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Title of Assessment: Systems Modelling Technical Report

School of Engineering & Design
Electronic and Computer Engineering

System Modelling Project

Technical Report

Brunel ID: 2161047

Name: Xukang Liu

1. Introduction

MATLAB (matrix laboratory) is a commercial mathematics software produced by MathWorks of the United States, which is used in data analysis, wireless communication, deep learning, image processing and computer vision, signal processing, quantitative finance and risk management, robots, control systems and other fields.

In the lab, we need use MATLAB Simulink to simulate **the thermal model of a house**. To explore the simulation of Simulink. Through simulation, we need to be proficient in using Simulink and further understand how the thermal mode of a house works. In addition, discuss the deficiencies in this model and the improvements we need to make.

The report will be divided into 6 sections. In section II, I will primary introduce what is Simulink and the thermal model of a house. In section III, I will change the parameters in the model and simulate and explain the impact of parameters on the system. In section IV, I will investigate the behavior of the system. Explain the principle of this model and the function of each block. The model is not perfect, it can only be heated, but not cooled. Thus, I will modify the cooling model based on the thermal model in section V. Finally, I will give the conclusion in section VI.

2. Theory

2.1. Simulink

Simulink is the graphical programming package that works in association with MATLAB and interacts as one combined package. It is employed for modelling, simulating, and analyzing dynamic systems, continuous and discrete systems, and so forth [1].

The characteristics of Simulink:

- **Interactive modeling**: provide many function modules to facilitate users to quickly establish models. Modeling only requires dragging and dropping function blocks with the mouse and connecting them.
- **Interactive simulation**: simulation results can be displayed dynamically, and parameters can be modified at any time during simulation.
- **Extension and customization**: provide an open environment, allowing users to expand functions.
- **Professional model library**: professional model library is provided for different industries and fields.

2.2. Introduction to the thermal model of a house

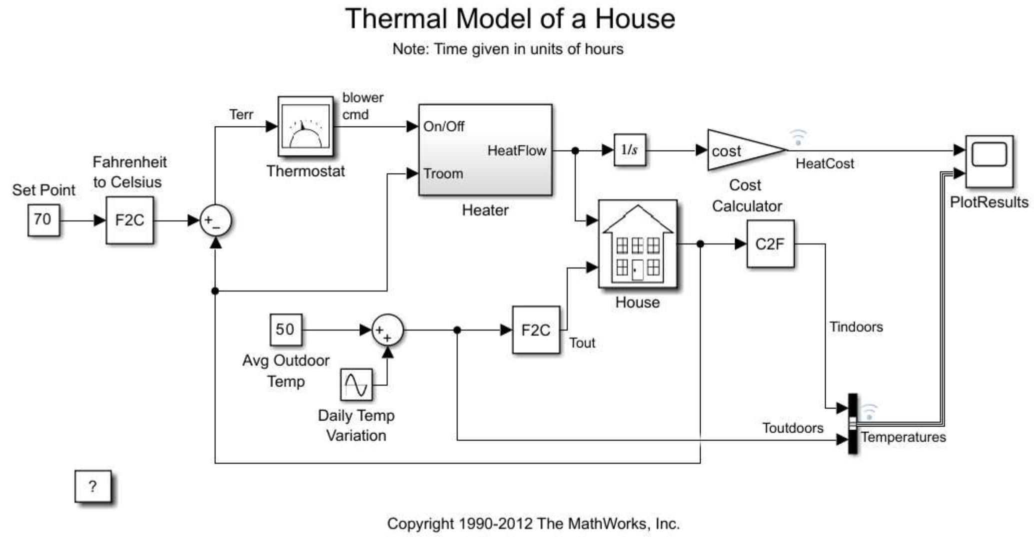


Fig. 1. Thermal model of a house

This model can be embodied in the household heating system of ordinary users in winter. This model can be used to calculate the heating cost of ordinary houses.

Figure 1 shows the schematic diagram of the model. The core of this model is the house. In winter, the outdoor temperature is lower than the indoor temperature. The heater will blow heat air into the house, if the temperature reaches near the specified temperature, the heater will stop working. However, the house will dissipate heat, that will cause a loss of heat. This requires the heater to continuously heat and stop heating This model can calculate the heating cost and simulate the real-time temperature inside and outside the house.

2.3. Details for each block

From the library browser, we can call many modules. Theses modules can form this model.

1) Constant module

This module can generate real or complex constant value signals. Use this module to provide constant signal inputs

2) F2C module

Fahrenheit to Celsius (F2C) module. It can convert the Fahrenheit to Celsius.

$$C = \frac{5}{9}(F - 32).$$

3) C2F module

Celsius to Fahrenheit (C2F) module. It can convert the Fahrenheit to Celsius.

$$F = \frac{9}{5}C + 32$$

4) Sum module

Add or subtract input. Outputs the calculated value of two or more input variables.

5) Inport module

The Inport module links signals from outside the system to inside the system and creates input ports for subsystems or external inputs.

6) Outport module

The Export module links signals from the system to targets outside the system and creates output ports for subsystems or external outputs.

7) Relay module

The output for the Relay block switches between two specified values. When the relay is on, it remains on until the input drops below the value of the **Switch off point** parameter. When the relay is off, it remains off until the input exceeds the value of the **Switch on point** parameter. The block accepts one input and generates one output.

Take this model as an example. The switch on point is 2.7778, and the switch off point is -2.7778. If the input number is within this range, output 0, otherwise output 1.

8) Gain module

The Gain module multiplies the input by a constant value.

9) Product module

The Product module outputs the multiplication result of the two inputs. For example, if input is 2 and 4, the output is $2 \times 4 = 8$.

10) Sine Wave module

Sine Wave module outputs sinusoidal waveform.

$$y = amplitude \times sin(frequency \times time + phase) + bias$$

11) Integrator module

Integrator module outputs the integral value of its input signal relative to time.

12) Bus Creator module

The Bus Creator block combines a set of input elements into a bus. Any element type can be connected to the input port, including other buses.

