Solar Decathalon House (Source Group)

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Project Abstract

Natural ecosystems have evolved over millions of years to sustainably harness energy, produce food, and recycle waste. Unfortunately human impacts on the nature and these ecosystems have been widely destructive. Therefore, over the past decades many individuals and organizations tried to point out this problem and provide a reasonable solution. A remarkable approach, which has been explored over the years, is to use and employ solar and renewable energy as a possible replacement for fossil energy resources. Designing and building a unique solar house which has the least impact on the nature would be a significant experiment in that regard. University of Maryland has a team in the U.S. Department of Energy Solar Decathlon 2011 who has dedicated itself to the development and enhancement of this approach. Here in this project we will focus on a case study to evaluate a design for a solar-powered house that is inspired and guided by the Chesapeake Bay ecosystem, landscape, and people who live in it. Furthermore we have developed a series of systems model for temperature and airflow of a room given different technologies. The Energy Sources Team will focus on identifying and modeling the separate inputs into the system including windows, appliances, etc. We will explore and analyze the extent to which this problem can be cast in systems engineering framework, use cases, requirements, models of system behavior and system structure. We will finally use the data that we collected to calculate the costs as well as the trade off analysis.

Before we discuss further details of our system we need to define the assumptions that we considered in our analysis:

1. Exterior Ambient Temperature is an infinite source/sink.
2. Interior Ambient Temperature experiences no diffusion.
3. Interior Airflow is negligible.
4. HVAC system operates at 100% efficiency.
5. ERV is constantly working.
6. No heat is absorbed in mediums (perfect conduction).
7. House is Wx2W sized plan with one window facing south.
8. Threshold for HVAC system is +/- 2 degrees from desired Interior Ambient Temperature.
9. R value (Insulation value) is proportional to k/d in conduction equation.
10. Each simulation starts with Interior Ambient Temperature at Desired Ambient

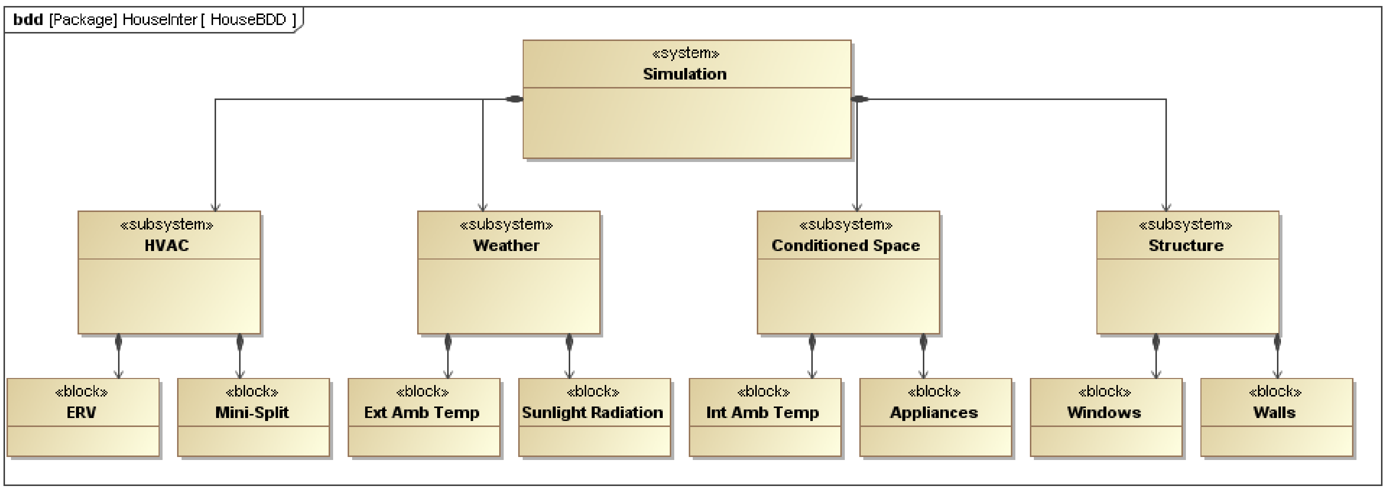
Temperature.

11. Minimum Ventilation standard is at 75 CFM[3].

Our simulation system will allow the user to set desired interior ambient temperature, wall properties, window properties, appliance properties, weather time frame and simulation time frame.

System Framework and Boundary

The temperature and airflow simulation system can be thought of as the composition of four freely coupled systems shown below:



The sub-systems are:

- **HVAC.** Has a significant role in this system. It controls the temperature changes through its structure. A better ventilation system would save a lot of energy.
- **Weather.** This subsystem describes the outside temperature and effect of sunlight radiation on room temperature.
- **Conditioned Space.** Most of the equipments and home appliances produce heat or thermal energy. In order to control the room temperature this factor has to be considered and analyzed completely. The lower the heat produced by these appliances the lower energy, HVAC would consume.
- **Envelopes.** Here we assume that the interior room temperature does very much depend on the types of windows and walls surrounding the area. The amount and type of insulation is an important factor in this subsystem.

Use Cases

The Actors

Actor is anything that interfaces with the system externally. Assuming the system structure is composed of the envelopes together with the HVAC system, and then the actors for our system are:

Actor (1): The Home Owner

We assume the home owner sets the temperature inside the house in order to make a desirable living space. Of course at different time of the day and based on the season the desired temperature would be different.

Actor (2): Appliances

Appliances used inside the house would have an impact on the conditioned space. Since they produce heat, which affect the interior ambient temperature.

Actor (3): Weather

At different time of the year the outside temperature varies, as a result the interior ambient temperature changes accordingly. Therefore the HVAC system would react upon it to reach the desired temperature inside the house.

