Module 1 Project Report: Solar House

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1 Background

The design of the structures we inhabit has always been a central part of our society, but now we're more pressed than ever to design structures that don't pose an environmental threat. Climate change is one of the single biggest issues we face globally, and we're well aware that if we don't make drastic change soon, it may be too late to change our planet's trajectory. Therefore, it is imperative that we explore scalable, cost effective methods of building construction that are not only sustainably sourced, but also require as little energy as possible to maintain comfortable living conditions.

A common structure that provides a reduced energy footprint is the passive solar house. Such a structure is designed to be heated solely through solar radiation, and relies on the thermal properties to regulate temperature inside. The major features of a passive house are controls that make the house hotter in winter than in summer, a window(s) for solar radiation, an absorber and thermal mass that take in and store heat, and some method of heat distribution throughout the house. The prevalence of such structures is increasing as a viable means of low-energy housing, not only in first world countries. As shown by Makaka et al. a major area of further development is the adaptation of these structures to environments where materials are limited, living standards are low, and there is little attention given to the thermal efficiency of low-cost housing [1].

2 Modeling

2.1 Overview

For this project, we created a simple model of a passive solar house using MATLAB. In creating a model we can play with, we're able to experiment to find optimal design parameters and learn how different design choices affect the thermal behavior of the solar house. According to Pacheco et al. the shape, presence of transparent surfaces, orientation, and thermal properties of a structure have a big impact on its energy consumption, and should therefore be considered when designing any new structure [2]. While an optimal thermal house design would likely be informed by aspects including location, material availability, and cost, we can still learn a fair amount about the design of such a structure by only focusing on a few key parameters.

With this in mind, we chose to parametrized our model so we can easily sweep across fun and interesting combinations of values. With the ability to modify aspects such as house dimensions, wall thicknesses, and absorber thickness, we can easily see how changing these values affects the output of the model.

2.2 Assumptions

Some of the key assumptions we're making are:

a) The sun heating the glass is negligible

b) The sun heating roof surfaces is negligible

c) The house is empty

d) The floor (the house's absorber and main thermal mass) and the air are the only objects that hold heat

e) The walls, roof, and glass are merely thermal resistances

f) The thermal mass has no heat conduction (i.e. it's floating. Magnets?)

g) Generally standard conditions apply

h) Standard properties of materials apply

i) Outside temperature stays at a constant -3 °C

j) The house is south-facing

2.3 Construction

Shown below in Figure 1 is a visualization of our model.

Here, we have sunlight flowing in through the window and hitting the absorber, which then convects it's heat to the air. The air then convects to the glass and walls which transfer heat out to the outside air. Note that we assume heat transfer through the glass is given by a single convection equation, and that only the air and absorber block have thermal heat capacities. With this given setup, we can draw out a resistive network as shown.

2.4 Materials

We're modeling the walls/roof as medium-weight concrete (k-value of around 0.6 $\mathrm{W\,m^{-1}\,K^{-1}}$), the floor/absorber as recycled ceramic tile (density of 3000kg $\mathrm{m^{-3}}$, and a thermal capacitance of 800J $\mathrm{K^{-1}}$), and glass as a single convection with h-value 0.7W $\mathrm{m^{-2}\,K^{-1}}$.