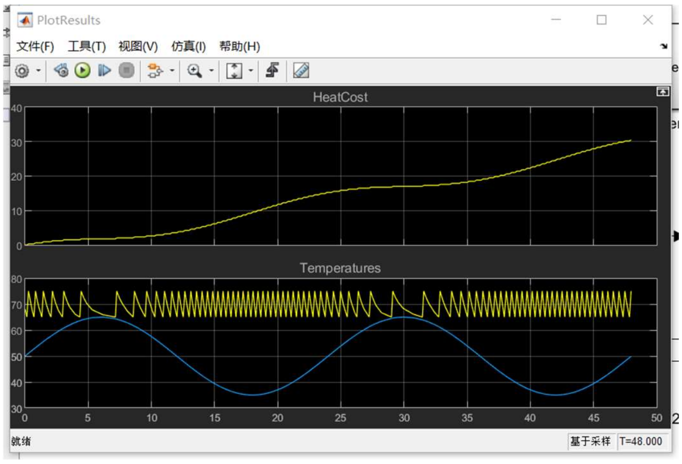
13) Scope module

Scope module can display signals generated during simulation.

3. Test the system

In this section, I will modify some parameters in the model and observe the changes of the simulation results.

- Firstly, simulate the **initial result.**

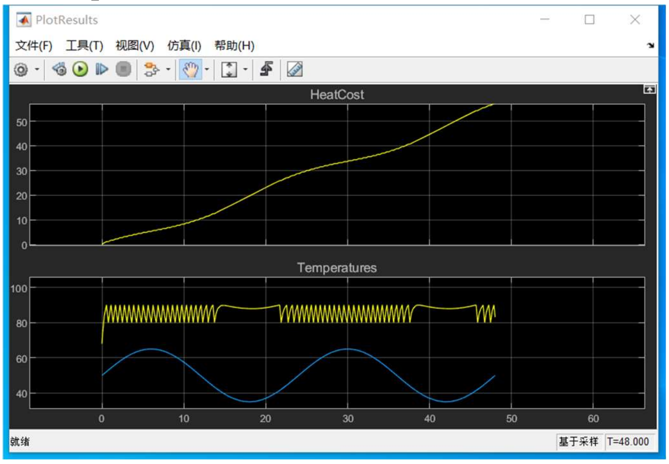


From this figure, I can find that the outdoor temperature is a sinusoidal wave, and its bias is **50**°F. The indoor temperature is up and down fluctuations around **70°F.** In addition, according to this model, the cost of heating the house for two days is about **$30.**

- Secondly, systematically change the parameters **outside the house**.

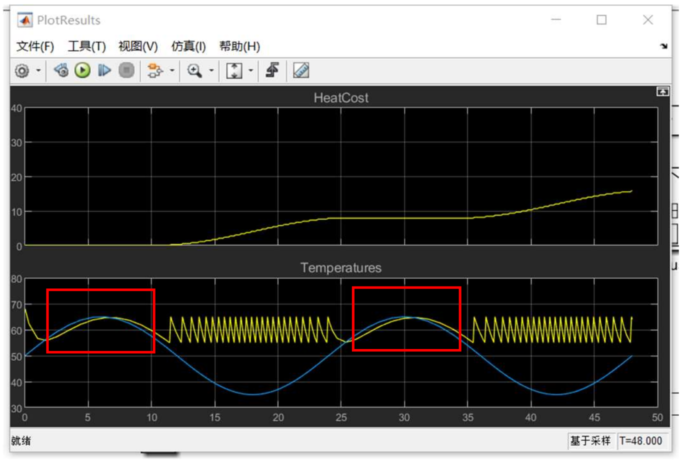
1) Set Point

The initial value of "set point" is 70. I increase this value first; I increase it to 85.



I can find that the outdoor temperature is not change obviously. However, the costs are increasing rapidly, the value from $30 to more than $50.

Then, I reduce the value and change it to 60°F.

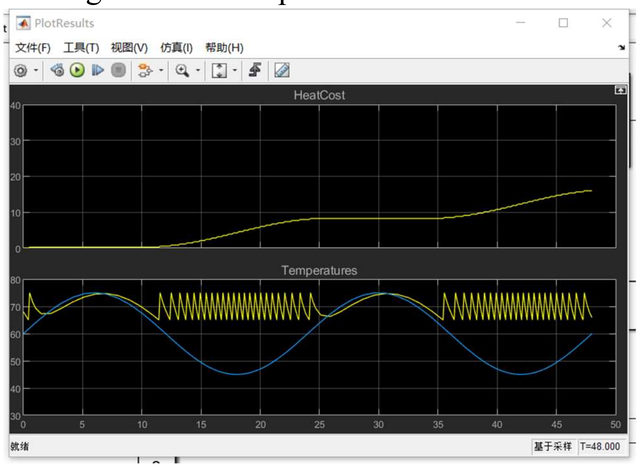


The indoor temperature is sometimes different from the initial figure. Due to the fluctuation of outdoor temperature, it is sometimes the same as or even higher than the indoor temperature. Therefore, the curve of indoor temperature sometimes coincides with that of outdoor temperature. In addition, the heat cost has decreased significantly, it dropped $30 to about $15.

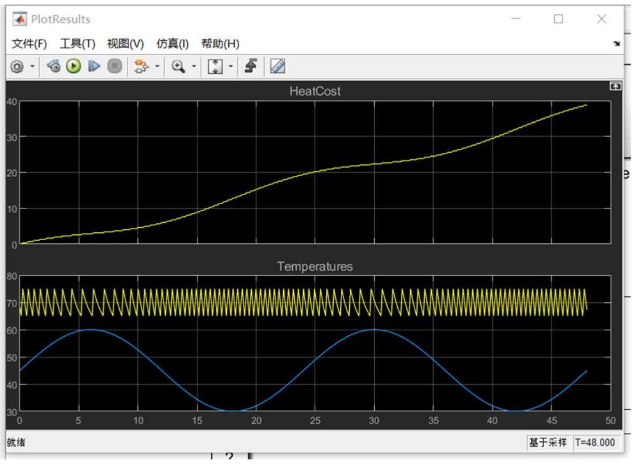
From the simulation results, if the value of “Set Point” is increase, the heat cost will increase. If the value is decrease, the cost will decrease. So, I can infer that **"set point" is the indoor temperature**, and the simulation result is consistent with the inference.