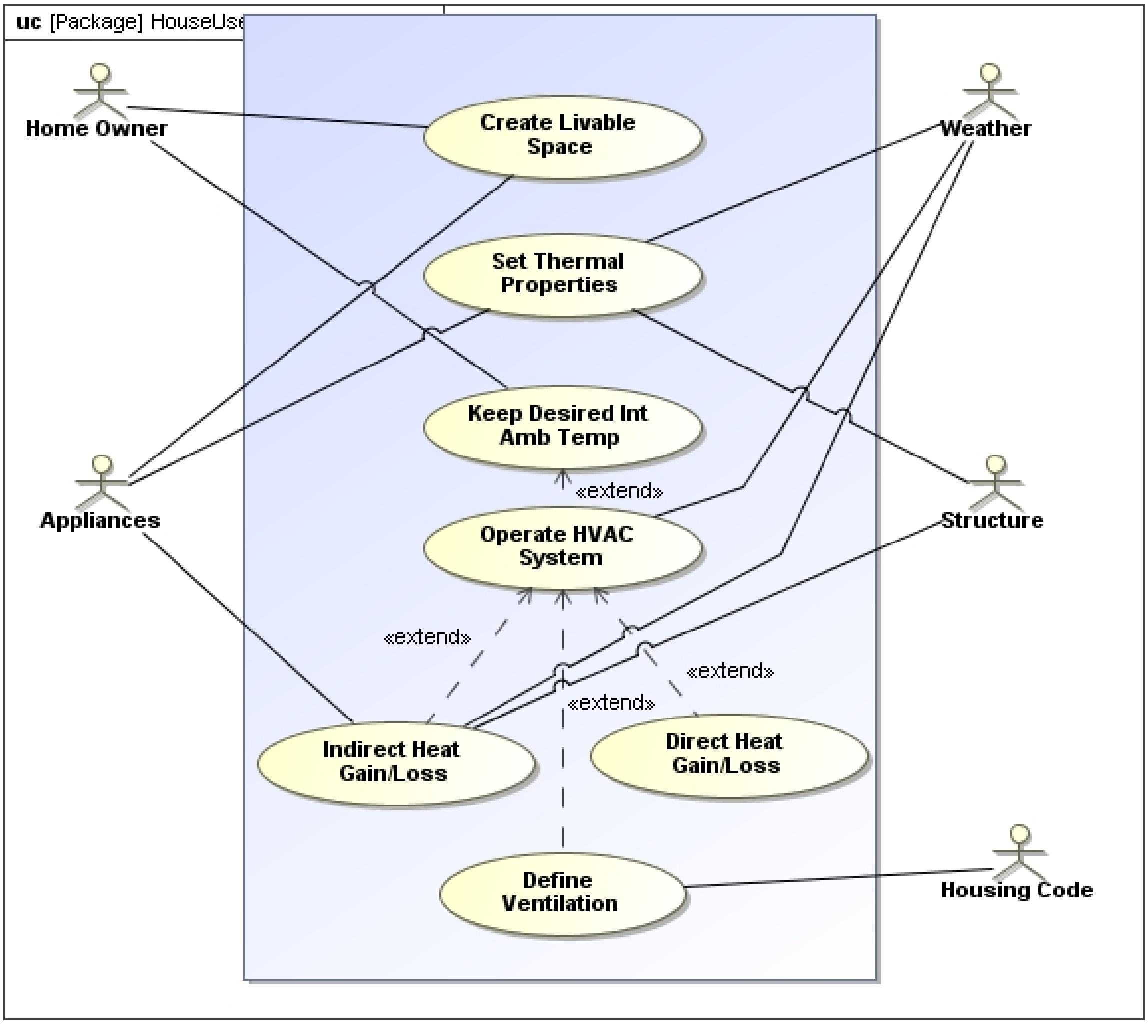
Actor (4): Structure

Materials used in building the solar house would definitely play significant roles in energy exchange between the house and its surrounding area. The better insulated walls or windows the less energy consumption.

Actor (5): Housing Code

According to laws and regulations in different regions we need to use certain ventilation standards.

The diagram below describes the impact of each actor on different parts of the system.



Now since we defined our actors we can consider the following use cases:

Use Case 1: The house minimizes the absorption of UV radiation

Description: Influx of heat in the form of solar radiation and conductance from outside ambient temperature.

- **Primary Actors:** Sun, Outside T, Inside T, Window properties
- **Pre-conditions:** Thermal Gradient across the window glass
- **Flow of Events:**
    1. Temperature gradient across the window glass causes flow of heat into house
    2. Heat flows through the window glass at a rate determined by conductivity of glass
    3. This energy heats the air on the inside of the house
- **Post-condition:** Heating of internal air
- **Alternative Flow of Events:**

1. Sunlight enters house through window at constant rate R
2. This light is absorbed by surfaces in the house
3. The energy is re-emitted into the air inside the house

- **Assumptions:** Hotter outside than inside (summer/day-time), Complete absorption/re-emitting of UV radiation
- **New Requirements**
    1. Select window material for minimal conductance and UV transmission

Use Case 2: The house insulates against outside temperature

- **Description:** Influx of heat in the form of solar radiation, conductance, and convection from outside ambient temperature through the building envelope, focusing on the walls
- **Primary Actors:** Sun, Outside T, Inside T, Wall properties
- **Pre-conditions:** Thermal Gradient across the wall
- **Flow of Events:**
    1. Temperature gradient across the wall causes flow of heat into house
    2. Heat flows through the wall at a rate determined by conductivity of insulating material
    3. This energy heats the air on the inside of the house
- **Post-condition:** Heating of internal air
- **Alternative Flow of Events:**
    1. Sunlight is absorbed by the exterior surface of the wall
    2. The energy is re-emitted into the air outside the house as well as flows through the wall at a rate determined by conductivity of insulating material
    3. This energy heats the air on the inside of the house
- **Assumptions:** Hotter outside than inside (summer/day-time), Wall material is homogeneous (no thermal breaks caused by studs)
- **New Requirements**
    1. Select wall material that has high insulation value

Use Case 3: The house ventilates the space with fresh, outdoor air

Description: Fresh outdoor air is brought into the conditioned space at a rate that is to code

- **Primary Actors:** Outside T, Inside T, Ventilator
- **Pre-conditions:** Thermal Gradient between indoor and outdoor air
- **Flow of Events:**
    1. Warm outdoor air is brought into the house through a fan
    2. The fan deposits the warm air into the cool, conditioned space at the registers
    3. Airflow of deposited air mixes the house air
- **Post-condition:** Heating of internal air
- **Alternative Flow of Events:**
    1. Exhaust fan collects cooler, conditioned air
    2. The exhaust fan deposits the cooler air outside

- **Assumptions:** Hotter outside than inside (summer/day-time), Exhaust air has no effect on outdoor temperature
- **New Requirements**
    1. Air flow rate must meet code standards

Use Case 4: The house is at the peak of UV absorption during the day particularly at noon

Description: Influx of heat and humidity in the form of solar radiation, conductance and convection through the walls, windows and ventilation system from outside.

- **Primary Actors:** Sun, weather conditions, Outside T, Inside T, Window and wall properties
- **Pre-conditions:** Thermal Gradient across the glass, ventilation systems and walls
- **Flow of Events:**

1. Temperature difference between the interior and exterior of the house causes the heat flow through convection into the house.
2. Window glass as well as wall material have significant impacts on the heat flow.
3. The air flow through the ventilation system is also affected by the outside temperature and eventually contributes to change of inside temperature.
4. All the heat which transfers into the house will change the inside temperature significantly.

- **Post-condition:** Heating of internal air
- **Alternative Flow of Events:**

1. UV radiation enters house through window at constant rate R
2. Ventilation pipes absorb heat since they are not perfectly insulated
3. Sunlight is absorbed by the exterior surface of the wall at a rate determined by conductivity of insulating material
4. This energy heats the air on the inside of the house

- **Assumptions:** Hotter outside than inside (summer/day-time), Complete absorption/re- emitting of UV radiation
- **New Requirements**

1. Select window, wall and ventilation pipes' material for minimal conductance and UV transmission

Goals, Scenarios, and User Requirements

We had four goals to accomplish in our simulation process. First, we tried to evaluate the system behavior for various time of the year. Second, we considered different wall materials used in building the final house. Since walls have the largest area in our buildings they have the most significant impact on our simulation. Third, we studied various window types and their effects on our system. Finally, different types of appliances were considered in order to find the optimum solution.

Goal 1. Allow homeowner to adjust conditioned space temperature.

- **Scenario 1.1:** January, Day
- **Scenario 1.2:** February, Day
- **Scenario 1.3:** March, Day
- ...
- **Scenario 1.13:** January, Night
- **Scenario 1.14:** February, Night
- **Scenario 1.15**: March, Night
- ...

Goal 2. Show the effect of changing the wall material on the temperature of a room. R is the insulation value.

- **Scenario 2.1:** Low R Value
- **Scenario 2.2:** Medium R Value
- **Scenario 2.3:** High R Value

Goal 3. Show the effect of changing the window material on the temperature of a room. SHGC describes the Solar Heat Gain Coefficient. The lower a window's solar heat gain coefficient, the less solar heat it transmits.

