SIMULINK – THERMAL MODEL OF A GREENHOUSE[1]

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1. Model overview

This model is an attempt to mimic the thermal model of a greenhouse. It considers a heating system, a cooling system, the outdoors temperature variations throughout a week, the greenhouse volume and the heat loss due to the thermal conductivity of the materials.

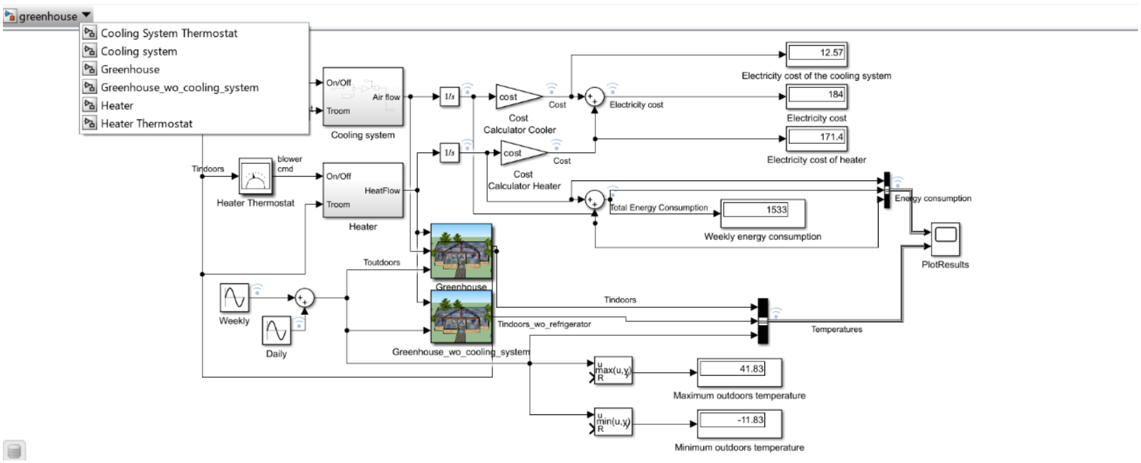

Figure 1. Thermal model of a greenhouse. Diagram overview. At the top left corner, a display of the 6 subsystems that form this model.

This model consists of 6 subsystems:

- **Greenhouse**, to simulate the indoors temperatures, taking all the variables into account.
- **Greenhouse_wo_cooling_system**, to simulate the lack of the cooling system.
- **Heater**, to maintain the indoors temperature above 17ºC. It turns on if the temperatures go under 17ºC and it turns off at 23ºC.
- **Heater Thermostat**, to control the heating system.
- **Cooling system**, to maintain the indoors temperature under 35ºC. It turns on if the temperatures go above 35ºC and it turns off at 29ºC.
- **Cooling system Thermostat**, to control the cooling system.

This greenhouse presents two versions: one **without greenhouse effect** and another **with greenhouse effect**. By default, when first opening the model the version **without greenhouse effect** will be shown. To generate the greenhouse effect, the following steps must be followed:

1. Go to the "**Greenhouse**" subsystem and **uncomment** the commented block.
2. Connect the block as shown in *Figure 10* (click on the underlined text to go to the diagram).
3. Go to the "**Greenhouse_wo_cooling_system**" subsystem and **uncomment** the commented block.
4. Repeat step 2 in this subsystem.

This model runs in conjunction with the greenhouse_data.m file.

2. Greenhouse geometry

The greenhouse was designed using the online tool SketchUp (link to the 3D model), having the shape shown in the following images.

Figure 2. Front view of the greenhouse.

Figure 3. Side view of the greenhouse.

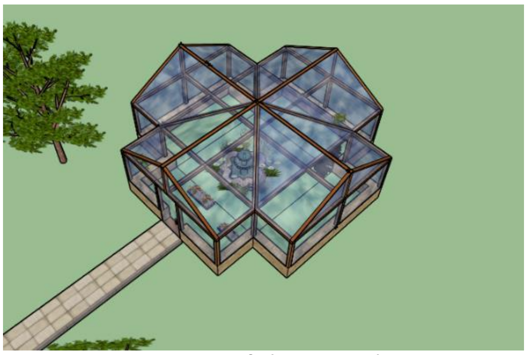

Figure 4. Top view of the greenhouse.