2) Avg Outdoor Temp

The initial value of average outdoor temperature is 50°F. I increase the value to 60°F.



The outdoor temperature has greatly changed. The amplitude of sine wave has not change but the bias has changed from 50 to 60. In addition, the heat cost has decreased significantly.

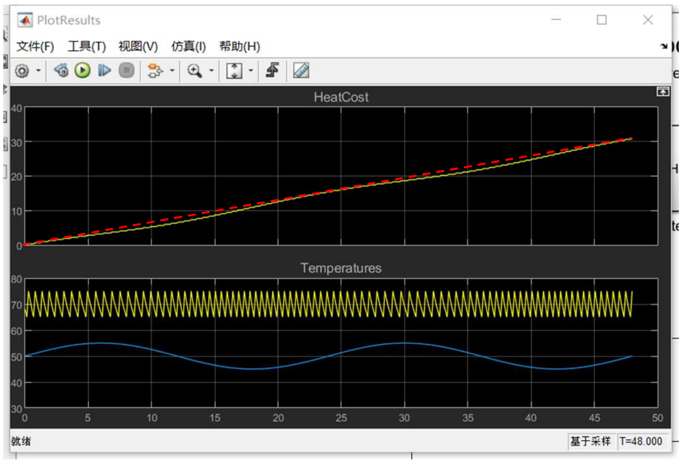


Then, I changed the outdoor average temperature to 45°F. It is like the previous case, the bias changed to 35, and the heat cost increase significantly.

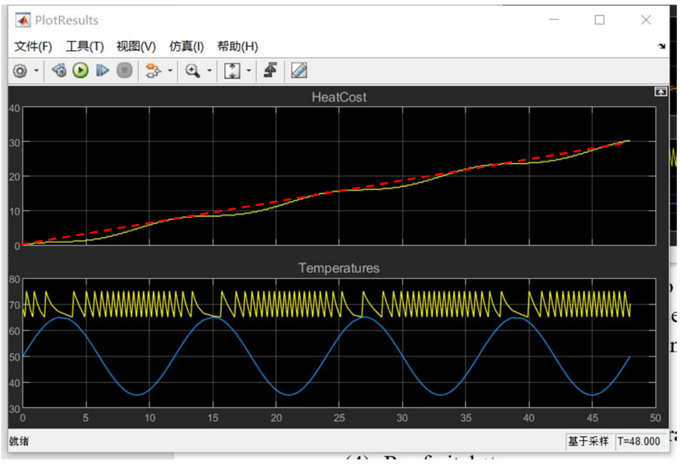
Therefore, it can be verified that this module controls the outdoor average temperature.

3) *Daily Temp Variation*

The initial value of frequency is $\frac{2\pi}{24}$ and amplitude is 15.



Then I change the amplitude to 5. The outdoor temperature variation is decrease. The fluctuation of heat cost decreases, but the final cost does not change significantly. As the amplitude decreases, the change of heat cost with time is nearly linear.



Return the amplitude to the initial value, and then change the frequency to $\frac{2\pi}{12}$. Contrary to the change in the previous situation. The outdoor temperature variation is increase, fluctuation of cost is increase, final cost does not change significantly.

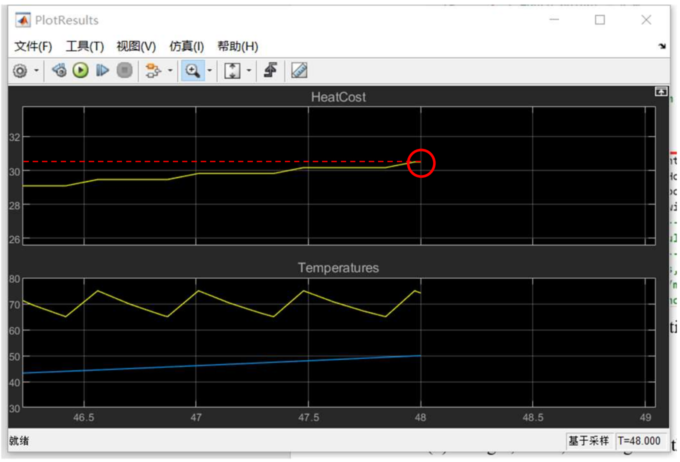
Therefore, I can conclude that the variation of outdoor temperature will not affect the heat cost.

- Thirdly, systematically vary parameters related to **dimensions of the house**.

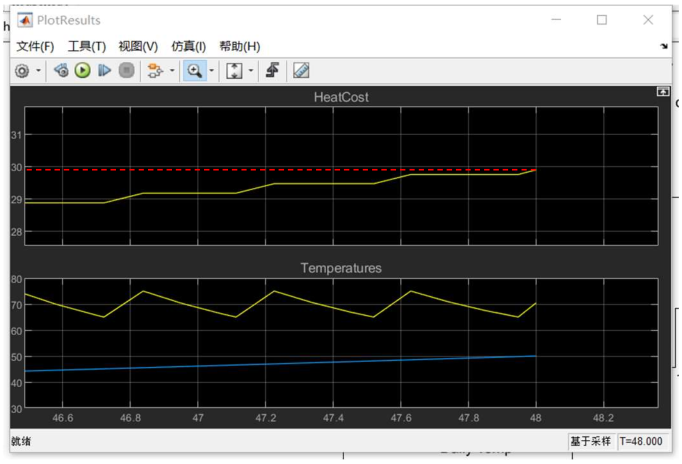
```
% -----------------------------
% House length = 30 m
lenHouse = 30;
% House width = 10 m
widHouse = 10;
% House height = 4 m
htHouse = 4;
% Roof pitch = 40 deg
pitRoof = 40/r2d;
% Number of windows = 6
numWindows = 6;
% Height of windows = 1 m
htWindows = 1;
% Width of windows = 1 m
widWindows = 1;
windowArea = numWindows*htWindows*widWindows;
wallArea = 2*lenHouse*htHouse + 2*widHouse*htHouse + ...
           2*(1/cos(pitRoof/2))*widHouse*lenHouse + ...
           tan(pitRoof)*widHouse - windowArea;
% -----------------------------
% Define the type of insulation used
% -----------------------------
% Glass wool in the walls, 0.2 m thick
% k is in units of J/sec/m/C - convert to J/hr/m/C multiplying by 3600
kWall = 0.038*3600;   % hour is the time unit
```