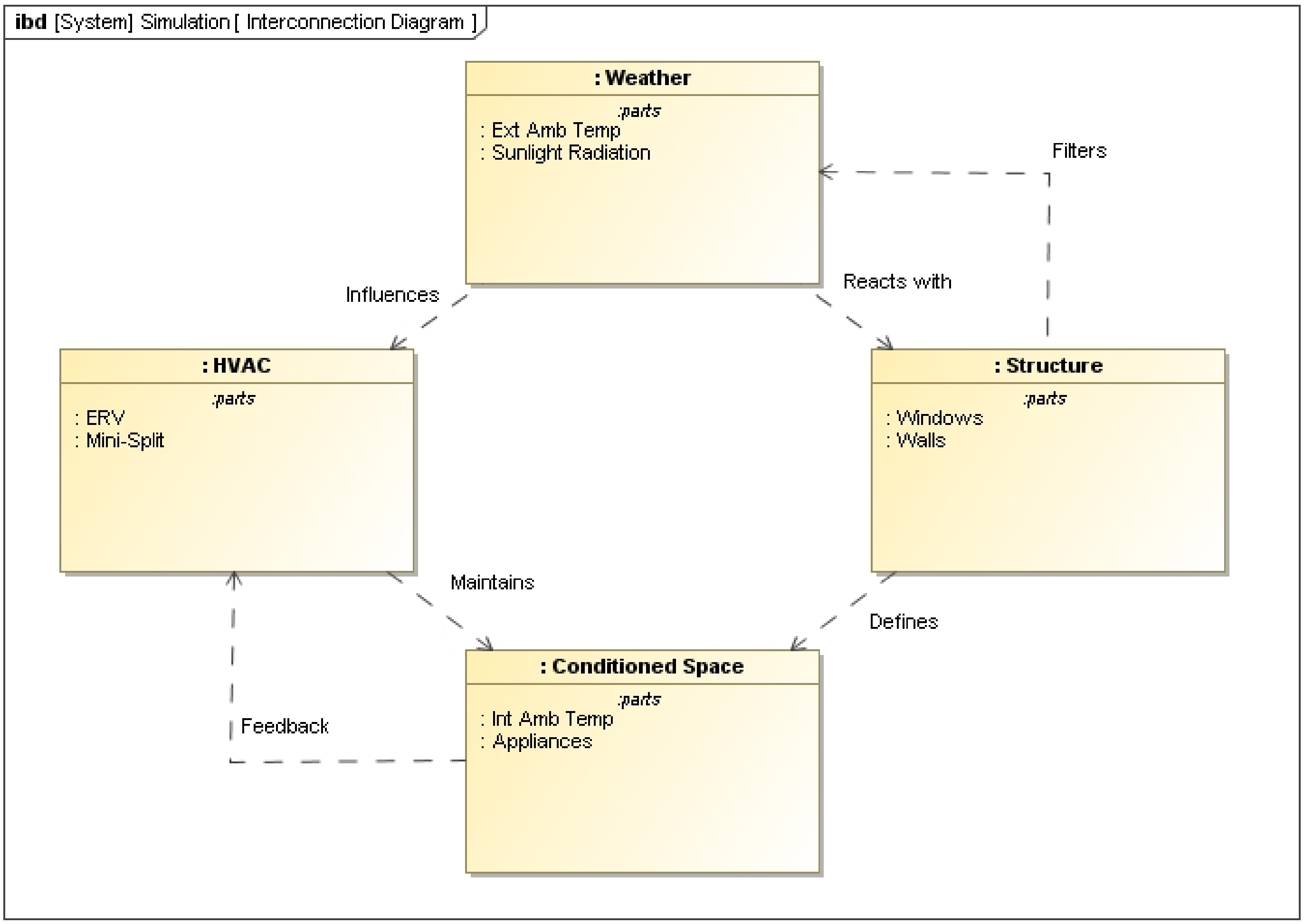
- **Scenario 3.1:** Single Pane, Low SHGC
- **Scenario 3.2:** Single Pane, High SHGC
- **Scenario 3.3:** Double Pane, Low SHGC
- **Scenario 3.4:** Double Pane, High SHGC
- **Scenario 3.5:** Triple Pane, Low SHGC
- **Scenario 3.6:** Triple Pane, High SHGC

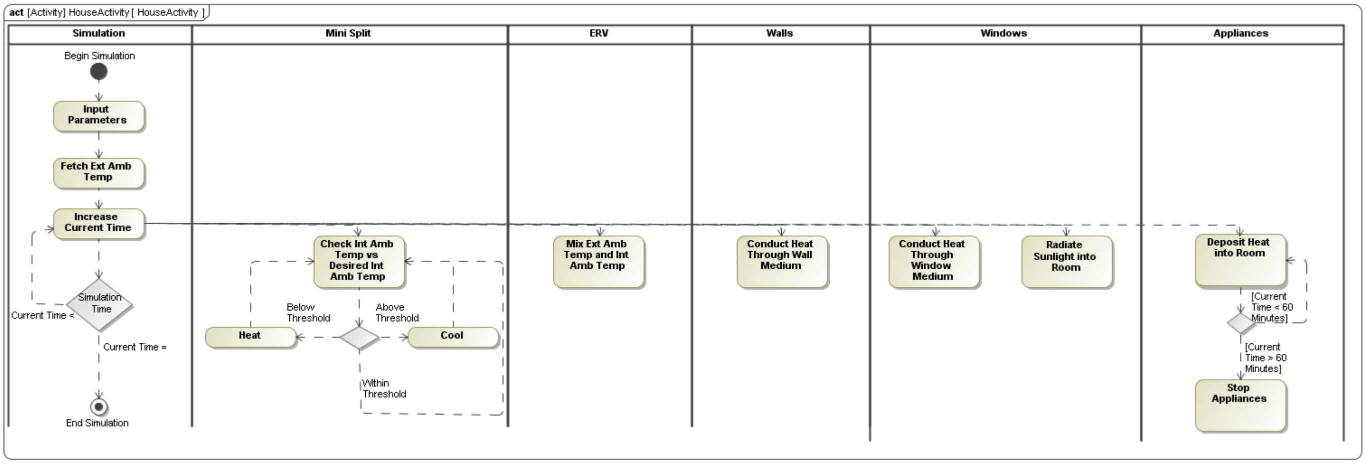
Goal 4. Show the effect of appliance type on the temperature of a room

