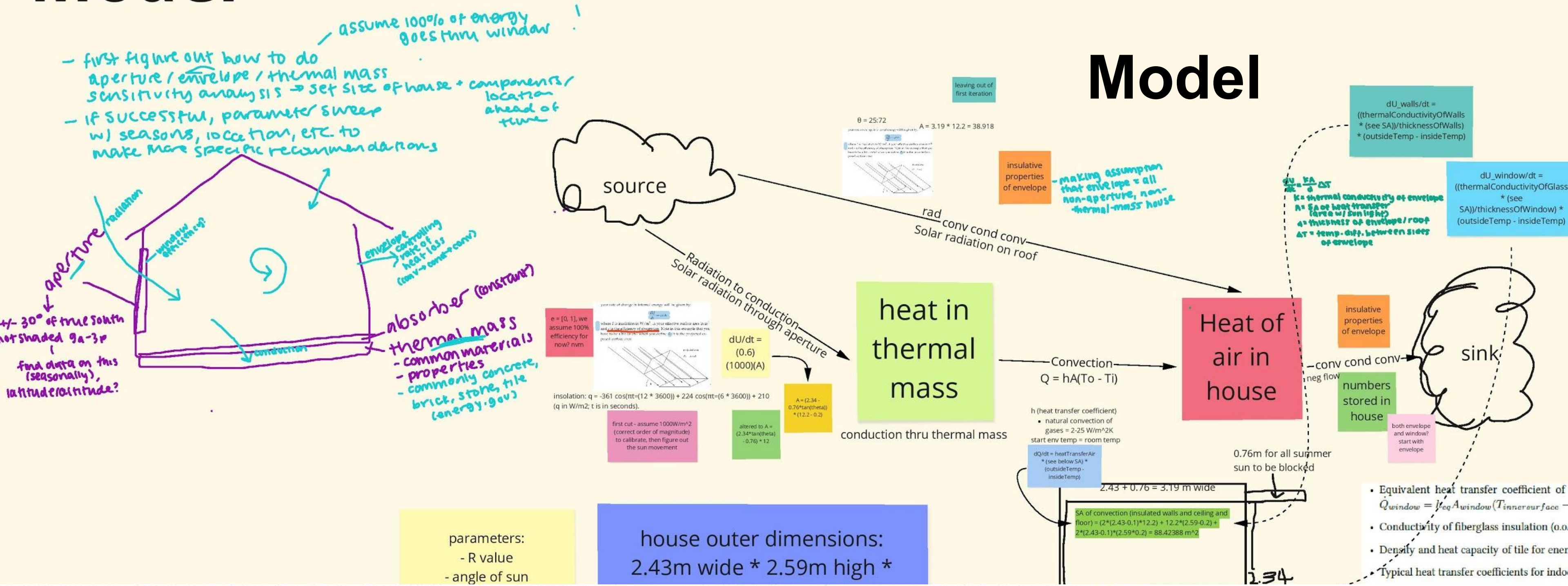
Building a Solar House
⛅🏡

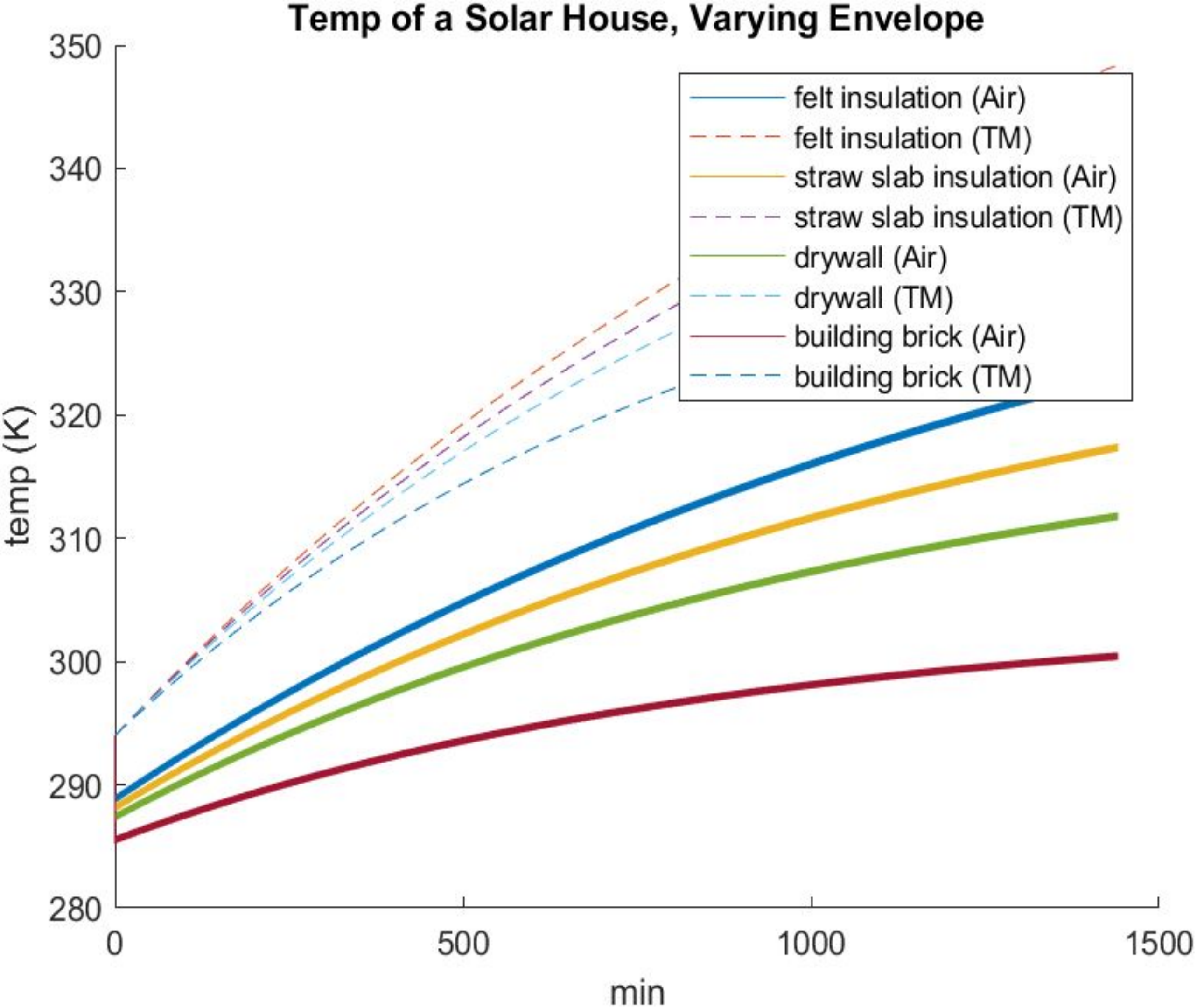
Team 2-13: Andrew DeCandia and Berwin Lan

How do we maximize the efficiency of a solar house with the least financial resources?