Fig. 2. Initial value of house parameters

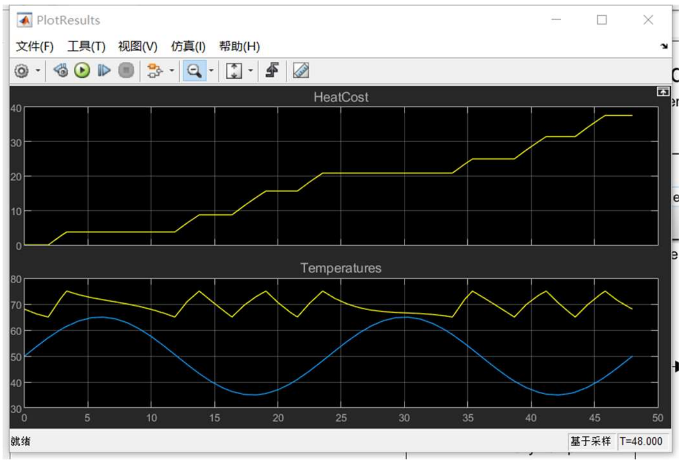
4) *Roof pitch*



This is the initial condition. The heat cost is about $30.5.



I change the value from 40 to 3. It means the roof pitch is 3°. The heat cost is about $29.9.

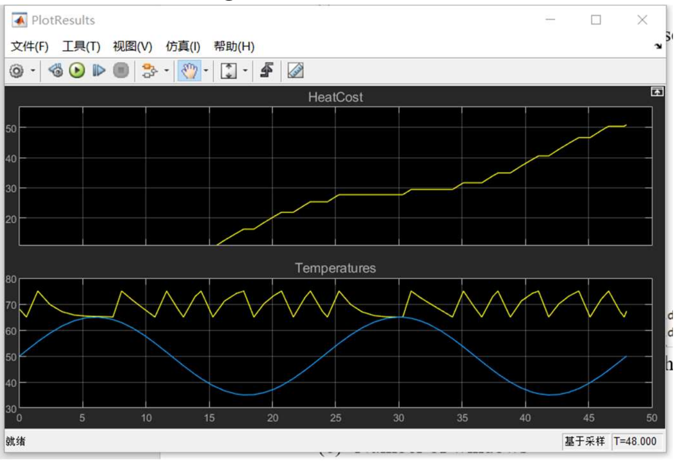


Then, I change the value to 89°. The heat cost increases significantly. Therefore, I can conclude that the change of roof pitch will affect the heat cost.

5) Length, width, and height of the house

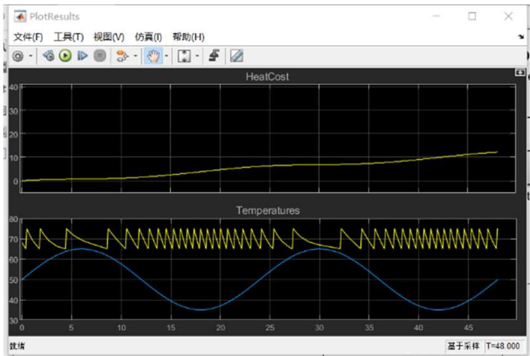
```
% ------------------------------
% House length = 30 m
lenHouse = 50;
% House width = 10 m
widHouse = 20;
% House height = 4 m
htHouse = 8;
% Roof pitch = 40 deg
pitRoof = 40/r2d;
% Number of windows = 6
numWindows = 6;
% Height of windows = 1 m
htWindows = 1;
% Width of windows = 1 m
widWindows = 1;
windowArea = numWindows*htWindows*widWindows;
wallArea = 2*lenHouse*htHouse + 2*widHouse*htHouse + ...
```

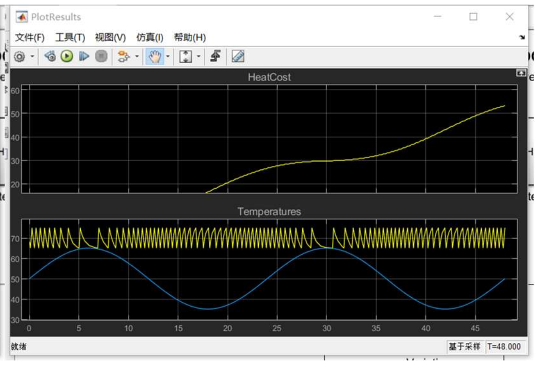
Increase the length, width, and height of the house, as shown in the above figure.



The heat cost increased to \$50. This is because the size of the house increases, so more heat is needed, and the corresponding heat cost also increases.

6) Number of windows

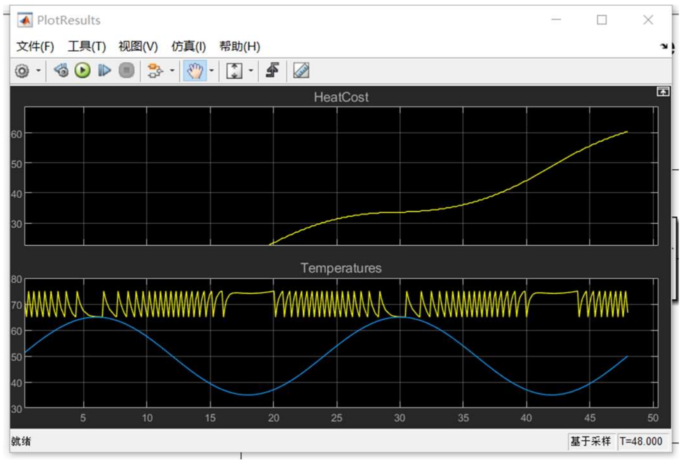




In the left figure, I change the number of windows to 1. In the left figure, I change this value to 12. I can find that as the number of windows increases, the heat cost will also increase.

