
	1.2	behavioral	when indoor humidity is out of the range between 40 and 50%, system start to working to change the humidity
indoor air quality	1	behavioral	system must maintain good indoor air quality
	1.3.1	behavioral	system will maintain indoor CO2 concentration must be less than 600 ppm
	1.3.2	behavioral	system will maintain indoor VOC concentration must be less than 0.4 ppm
	1.3.3	behavioral	system will maintain indoor particulate matter concentration less than 1000ppm
maintenance	1.3.4	behavioral	system must maintain ventilation rate between 15 cfm and 200 cfm
	1.4	behavioral	if the cooling capacity is below 5.275 kw, system send message to technicians to repair this
	1.5	behavioral	system must generate not more than 42 dB of sound
	2	behavioral	system maintain a reasonable energy efficient
	4.1	behavioral	when there is any error, system send notification to user to maintain the system
	4.1.1	structure	system need to monitor the components status
installation	1.1.1	structure	a interface allow user to set desire condition
	1.1.2	structure	user use the iPad2 to control the system
	3.1	behavioral	installation cost should not exceed $6000

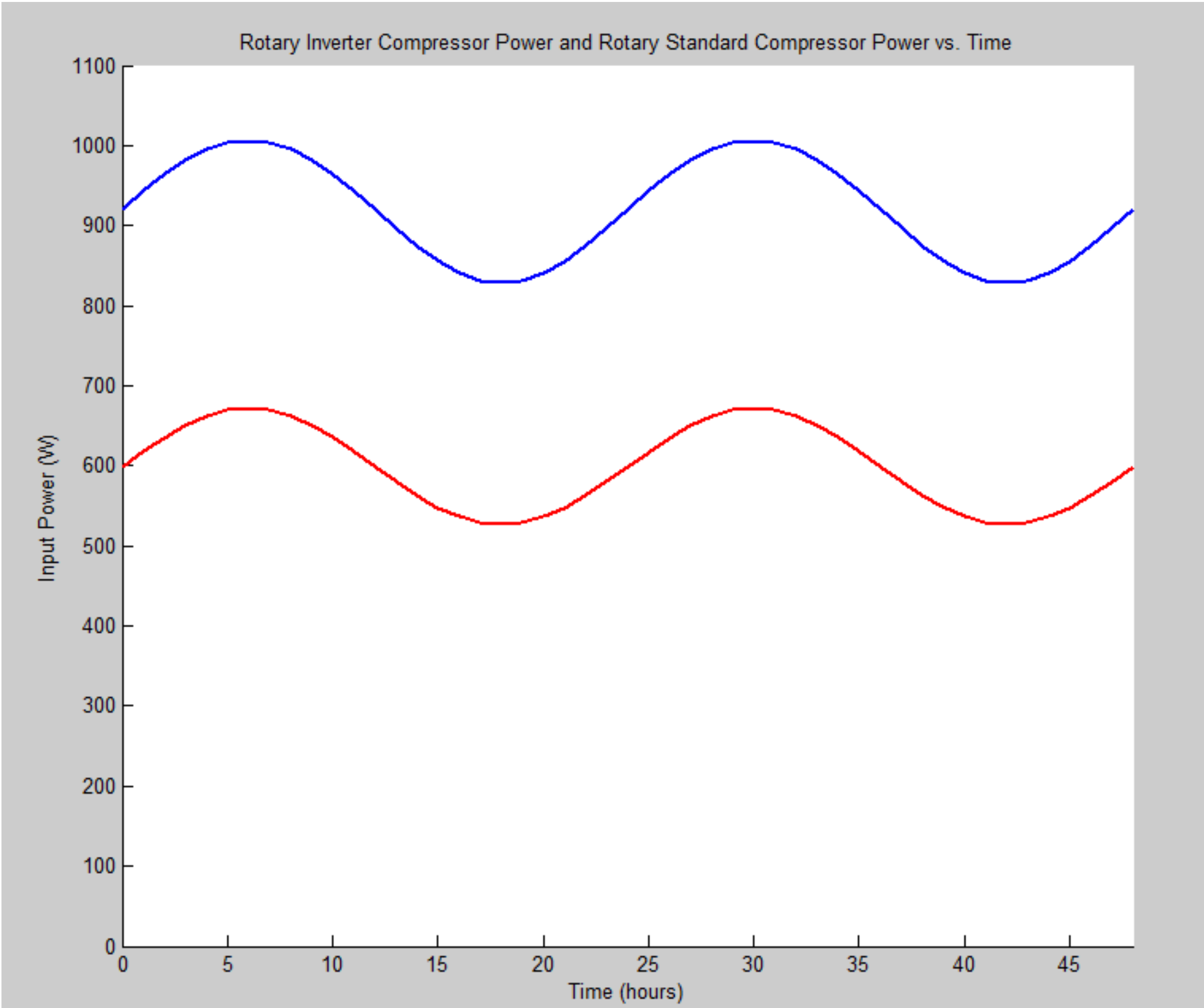
Part 6. Simplified Approach to Tradeoff Analysis