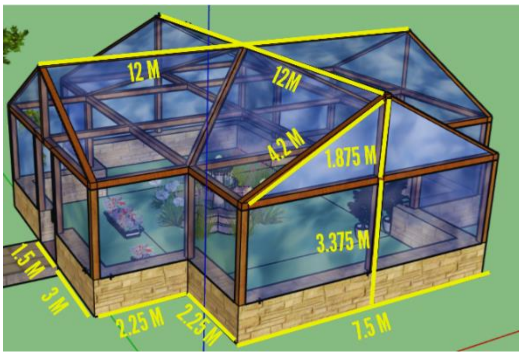

Figure 5. Measurements of the greenhouse **in meters(M).** The yellow lines represent the measured fragments of the greenhouse. By geometry, the sides that are not measured have the same length as the measured sides shown in the picture.

The **total volume** of the greenhouse was calculated as: $Total\ Volume\ =\ Base\ Volume\ +\ Roof\ Volume$

The **Base Volume** represents the volume of the lower part of the greenhouse, which is formed of two types of prisms: one prism with a square base and four rectangular prisms.

$$Prism1\ Volume = side1^2 * base\ height = 7.5^2 * 3.375\ m^3$$

$$Prisms2\ Volume = 4 * side1 * side2 * base\ height = 4 * 7.5 * 2.25 * 3.375\ m^3$$

$$Base\ Volume = Prism1\ Volume + Prisms2\ Volume = 417.6563\ m^3$$

The **Roof Volume** represents the volume of the top part of the greenhouse, which is formed by two triangular prisms intersecting each other at the centre of the greenhouse. Therefore, it will be necessary to subtract the volume duplicated at the intersection (which is the volume of a pyramid).

$$Triangular\ prisms\ volume = 2 * \frac{triangle\ base * triangle\ height}{2} * prism\ length$$
$$= 2 * \frac{7.5 * 1.875}{2} * 12\ \ m^3$$

$$Pyramid\ Volume = \frac{base1^2 * pyramid\ height}{3} = \frac{7.5^2 * 1.875}{3}\ m^3$$

$$Roof\ Volume = Triangular\ prisms\ volume\ - Pyramid\ Volume = 133.5938\ m^3$$

Therefore the $\boldsymbol{Total\ Volume = 551.2500\ m^3}$**.**

The greenhouse is made of three different materials: polycarbonate, brick, and wood. However, since the **wood area is insignificant as it only represents around 4% of the whole greenhouse, it won't be considered for future calculations.** Therefore, only the area of the brick and the polycarbonate (**from now on "PC"**) will be calculated.

The brick constitutes the lower part of the greenhouse, therefore there are 8 short sides in the four corners of the building and 4 long sides, of which one of them contains the door, which is made exclusively of polycarbonate, so only the door sides will be considered for the calculation. Therefore, the $\boldsymbol{Brick\ Area = 52.3125\ m^2}$**.**

The rest of the building is made of PC, so the $\boldsymbol{PC\ Area = 276.4125\ m^2}$.

Therefore the $\boldsymbol{Greenhouse\ area = Brick\ Area + PC\ Area = 328.725\ m^2}$**.**

3. Thermic properties of the materials used in building the greenhouse

As said in the previous section, the greenhouse is made of **polycarbonate, brick, and wood**. Since the wood constitutes barely 4% of the whole building area, it won't be taken into account as one of the materials for the building.

The thermic properties of any material is defined by the thermal conductivity *k,* which indicates the ability of the material to conduct heat. For this specific model, it is measured in $kW * m^{-1} * K^{-1}$(Kilowatts of heat conducted per meter and Kelvin). The lower the thermal conductivity, the more insulation is provided by the materials used.

The brick used has a thermal conductivity $\boldsymbol{k = 0.00012\ kW * m^{-1} * K^{-1}}$ [2]. The brick is used as a base on which the rest of the greenhouse is built. It brings sturdiness and stability. Furthermore, it provides thermal insulation in the lowest part of the greenhouse since air tends to be colder at ground level and it has one of the lowest thermal conductivities amongst the building materials.