Because if the number of windows increases, the equivalent thermal resistance of windows will also increase. Moreover, the thermal conductivity of glass is higher than that of the wall, so the heat losses of the house will increase, eventually leading to an increase in the heat cost.

7) *Length and width of windows*



I set the length and width of the window to 1.5m. The heat cost increased to $60.

In this section, I changed various parameters of the house and simulated. The **roof pitch, length, width, and height** of the house will affect the area of the wall and the volume of the house, thus affecting the heating cost of the whole house. Because if the house is large, the heating required will increase, and the heat cost will also increase.

4. Investigate the behavior of the system

This section will investigate the behavior of the system. Explain the principle of the model, list the formula, and explain each module.

The thermal model of a house is shown in figure 1. This model simulates a winter heating system with an outdoor temperature of 50°F and an indoor temperature of 70°F. In addition, the outdoor temperature changes sinusoidally with time, the amplitude is 15°F, and the frequency is $\frac{2\pi}{24}$. The thermostat allows the indoor temperature to fluctuate within 5°F above and below 70°F. When the temperature is below this range, the thermostat will trigger the heater to start. When the heater is turned on, 122 °F hot air is blown out at a constant flow rate of 3600 kg/hr. The cost collector will integrate the hot air and multiply it by the unit price to calculate the 48 hours heat cost. Part of the outdoor temperature is input into the house block, and part is input into the bus-creator. House block is the core of the model. The hot air generated by the heater will flow into the house, but at the same time, the cold air outside will also cause the house to lose heat. In output region, we can find the simulation results of heat cost, indoor temperature, and outdoor temperature [2].

Next, I will introduce the three subsystems of **House**, **Thermostat** and **Heater** in detail.

1) House

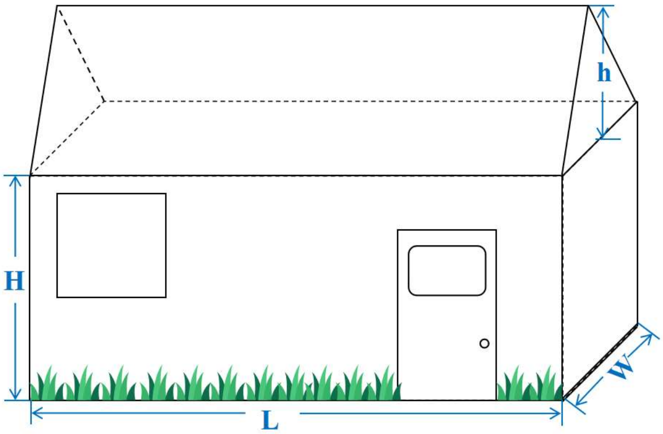


Fig. 3. House model

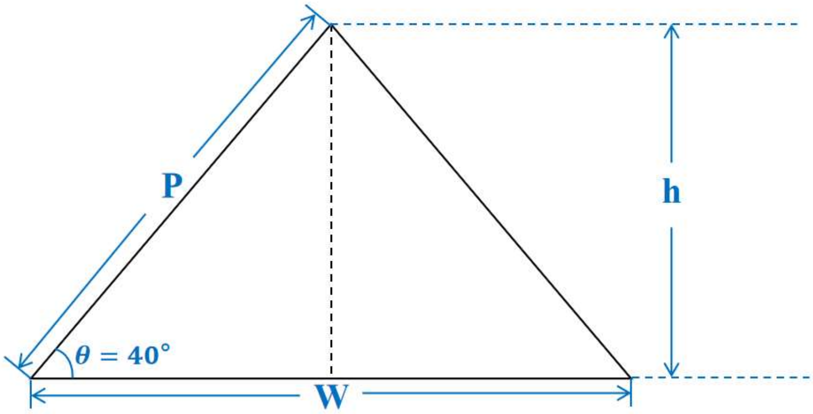


Fig. 4. Triangular roof

i. Wall areas

The formula of wall areas: $2WH + 2LH + 2PL + 2 \times \frac{1}{2}Wh - S_{window}$. The length, width, height, and roof pitch of the house are known. Thus, we can use W, H, L, and θ. P and h is the unknown quality.

$$tan40° = \frac{h}{\frac{W}{2}}$$

Thus, the height of the roof is:

$$h = \frac{tan40° \cdot W}{2}$$

$$\boldsymbol{W \cdot h = \frac{tan40^{\circ} \cdot W^2}{2}}$$

$$cos\theta = \frac{W}{2P} \Rightarrow \boldsymbol{P = \frac{W}{2cos\theta}}$$

$$\boldsymbol{Wall\ Areas} = 2WH + 2LH + 2PL + Wh - S_{window}$$

$$\boldsymbol{= 2WH + 2LH + \frac{WL}{cos40^{\circ}} + \frac{W^2 tan40^{\circ}}{2} - S_{window}}$$

In addition, the wall thickness is 0.2m, the window thickness is 0.01m. The number of windows is 6m, the length and width of window is 1m. Thus, the area of windows is

$$S_{window} = 6 \times 1 \times 1 = 6\, m^2$$

ii. Thermal conductivity of Walls

$$K_{BR} = 0.038\ \ [W \cdot s^{-1} \cdot k^{-1} \cdot m^{-1}]$$

J means joule, h means hour, k means Kelvin, and m means meter. In this model, we need use hour based. Thus:

$$\boldsymbol{K_{BR} = 3600 \times 0.038\ \ [J \cdot h^{-1} \cdot k^{-1} \cdot m^{-1}]}$$

iii. Thermal conductivity of the glass

$$K_{GL} = 0.78\ \ [J \cdot s^{-1} \cdot k^{-1} \cdot m^{-1}]$$

Use hour based:

$$\boldsymbol{K_{GL} = 3600 \times 0.78\ \ [J \cdot h^{-1} \cdot k^{-1} \cdot m^{-1}]}$$

iv. Walls: Thermal conductance and resistance

$$C_{wall}\ [J \cdot h^{-1} \cdot k^{-1}] = \frac{K_{BR}\ \ [J \cdot h^{-1} \cdot k^{-1} \cdot m^{-1}]\ \cdot (A_{wall} - A_{window})\ [m^2]}{Thickness\ wall\ [m]}$$

