Insulator

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1 Project 2

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A project examining the relationship and lag time between inner and outer temperatures of a house, and how insulation can be optimized for climate.

```
In [380]: # Configure Jupyter so figures appear in the notebook
          %matplotlib inline

          # Configure Jupyter to display the assigned value after an assignment
          %config InteractiveShell.ast_node_interactivity='last_expr_or_assign'

          # import functions from the modsim.py module
          from modsim import *
```

1.1 Question: How much insulation of what type should be installed in a house to maintain a chosen comfortable temperature over the course of eighty hours in a house in London?

When building a house, the person building it has to decide on what type and thickness of insulation to include in the house. The solution to this problem varies greatly with the location of the house.

When visiting online stores and suppliers of insulation, we found that they provided a standard "R-value" rating per inch of a given insulation that was sold. However, it was difficult to find any visualization of this rating that a non-expert could understand easily. We decided that it could be useful to produce a model that is able to give a rough approximation of temperature curves over time to help people decide what insulation would be best to use.

By further tuning this model, it could be customized to other regions and help homeowners choose an insulation and visualize their insulation scenario. We give a rough example of this tuning in the validation section.

1.2 Model:

We started by importing a selection of r-values for commercially available insulation into a dataframe, which we will later use as input for a sweep of temperature simulations.

```
In [320]: R_data = pd.read_csv('r_values.csv', header=0, index_col=0, usecols=range(1,2))
```

```
Out[320]: Empty DataFrame
          Columns: []
          Index: [1.25, 3.71, 3.85, 4.0, 4.13, 4.29, 5.0, 5.0, 6.5, 7.2, 26.0]
```

Next, we imported the exterior temperature data from a study that examines the characteristics of a wall in London. We are only concerned with the T_ext column of this data as a convenient dataset for exterior temperature over a few days in london.

The paper used here is Gori, Marincioni, Biddulph, Elwell, "Inferring the thermal resistance and effective thermal mass distribution of a wall from in situ measurements to characterise heat transfer at both the interior and exterior surfaces", *Energy and Buildings*, Volume 135, 15 January 2017, Pages 398-409, It can be downloaded here.

```
In [321]: # Load dataset values
          ext_data = pd.read_csv('DataOWall.csv', parse_dates=[0],
                                 index_col=0, header=0, skiprows=[1,2])
          ext_data.head()

Out[321]:                       Q_in   Q_out   T_int   T_ext
          2014-10-05 16:30:00  10.994   6.840   16.92   14.68
          2014-10-05 16:35:00  10.952   6.012   16.92   14.69
          2014-10-05 16:40:00  10.882   7.040   16.93   14.66
          2014-10-05 16:45:00  10.798   8.880   16.93   14.59
          2014-10-05 16:50:00  10.756  10.491   16.94   14.50
```