MATLAB and Engineering Equation Solver (EES) were used to model system behavior in order to highlight key design trade-offs. Inputs to the programs just as in the system itself consist of a calculated building cooling load based on external environmental conditions, mainly temperature. As the outdoor temperature is varied with time, performance of components in the HVAC system can be analyzed. Any given component can be replaced in the model such that conclusions can be drawn about performance and trade-offs in component selection can observed. The main component trade-offs modeled were the compressor, evaporator fan, evaporator coil, compressor fan, compressor coil, and expansion valve.

The theory behind the design of the smart HVAC system is implementing continuously variable drive fan motors, expansion valve pressure drop, and most importantly of all, compressor motor. By having variable frequency drives on all of these components, it is possible for the control module to calculate the optimal speed for each device yielding the best system efficiency for any given cooling load. The major drawback to having these variable frequency drives is high initial cost. Since our team found it rather difficult to access the retail prices for individual components that suited the requirements of the system, this section focuses on trade-offs in operating power consumption which is effectively operating cost at the end of the day. While the variable speed components cost a considerable premium over standard components, they appear to pay for themselves over time due to their superior efficiency.

Compressor Tradeoffs

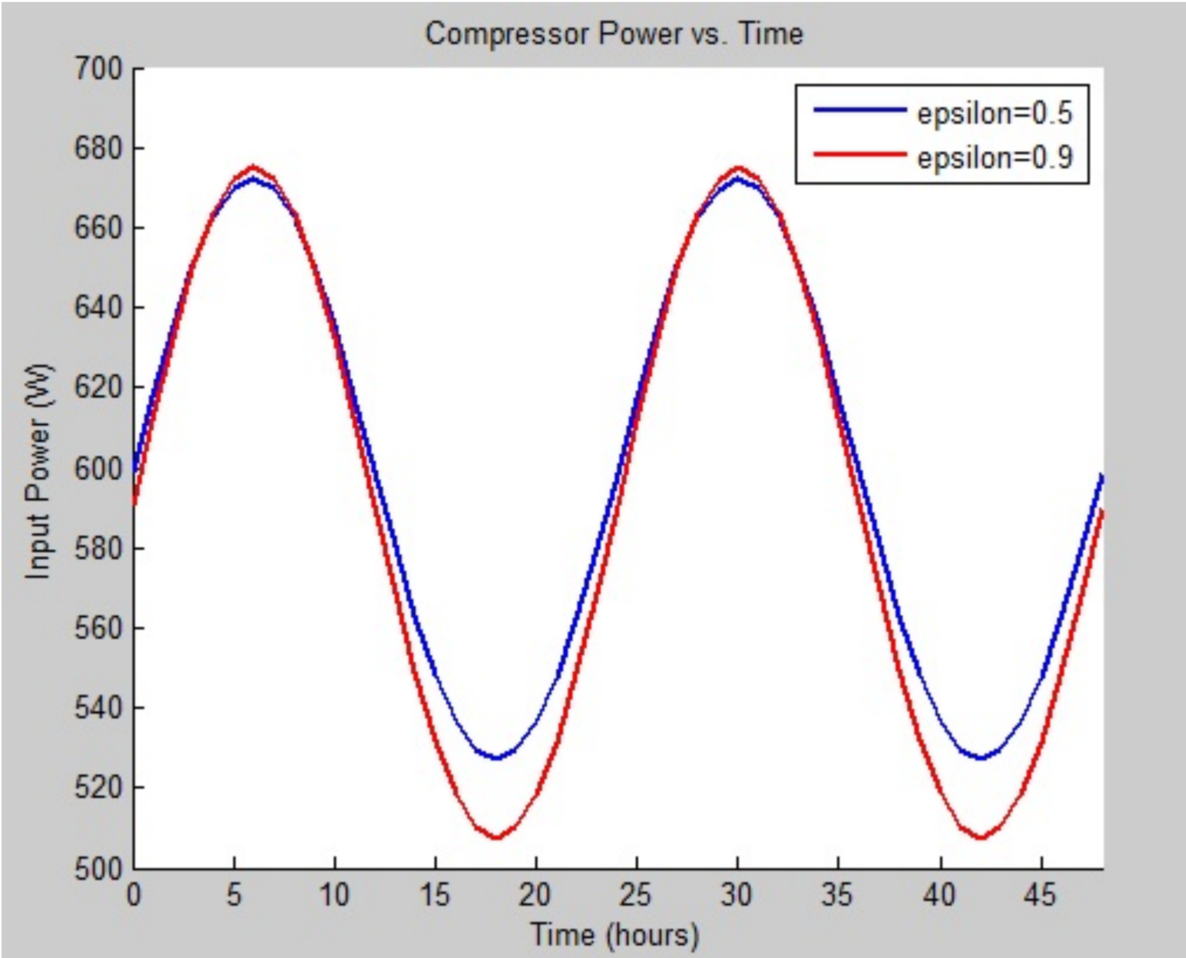
Traditionally, standard rotary compressors have been used in HVAC systems. These compressors run at one speed, and cycle on or off with a thermostat control. Standard rotary compressors are highly inefficient as they cycle on and off over time. In recent years rotary inverter compressors with variable speed drives became an option. While they cost considerably more, their efficiency exceed that of standard compressors tremendously. It was challenging to find many rotary inverter compressor power maps to use as a basis for our model, however one compressor map was found that met the level three requirements. Compressor map points were converted to curves for modeling purposes. A 48 hour period was simulated for the smart HVAC system for both an inverter compressor and a standard compressor with comparable performance at 60 Hz. The standard compressor was run at 60 Hz continuously for the 48 hour period as the cooling load increases during the day and decreases through the night following a sinusoidal curve. The inverter compressor was simulated in a similar manner, however, the program calculates optimal operating frequency for the given cooling load at the time and the compressor is simulated at that frequency for that given instant. The results are shown in the figure below.



Over the two day period simulating two identical back to back summer days , the inverter compressor consumes 33 % less power as it operates at the most efficient frequency at all times. The inverter compressor would most likely make up for the high initial cost rather quickly.