- Considering price, what aspects of a solar home are worth investing in?




```
rate_func = @(T,x) [((-1 * (heat_to_temp(x(1), massOfAir, specificHeatOfAir) - outsideTemperature)) ...
          / (1 / ((1 / (thermal_Resistance_Convection(internalAreaOfTransfer, heatTransferAir) ...
          + thermal_Resistance_Conduction(internalAreaOfTransfer, thicknessOfWalls, thermalConductivityOfWalls) ...
          + thermal_Resistance_Convection(externalAreaOfTransfer, heatTransferAir))) ...
          + (1 / (thermal_Resistance_Convection(glassAreaOfTransfer, heatTransferAir) ...
          + thermal_Resistance_Conduction(glassAreaOfTransfer, thicknessOfGlass, thermalConductivityOfGlass) ...
          + thermal_Resistance_Convection(glassAreaOfTransfer, heatTransferAir)))))) ...
          + (-1 * ((-1 * (heat_to_temp(x(2), massOfConcrete, specificHeatOfConcrete) - heat_to_temp(x(1), massOfAir, specificHeatOfAir)))...
          / thermal_Resistance_Convection(thermalMassAreaOfTransfer, heatTransferAir))); ...
          (concreteEVal * solarInsolation * ((ledgeDepth * tand(angleOfSun)) * lengthInternal)) ...
          - (-1 * ((-1 * (heat_to_temp(x(2), massOfConcrete, specificHeatOfConcrete) - heat_to_temp(x(1), massOfAir, specificHeatOfAir)))...
          / thermal_Resistance_Convection(thermalMassAreaOfTransfer, heatTransferAir)))];
```



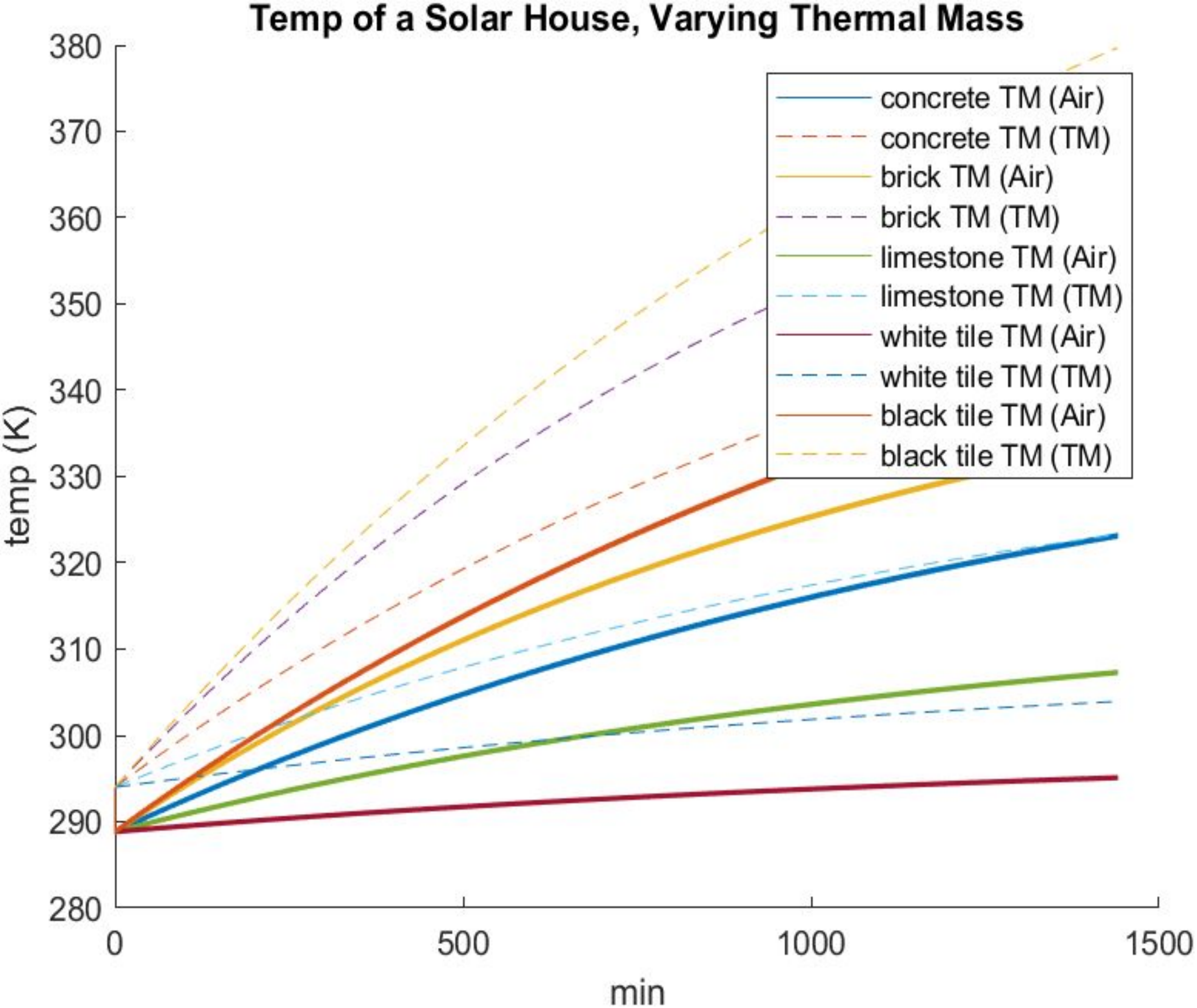
Envelope Costs ($/m^2)