The polycarbonate has a thermal conductivity $\boldsymbol{k = 0.00021\ kW * m^{-1} * K^{-1}}$[3]. Polycarbonate is a common material used in greenhouses since it has greater insulation properties than glass, but at the same time allowing the warmth and the sunlight to pass through it. It can withstand harsh weather and it has a great sturdiness and durability.

Another thermal property of materials, which is a variation of the thermal conductivity, is the thermal resistance **R**. The thermal resistance is a measure of how well a material resists the conductive flow of heat. **This will be the main thermal property used in the model**. It is calculated as $R = \frac{thickness\ of\ the\ material\ used}{k * area\ of\ the\ material\ used}$.

The brick has a $thickness = 0.2624\ m$, and an $\boldsymbol{R = \frac{0.2624}{0.00012 * 53.3125} = 41.8001\ K/kW}$.

The polycarbonate has a $thickness = 0.06\ m$ and an $\boldsymbol{R = \frac{0.06}{0.00021 * 276.4125} = 1.0337\ K/kW}$.

The thermal resistance of the whole building is $\boldsymbol{R = \frac{RBrick * RPC}{RBrick + RPC} = 1.0087\ K/kW}$. This method of calculating the total thermal resistance was taken from the Simulink Model of Thermal Model of a House.

4. Properties of the heating system

The heating system turns on when the indoors temperature of the greenhouse is below 17ºC and turns off when the indoors temperature has a value above 23 ºC. It is controlled by a thermostat (subsystem **Heater Thermostat**). **The air exits the heating system with a flow of 3600 kg/hour at a constant temperature of 47ºC**. The air temperature of 47ºC was chosen since it is the minimum temperature that keeps the indoors temperature above 17ºC.

5. Properties of the cooling system

The cooling system turns on when the indoors temperature of the greenhouse is above 35ºC and turns off when the indoors temperature has a value under 29 ºC. It is controlled by a thermostat (subsystem **Cooling system Thermosat**). **The air exits the cooling system with a flow of 3600 kg/hour at a constant temperature of 10ºC**. The air temperature of 10ºC was chosen since it is the best temperature that keeps the indoors temperature below 35ºC, including the greenhouse effect.

6. Graphic representation of the changes in outdoors and indoors temperatures

The following graph represents the oscillation of indoors and outdoors temperatures during a week. The outdoors temperatures are obtained by adding the weekly and daily variation of temperatures. The indoors temperature is influenced by the heating system, the cooling system, and the heat loss due to the thermal conductivity of the greenhouse walls.

As seen in the plot, the outdoors weekly temperatures (yellow line) present great variations, being the **minimum registered temperature -11.83 ºC** and **the maximum registered temperature 41.83ºC.** The low outdoors temperatures cause great heat losses through the walls. This has a great impact on the indoors temperature, being maintained in the recommended ranges by the heater. Looking at the behaviour of the pink line (indoors temperature), there are many periods in which the temperature raises and descends quickly. The quick descend is due to the heat losses through the walls or due to the cooling system, while the quick rises are due to either the heater effect or due to the high outdoors temperatures. **The indoors temperatures are maintained between 17ºC and 35ºC by the heating and cooling systems.**