<u>Evaporator Trade-offs</u>

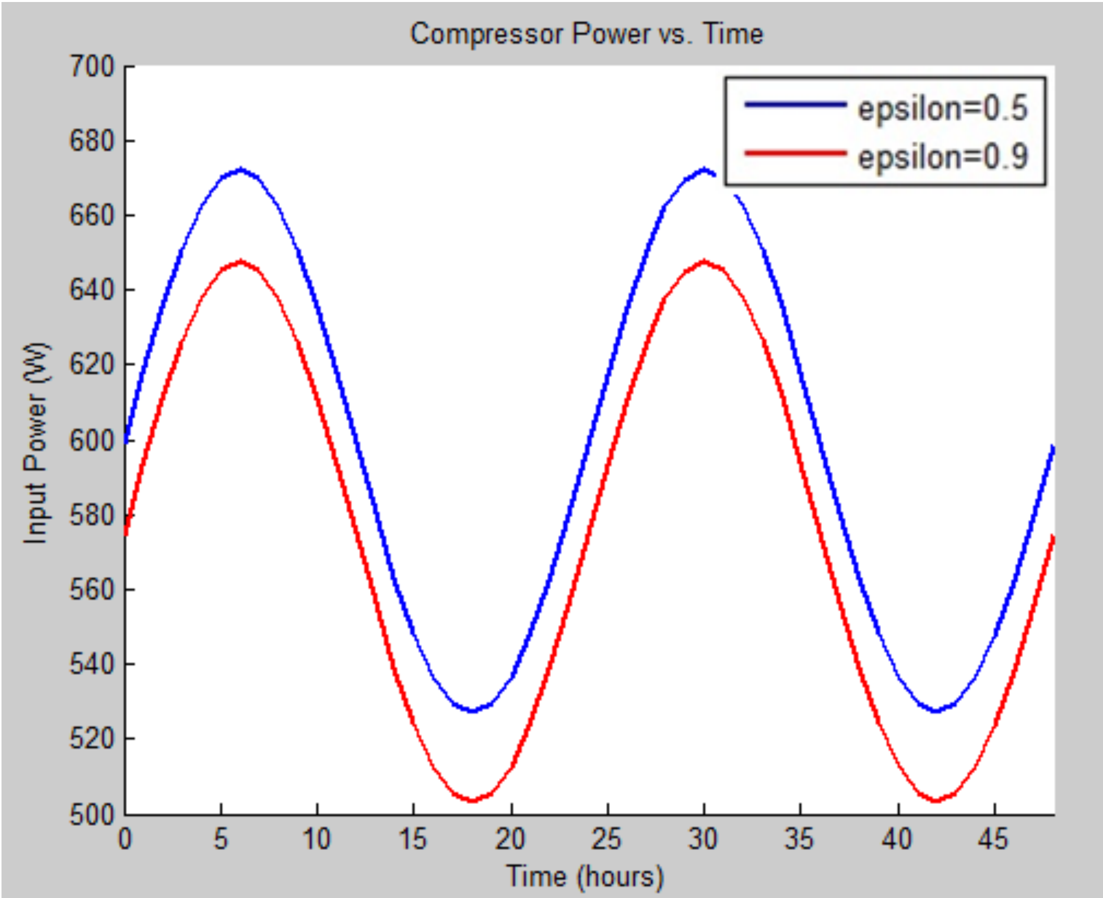
Evaporator effectiveness (ε) affects HVAC system performance greatly. Effectiveness is increased with a higher NTU coil (number of transfer units), higher overall heat transfer coefficient, and more powerful fan. Evaporators increase in cost with effectiveness, so examining the effect on cycle performance is important. In the figure below, the simulation is run with an evaporator of epsilon=0.5 and then epsilon=0.9. Top of the line evaporator coils may approach closer to 1 but never reach or exceed it.



There is a modest efficiency gain seen by using an evaporator with increased effectiveness. The savings from operational costs would likely exceed the premium in initial cost for a more effective evaporator.

<u>Condenser Trade-offs</u>

As with the evaporators, condenser performance and initial cost increase with effectiveness. As seen in the figure below, however, condenser effectiveness has a more pronounced effect on efficiency.



By paying an initial premium for variable speed motors and high effectiveness heat exchangers, the operating costs of the system are far lower in the long run.

Part 7. Summary and Conclusions

In summary, we have shown the development of use cases and requirements for an intelligent HVAC system. While we do not present a detailed system design in this report, our work shows that utilizing system-wide sensing and variable speed drives has extraordinary potential to reduce energy use in HVAC systems.

SysML has been used to model system architecture, track requirements, and visualize system behavior.

Design tradeoffs have been considered and support our work towards designing an intelligent HVAC system.