felt = 7.16

straw slab = 1506.95

drywall = 3.99

brick = 387.50



Thermal Mass Costs

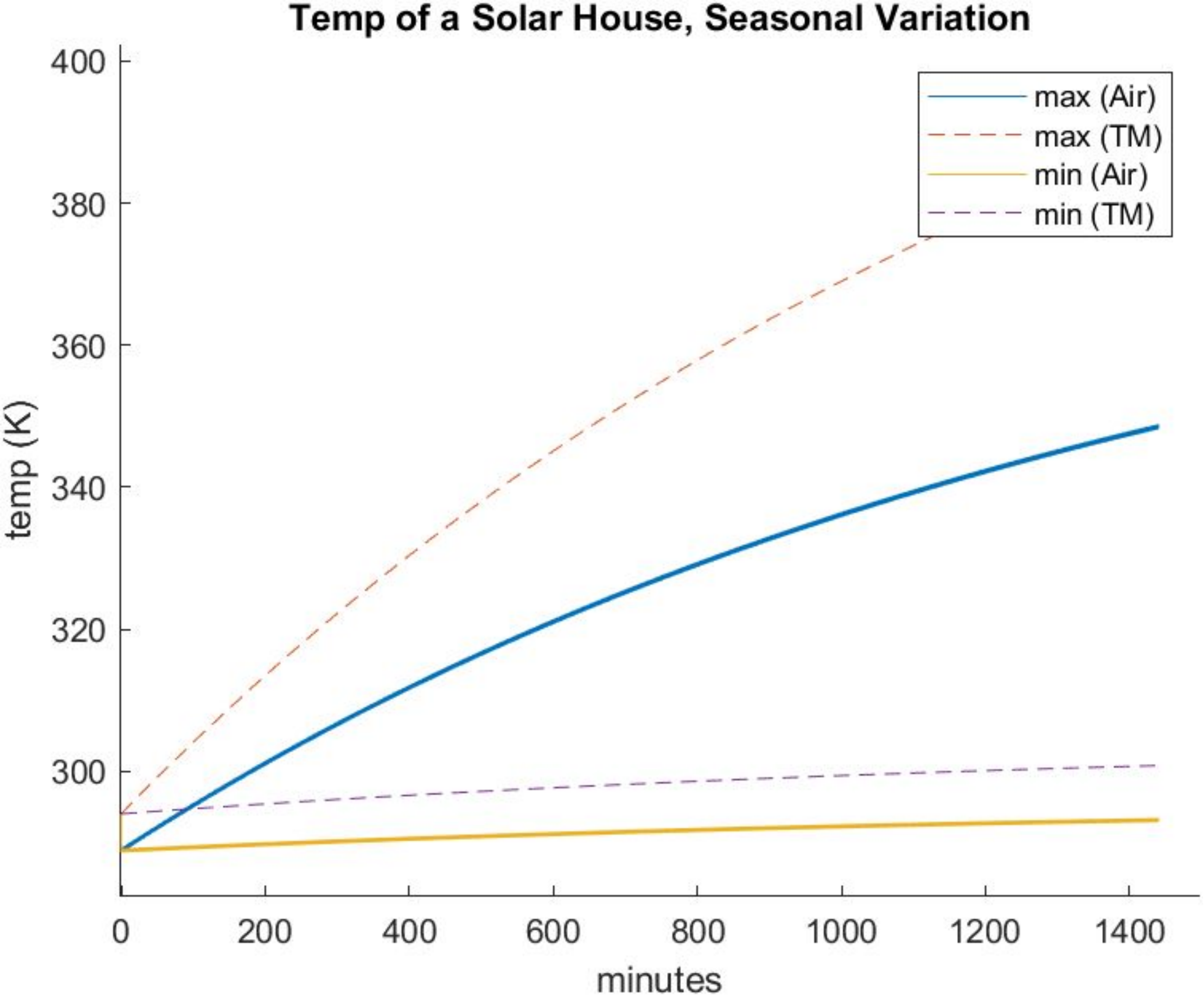
Concrete: $21-323 per m^2

Brick: $54-215 per m^2

Limestone: $32-108 per m^2

requires regular maintenance

Tile: $11-215 per m^2



max = 72 deg from horizontal, summer

min = 25 deg from horizontal, winter

Resources

- https://www.smarterhomes.org.nz/smart-guides/design/thermal-mass-for-heating-and-cooling/#:~:text=Concrete%20slab%20floors%20should%20be,won't%20store%20enough%20heat
- https://www.yourhome.gov.au/passive-design/thermal-mass
- https://www.engineeringtoolbox.com/thermal-conductivity-d_429.html
- https://www.engineeringtoolbox.com/solar-radiation-absorbed-materials-d_1568.html
- https://www.pveducation.org/pvcdrom/properties-of-sunlight/calculation-of-solar-insolation
- https://nsrdb.nrel.gov/data-sets/archives.html
- https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/solar-radiation
- https://www.nrel.gov/gis/solar.html
- https://www.energy.gov/energysaver/energy-efficient-home-design/passive-solar-home-design
- https://home.costhelper.com/limestone-tile.html
- https://www.hgtv.com/design/remodel/interior-remodel/average-cost-install-tile-floor
- https://www.concretenetwork.com/concrete/interiorfloors/cost.html#:~:text=Concrete%20flooring%20cost%20ranges%20between,a%20high%2Dend%2C%20customized%20floor
- https://www.improvenet.com/r/costs-and-prices/brick-paver-flooring
- https://www.homedepot.com/p/USG-Sheetrock-Brand-1-2-in-x-4-ft-x-8-ft-Ultralight-Gypsum-Board-14113411708/202530243
- https://www.homeadvisor.com/cost/walls-and-ceilings/install-a-brick-stone-or-block-wall/
- https://www.grainger.com/product/ROXUL-4-in-x-48-in-x-24-in-Mineral-19NE80
- https://www.buildingwithawareness.com/cost/

ModSim Project 2 - Solar House

Andrew DeCandia and Berwin Lan

Modeling and Simulation - Fall 2020

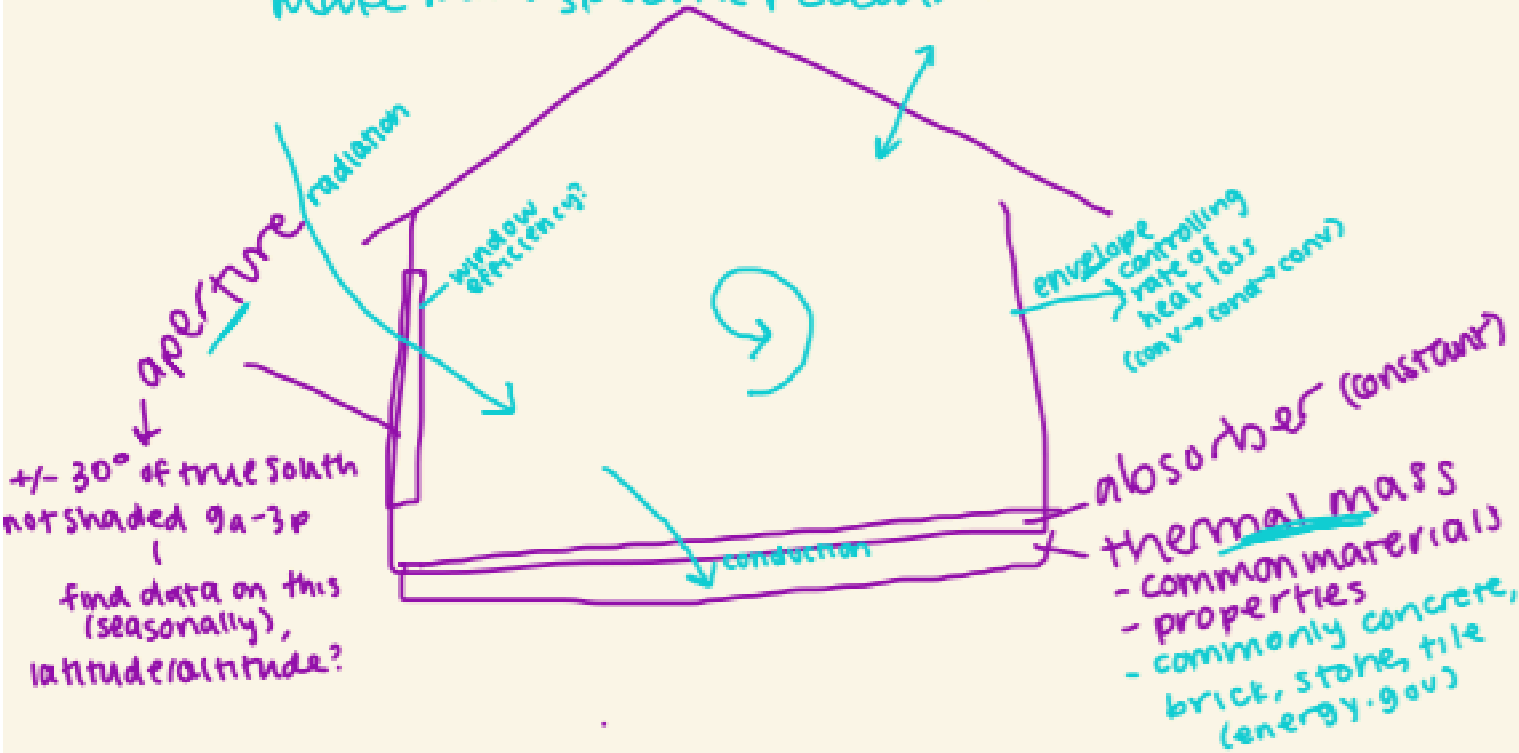
Question: What aspect of a solar house is worth upgrading in order to maximize its efficiency?

Our question is a mainly a design question, although it has implications in explaining and predicting human behavior as well. It is important to answer this question due to budget limitations as real-world constraints and scarcity of resources, and by investigating, we hope to be able to make an informed and cost-conscious recommendation of solar house materials.