The data was imported with timestamps that are not very useful for us. In order to easily match our equations, we converted these timestamps to hours.

```
In [322]: # Convert Index entries to seconds, noticing the spacing between recordings
          timestamp_0 = get_first_label(ext_data)
          time_deltas = ext_data.index - timestamp_0;

          ext_data.index = time_deltas.days * 86400 + time_deltas.seconds

In [323]: # convert index entries to hours
          ext_data.T_ext.head()
          T_ext_external = ext_data.T_ext
          for i, v in ext_data.T_ext.items():
              scaled = i / 3600
              T_ext_external = T_ext_external.rename(index={i: scaled})

          T_ext_external.head()

Out[323]: 0.000000    14.68
          0.083333    14.69
          0.166667    14.66
          0.250000    14.59
          0.333333    14.50
          Name: T_ext, dtype: float64
```
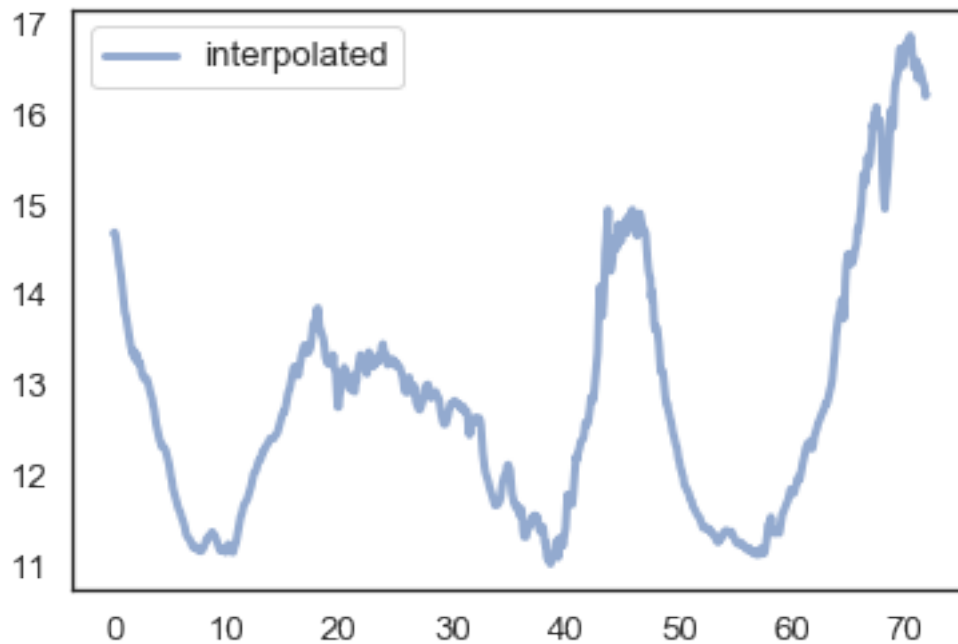
Here, we plotted the temperature versus time of this data for T_ext. The highs and lows as days progress are clear in the plot.

```
In [324]:  # plot the exterior temp data on top of the interpolation of the data
           t_ext_func = interpolate(T_ext_external)
           plot(T_ext_external.index, t_ext_func(T_ext_external.index), label="interpolated")
           legend()
```


In our system we made many assumptions about the exact specifications of our house. The dimensions of the house are adjustable, but the model is only built for rectangular prisms. We also created a house in which the floor, ceiling, and walls are all made of the same insulation.

We set dt to be half an hour, assuming that there is no change in temperature over each step. In order to adapt the outside temperature data from OWall to fit this time step, we converted the timestamps to hours and used the interpolate function to estimate intermediate values in the data.

When we chose an assortment of R values, we used the R that corresponds to one inch of each material. When you stack insulation together, their R values simply add. By using one inch of every material, we can easily calculate the R-value of increased depths of insulation if necessary.

```
In [325]:  def make_system(params):
               """Make a system object for insulation model.

               params object should contain
               T_ext: the starting exterior temperature
               T_int: the starting interior tempature
               R: the R-rating of the insulation, in units ft^2*deg5/btu/hr/in
               d: the depth of the insulation, in units inches
```

3

```python
    l: house length in meters
    w: house width in meters
    h: house height in meters
    c: c value of air for Newton's law of cooling, in units btu/lbm*R

    returns: System
    """
    T_int, T_ext, R, d, l, w, h, c = params

    # density of air
    rho = 1

    # m/s^2, acceleration due to gravity
    g = 9.8

    # air volume inside house m^3
    V = l * w * h

    # mass of air in room in lb
    m = (rho * V * g) * 2.2

    # calculate surface area, and convert from m^2 to ft^2
    SA = (l * w * 4 + h * l * 2) * 10.7639

    first = State(T_int=T_int, T_ext=T_ext)

    # time constants
    t0 = 0
    t_end = 80
    dt = .5

    return System(init=first, t0=t0, t_end=t_end, dt=dt, R=R, d=d,
                  SA=SA, m=m, c=c)

In [381]: def run_simulation(system, update_func):
    """Runs a simulation of the system.

    system: System object
    update_func: function that updates state

    returns: TimeFrame
    """
    frame = TimeFrame(columns=system.init.index)
    frame.row[system.t0] = system.init

    for t in linrange(system.t0, system.t_end,system.dt):
        frame.row[t+system.dt] = update_func(frame.row[t], t, system)
```

```
        return frame
```

We assumed that all heat flows directly out of the house. This allows our model to quantify all heat loss during a given time frame. We allowed outside temperature to influence inside temperature, but we did not allow heat flow to the outside to influence the outside temperature. This assumption makes sense when analyzing a free-standing structure, but it would not make sense on a densely packed city block.