Part 8. References

- **http://www.allstyle.com/allstyle/pdffiles/manual/mini-split-install-english.pdf (installation)**
- **http://www.driamerica.com/articles/iaq-enthalpy.pdf**
- **http://www.scipub.org/fulltext/ajes/ajes13209-212.pdf**
- **http://www.ibpsa.org/proceedings/BS2005/BS05_0859_866.pdf**
- **http://www.inive.org/members_area/medias/pdf/Inive%5CIBPSA%5CUFSC456.pdf**
- **http://www.epa.gov/iaq/voc.html**
- **http://financialplan.about.com/od/savingmoney/a/CoolingCosts.htm**
- **http://www.jeacoustics.com/library/pdf/70-Himmel.pdf**
- **http://www.mylinkdrive.com/MrSlim/M_Series/Service_Manuals/R410a/MSZ-FE09~12NA_Service_Manual_OBH542_7-27-09.pdf**
- **McQuiston, *et al.* HVAC System Design and Analysis.**
- Shi, WX. "Performance representation of variable-speed compressor for inverter air conditioners based on experimental data ". INTERNATIONAL JOURNAL OF REFRIGERATION-REVUE INTERNATIONALE DU FROID 27 (8): 805-815 DEC 2004. http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V4R-4D09GC2-1&_user=961305&_coverDate=12%2F31%2F2004&_rdoc=1&_fmt=high&_orig=gateway&_origin=gateway&_sort=d&_docanchor=&view=c&_acct=C000049425&_version=1&_urlVersion=0&_userid=961305&md5=efd4dca10eb1693c7a37aeebec053e61&searchtype=a
- **Watershed Team Manual. US DOE Solar Decathlon 2011.**

Part 9. Credits

Bob Hayes

- SysML block definition diagram
- SysML parametric diagram
- SysML use case diagram
- SysML sequence diagram
- Write up: Problem statement, system structure, use case development
- Supported use case development

William Seeber:

- Generated use cases and flow of events
- Generated requirements
- MATLAB and EES Modeling and Simulation
- Tradeoffs