Methodology & Models:

- assume 100% of energy goes thru windo

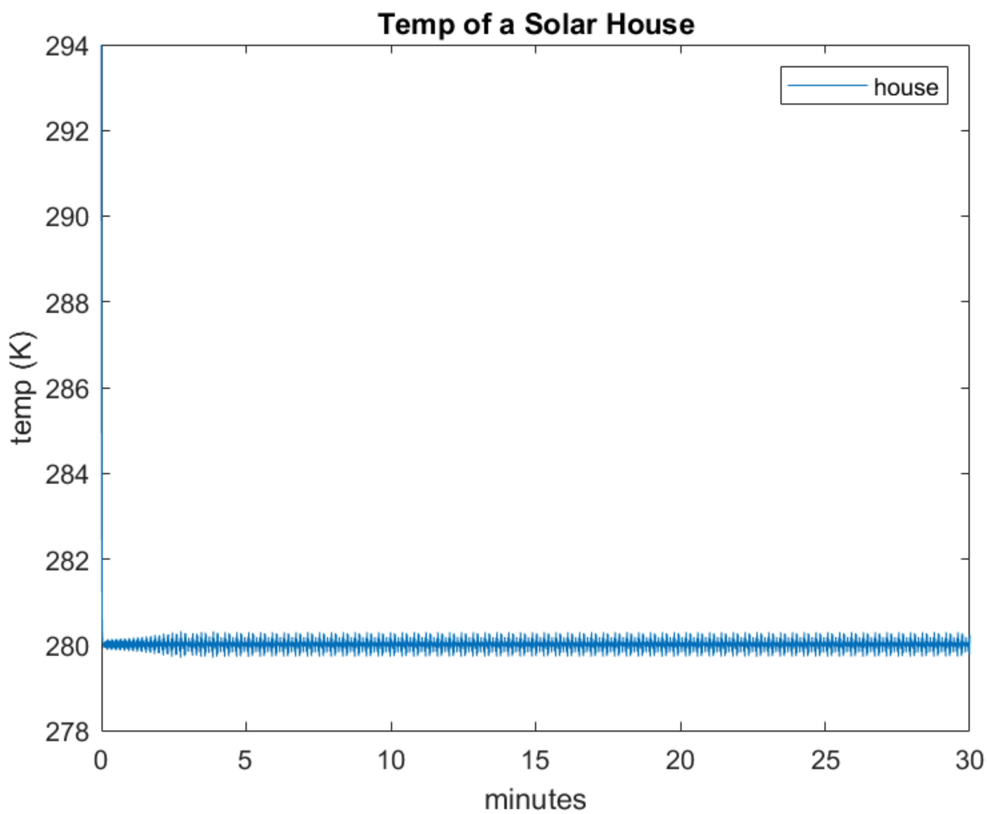
- first figure out how to do aperture / envelope / thermal mass sensitivity analysis → set size of house + componen locatio ahead o time
- if successful, parameter sweep w/ seasons, location, etc. to make more specific recommendations



parameters:
- R value
- angle of sun
- intensity of sun
- thermal mass' mass and specific heat
- outdoor temp

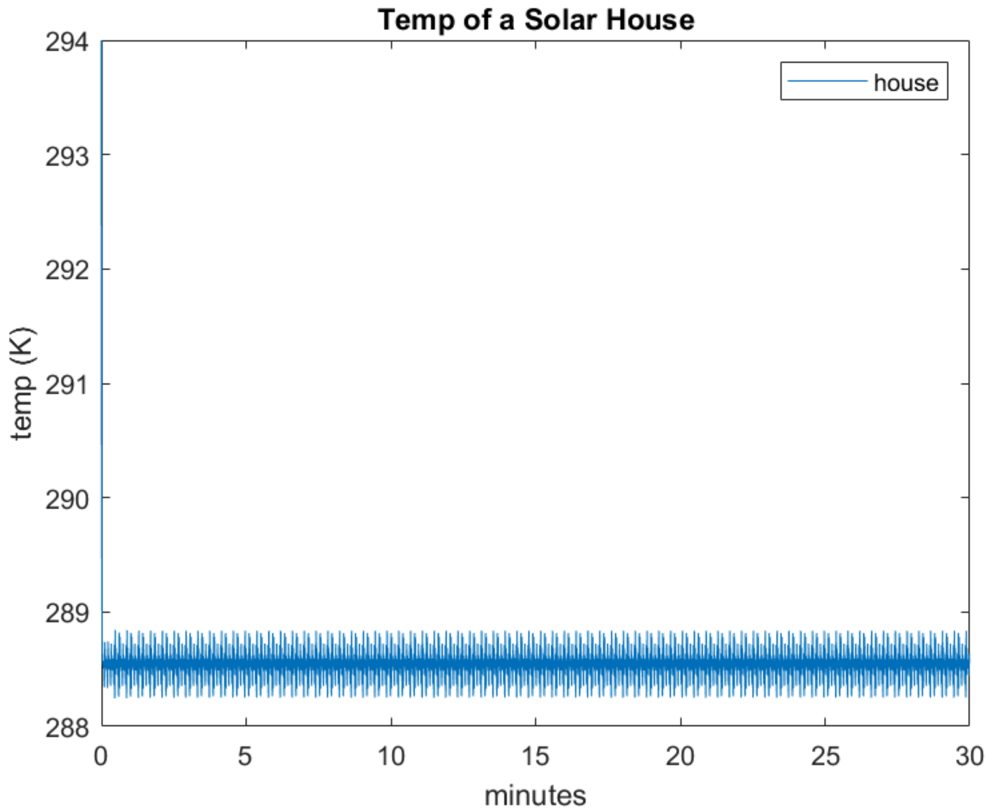
The most basic version of the model had no solar input at all, and it considered the house as a single stock.

```
[time, temps] = firstCutNoSolarInput();
figure(1); clf;
plot(time, temps); label1 = 'house';
title('Temp of a Solar House');
xlabel('minutes'); ylabel('temp (K)');
legend({label1});
```



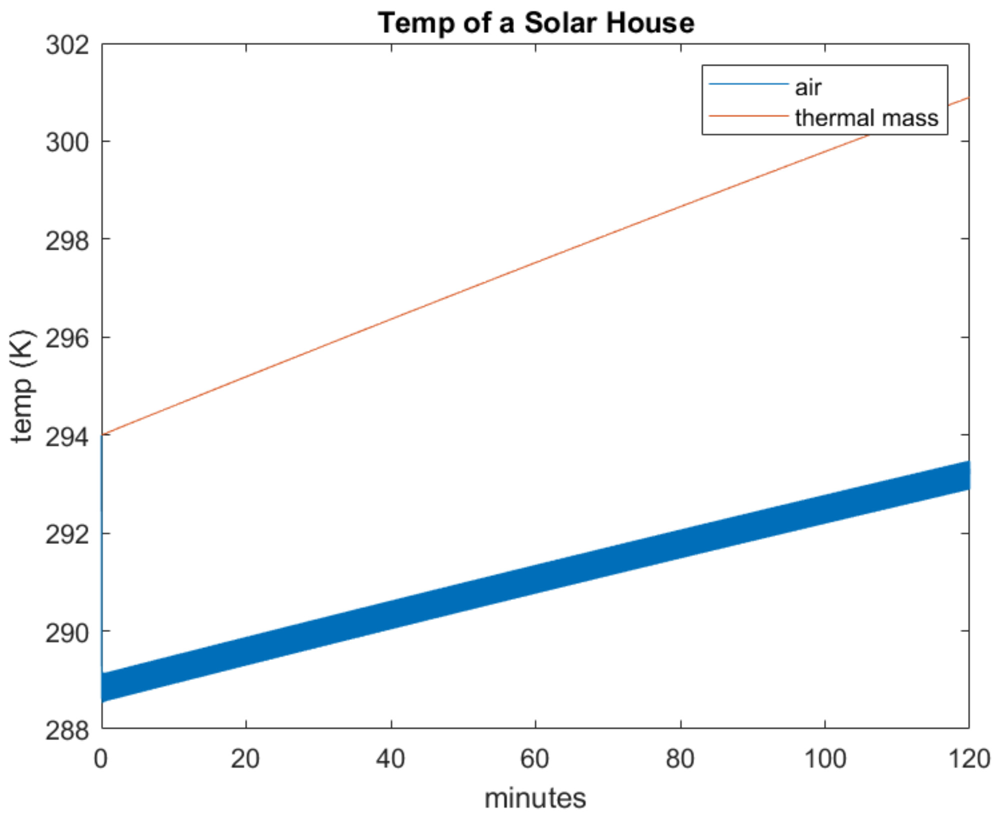
The first iteration introduced an arbitrary solar input, still considering the entire house as a single stock.

```
% Second cut
[time, temps] = Version2fakeSolarInput();
figure(2); clf;
plot(time, temps); label1 = 'house';
title('Temp of a Solar House');
xlabel('minutes'); ylabel('temp (K)');
legend({label1});
```



Hey look, multiple stocks! The temperature of the air and the thermal mass are now being tracked separately.

```
[times, tempss] = firstAttemptAtMultipleStocks();
figure(3); clf;
plot(times, tempss);
title('Temp of a Solar House');
xlabel('minutes'); ylabel('temp (K)'); legend('air','thermal mass');
```



For verification, we made sure that the temperature remained reasonable (no negatives or extremely large values).