We also assumed that heat flows evenly through all sides of the house, again an assumption that would work for a free-standing house, but not a series of row houses. Embedded in this assumption is the idea that outside temperature is equal at every point around the house. We didn't take into account sun or shade surrounding the house, or that the ground might be an entirely different temperature than the air. This causes our model to be simplistic, but it could be iterated into a model that incorporates the difference between air and ground temperature.

```
In [327]: def update_func(state, t, system):
              """Update the model.

              state: State with variables T_int, T_ext
              dt: time step
              system: System

              returns: State object
              """

              T_int, T_ext = state

              # use the dataset values by overwritting state value
              T_ext = t_ext_func(t) * 9 / 5 + 32

              delta_T = T_int - T_ext

              dQ = (system.SA * delta_T / (system.R * system.d)) * system.dt

              if system.c == 0:
                  system.c = dQ / delta_T

              dT = dQ / (system.c * system.m)

              T_int = T_int - dT

              return State(T_int = T_int, T_ext = T_ext)
```

In order to better visualize our model, we also wrote an update function and run_simulation which does not consider exterior temperature data which can be used for testing and validation of the basis of our model.

```
In [328]: def update_func_isolated(state, t, system):
              """Update the model.
```

5

```python
            state: State with variables T_int, T_ext
            dt: time step
            system: System

            returns: State object
            """

            T_int, T_ext = state

            delta_T = T_int - T_ext

            dQ = (system.SA * delta_T / (system.R * system.d)) * system.dt

            if system.c == 0:
                system.c = dQ / delta_T


            dT = dQ / (system.c * system.m)

            T_int = T_int - dT

            return State(T_int = T_int, T_ext = T_ext)

In [329]: def run_simulation_isolated(system, update_func):
            """Runs a simulation of the system.

            system: System object
            update_func: function that updates state

            returns: TimeFrame
            """
            frame = TimeFrame(columns=system.init.index)
            frame.row[system.t0] = system.init

            for t in linrange(system.t0, system.t_end,system.dt):
                frame.row[t+system.dt] = update_func_isolated(frame.row[t], t, system)

            return frame
```

The following plot is of a test run of the simulation which includes only one R-value of 3 to see if the results look reasonable. Knowing that an isolated R-value of 3 with an insulation depth of four inches should follow the exterior curve quite closely, this looks pretty reasonable. Also included is a plot of external temperature with constant external temperature to show the character of our equation.

```python
In [386]: params = Params(T_int = 60,
                          T_ext = 47,
                          R = 3,
```

```
                         d = 4,
                         l = 6,
                         w = 6,
                         h = 6,
                         c = 0.171)

          system = make_system(params);
```