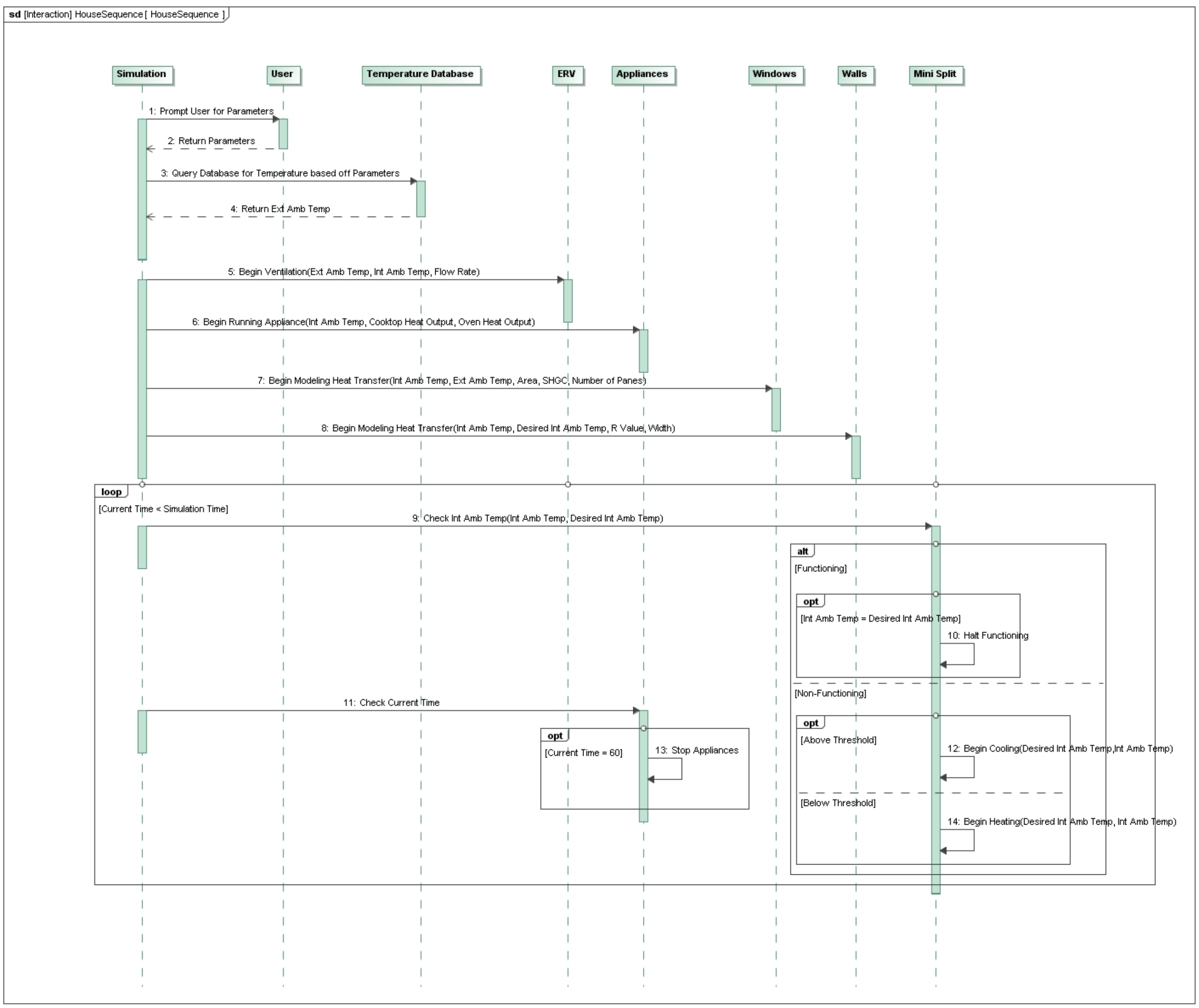
- **Scenario 4.1:** High Efficiency Appliances
- **Scenario 4.2:** Standard Appliances

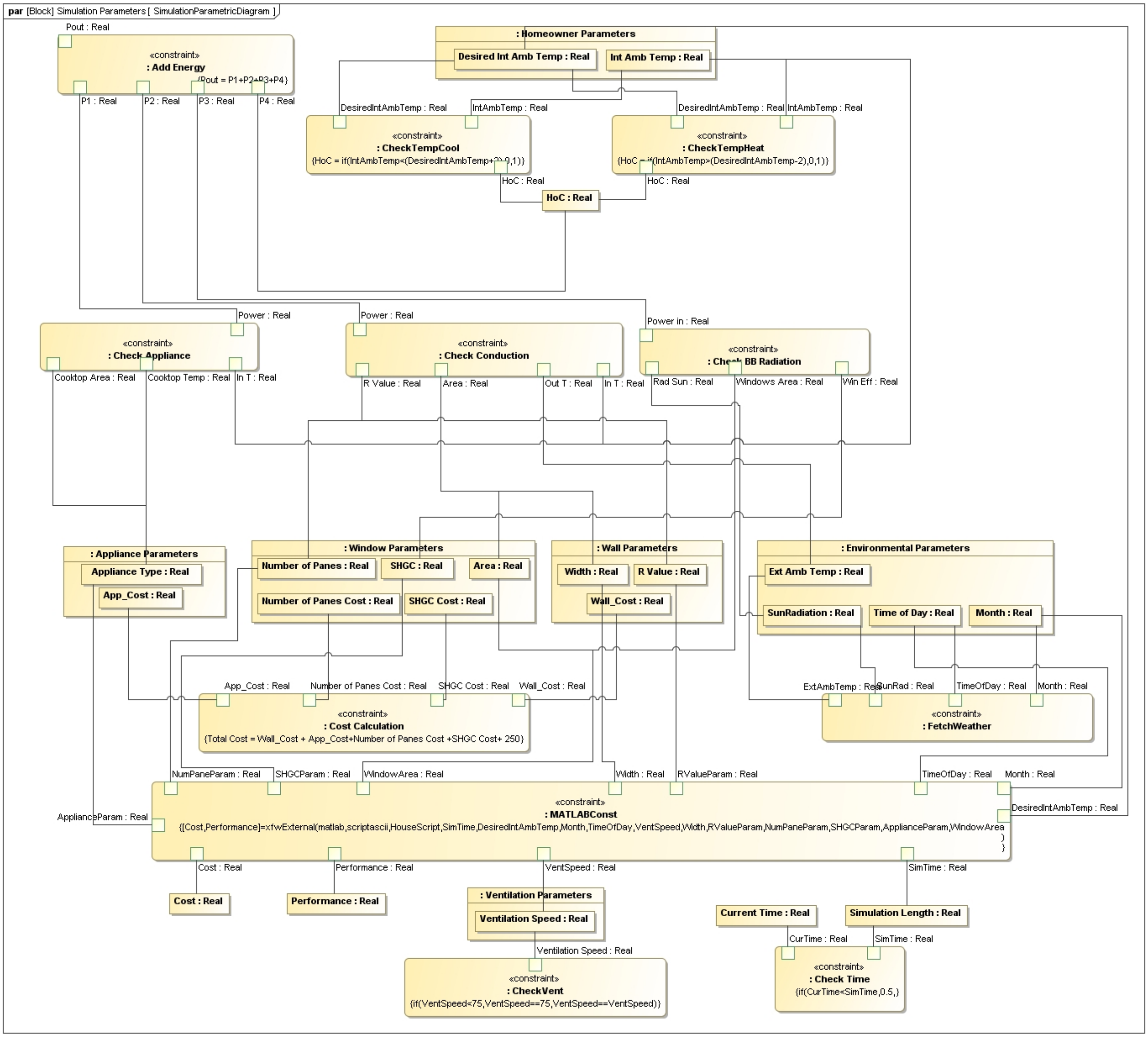
Simplified Models of System Behavior

Following are the behavior, relationship, activity, and sequence diagrams for the system. In general the system will run in a cyclic manner for a user-defined amount of time. The simulation time (SimTime) will be split into a user-defined number of intervals. During each interval the simulation will record the behavior of all parts (windows, walls, etc) and sum them all up to determine the behavior of the system as a whole. Changes will be applied to the value of interest, interior ambient temperature (IntAmbTemp), during each interval, and then the simulation will progress to the next.




act [Activity] HouseActivity [HouseActivity]
Simulation
Mini Split
ERV
Walls
Windows
Appliances
Begin Simulation
Input Parameters
Fetch Ext Amb Temp
Increase Current Time
Simulation Time
Current Time <
Current Time =
End Simulation
Check Int Amb Temp vs Desired Int Amb Temp
Below Threshold
Above Threshold
Heat
Cool
Within Threshold
Mix Ext Amb Temp and Int Amb Temp
Conduct Heat Through Wall Medium
Conduct Heat Through Window Medium
Radiate Sunlight into Room
Deposit Heat into Room
[Current Time < 60 Minutes]
[Current Time > 60 Minutes]
Stop Appliances


sd [Interaction] HouseSequence [HouseSequence]
Simulation
User
Temperature Database
ERV
Appliances
Windows
Walls
Mini Split
1: Prompt User for Parameters
2: Return Parameters
3: Query Database for Temperature based off Parameters
4: Return Ext Amb Temp
5: Begin Ventilation(Ext Amb Temp, Int Amb Temp, Flow Rate)
6: Begin Running Appliance(Int Amb Temp, Cooktop Heat Output, Oven Heat Output)
7: Begin Modeling Heat Transfer(Int Amb Temp, Ext Amb Temp, Area, SHGC, Number of Panes)
8: Begin Modeling Heat Transfer(Int Amb Temp, Desired Int Amb Temp, R Value, Width)
loop
[Current Time < Simulation Time]
9: Check Int Amb Temp(Int Amb Temp, Desired Int Amb Temp)
alt
[Functioning]
opt
[Int Amb Temp = Desired Int Amb Temp]
10: Halt Functioning
[Non-Functioning]
opt
[Above Threshold]
12: Begin Cooling(Desired Int Amb Temp,Int Amb Temp)
[Below Threshold]
14: Begin Heating(Desired Int Amb Temp, Int Amb Temp)
11: Check Current Time
opt
[Current Time = 60]
13: Stop Appliances