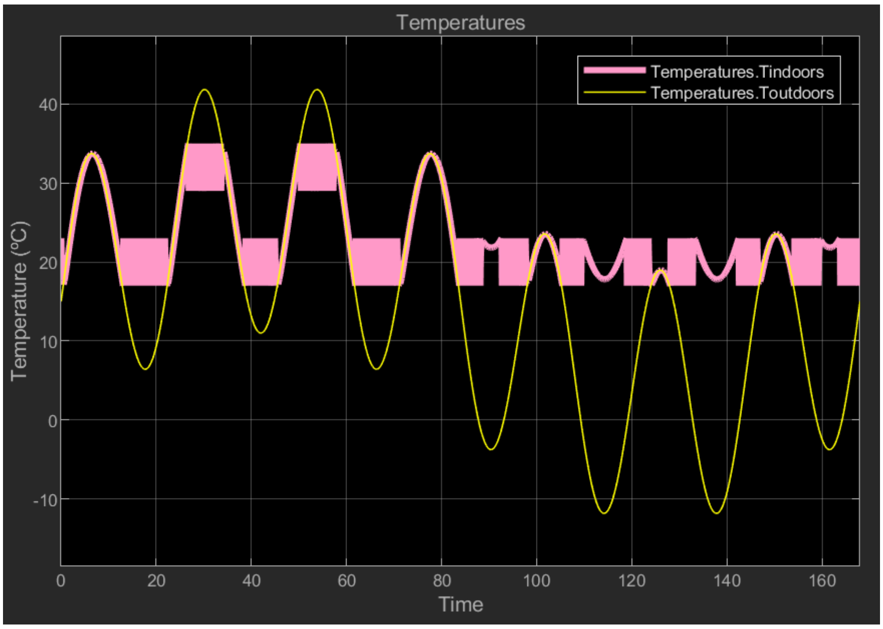

Figure 6. Indoors (**pink line**) and outdoors (**yellow line)** temperatures during a week. Temperature is measured in Celsius degrees and time in hours. The time frame is 168 hours (24 hours/day *7 days).

7. Electricity consumption and cost

The following plot shows the electricity consumption in kW*k by the heating system, the cooling system (refrigerator) and the total energy consumption. As it can be observed, the cooling system (blue line) has a low energy use, while the main contribution to the consumption is made by the heater. The cooling system doesn't turn on that much since there is a lot of heat loss through the walls, mainly when the outdoors temperatures get low. Furthermore, the highest outdoors temperatures are not much higher than the maximum required indoors temperatures, so the cooling system doesn't have to activate often. On the other hand, the heater consumption skyrockets due to the fact that the outdoors temperatures suffer important decreases reaching values below zero, causing bigger heat losses through the walls. Since the minimum temperature required indoors is 17ºC, the heater must turn on much more often, consuming more electricity.

The total consumption by the heating and cooling systems is of **1533 kW*h.** If the **electricity cost is 0.12€/kW**, the electricity cost for **the heating system is 171.4 €** and for the **cooling system is 12.57 €**. The **total electricity** cost is **184 € every week**.

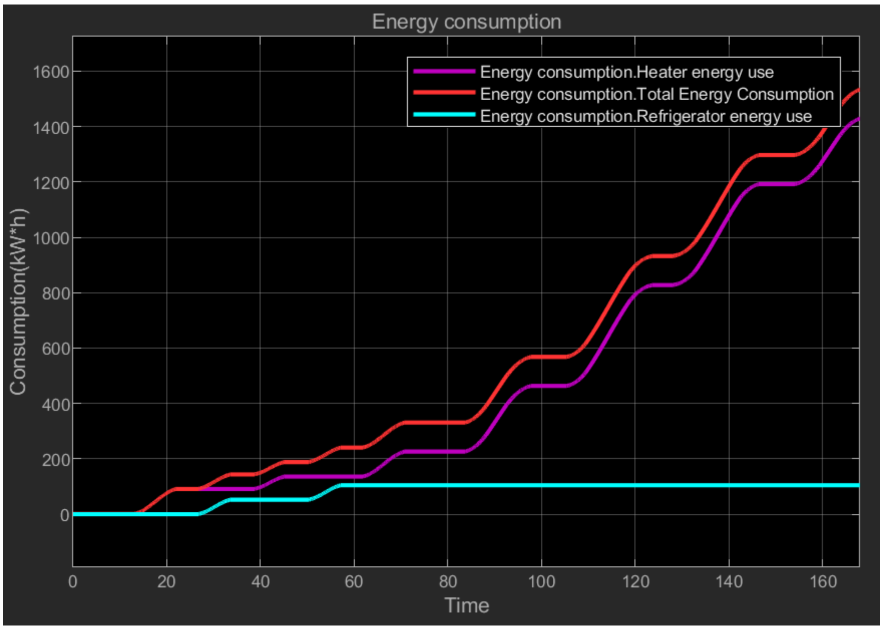

Figure 7. Energy consumption (kW*h) in a week. **Blue line** represents the energy consumption corresponding to the cooling system. **Purple line** represents the energy consumption corresponding to the heater. **Red line** represents the total energy consumption, resulting by adding the consumptions of both systems.