In [391]:
```python
# test the simulation with the r value set in params
results = run_simulation(system, update_func)
results_const = run_simulation(system, update_func_isolated)

# plot decoration
fig1 = plt.figure(figsize=(12, 10), dpi=120,)
ax1 = fig1.add_subplot(211)
ax1.plot(results.T_int)
decorate(title = 'Temperature vs Time using Experimental External Temperature',
         xlabel = 'time(hrs)',
         ylabel = 'Temperature(degrees F)')

fig2 = plt.figure(figsize=(12, 10), dpi=120,)
ax1 = fig2.add_subplot(211)
ax1.plot(results_const.T_int)
decorate(title = 'Temperature vs Time using Constant External Temperature of 47 Degre
         xlabel = 'time(hrs)',
         ylabel = 'Temperature(degrees F)')
```
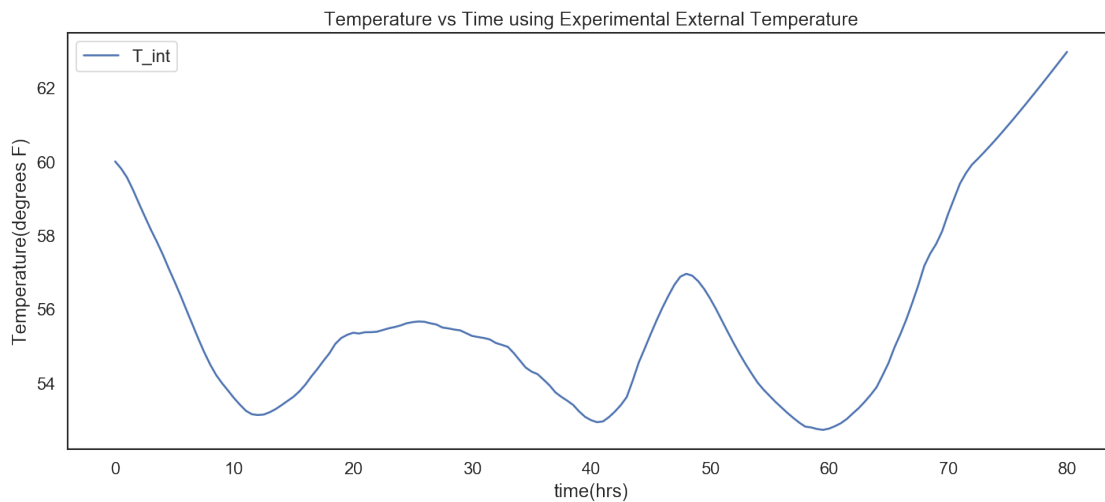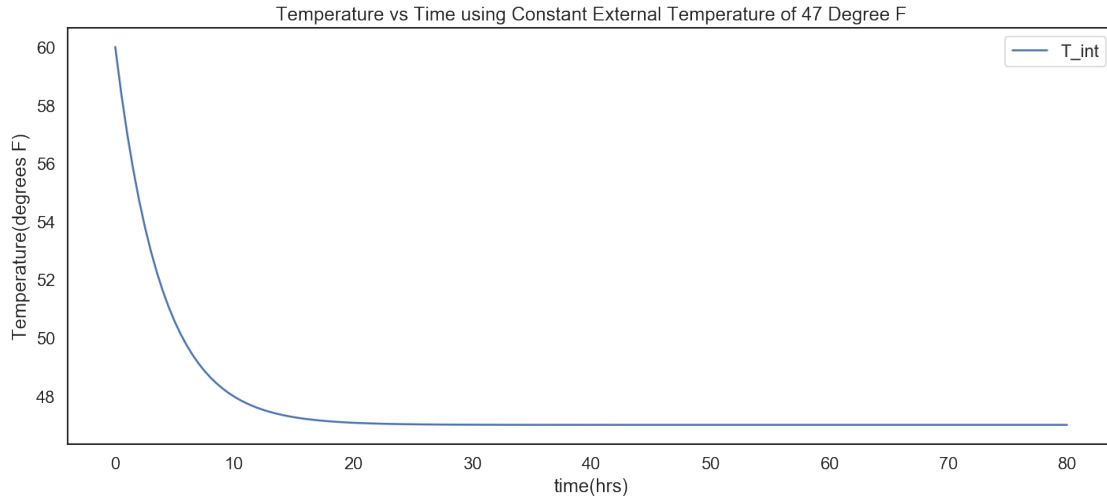

Temperature vs Time using Experimental External Temperature

Temperature vs Time using Constant External Temperature of 47 Degree F

1.3 Results:

1.3.1 Validation

This plot is of a test run of the simulation which is compared to a different paper's experimental data of exterior versus interior temperature of a house in California to see if the results look reasonable. In the paper, they warmed the house up to 70 degrees and then let the interior temperature decay over time, measuring the temperature values. We tuned the system parameters to match those indicated in the paper as much as possible. Looking at the curves of the two plots, our own and the one from the article, the results look reasonable.