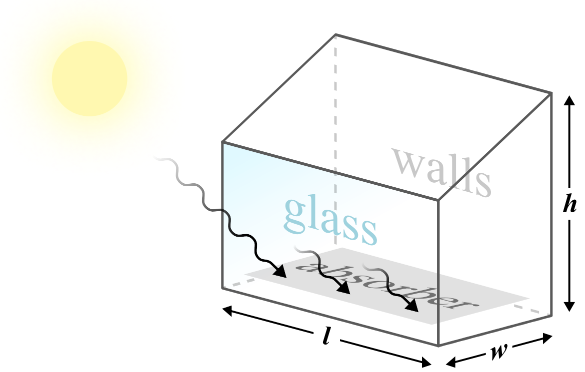

Figure 1: Energy Flow Into House

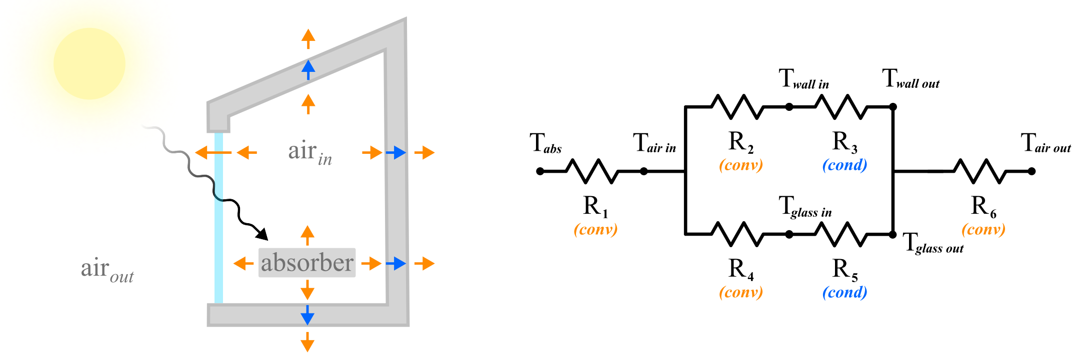

Figure 2: Energy Flow & Resistive Network

2.5 Numbers

In order to easier find the temperature of the air, we modeled it as a thermal mass. This is interesting because we usually neglect air as a thermal mass and instead model it as a thermal resistance. However, this means we have to use voltage divider equations to find the air temperature at any given time, which is inconvenient when the actual calculations are so parametrized.

This gives us three heat flows:

$$\dot{Q}_{SF} = qA_g$$
$$\dot{Q}_{FA} = \frac{T_{floor} - T_{air}}{R_{FA}}$$
$$\dot{Q}_{AO} = \frac{T_{air} - T_{outside}}{R_{AO}}$$

with q as solar flux, A_g as window area, the various Rs as equivalent thermal resistances, and the various $\dot{Q}$s as heat flows.

This then gives us two thermal differential equations for the temperatures of the absorber and air inside the room, respectively:

$$\frac{dT_{abs}}{dt} = \frac{1}{C_{abs}}(qA_g - \frac{T_{floor} - T_{air}}{R_{FA}})$$
$$\frac{dT_{air}}{dt} = \frac{1}{C_{air}}(\frac{T_{floor} - T_{air}}{R_{FA}} - \frac{T_{air} - T_{outside}}{R_{AO}})$$

Our resistor networks (as seen in Figure 2) can then be found with

$$R_{FA} = \frac{1}{h_{in} \cdot A_{abs}}$$
$$R_{AO} = 1/(1/(R_{air-wall} + R_{wall-wall}) + 1/(R_{air-glass} + R_{glass-glass}) + R_{outer-air}$$

3 Optimization

The thickness of the storage unit affects the temperature range experienced by the floor and air in the house, but does not influence the average temperature over time. The thinner the absorber, the more fluctuation occurs on a daily basis, and the longer it would take for the house to reach a comfortable average temperature over time.

The thickness of the insulation controls the asymptotic behavior of the system, and in turn the resultant temperature in the house, as well as the time it takes to get there. The thinner the insulation, the less time it takes to reach a steady state, and the lower the steady state temperature will be. Reversing this, with thicker walls, there's more insulation and therefore a higher resultant internal temperature, but it will take longer to achieve this state.

In establishing why the above behavior is present, we can compare the the absorber to an electrical capacitor and the insulation to an electrical resistor, which means we've modeled something similar to an RC circuit. In varying the thicknesses of each of these parts, we're effectively changing the resultant air temperature (analogous to voltage, affected by resistance) and the smoothing on the air temperature (analogous to the cutoff frequency of an electronic filter, which affects voltage over time).

4 Results

Figures 3 and 4 show temperatures across varying lengths of time with absorber thickness 0.8, insulator thickness 0.3, house length 6, window height 2, house height 3, and house depth 2 (all units in meters).