Zhen Kuang

- Supported tradeoff analysis
- Supported use case development

Zhen Zhao

- SysML activity diagrams
- Supported use case development
- Traceability matrix

Appendix A: Code used for tradeoff analysis

CODE 1

```
Tindoor=23.333;
t=[0:1:24];
Tevapmat=[0:1:24];
Tcondmat=[0:1:24];
q_loadmat=[0:1:24];
Pcompmat=[0:1:24];
COPcompmat=[0:1:24];
Toutdoor=[0:1:24];
speedmat=[0:1:24];
for n=1:25
  Toutdoor(1,n)=30.8333+4.167*sin(2*3.14*t(1,n)/24);
  q_load=(1887.5)*sin(2*3.14*t(1,n)/24)+((1887.5)+1500);
  if Toutdoor(1,n) <= 33;
    Tevap30=log(q_load/1650.2)/0.04;
    Tevap60=log(q_load/3769.4)/0.04;
    Tevap90=log(q_load/5995.5)/0.04;
    Pcomp30=-0.0735*Tevap30^2 + 2.6765*Tevap30 + 620.89;
    Pcomp60=-0.1491*Tevap60^2 + 3.6596*Tevap60 + 1071.2;
    Pcomp90=-0.2483*Tevap90^2 + 6.0707*Tevap90 + 1671.4 ;
    Tcond=40;

  else
    Tevap30=log(q_load/1454.4)/0.04;
    Tevap60=log(q_load/3279.1)/0.04;
    Tevap90=log(q_load/5226.3)/0.04;
    Pcomp30=-0.0019*Tevap30^2 + 4.2207*Tevap30 + 729.04;
    Pcomp60=-0.1000*Tevap60^2 + 7*Tevap60+1300.00;
    Pcomp90=-0.279*Tevap90^2 + 10.8*Tevap90 + 1964.9;
    Tcond=50;
  end

  if (Tevap30<15) && (Tevap30>-10)
    q30=1;
  else
    q30=2;
  end
  if (Tevap60<15) && (Tevap60>-10)
    q60=1;
  else
    q60=2;
  end
  if (Tevap90<15) && (Tevap90>-10)
    q90=1;
  else
    q90=2;
  end
```

```
  if (q30==1) && (q60==1) && (q90==1)
    Pcomp=min([Pcomp30,Pcomp60,Pcomp90]);

  elseif (q30==1) && (q60==1) && (q90==2)
    Pcomp=min([Pcomp30,Pcomp60]);
  elseif (q30==1) && (q60==2) && (q90==1)
    Pcomp=min([Pcomp30,Pcomp90]);
  elseif (q30==2) && (q60==1) && (q90==1)
    Pcomp=min([Pcomp60,Pcomp90]);
  elseif (q30==2) && (q60==2) && (q90==1)
    Pcomp=Pcomp90;
  elseif (q30==1) && (q60==2) && (q90==2)
    Pcomp=Pcomp30;
  elseif (q30==2) && (q60==1) && (q90==2)
    Pcomp=Pcomp60;
  else
    Pcomp=0.1234567;
  end
  if (Pcomp==Pcomp30)
    Tevap=Tevap30;
    speed=30;
  elseif (Pcomp==Pcomp60)
    Tevap=Tevap60;
    speed=60;
  else
    Tevap=Tevap90;
    speed=90;
  end
  Pcompmat(1,n)=Pcomp;
  q_loadmat(1,n)=q_load;
  Tevapmat(1,n)=Tevap;
  Tcondmat(1,n)=Tcond;
  COPcomp=q_load/Pcomp;
  COPcompmat(1,n)=COPcomp;
  Speedmat(1,n)=speed;
end


Toutdoor
q_loadmat
Tevapmat
Tcondmat
Pcompmat
COPcompmat
Speedmat
```

```
subplot(3,2,1)
plot(q_loadmat,Pcompmat)
xlabel('Cooling Load (W)')
ylabel('Compressor Power (W)')
title('Compressor Power Input Vs. Cooling Load')
subplot(3,2,2)
hold on
plot(t,q_loadmat)
plot(t,Pcompmat)
xlabel('Time (hours)')
ylabel('Watts')
title('Cooling Load and Compressor Power Input vs. Time')
hold off
subplot(3,2,3)
plot(t,COPcompmat)
xlabel('Time (hours)')
ylabel('COP')
title('Coefficient of Performance Vs. Time')
subplot(3,2,4)
hold on
plot(t,Toutdoor)
plot(t,Tevapmat)
xlabel('Time (hours)')
ylabel('Temperature (C)')
title('Outdoor Temperature And Evaporator Temperature Vs. Time')
hold off
subplot(3,2,5)
plot(t,Speedmat)
xlabel('Time (hours)')
ylabel('Compressor Speed')
title('Compressor Speed Vs. Time')
```

CODE 2:

```
time=[0:48];
T_e=7;
T_cmat=[0:48];
P_compmat=[0:48];
for n=0:48
   f=60;
   T_c=42.5+7.5*sin(2*3.14*n/24);
   P_comp=((-5E-07)*f^3 + 0.0001*f^2 - 0.0082*f + 0.1819)*T_c^2+((1E-04)*f^3 - 0.0203*f^2 + 1.452*f -
20.657)*T_c+((1E-06)*f^3-0.0002*f^2+0.0144*f-0.0942)*T_c*T_e+(( -6E-07)*f^3+0.0001*f^2 -
0.0097*f+0.1115)*T_e^2+(( -3E-05)*f^3 + 0.006*f^2 - 0.5125*f + 4.2074)*T_e+(-0.0009*f^3 + 0.2857*f^2 -
15.363*f + 489.12);
   P_compmat(1,n+1)=P_comp;
   T_cmat(1,n+1)=T_c;
end
avgPnoninv=mean(P_compmat);
Wtotni=avgPnoninv*48
hold on
```