The paper used for validation is J.E. Janssen, A.N. Pearman, "Comparison of BTR Measurements", from the Thermal Performance of the Exterior Envelopes of Whole Buildings XIII International COnference, it can be downloaded here.

```
In [397]: params = Params(T_int = 74,
                          T_ext = 47,
                          R = 3.3,
                          d = 6,
                          l = 9.8,
                          w = 14,
                          h = 7,
                          c = 0.171)

         system = make_system(params)

         #test the simulation with the r value set in params
         results = run_simulation_isolated(system, update_func)

         fig1 = plt.figure(figsize=(7, 5), dpi=120,)
         ax1 = fig1.add_subplot(121)
         ax1.plot(results.T_int)
```
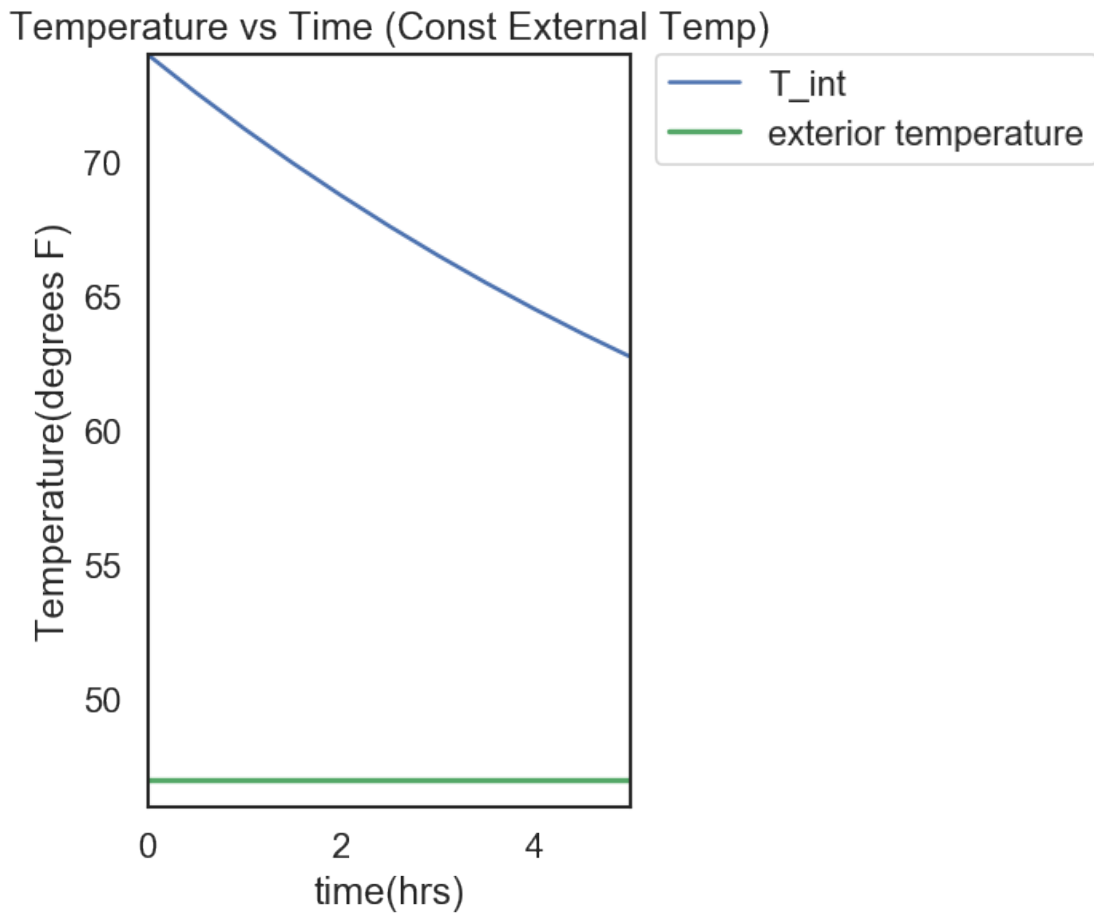
8

```
plt.xlim(0, 300/60)
plt.ylim(46, 74)
ax1.plot([0, 14], [47, 47], color='g', linestyle='-',
         linewidth=2, label="exterior temperature")

decorate(title = 'Temperature vs Time (Const External Temp)',
         xlabel = 'time(hrs)',
         ylabel = 'Temperature(degrees F)')
plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)
plt.show()
```