Results:

Testing different envelope materials:

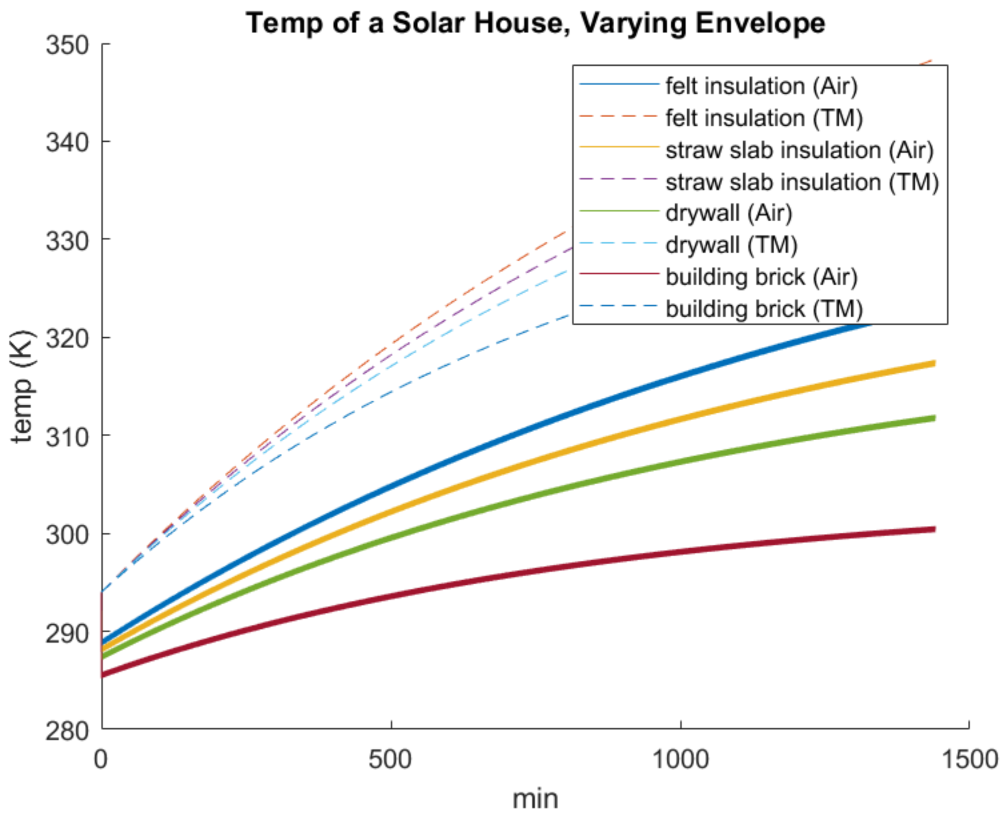
(data from The Engineering Toolbox)

envelope material	thermal conductivity
felt insulation	-1
Straw slab insulation, compressed	0.09
Gypsum board (drywall)	0.17
Brickwork, common (Building Brick)	0.8

```
% Use function MultistockParameters to set all values to default besides
% thermal conductivity of envelope
[timeFelt, tempsFelt] = MultistockParameters(-1, -1, -1, -1);   % 0.04
```

```
[timeStraw, tempsStraw] = MultistockParameters(-1, -1, -1, 0.09);
[timeDrywall, tempsDrywall] = MultistockParameters(-1, -1, -1, 0.17);
[timeBrick, tempsBrick] = MultistockParameters(-1, -1, -1, 0.8);

% Plot
figure(4); clf; hold on;
plot(timeConcrete, tempsFelt(:,1)); label1 = 'felt insulation (Air)';
plot(timeConcrete, tempsFelt(:,2), '--'); label2 = 'felt insulation (TM)';
plot(timeStraw, tempsStraw(:,1)); label3 = 'straw slab insulation (Air)';
plot(timeStraw, tempsStraw(:,2), '--'); label4 = 'straw slab insulation (TM)';
plot(timeDrywall, tempsDrywall(:,1)); label5 = 'drywall (Air)';
plot(timeDrywall, tempsDrywall(:,2), '--'); label6 = 'drywall (TM)';
plot(timeBrick, tempsBrick(:,1)); label7 = 'building brick (Air)';
plot(timeBrick, tempsBrick(:,2), '--'); label8 = 'building brick (TM)';
title('Temp of a Solar House, Varying Envelope');
xlabel('min'); ylabel('temp (K)'); legend({label1, label2, label3, label4, label5, label6, labe
```



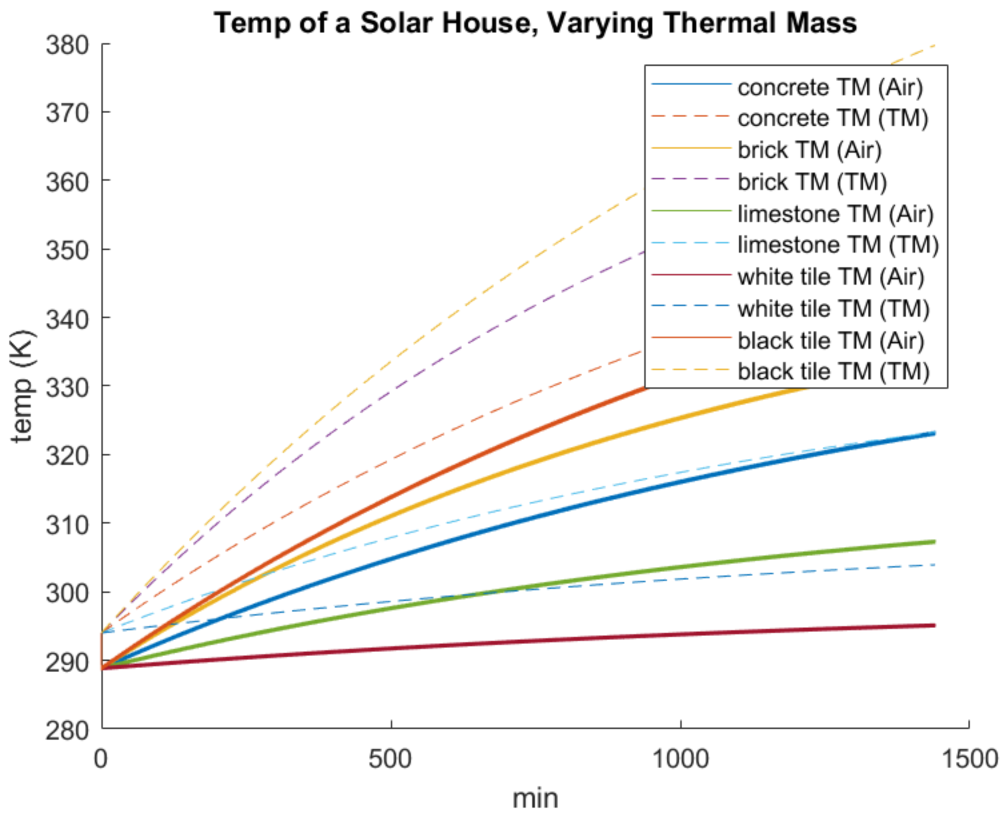
Testing different thermal mass materials:

(data from The Engineering Toolbox)

TM Material	specific heat	density	efficiency of ab
concrete	-1	-1	-1
Brick, common red	840	2000	0.68
Limestone, light	909	2150	0.35
White Dutch tile	1085	2000	0.18

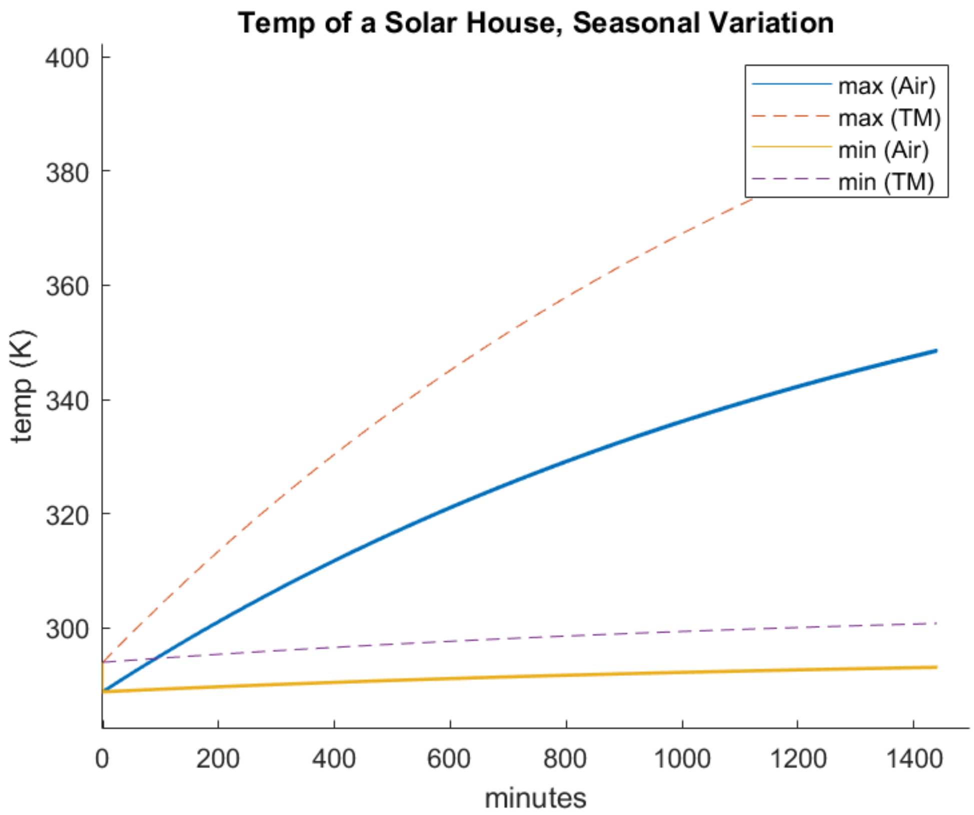
```
% Use function MultistockParameters to set all values to default besides
% thermal mass properties
[timeConcrete, tempsConcrete] = MultistockParameters(-1, -1, -1, -1);
[timeBrick, tempsBrick] = MultistockParameters(840, 2000, 0.68, -1);
[timeLimestone, tempsLimestone] = MultistockParameters(909, 2150, 0.35, -1);
[timeTile, tempsTile] = MultistockParameters(1085, 2000, 0.18, -1);
[timeTileB, tempsTileB] = MultistockParameters(1085, 2000, 0.91, -1);   % concrete black tile

% Plot
figure(5); clf; hold on;
plot(timeConcrete, tempsConcrete(:,1)); label1 = 'concrete TM (Air)';
plot(timeConcrete, tempsConcrete(:,2), '--'); label2 = 'concrete TM (TM)';
plot(timeBrick, tempsBrick(:,1)); label3 = 'brick TM (Air)';
plot(timeBrick, tempsBrick(:,2), '--'); label4 = 'brick TM (TM)';
plot(timeLimestone, tempsLimestone(:,1)); label5 = 'limestone TM (Air)';
plot(timeLimestone, tempsLimestone(:,2), '--'); label6 = 'limestone TM (TM)';
plot(timeTile, tempsTile(:,1)); label7 = 'white tile TM (Air)';
plot(timeTile, tempsTile(:,2), '--'); label8 = 'white tile TM (TM)';
plot(timeTileB, tempsTileB(:,1)); label9 = 'black tile TM (Air)';
plot(timeTileB, tempsTileB(:,2), '--'); label10 = 'black tile TM (TM)';
title('Temp of a Solar House, Varying Thermal Mass');
xlabel('min'); ylabel('temp (K)'); legend({label1, label2, label3, label4, label5, label6, labe
```



Variation of Sun Angle - the angle of the sun varies with the seasons

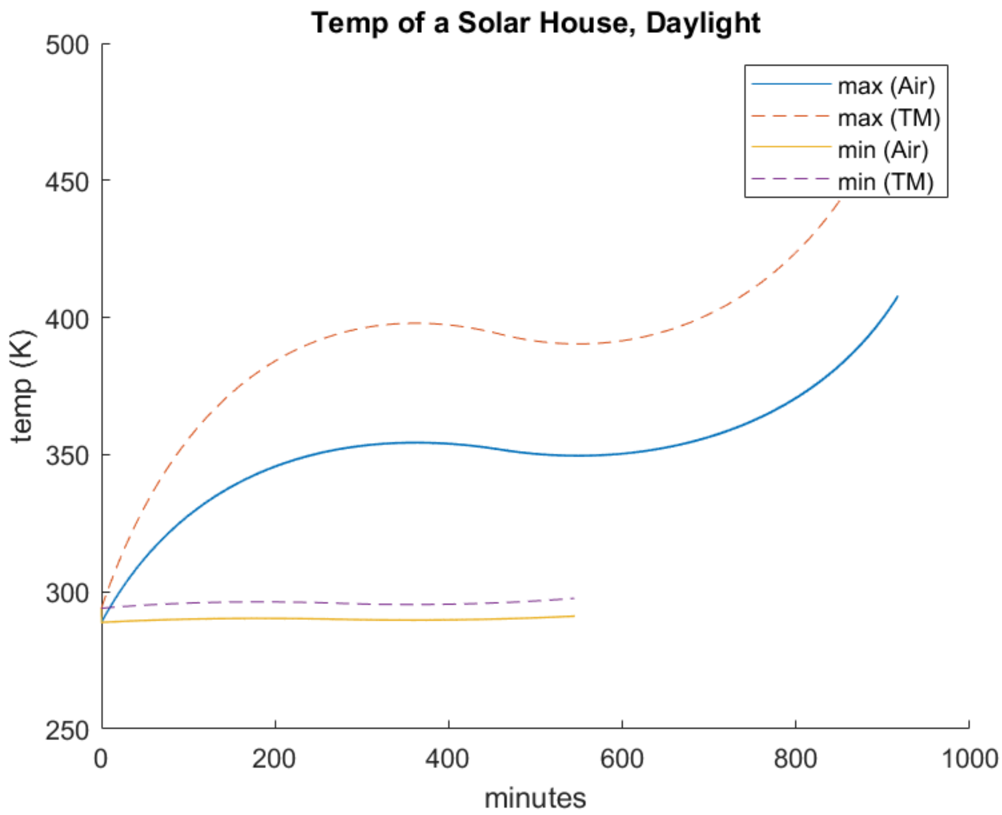
```
[timeMax, temps] = angleOfSun(72);  % summer, all sun is blocked by ledge
[timeMin, tempsMin] = angleOfSun(25);  % winter, least sun is blocked by ledge
figure(7); clf; hold on;
plot(timeMax, temps(:,1)); label1 = 'max (Air)';
plot(timeMax, temps(:,2), '--'); label2 = 'max (TM)';
plot(timeMin, tempsMin(:,1)); label3 = 'min (Air)';
plot(timeMin, tempsMin(:,2), '--'); label4 = 'min (TM)';
title('Temp of a Solar House, Seasonal Variation');
xlabel('minutes'); ylabel('temp (K)'); legend({label1, label2, label3, label4});
```



This is pretty unrealistic, since it assumes 24 straight hours of sunlight.