8. Indoors temperatures if the cooling system were to break down

The following plot shows the variation of temperatures in a week. There are three curves represented: **outdoors temperature** (yellow line), **indoors temperature when both the heater and the cooling systems are working** (pink line) and **the indoors temperature when the cooling system is broken** (blue line). To visualize the temperature when the cooling system is broken, a new subsystem called "**Greenhouse_wo_cooling_system**" was added. This subsystem represents a new greenhouse, with the same dimensions and in the same environment as the one previously used. However, this one **is only connected to the heater** (with the same properties as the greenhouse connected to both heater and cooling system), so it acts as if the cooling system doesn't work.

Therefore, the greenhouse temperature is maintained **above 17 ºC due to the heating system** but by lacking the cooling system, **it escalates above the maximum of 35ºC required** reaching the same temperatures as presented outdoors. The indoors temperature can only be lowered due to the heat loss through the walls adjusting to the descend of outdoors temperature.

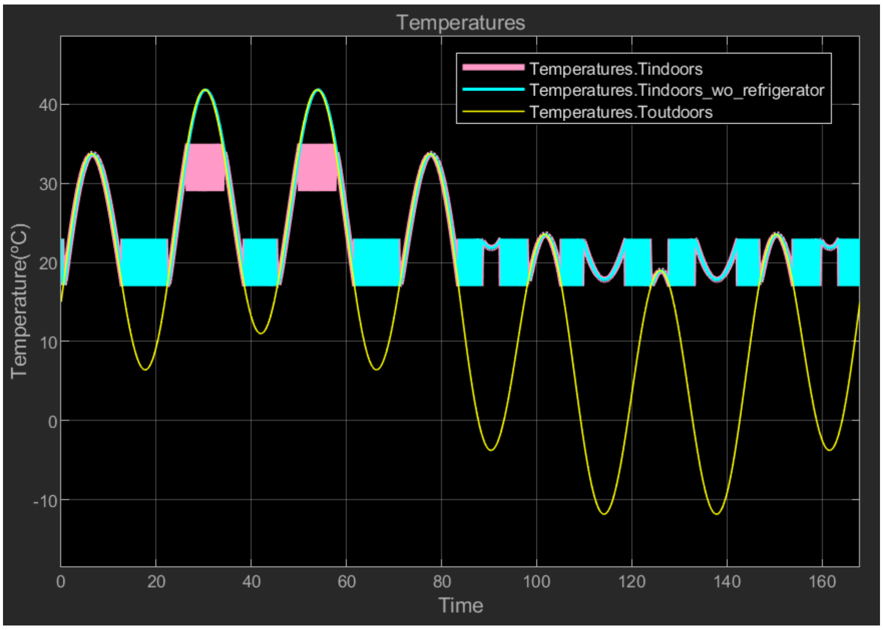

Figure 8. Temperatures in a week. Temperature is measured in Celsius degrees and time in hours. The time frame is 168 hours (24 hours/day *7 days). The **yellow line** represents the **outdoors temperature**. The **pink line** represents the **indoors temperature when both the heating and cooling system work**. The **blue line** represents **the indoors temperature when the cooling system is broken**.

9. Indoors temperature considering the greenhouse effect

To create the greenhouse effect, the **"Greenhouse"** and "**Greenhouse_wo_cooling system**" **subsystems** were modified by adding a new subsystem called **"Solar radiation".**

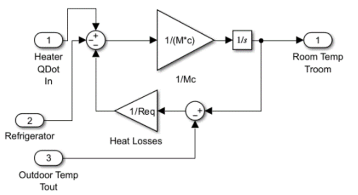

Figure 9. "**Greenhouse**" subsystem without greenhouse effect.

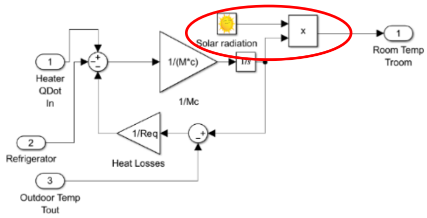

Figure 10. "**Greenhouse**" subsystem with greenhouse effect.