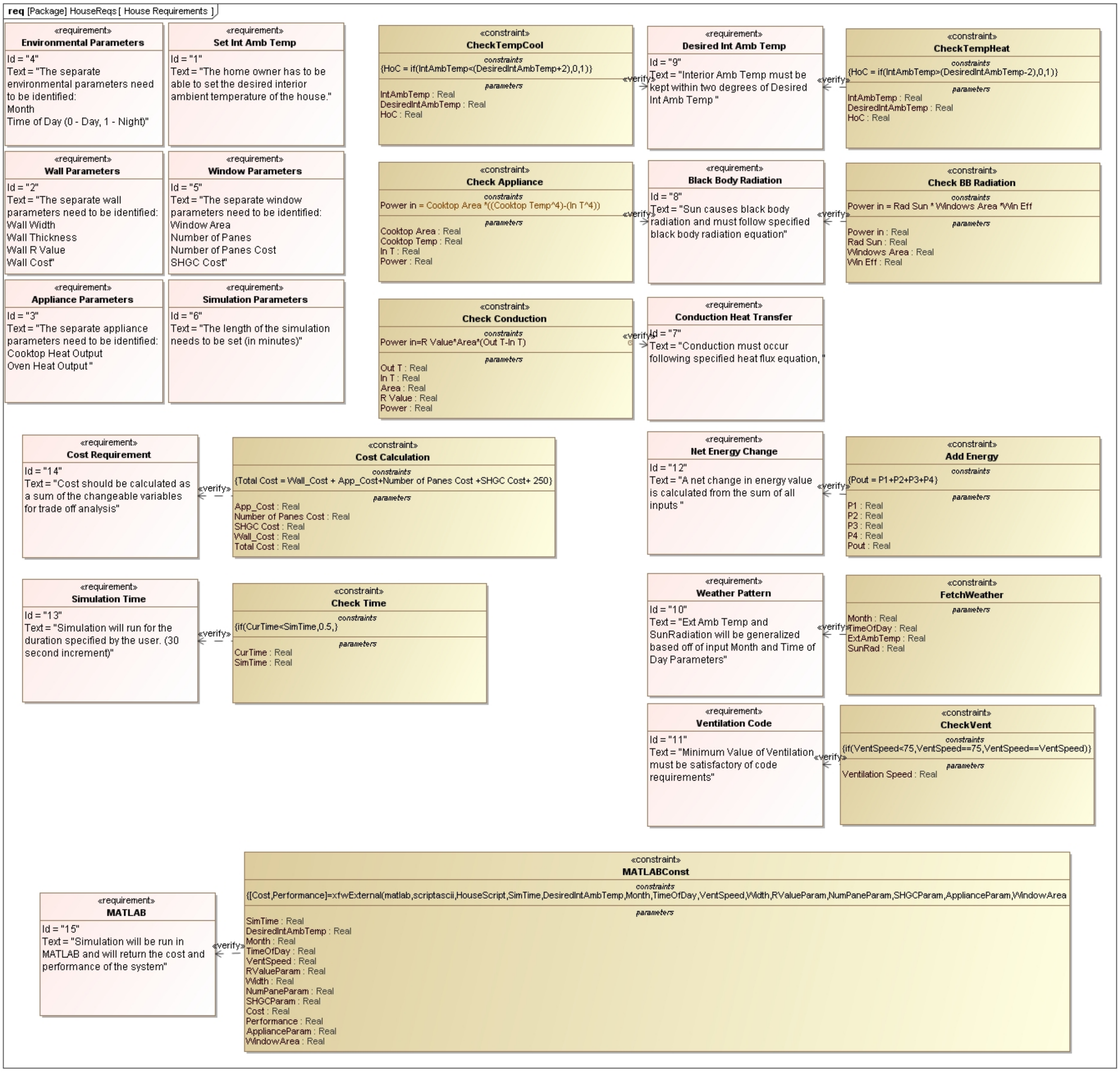
Requirements Engineering

We chose to split the requirements into two groups: Functional and Non-Functional. The non-functional requirements are those that deal with user settings. These requirements represent those things that will become the inputs to the simulation. The functional requirements are constraints made on how the system must behave. These come from assumptions made to simplify the model as well as building codes set by local government.

	User must be able to set:	Variable(s)
Requirement 1	Desired int. amb. Temp.	DesIntAmbTemp
Requirement 2	Wall properties	Rvalue
Requirement 3	Window properties	SHGC, #Panes
Requirement 4	Appliance properties	High Eff or normal
Requirement 5	Time of year/day	SunRad, ExtTemp
Requirement 6	Simulation Time Frame	SimTime and timestep

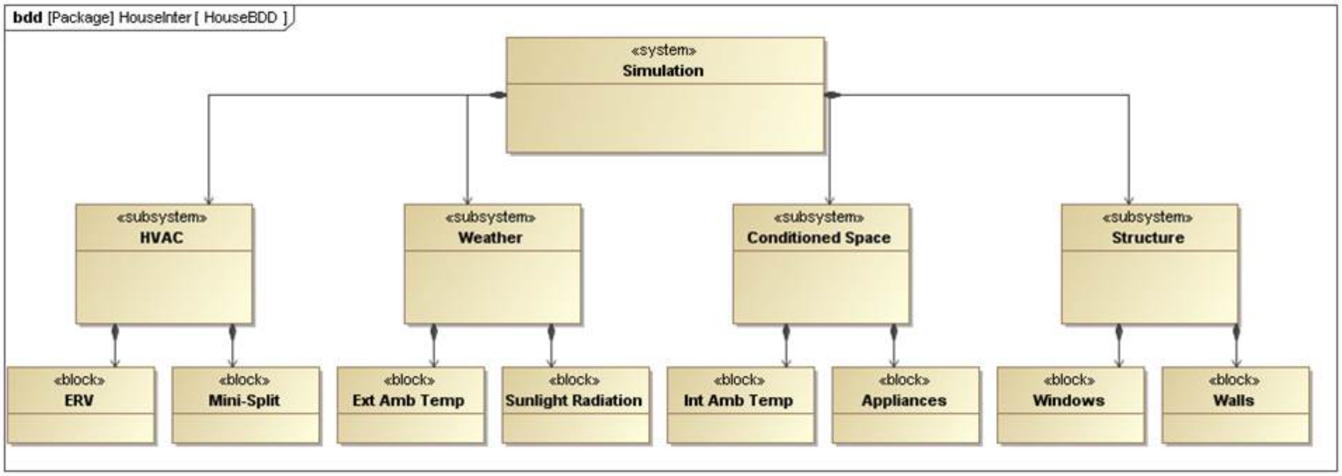
	Requirement	Object; Behavior
Requirement 1	System should model and follow equations for heat flux and black-body radiation	Window, wall, appliance; These follow equations for conduction and radiation (see below)
Requirement 2	System should follow a set weather condition based on weather time frame parameter	Time of year determines properties of SunRad and ExtTemp, which in turn go into the aforementioned equations
Requirement 3	HVAC is activated when a difference of 2 degrees from Desired Temperature is present	HVAC activates whenever abs(IntAmbTemp - DesAmbTemp) >= 2
Requirement 4	Minimum Ventilation standard is at 75 CFM	Sets the exchange rate for the ERV
Requirement 5	Cost should be calculated as a sum of the changeable variables for trade off analysis	Cost ($) will be compared with performance (time t until HVAC is switched on in the simulation) in trade-off