A_{wall} *and* A_{window} means the area of walls and windows. The equivalent resistance:

$$\boldsymbol{R_{thermal\ wall} = \frac{1}{C_{wall}} = \frac{Thickness\ wall}{K_{BR} \cdot (A_{wall} - A_{window})}}$$

v. Glass: Thermal conductance and resistance

$$C_{glass}\ [J \cdot h^{-1} \cdot k^{-1}] = \frac{K_{GL}\ [J \cdot h^{-1} \cdot k^{-1} \cdot m^{-1}] \cdot A_{glass}\ [m^2]}{Thickness\ glass\ [m]}$$

Resistance:

$$\boldsymbol{R_{thermal\ glass}} = \frac{\mathbf{1}}{\boldsymbol{C_{glass}}} = \frac{\boldsymbol{Thickness\ glass}}{\boldsymbol{K_{GL}} \cdot \boldsymbol{A_{glass}}}$$

vi. Some descriptions of heat loss and equivalent resistance

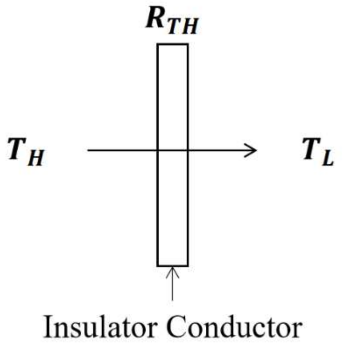


Fig. 5. Equivalent resistance

In this model, "insulator conductor" means walls or windows. Walls or windows can be seen as a resistance because they have some characteristics like resistance, such as Ohm's law. In Ohm's law: $I = \frac{V}{R}$. In this model, the heat loss is:

$$\boldsymbol{P_{flow}[J \cdot s^{-1}]} = \frac{\boldsymbol{T_H - T_L}}{\boldsymbol{R_{TH}}}$$

T_H is the indoor temperature, T_L is the outdoor temperature, and R_{TH} is the equivalent resistance of walls or windows.

From this formula, we can draw a conclusion. Heat loss is proportional to the temperature difference between inside and outside, and inversely proportional to the thermal resistance R_{TH}. $R_{TH} \propto thickness$.

vii. The final equivalent resistance as the parallel combination

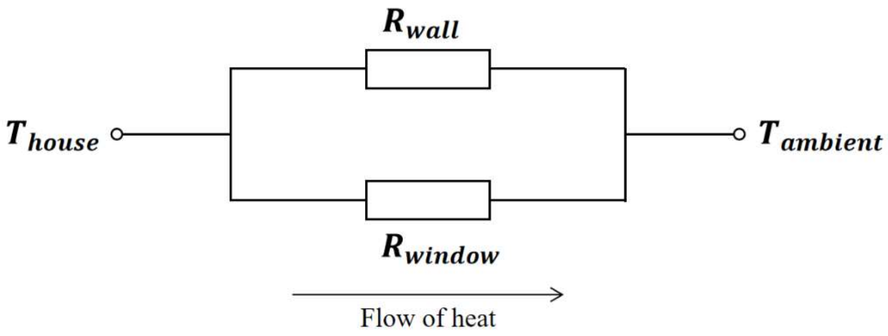


Fig. 6. Parallel equivalent resistance

Heat flow can be lost through windows or walls. Therefore, their relationship can be equivalent to the parallel circuit in the circuit.

$$\boldsymbol{R_{eq}} = \frac{\boldsymbol{R_{wall} \cdot R_{window}}}{\boldsymbol{R_{wall} + R_{window}}}$$

$$\frac{dQ}{dt} = \frac{\Delta T}{R_{eq}}$$

Finally, I will explain the house subsystem.

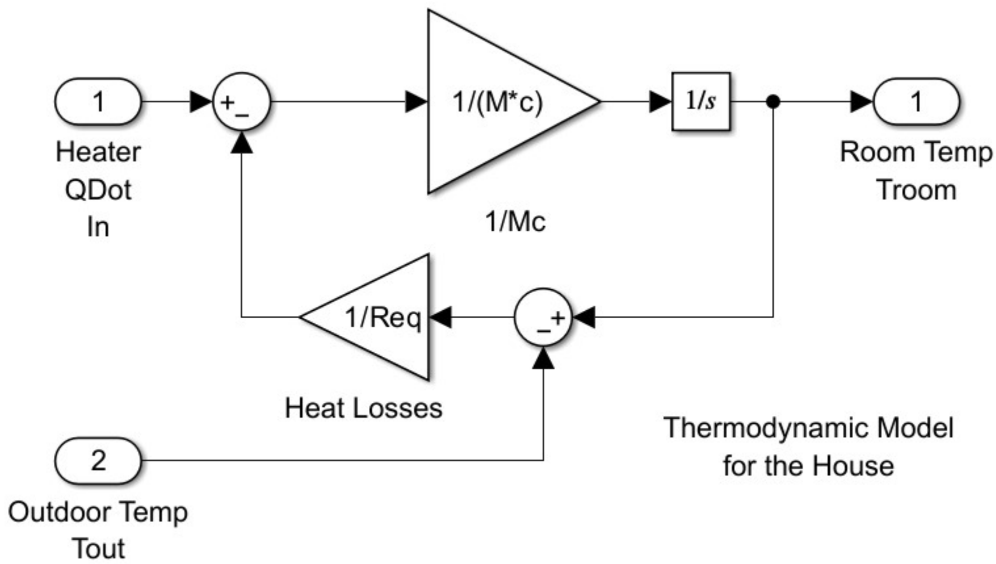


Fig. 7. Thermodynamic model for the house

House is a subsystem for calculating room temperature changes. It considers the heat flow from the heater and the heat loss in the environment. The heat loss and temperature time derivative are given by the following equation.

$$\left(\frac{dQ}{dt}\right)_{losses} = \frac{T_{room} - T_{out}}{R_{eq}}$$

$$\frac{dT_{room}}{dt} = \frac{1}{M_{air} \cdot c} \cdot \left(\frac{dQ_{heater}}{dt} - \frac{dQ_{losses}}{dt}\right)$$

$$M_{air} = mass\ of\ air\ inside\ the\ house$$
$$R_{eq} = equivalent\ thermal\ resistance\ of\ the\ house$$

The hot air generated by the heater enters from "1". After subtracting the heat losses, times $\frac{1}{M*c}$. M is the total internal air mass.

$$M = \rho \cdot V = \rho \cdot (L \cdot W \cdot H + \frac{1}{4} W^2 \cdot tan\theta \cdot L)$$

ρ means air density, the value is $1.2250\ kg/m^3$. L, W, H means the length, width, height of the house respectively. θ is the roof pitch, the default value is $40°$. c=1005.4. As the house has heat loss, negative feedback is formed through a gain module.