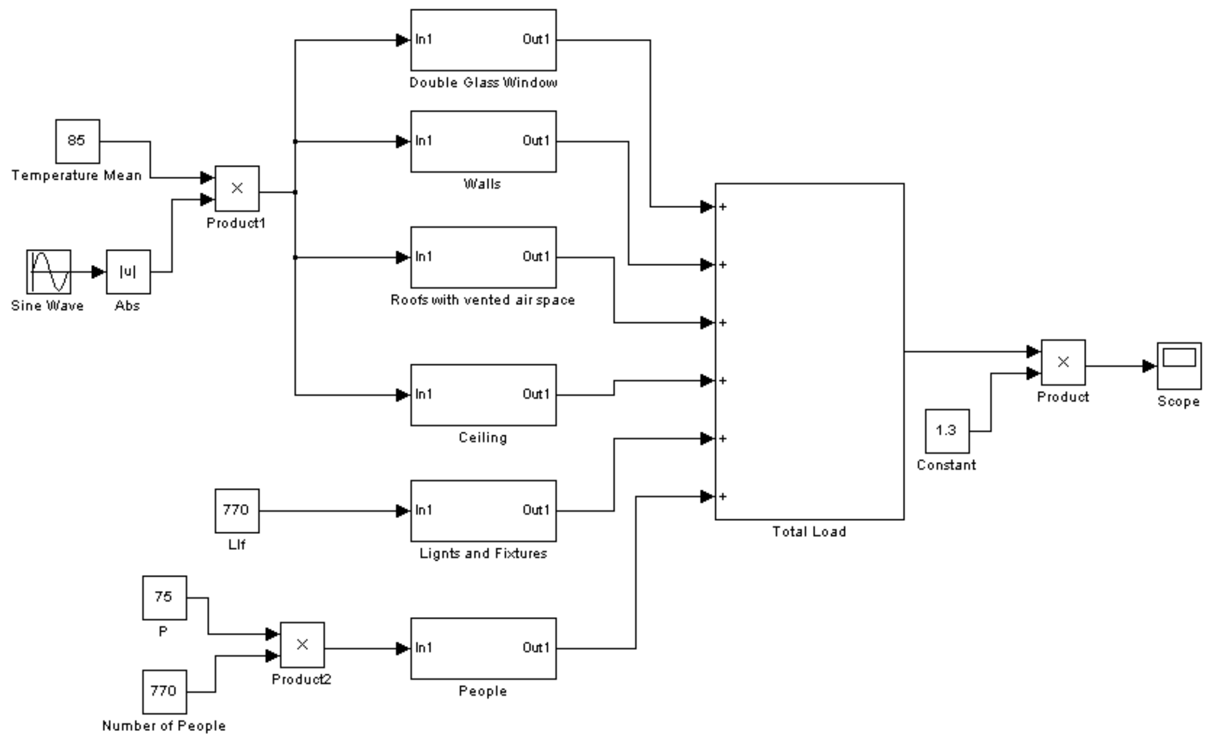
```
plot(time,P_compmat,'linewidth',2)
title('Rotary Inverter Compressor Power and Rotary Standard Compressor Power vs. Time')
xlabel('Time (hours)')
ylabel('Input Power (W)')
axis([0 48 0 1100])
P_compmat2=[1:90];
for n=0:48
  for f=30:120
    T_c=42.5+7.5*sin(2*3.14*n/24);
    P_comp=((-5E-07)*f^3 + 0.0001*f^2 - 0.0082*f + 0.1819)*T_c^2+((1E-04)*f^3 - 0.0203*f^2 + 1.452*f -
20.657)*T_c+((1E-06)*f^3-0.0002*f^2+0.0144*f-0.0942)*T_c*T_e+(( -6E-07)*f^3+0.0001*f^2 -
0.0097*f+0.1115)*T_e^2+(( -3E-05)*f^3 + 0.006*f^2 - 0.5125*f + 4.2074)*T_e+(-0.0009*f^3 + 0.2857*f^2 -
15.363*f + 489.12);
    P_compmat2(1,f-29)=P_comp;
  end
  P_compmat(1,n+1)=min(P_compmat2);
  T_cmat(1,n+1)=T_c;
end
plot(time,P_compmat,'color','red','linewidth',2)
avgPinv=mean(P_compmat);
Wtotinv=avgPinv*48
PercentSavings=1-Wtotinv/Wtotni
```