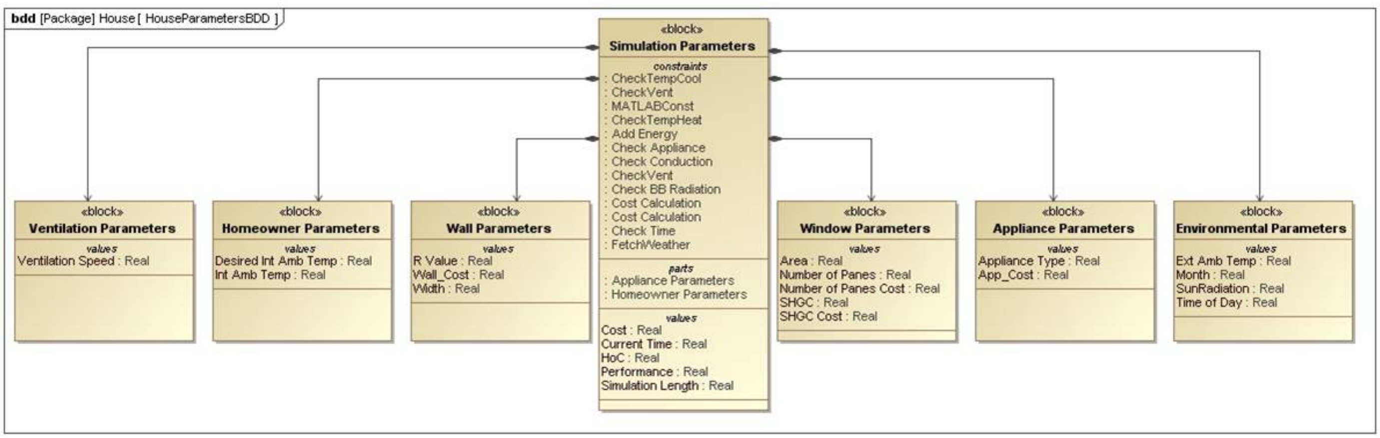
Below are the requirements translated into MagicDraw


req [Package] HouseReqs [House Requirements]
«requirement» Environmental Parameters
Id = "4"
Text = "The separate environmental parameters need to be identified: Month Time of Day (0 - Day, 1 - Night)"
«requirement» Set Int Amb Temp
Id = "1"
Text = "The home owner has to be able to set the desired interior ambient temperature of the house."
«constraint» CheckTempCool
constraints
{HoC = if(IntAmbTemp<(DesiredIntAmbTemp+2),0,1)}
parameters
IntAmbTemp : Real
DesiredIntAmbTemp : Real
HoC : Real
«verify»
«requirement» Desired Int Amb Temp
Id = "9"
Text = "Interior Amb Temp must be kept within two degrees of Desired Int Amb Temp "
«verify»
«constraint» CheckTempHeat
constraints
{HoC = if(IntAmbTemp>(DesiredIntAmbTemp-2),0,1)}
parameters
IntAmbTemp : Real
DesiredIntAmbTemp : Real
HoC : Real
«requirement» Wall Parameters
Id = "2"
Text = "The separate wall parameters need to be identified: Wall Width Wall Thickness Wall R Value Wall Cost"
«requirement» Window Parameters
Id = "5"
Text = "The separate window parameters need to be identified: Window Area Number of Panes Number of Panes Cost SHGC Cost"
«constraint» Check Appliance
constraints
Power in = Cooktop Area *((Cooktop Temp^4)-(In T^4))
parameters
Cooktop Area : Real
Cooktop Temp : Real
In T : Real
Power : Real
«verify»
«requirement» Black Body Radiation
Id = "8"
Text = "Sun causes black body radiation and must follow specified black body radiation equation"
«verify»
«constraint» Check BB Radiation
constraints
Power in = Rad Sun * Windows Area *Win Eff
parameters
Power in : Real
Rad Sun : Real
Windows Area : Real
Win Eff : Real
«requirement» Appliance Parameters
Id = "3"
Text = "The separate appliance parameters need to be identified: Cooktop Heat Output Oven Heat Output "
«requirement» Simulation Parameters
Id = "6"
Text = "The length of the simulation needs to be set (in minutes)"
«constraint» Check Conduction
constraints
Power in=R Value*Area*(Out T-In T)
parameters
Out T : Real
In T : Real
Area : Real
R Value : Real
Power : Real
«verify»
«requirement» Conduction Heat Transfer
Id = "7"
Text = "Conduction must occur following specified heat flux equation, "
«requirement» Cost Requirement
Id = "14"
Text = "Cost should be calculated as a sum of the changeable variables for trade off analysis"
«verify»
«constraint» Cost Calculation
constraints
{Total Cost = Wall_Cost + App_Cost+Number of Panes Cost +SHGC Cost+ 250}
parameters
App_Cost : Real
Number of Panes Cost : Real
SHGC Cost : Real
Wall_Cost : Real
Total Cost : Real
«requirement» Net Energy Change
Id = "12"
Text = "A net change in energy value is calculated from the sum of all inputs "
«verify»
«constraint» Add Energy
constraints
{Pout = P1+P2+P3+P4}
parameters
P1 : Real
P2 : Real
P3 : Real
P4 : Real
Pout : Real
«requirement» Simulation Time
Id = "13"
Text = "Simulation will run for the duration specified by the user. (30 second increment)"
«verify»
«constraint» Check Time
constraints
{if(CurTime<SimTime,0.5,)}
parameters
CurTime : Real
SimTime : Real
«requirement» Weather Pattern
Id = "10"
Text = "Ext Amb Temp and SunRadiation will be generalized based off of input Month and Time of Day Parameters"
«verify»
«constraint» FetchWeather
parameters
Month : Real
TimeOfDay : Real
ExtAmbTemp : Real
SunRad : Real
«requirement» Ventilation Code
Id = "11"
Text = "Minimum Value of Ventilation must be satisfactory of code requirements"
«verify»
«constraint» CheckVent
constraints
{if(VentSpeed<75,VentSpeed==75,VentSpeed==VentSpeed)}
parameters
Ventilation Speed : Real
«requirement» MATLAB
Id = "15"
Text = "Simulation will be run in MATLAB and will return the cost and performance of the system"
«verify»
«constraint» MATLABConst
constraints
{[Cost,Performance]=xfwExternal(matlab,scriptascii,HouseScript,SimTime,DesiredIntAmbTemp,Month,TimeOfDay,VentSpeed,Width,RValueParam,NumPaneParam,SHGCParam,ApplianceParam,WindowArea
parameters
SimTime : Real
DesiredIntAmbTemp : Real
Month : Real
TimeOfDay : Real
VentSpeed : Real
RValueParam : Real
Width : Real
NumPaneParam : Real
SHGCParam : Real
Cost : Real
Performance : Real
ApplianceParam : Real
WindowArea : Real

System--Level Design

We broke the simulation up into a structure diagram which depicts how the system is broken up into components, and a parameter structure diagram which depicts how the user-defined values become inputs for the simulation.