Sweeping across daylight hours (sunrise-sunset) with a default (concrete/felt) house [source]

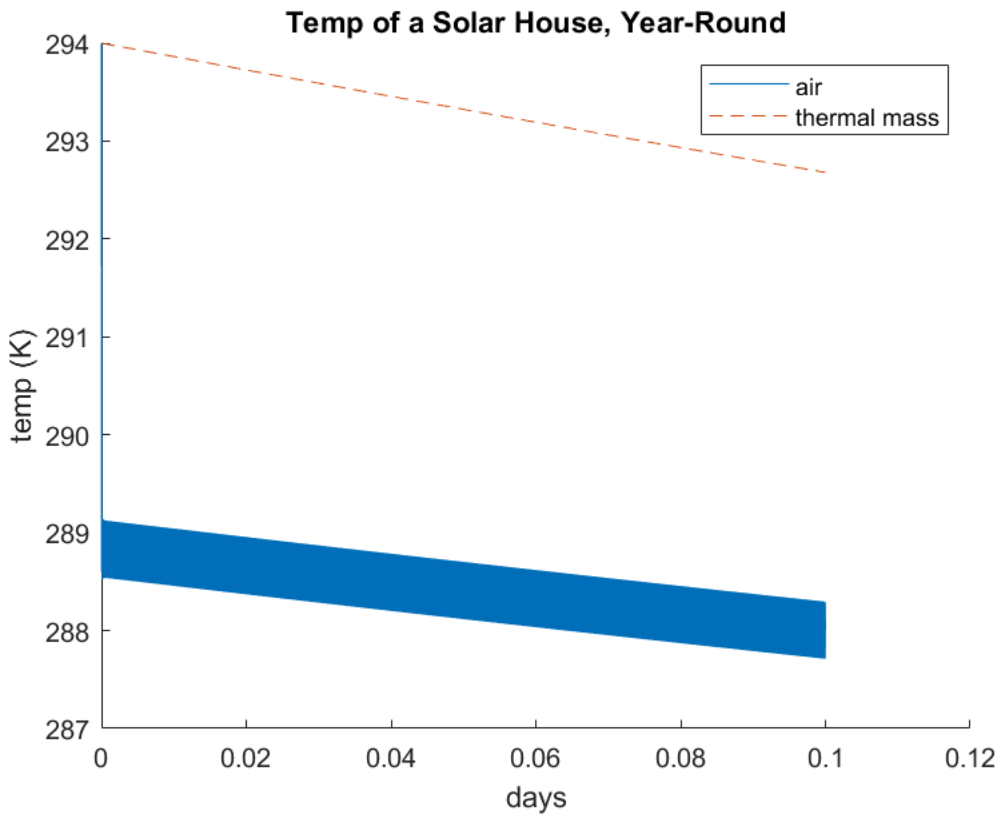
```
[timeMax, temps] = theSunIsMoving(72, 55023);  % summer, all sun is blocked by ledge
[timeMin, tempsMin] = theSunIsMoving(25, 32674);  % winter, least sun is blocked by ledge
figure(11); clf; hold on;
plot(timeMax, temps(:,1)); label1 = 'max (Air)';
plot(timeMax, temps(:,2), '--'); label2 = 'max (TM)';
plot(timeMin, tempsMin(:,1)); label3 = 'min (Air)';
plot(timeMin, tempsMin(:,2), '--'); label4 = 'min (TM)';
title('Temp of a Solar House, Daylight');
xlabel('minutes'); ylabel('temp (K)'); legend({label1, label2, label3, label4});
```



We see that while the default concrete house maintains a relatively stable temperature during the winter daylight hours, the same house exhibits fluctuations in temperature near sunrise and sunset during the summer. Thus, it is unlikely that a true year-round house can be built, as trade-offs in performance will need to be made throughout the year. That being said, the temperature fluctuation during the summer is unsuitable for an actual house; at this point, it is unclear whether it is caused by an issue in the code or if it can be fixed by choosing different materials (with different properties) for parts of the house.

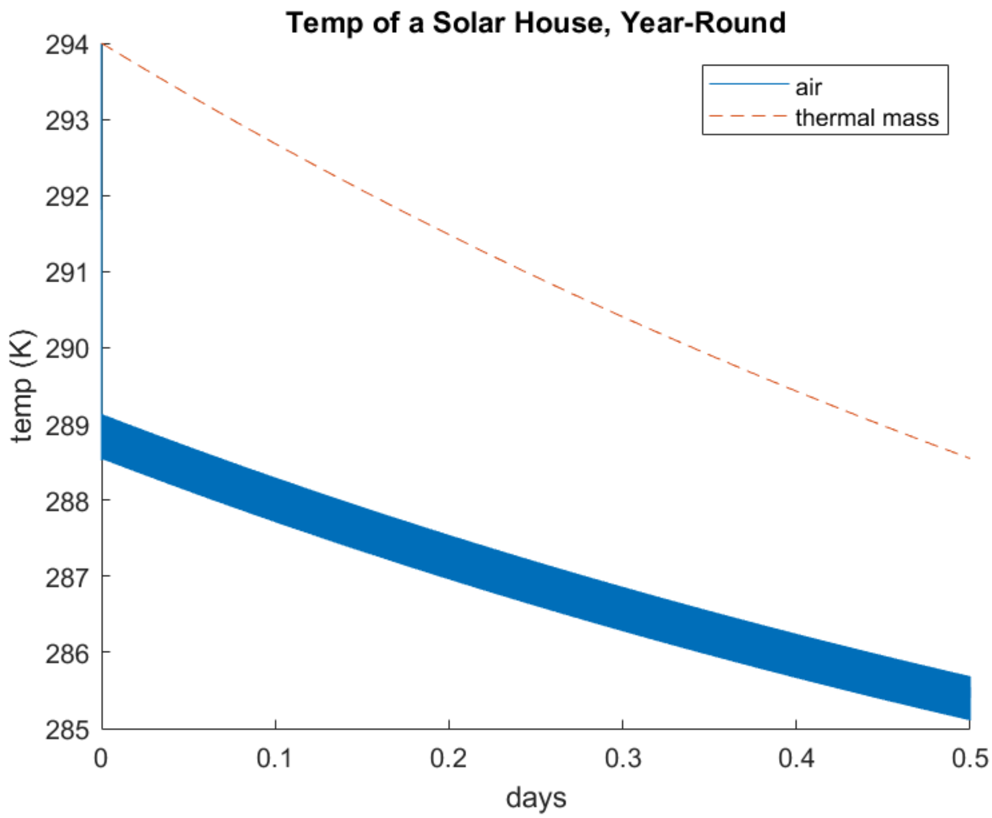
We believe that the current modeling of insolation is a valid representation based on the following tests with small durations of time; however, the way it's implemented takes a prohibitively long time (>7 h) to run a full year on an Olin laptop.

```
[time, temps] = insolationYear(0.1);    % time in days
figure(12); clf; hold on;
plot(time, temps(:,1)); label1 = 'air';
plot(time, temps(:,2), '--'); label2 = 'thermal mass';
title('Temp of a Solar House, Year-Round');
xlabel('days'); ylabel('temp (K)'); legend({label1, label2});
```