2) Thermostat

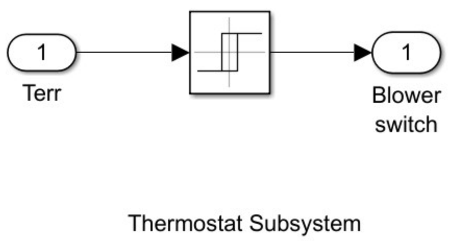


Fig. 8. Thermostat subsystem

Figure 3 shows the thermostat block. This block includes a "relay" module. The value of switch on point is $\frac{5}{9} \times 5$ and switch off point is $-\frac{5}{9} \times 5$. If it is lower than this range, it will output 1 and trigger the heater to start, otherwise output 0. It means the thermostat allows the temperature to fluctuate within 5°F above and below the ideal room temperature. If the air temperature drops below 65°F, the thermostat will turn on the heater.

3) Heater

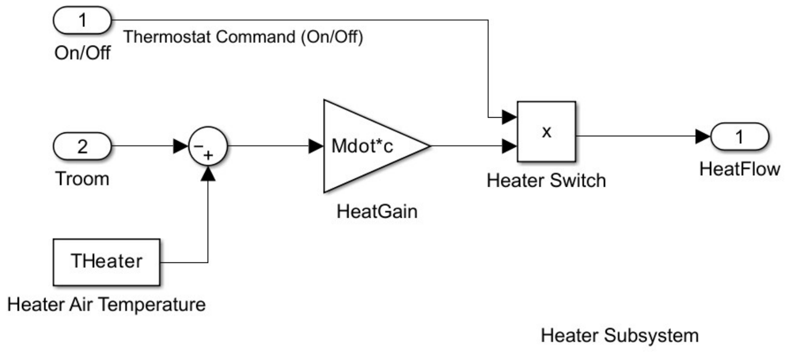


Fig. 9. Heater subsystem

The heater subsystem models the constant air flow rate Mdot, and the thermostat signal is used to turn the heater on or off. When the heater is turned on, it blows hot air at a constant Mdot flow rate (default 1 kg/s=3600 kg/hr) with a temperature of THeater (default 50 °C=122 °F). The following equation represents the heat flow entering the room.

$$\frac{dQ}{dt} = (T_{heater} - T_{room}) \cdot Mdot \cdot c$$

$$\frac{dQ}{dt} = heat\ flow\ from\ the\ heater\ into\ the\ room$$

$$c = heat\ capacity\ of\ air\ at\ constant\ pressure$$

$$Mdot = air\ mass\ flow\ rate\ through\ heater (kg/hr)$$

$$T_{heate} = temperature\ of\ hot\ air\ from\ heater$$

$$T_{room} = current\ room\ air\ temperature$$

"Heater air temperature" is a constant module, it continuously outputs the constant of 50. "Troom" input is the temperature of the house currently. Through the "Sum" module, it realizes $T_{heater} - T_{room}$. Then, times Mdot and c. The value of **c** is 1005.4. Thermostat command controls the opening and closing of the heater. If the heater is open, the command will input "1". The output is $(T_{hea} - T_{room}) \cdot Mdot \cdot c \cdot 1 = (T_{hea} - T_{room}) \cdot Mdot \cdot c$. If the heater is off, the command will input "0". Then the output is $(T_{heater} - T_{room}) \cdot Mdot \cdot c \cdot 0 = 0$. Due to output 0, this means that the heater is not turned on.

5. Cooler subblock

The model also has some disadvantages. This model can only heat, but when the outdoor temperature is higher than the indoor temperature in summer, it cannot cool.

Therefore, I need to modify to change it into a cooling model.

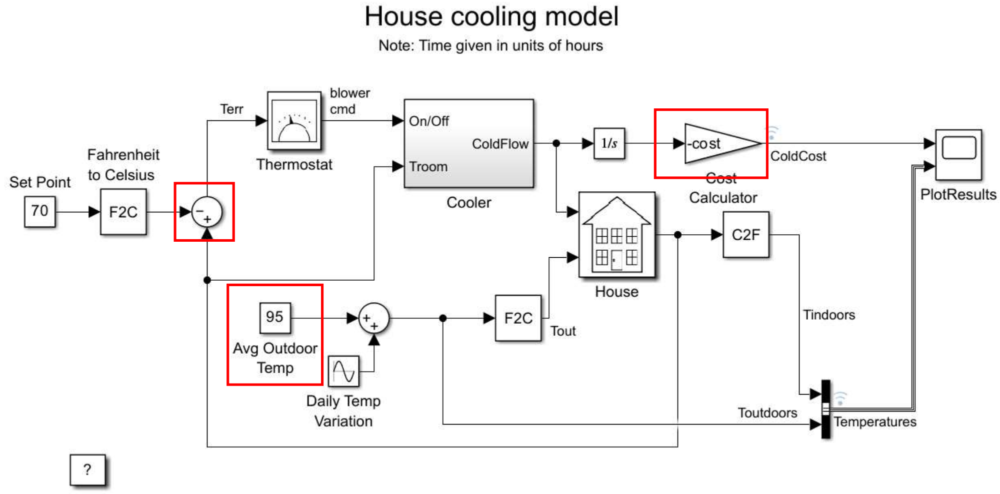


Fig. 10. House cooling model

The house cooling model shows in figure10. In the external model, I changed the average outdoor temperature, cost calculator, and "sum" module. In summer, the average outdoor temperature is $35℃ = 95℉$. Because cold air is blown out, if you do not add a minus sign before "cost", the cold cost is a negative number.