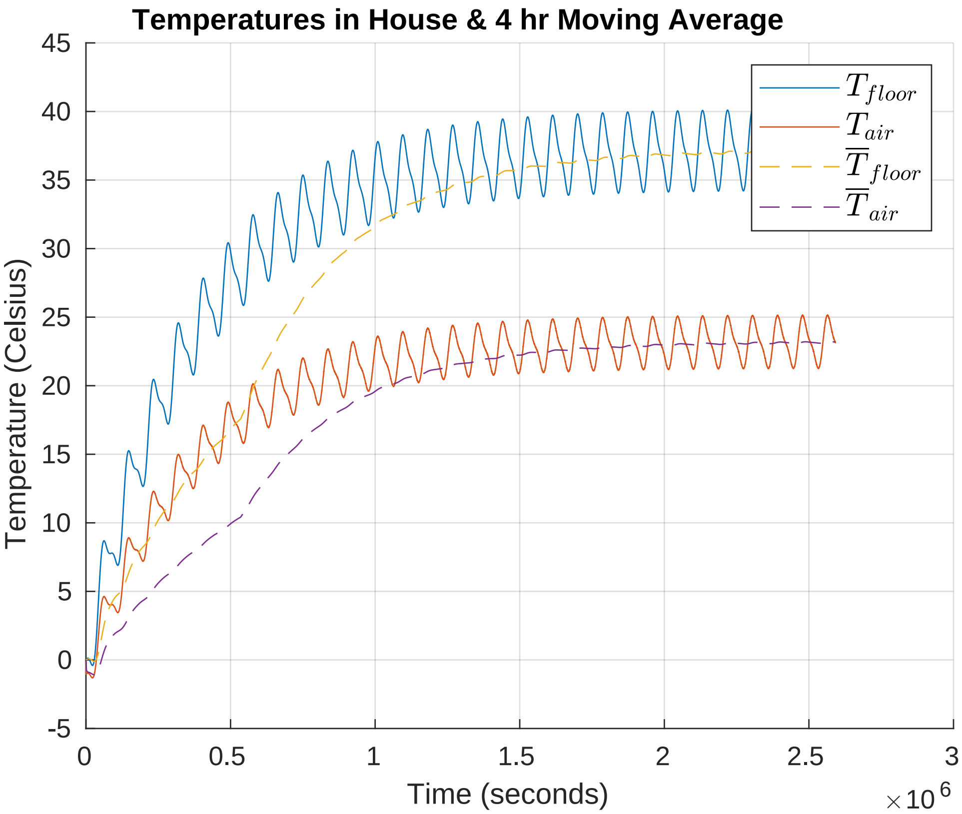

Figure 3: Temperature response across 30 days.