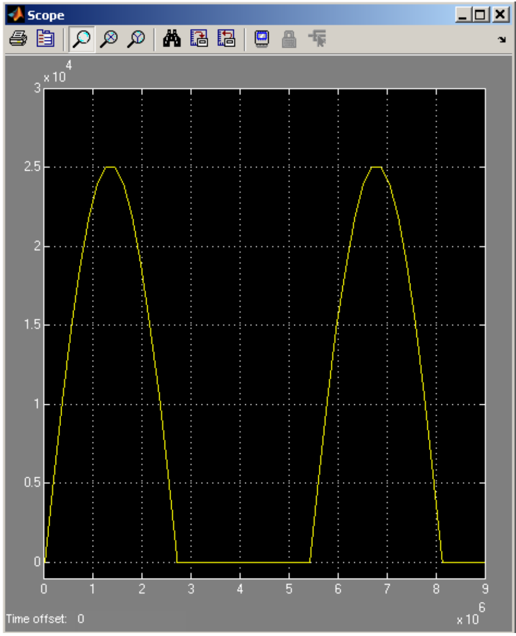
EES:

```
T_indoor_ret=23.33
f=60
T_c=40

m_dot_R410a=( ((-4*10^(-9))*f^3+(4*10^(-7))*f^2+(8*10^(-6))*f -0.0014)*T_c^2+((8*10^(-7))*f^3 - 0.0001*f^2 -
0.0036*f+ 0.0873)*T_c+( (-1*10^(-8))*f^3 + (1*10^(-6))*f^2 - 0.0002*f - 0.0003)*T_c*T_e+( 0.0008*f -
0.0047)*T_e^2+(0.0643*f - 0.4715)*T_e+(1.6904*f - 8.7054))/3600
P_comp=((-5E-07)*f^3 + 0.0001*f^2 - 0.0082*f + 0.1819)*T_c^2+((1E-04)*f^3 - 0.0203*f^2 + 1.452*f -
20.657)*T_c+((1E-06)*f^3-0.0002*f^2+0.0144*f-0.0942)*T_c*T_e+(( -6E-07)*f^3+0.0001*f^2 -
0.0097*f+0.1115)*T_e^2+(( -3E-05)*f^3 + 0.006*f^2 - 0.5125*f + 4.2074)*T_e+(-0.0009*f^3 + 0.2857*f^2 -
15.363*f + 489.12)


P_1=Pressure(R410A,T=T_e,x=1)
T_1=T_e
h_1=Enthalpy(R410A,P=P_1,T=T_1)
s_1=Entropy(R410A,P=P_1,T=T_1)


P_2=P_3
T_2=Temperature(R410A,P=P_2,s=s_2)
h_2=Enthalpy(R410A,P=P_2,s=s_2)
s_2=s_1
```

```
P_3=Pressure(R410A,T=T_c,x=0)
T_3=Temperature(R410A,P=P_3,x=0)
h_3=Enthalpy(R410A,P=P_3,T=T_3)


P_4=P_1
T_4=T_1
h_4=h_3

W_dot_comp=m_dot_R410a*(h_2*1000-h_1*1000)
q_dot_evaps=m_dot_R410a*(h_1*1000-h_4*1000)
COP=q_dot_evaps/P_comp

q_dot_cond=m_dot_R410a*(h_2*1000-h_3*1000)
```

Appendix B: Generating Heat Load Condition




Scope
x 10^4
3
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
7
8
9
Time offset: 0
x 10^6