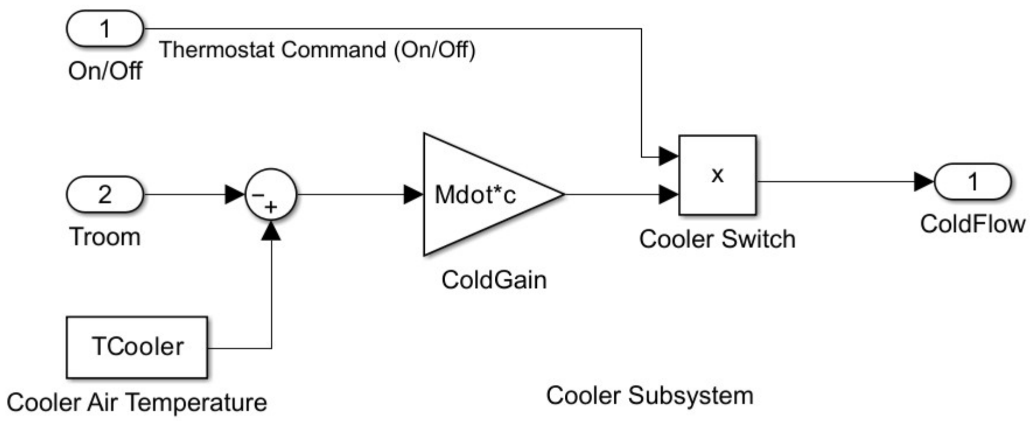
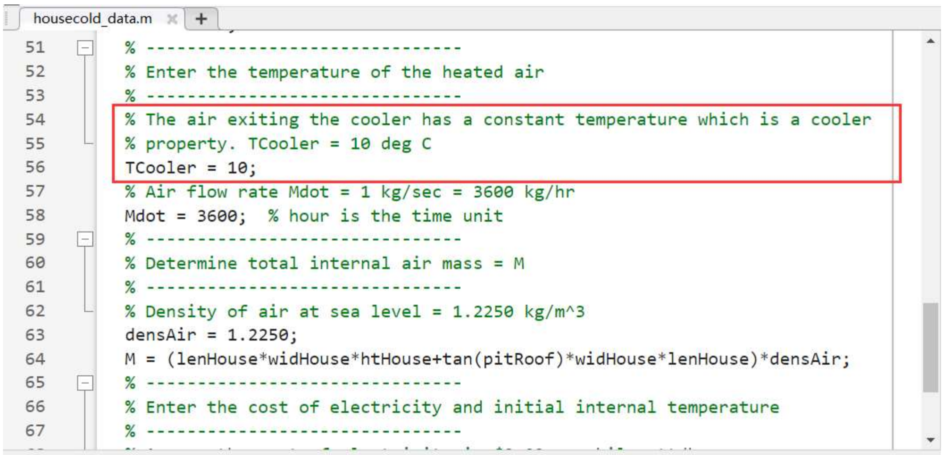


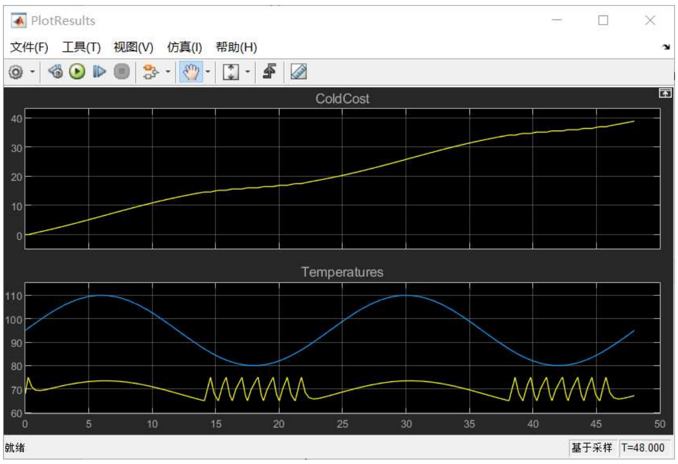
Fig. 11. Cooler subsystem



```
% ------------------------------
% Enter the temperature of the heated air
% ------------------------------
% The air exiting the cooler has a constant temperature which is a cooler
% property. TCooler = 10 deg C
TCooler = 10;
% Air flow rate Mdot = 1 kg/sec = 3600 kg/hr
Mdot = 3600;  % hour is the time unit
% ------------------------------
% Determine total internal air mass = M
% ------------------------------
% Density of air at sea level = 1.2250 kg/m^3
densAir = 1.2250;
M = (lenHouse*widHouse*htHouse+tan(pitRoof)*widHouse*lenHouse)*densAir;
% ------------------------------
% Enter the cost of electricity and initial internal temperature
% ------------------------------
```

Fig. 12. Housecold_data.m

In addition, I changed the Cooler, which is the original Heater. The Cooler subsystem is shown in figure11. In this subsystem, I changed the value of “TCooler”, which is the original “THeater”. Before, because it was a heater, it was necessary to blow out the warm air, and the value of “THeater” is 50. However, in this situation, we want the Cooler to blow cold air, so I changed the value of “TCooler” to 10. The changed data is shown in figure 12. These operations change the thermal model of the house into the cooling model of the house.



Finally, simulate the model. The outdoor temperature is higher than the indoor temperature. The indoor temperature can basically maintain a stable level of 70°F. ColdCost is a normal value, it is not a negative value. Therefore, it can be explained that the operation of modifying the air conditioner by the heater is successful.

6. Conclusions

In this MATLAB simulation lab, I investigate the thermal model of a house. This study set out to primary understand the MATLAB and Simulink, investigate specific models through simulation. The study contributes to our understanding of how to study a model of MATLAB’s Simulink. Through this research, I changed many data in the model and carried out simulation to explore the difference of output. In addition, investigate the theorems and principles of the model. Finally, I modified part of the model from Heater to air conditioner.

However, a limitation of this study is that some formulas have not been thoroughly studied, the correctness of some formulas in this report is still controversial. Furthermore, in the final refrigeration system study, the air conditioning system is not combined with the heating system, resulting in only refrigeration but no heating.

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