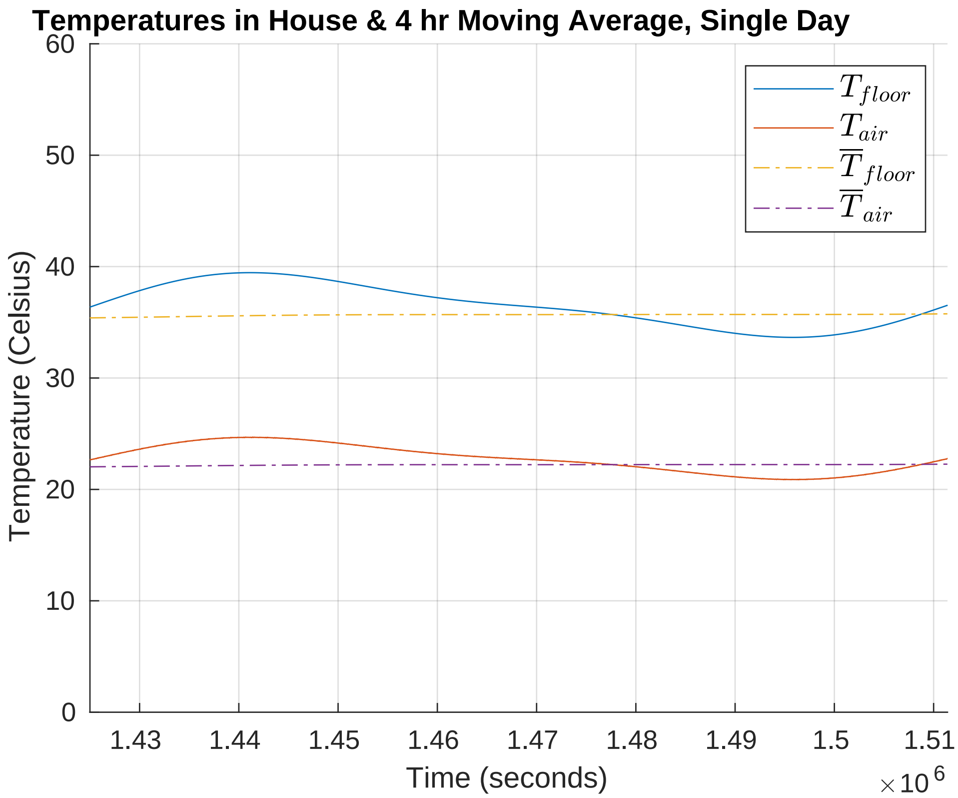

Figure 4: Temperature response across a single day after initial warming.

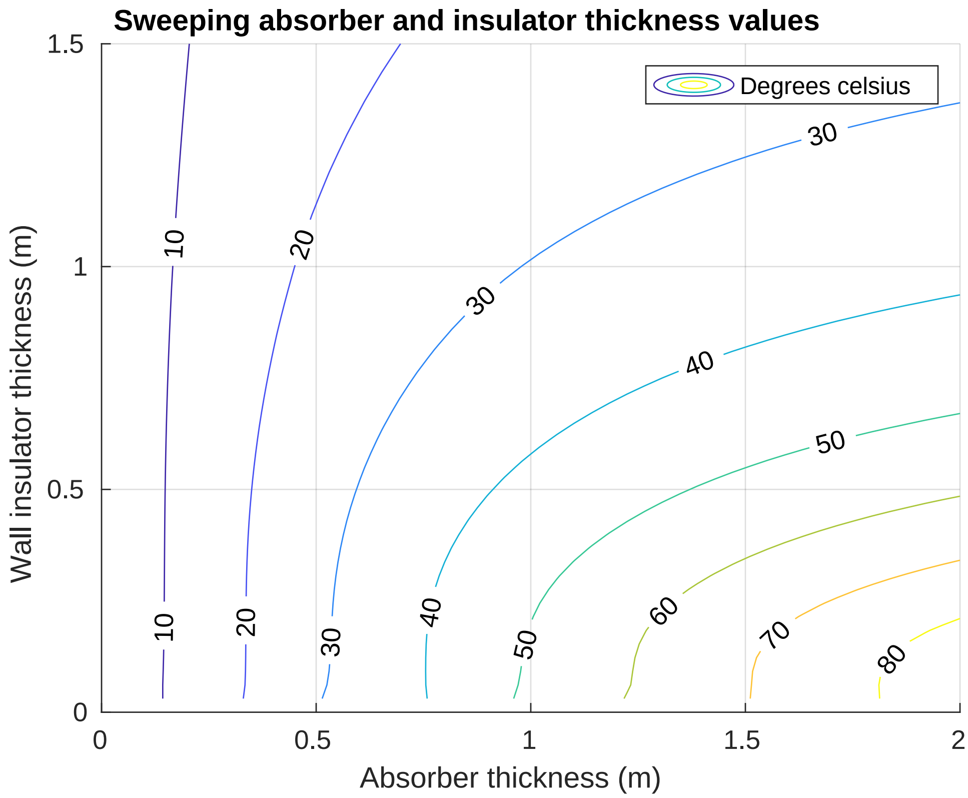

Figure 5: A contour map of the final 4-hour running air temperature average across different absorber thicknesses and wall insulation thicknesses with house length 6, window height 2, house height 3, and house depth 2 (all units in meters).