This new subsystem does the following:

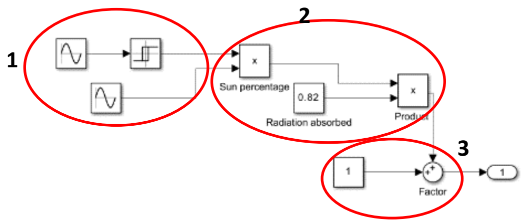

Figure 11. "**Solar radiation**" subsystem.

1. Defines two periods: night-time and daytime. At night, the sunlight fraction is zero. During the day, the sunlight fraction increases and decreases from morning until sunset.
2. Calculates the percentage of radiation typically absorbed by the greenhouse accordingly to the sunlight fraction throughout the day. The percentage is expressed as $r\% = \frac{r}{100}$. According to different sources, a greenhouse absorbs around 82% of the solar radiation at a given moment, therefore the fraction of temperature increase will be calculated as $82\% * sunlight\ fraction\ at\ a\ given\ moment.$
3. It creates a factor that can be multiplied with the normal temperature in the greenhouse if there was no greenhouse effect. This factor is calculated by adding the amount obtained in step 2 and a constant equal to 1. This was calculated according to the mathematical concept of increasing a certain quantity c by r%, obtained as $c * (1 + \frac{r}{100})$, where c is the greenhouse temperature.
4. The result obtained from $1 + \frac{r}{100}$ is multiplied with the greenhouse temperature, causing a small increase in the indoors temperature due to the greenhouse effect.

Results

If the heating and cooling systems airflow maintains the same properties as the greenhouse without greenhouse effect, the minimum indoors temperature would be 17ºC and the maximum indoors temperature 35ºC.

Furthermore, since the indoors temperature increases considerably, the cooling system needs to turn on more often, therefore its electricity consumption also increases. The weekly **energy consumption rises to 1939 kW*h.** If the **electricity cost is 0.12€/kW**, the electricity cost for **the heating system is 163.5 €** and for the **cooling system is 69.15 €**. The **total electricity** cost is **232.6€ every week**.

If the cooling system broke down, the indoors temperature skyrockets, achieving **a maximum of 76.07 ºC**, so the plants wouldn't survive in such high temperatures.

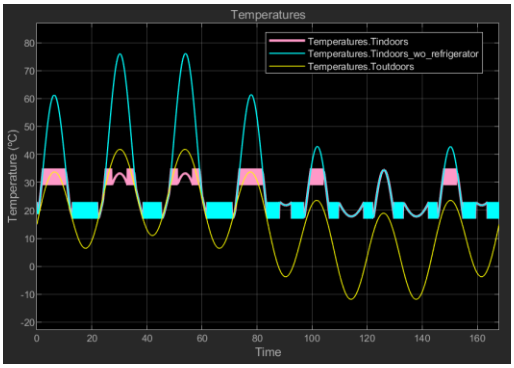

Figure 12. Temperatures in a week. Temperature is measured in Celsius degrees and time in hours. The time frame is 168 hours (24 hours/day *7 days). The **yellow line** represents the **outdoors temperature**. The **pink line** represents the **indoors temperature when both the heating and cooling system work**. The **blue line** represents **the indoors temperature when the cooling system is broken**.

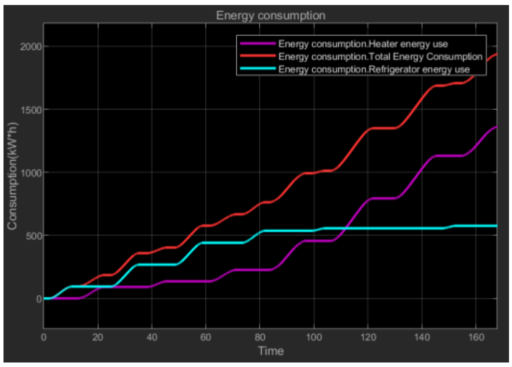

Figure 13. Energy consumption (kW*h) in a week. **Blue line** represents the energy consumption corresponding to the cooling system. **Purple line** represents the energy consumption corresponding to the heater. **Red line** represents the total energy consumption, resulting by adding the consumptions of both systems.

10. References

1. **Thermal Model of a House – Matlab Documentation**
2. https://retak.com.ar/por-que-elegirnos/
3. https://en.wikipedia.org/wiki/Polycarbonate