Below is the curve given by the paper. It is important to note the discontinuity of the axis of the paper's plot between 48 and 64 degrees F
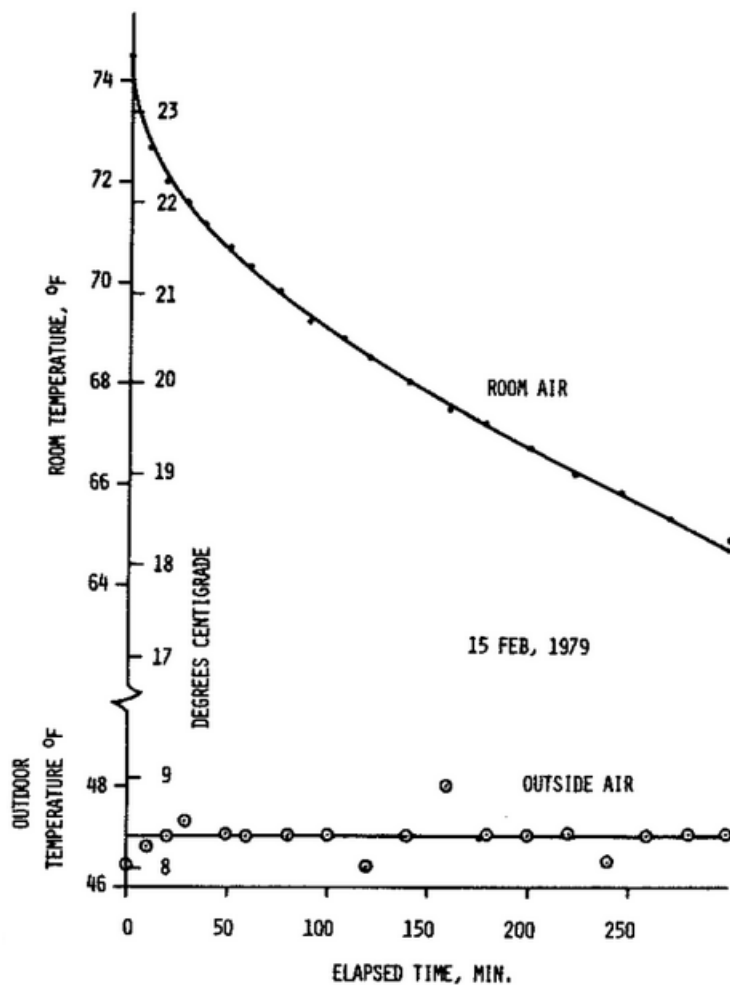
Then, we composed a function that runs the simulation for all of the commercially-available r-values we recorded and overlays the results on the same plot along with the exterior temperature data for comparison. We are using our intuition as humans to say that 55 degrees F is a pretty comfortable temperature for the inside of a house to be.

```
In [400]: def sweep_R(R_data):
              """
              Sweep a range of values of R and plot them
              R_data: list of r values

              returns: matplotlib figure
              """

              # names of the commercially available insulations, index of this list matches th
              insulation = ['plywood','EcoTouch','R-tech','Kingspan','Comfortbatt gold',
                          'Comfortbatt blue', 'Foamular','SilveRboard','Super TUFF',
                          'polyisocyanurate (foil-faced)', 'miracle material']

              fig1 = plt.figure(figsize=(18, 16), dpi=180)
```