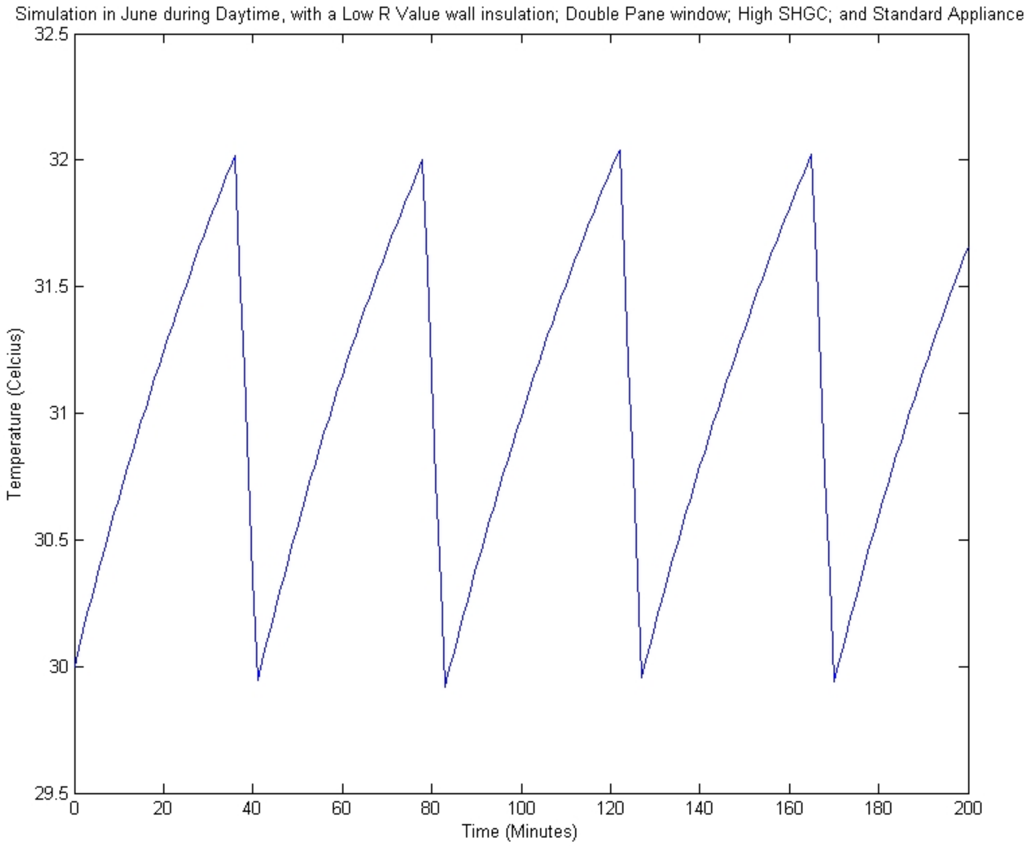




Trade Off Analysis

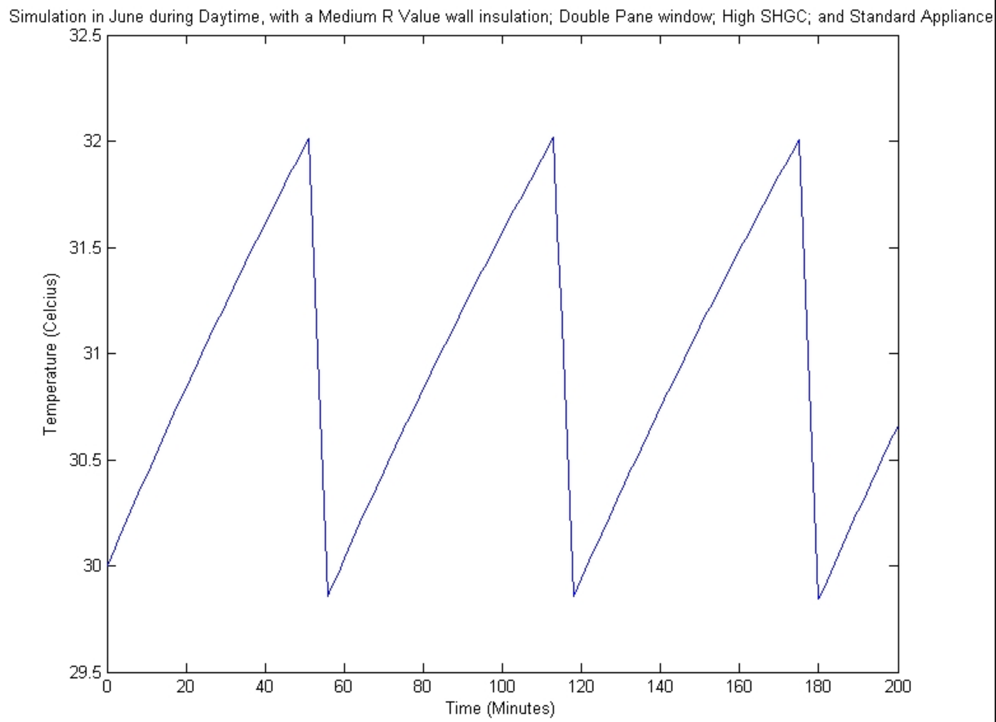
With the way our system is designed, the input parameters are entered into MagicDraw which then feeds the data to the MATLAB program which runs the simulation and does all of the calculations. With the amount of variables we have there are 846 different iterations of possible inputs for our house. This is something which would be tedious to do in MagicDraw. Instead, we have created a second MATLAB program which can run all of the desired iterations at once.

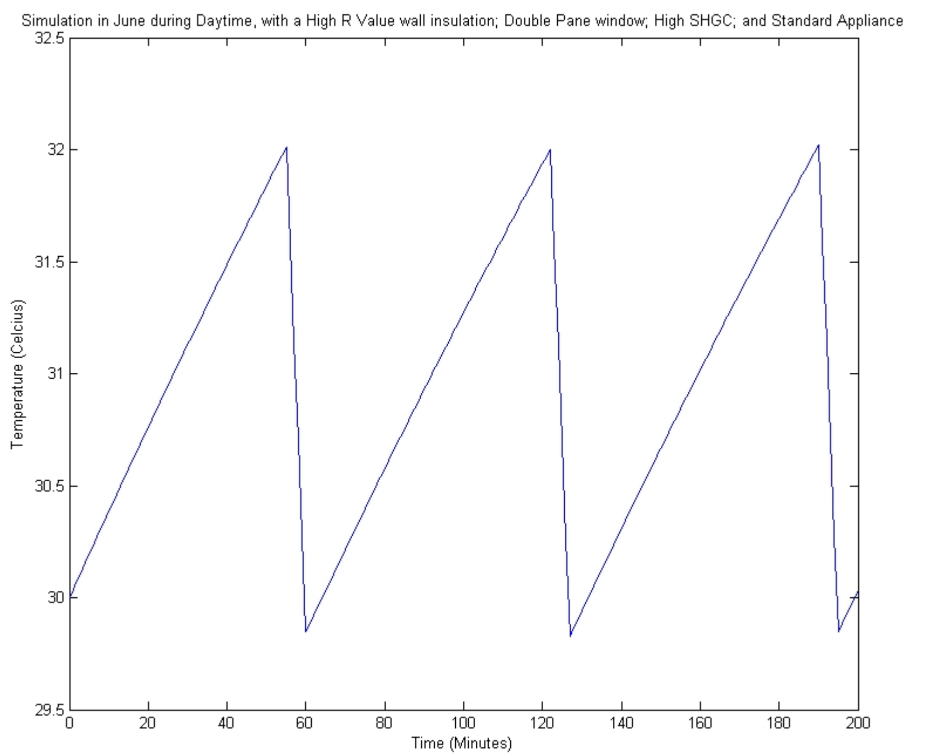
The simulation results in a graph of Temperature vs. Time similar to the figure below.