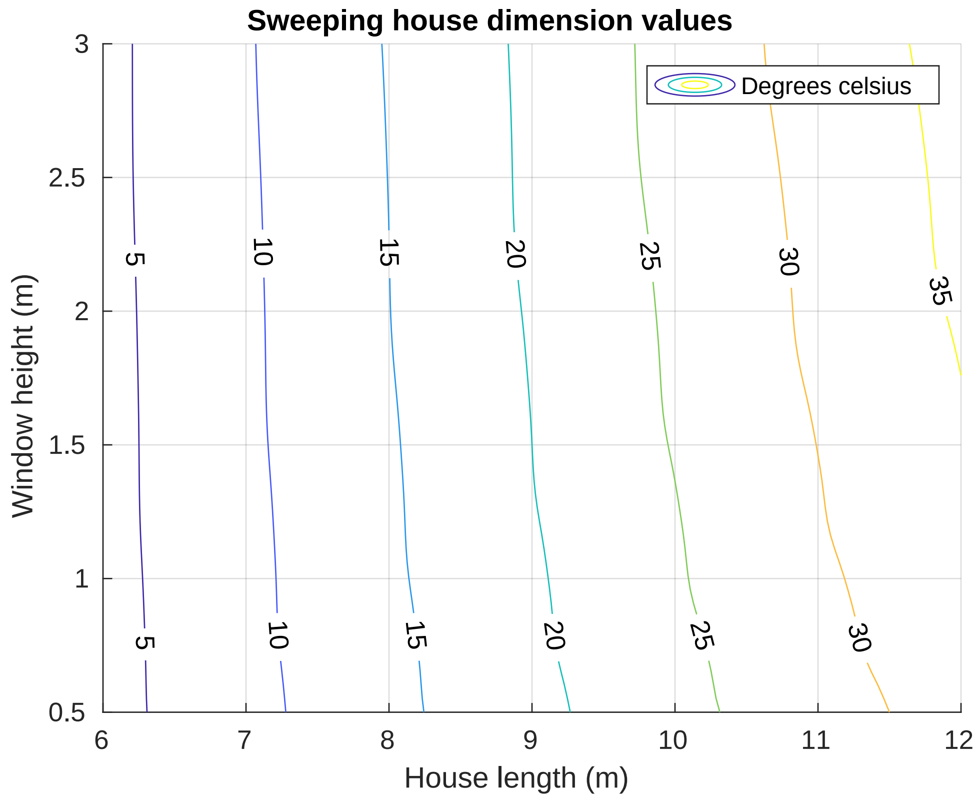

Figure 6: A contour map of the final 4-hour running air temperature average across different house dimensions, with absorber thickness 0.8, insulator thickness 0.3, house height 3, and house depth 2 (all units in meters).

5 Discussion

With respect to occupant comfort, we were able to achieve a relatively stable temperature in a comfortable range hovering at ≈ 23°C. It appears that although concrete is a bad insulator, by making the walls thick enough we manage to keep heat in. This allows us to keep our goal of easily prefabricated parts, because all the wall parts are just solid slabs of concrete.

While our structure is cozy when the outside temperature is constant, we did not take into account a change in seasons, which would likely cause the house to overheat when the temperature rises above −3°C. According to Zhu et al. a potential improvement to temperature regulation over the span of multiple seasons includes changing the thermal response absorber [3]. In their exploration, a simple set of colored blinds is used to vary the amount of light hitting the absorber between seasons.

In the future we'd like to explore how manufacturing methods could influence the thermal behavior of the structure, especially goals include easy fabrication and install.

6 References

1. Pacheco, R., et al. "Energy Efficient Design of Building: A Review." Renewable and Sustainable Energy Reviews, vol. 16, no. 6, 2012, pp. 3559–3573., doi:10.1016/j.rser.2012.03.045.

2. Makaka, Golden, et al. "Thermal Behaviour and Ventilation Efficiency of a Low-Cost Passive Solar Energy Efficient House." Renewable Energy, vol. 33, no. 9, 2008, pp. 1959–1973., doi:10.1016/j.renene.2007.11.014.

3. Zhu, Jiayin, and Bin Chen. "Simplified Analysis Methods for Thermal Responsive Performance of Passive Solar House in Cold Area of China." Energy and Buildings, vol. 67, 2013, pp. 445–452., doi:10.1016/j.enbuild.2013.07.038.