10

```python
        ax1 = fig1.add_subplot(211)

        for R in R_data.index.values:
            # change our R to the one in this loop of the sweep
            params[2] = R
            systemr = make_system(params)
            results = run_simulation(systemr, update_func)
            location = np.where(R_data.index == R)
            location = location[0].tolist()
            ax1.plot(results.T_int, label=str(R)
                        + ' times ' + str(systemr.d)
                        + ' inches of ' + insulation[location[0]])

        ax1.plot(results.T_int.index,
                    t_ext_func(results.T_int.index)  * 9 / 5 + 32,
                    label="interpolated exterior data")

        ax1.plot([0, 80], [55, 55], color='k', linestyle='-', linewidth=2,
                    label="minimum acceptable interior temperature")

        decorate(title = 'Temperature vs Time using Experimental External Temperature',
                    xlabel = 'time(hrs)',
                    ylabel = 'Temperature(degrees F)')
        #plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)
        plt.legend(bbox_to_anchor=(0, 1.06, 1., .102), loc=3, mode="expand", borderaxespa
        fig1.show()

        return fig1

In [401]: params = Params(T_int = 60,
                    T_ext = get_first_value(ext_data.T_ext)*9/5+32,
                    R = 3,
                    d = 4,
                    l = 6,
                    w = 6,
                    h = 6,
                    c = 0.171)

        fig_sweep = sweep_R(R_data);

C:\Miniconda3\lib\site-packages\matplotlib\figure.py:457: UserWarning: matplotlib is currently
  "matplotlib is currently using a non-GUI backend, "
```
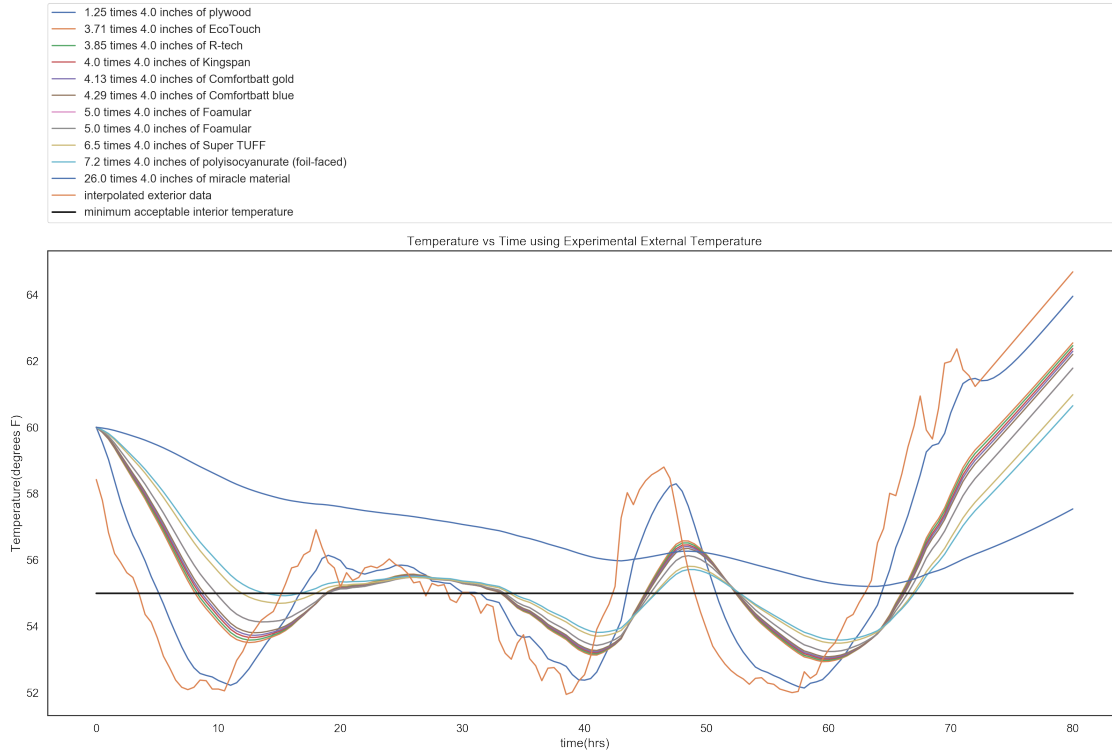
11

Temperature vs Time using Experimental External Temperature

Legend:
- 1.25 times 4.0 inches of plywood
- 3.71 times 4.0 inches of EcoTouch
- 3.85 times 4.0 inches of R-tech
- 4.0 times 4.0 inches of Kingspan
- 4.13 times 4.0 inches of Comfortbatt gold
- 4.29 times 4.0 inches of Comfortbatt blue
- 5.0 times 4.0 inches of Foamular
- 5.0 times 4.0 inches of Foamular
- 6.5 times 4.0 inches of Super TUFF
- 7.2 times 4.0 inches of polyisocyanurate (foil-faced)
- 26.0 times 4.0 inches of miracle material
- interpolated exterior data
- minimum acceptable interior temperature

1.4   Interpretation:

As evidenced by our plot, no one insulation would keep the temperature of the house from falling below the cutoff temperature of 55 degrees Fahrenheit. Realistically though, not many people would have only four inches of insulation in the exterior walls of their house and a heating system that only ran once over the course of 80 hours. In our model we added a "Miracle Material" with an R of 26, to demonstrate how that high of an R value would affect its reaction outside temperature. As it turns out, 26 is the perfect R to keep the house temperature always above the cutoff temperature.