12 hour simulation

```
[time, temps] = insolationYear(0.5);    % time in days
figure(13); clf; hold on;
plot(time, temps(:,1)); label1 = 'air';
plot(time, temps(:,2), '--'); label2 = 'thermal mass';
title('Temp of a Solar House, Year-Round');
xlabel('days'); ylabel('temp (K)'); legend({label1, label2});
```



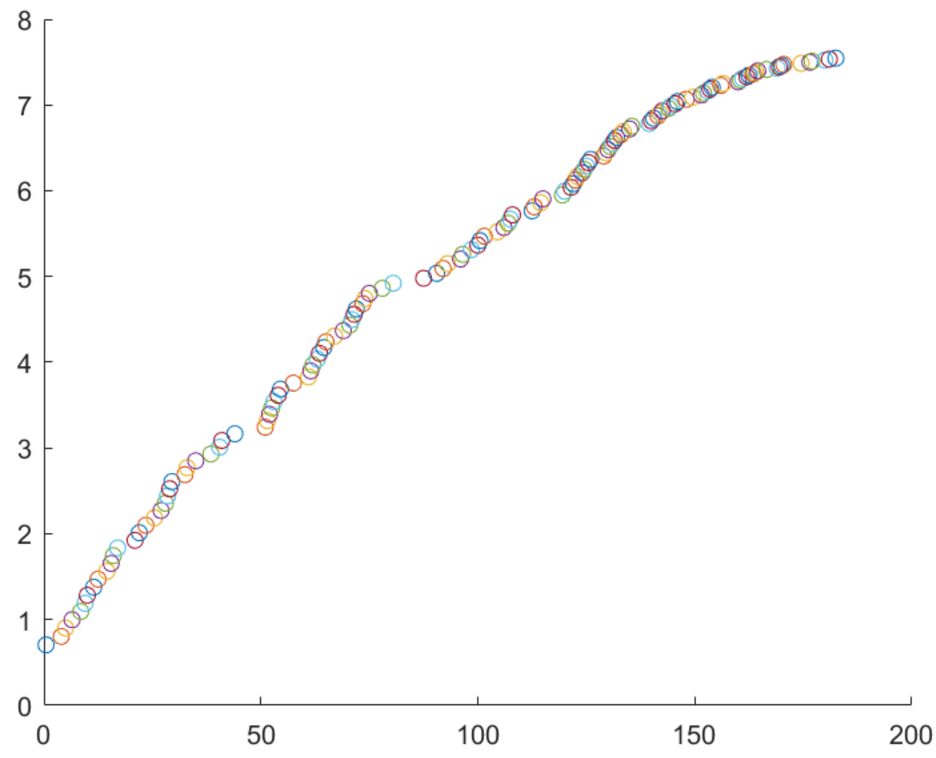
Full year simulation

```
% [time, temps] = insolationYear(365);    % time in days
% figure(14); clf; hold on;
% plot(time, temps(:,1)); label1 = 'air';
% plot(time, temps(:,2), '--'); label2 = 'thermal mass';
% title('Temp of a Solar House, Year-Round');
% xlabel('days'); ylabel('temp (K)'); legend({label1, label2});
```

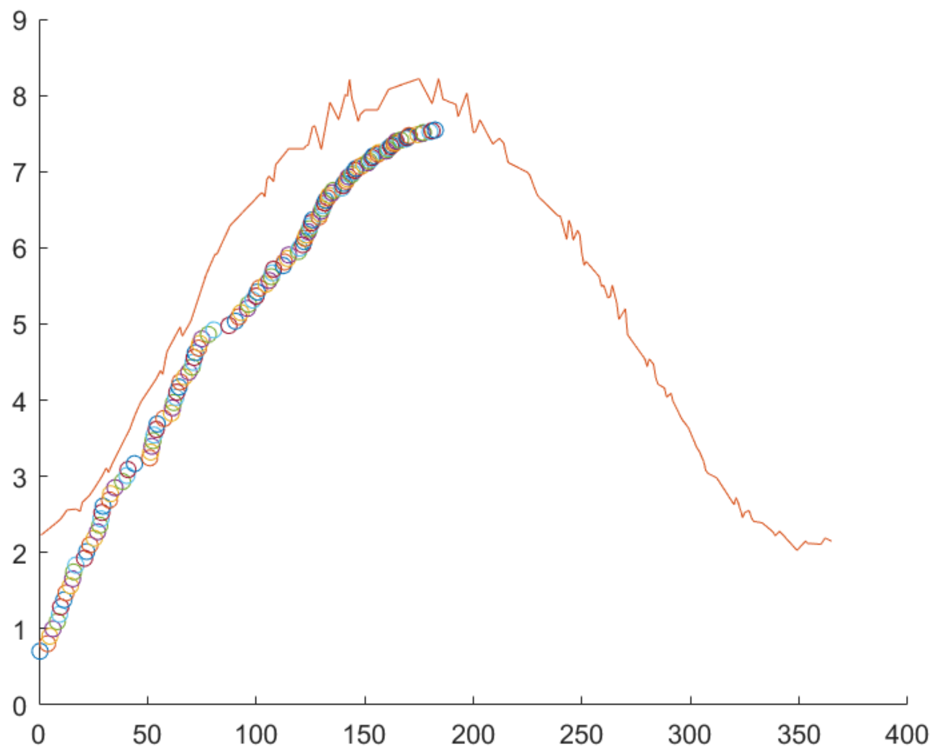
Another way we tried implementing insolation was by fitting an equation to existing data; ultimately, we pivoted to the above method.

Insolation Data Source, 2015 data for the Oval

```
[p, S] = polyfit(insolationData(:,2), insolationData(:,1), 3);
figure(8); clf; hold on;
for x = 1:length(insolationData)
    y = polyval(p, x);
    scatter(insolationData(x,2)/2, y);
end
```




```
figure(8);
plot(insolationData(:, 2), insolationData(:, 1));
```



Interpretation

Envelope

Costs ($/m^2)

- felt = 7.16
- straw slab = 1506.95
- drywall = 3.99
- brick = 387.50

The efficiency of the envelope is evaluated as its ability to retain heat. Thus, the felt insulation is the most successful at heat retention. The cost of felt is noticeably greater than drywall, the least expensive material, but the difference in effectiveness becomes more pronounced (by the end of two hours, the drywall is about 5 K less effective than the felt); therefore, in areas where heat retention is more important, it may be in the best interest to invest in the envelope.

Thermal Mass

- Concrete: $21-323 per m^2
- Brick: $54-215 per m^2
- Limestone: $32-108 per m^2 requires regular maintenance
- Tile: $11-215 per m^2

What we consider the "best" thermal mass material depends on the goal. If the goal is to retain heat throughout the day and release it gradually throughout the night or times with no solar input, then the white tile is the best material for the thermal mass. If the homeowner would like a thermal mass that releases solar energy into the air as quickly and as efficienctly as possible, then black tile or brick would be the best material for the home's thermal mass. Taking cost into account, using tile as the material of the thermal mass is likely the best.

Seasonal Variation

The aperture is designed in a way that blocks all sunlight during the summer and allows the maximum amount of sunlight in the winter. Looking at Fig. 7, this allows the air and thermal mass to remain at a constant or gradually decreasing temperature during the summer and retain heat during the winter.

Sunlight Hours

By examining the daylight hours on the summer and winter solstices (the max and mins of sunlight angle and sunlight hours) in Fig.11, we conclude that it is unlikely that a single material can sufficiently regulate the house's temperature during both the summer and winter.