This is what one would reasonably expect the system to perform at. The temperature change experiences an exponential decay as the temperature differential between the Interior Ambient Temperature and the Exterior Ambient Temperature decreases. This occurs until the temperature reaches the threshold, at which point, the HVAC turns on and quickly cools until the temperature returns to the desired temperature.

With the new MATLAB code, we are able to perform and graph muliple iterations. The figure above is the result of Low R-Value Wall Insulation while the following graphs are the result of all of the same parameters as above, except with medium and high R-Value Wall Insulation respectively.

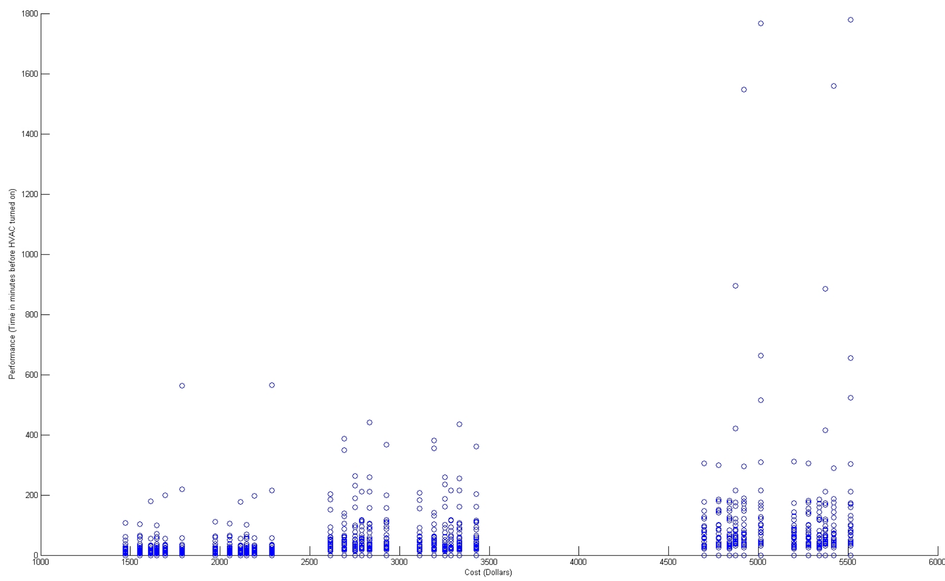




As the insulation value increases, so does the period of the curve. For the trade off analysis, we chose performance as one of the variables. We measured performance as a measure of the period lenght. In real world terms, performance is based on the lenght of time required before the HVAC is required to turn on. The longer it takes until it is necessary to cool or heat the house, the better the house is doing at retaining the energy put into the system. If the lenght is longer, that means for the same amount of time, the HVAC would use less energy to keep the system within the acceptable temperature, resulting in a greater performance.

We also chose cost as the other trade of analysis variable. Each version of each technology was assigned an estimated cost value. If the technology was used, the cost was added to the total cost. In the end, we had a total cost for just the technologies which are under observation, not the cost of the entire house. It is assumed that the cost for the house is static and that only the cost for the technologies changes.

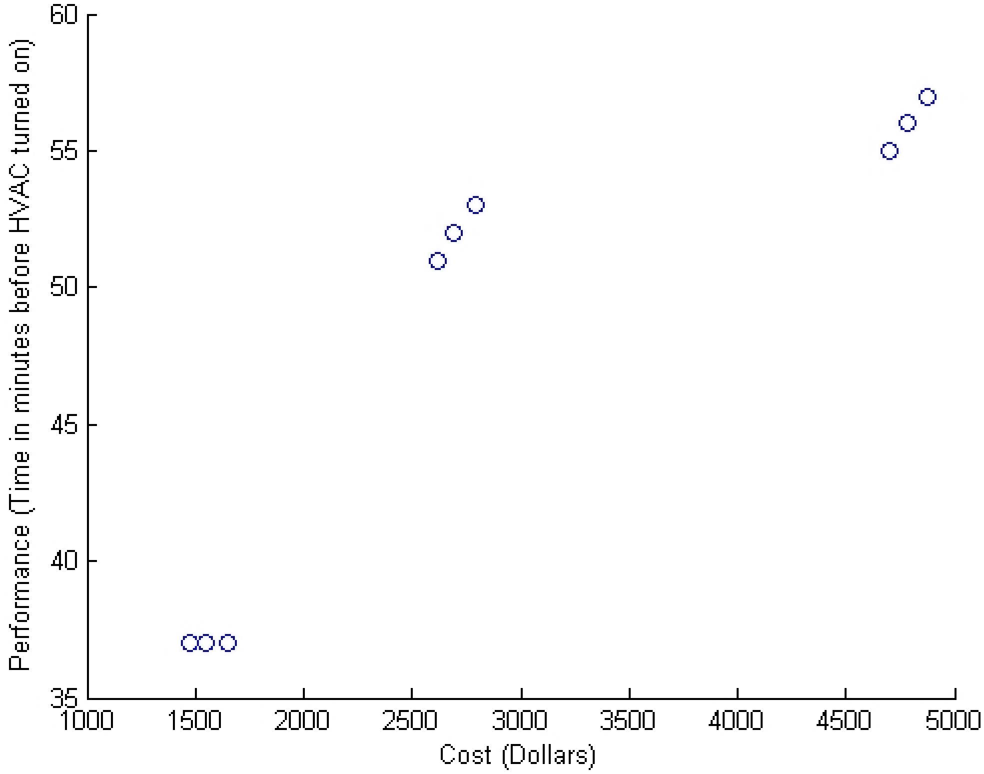
Below is a plot of Cost vs. Performance for every single possible iteration.



The values of most significance are along the top of each of the "columns" of points, as they give you the most performance for the cost value.

Summary and Conclusions

In order to gather more meaningful information from our trade off analysis, chose to plot the different R-Value and Different U-Value situations for the same weather period. The resulting trade off graph is below.



The clusters of points relates to the same R-Value scenarios while the increasing cost of each cluster relates to the decreasing U-Value windows. The conclusion we came to is that the R-Value of the walls had the most significant impact on the performance of the house. The U-Value of the windows was the next most significant source, however, it pales in comparison the effect the R-Value has. We also found that the other inputs such as appliances and ERV were negligible.

Another conclusion we drew is in reference to the trade off analysis figure which has all of the iterations. On a few occasions, there are zero points. These scenariors where when the Exterior Ambient Temperature was within the threshold range. The house would decay until it was at the Exterior Ambient Temperature and would not need to turn on the HVAC system. This is theoretically the most ideal situation. If the HVAC never has to turn on, then absolutely no energy is used in conditioning the space. However, this is a result of the weather and not the technologies used. In this situation, a Low R-Value house would be just as efficient as an High R-Value house, which we have shown to be false. This forced us to conclude that in future analysis, the performance of the house parameters should be an average over the entire course of the year and not just one month. This would eliminate this inconsistency.

References

1. http://hyperphysics.phy-astr.gsu.edu/hbase/mod6.html (for heat equations)
2. http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html (for heat equations
3. International Residential Code 2009 (for ventillation code requirements)

4. www.homedepot.com (for pricing of materials)
5. http://160.36.48.42/escurriculum/index.htm (for solar data)

Credits

David Daily - Write MATLAB code for simulation and trade off analysis, created and formatted MagicDraw diagrams

Iman Malakooti – created and developed parts for MagicDraw simulation. Researched about the material costs and their properties. Studied different use cases and helped with formatting the power point presentation.

Iain Kierzewski - Researched and included the heat equation formulas used in the simulation. Performed testing and debugging for accuracy of simulation. Developed conceptual framework of simulation.

Special thanks to Parastoo Delgoshaei for assisting us with conceptualization and MagicDraw diagrams