The next step in the project would be to add the rest of walls, like plywood and drywall, to the R values of the insulation, just to truly model a wall. This wouldn't change the results of the model by very much, but it would do away with some of the assumptions. We could also split the house into different segments, walls are typically constructed differently than roofs and floors.

to figure out exactly how much of each insulation would be required to create an R value of 26, and, ultimately, our model seems to say that the type of insulation would matter less than the overall depth of the wall. It feels obvious that the higher the R value, the more it stabilizes the temperature. A deeper wall, then, would naturally be more insulating than a thinner wall, but from here we could add in a optimization function to optimize wall depth based on cost of materials.

1.5 Abstract

We answered the question of how much insulation of what type should be installed in a house heated initially to 60 degrees Fahrenheit to maintain a chosen comfortable temperature of 55 degrees over the course of eighty hours in a house in London. The answer was that there must be an insulation with an R value of at least 26 and a depth of 4 inches to maintain a temperature above 55 degrees for the eighty hour period.

```
In [402]: #plot our sweep again
          fig_sweep
```

Out[402]:
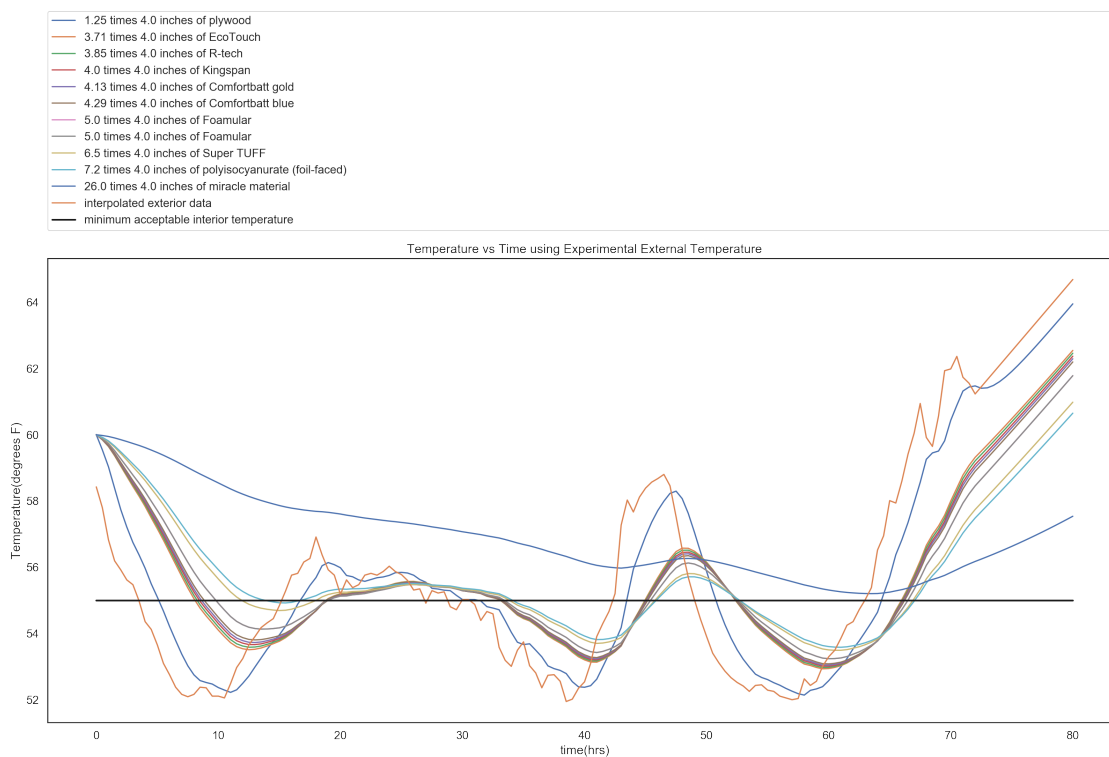
We plotted temperature over time for several r-value simulations to see how different insulation types would hold up over a longer period of time. As expected, those with higher R values fluctuate less with respect to the outside temperature.