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4GCU

Toy Model House

Group 5 - Energy management in buildings

I. Description of the object

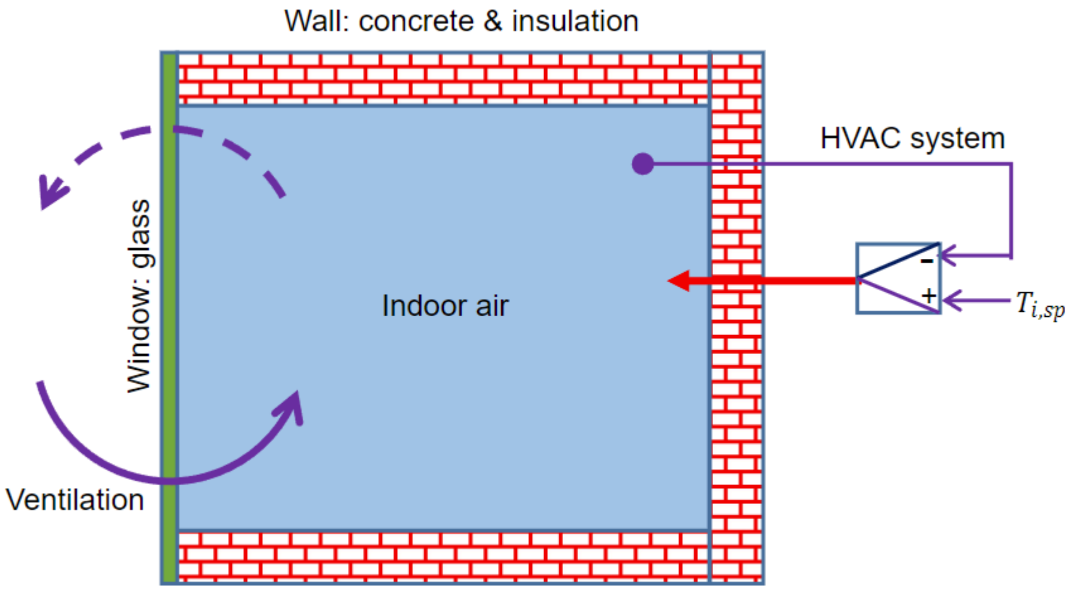


Figure 1 : Top View of the studied building

The physical object studied is a toy model, which is a simple model with few details.
It consists of a cube of side 3m, with five opaque walls and one transparent wall.
The five opaque walls are composed of a 20cm external layer of concrete and a 8cm internal layer of insulation.
The transparent wall is composed of a 4cm layer of glass.
The thermo-physical properties of each of these materials are detailed further down below.

material	conductivity [W/m.K]	density [kg/m^3]	specific heat (J/kg.K]
concrete	1,4	2300	880
insulation	0,027	55	1210
glass	1,4	2500	1210

The emissivity (long waves), absorptivity (short waves) and transmittance (short waves) for the different walls are exposed below.

material	emissivity	absorptivity	transmittance
concrete	0,85	0,25	0
glass	0,90	0,38	0,30

Table : characteristics of each material

The convection coefficients are 8 W/m².K for the indoor and 25 W/m².K for the outdoor.

We must also consider the air infiltration and the HVAC system which controls the indoor air temperature.

II. Model

The heat transfer in the building can pass through the concrete walls and the glass wall, can come from the ventilation, from indoor auxiliary sources (inhabitants, lights, devices…) and from the HVAC system. It is represented down below.

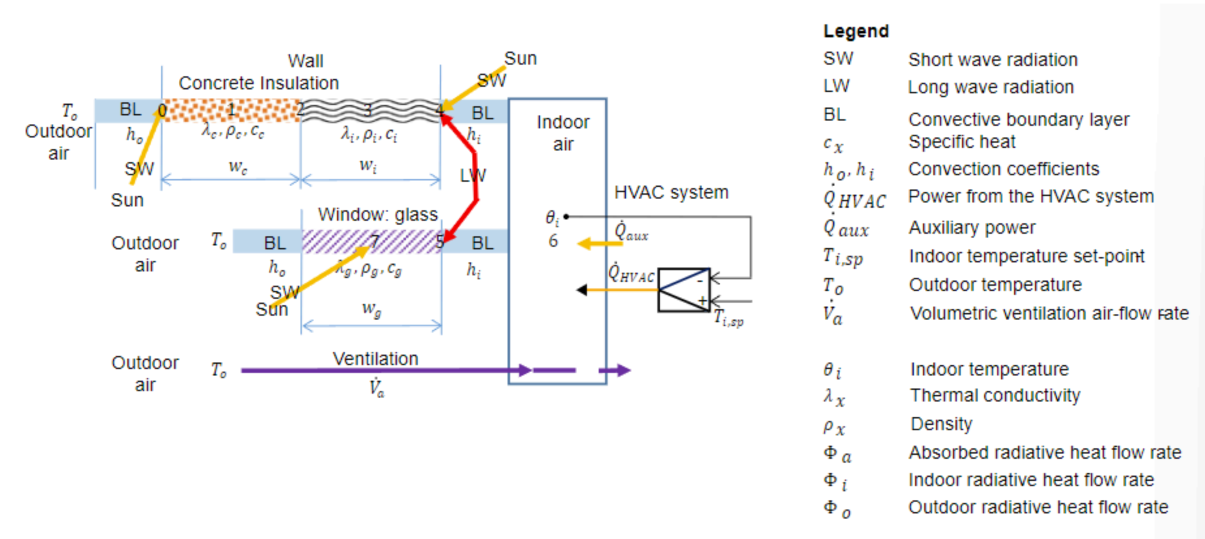
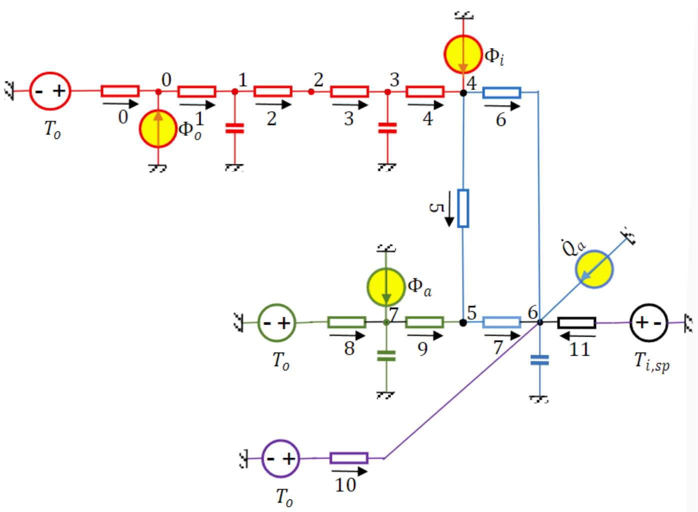


Figure 2 : representation of the heat transfers in the cubic building

We make the following hypothesis :

- the indoor and outdoor temperatures are homogeneous
- heat transfers are only unidirectional
- we do not consider any thermal bridge

We can model the heat transfers by the following thermal circuit.



- red : concrete and insulation wall
- green : glass wall
- purple : ventilation
- blue : indoor air
- black : HVAC system

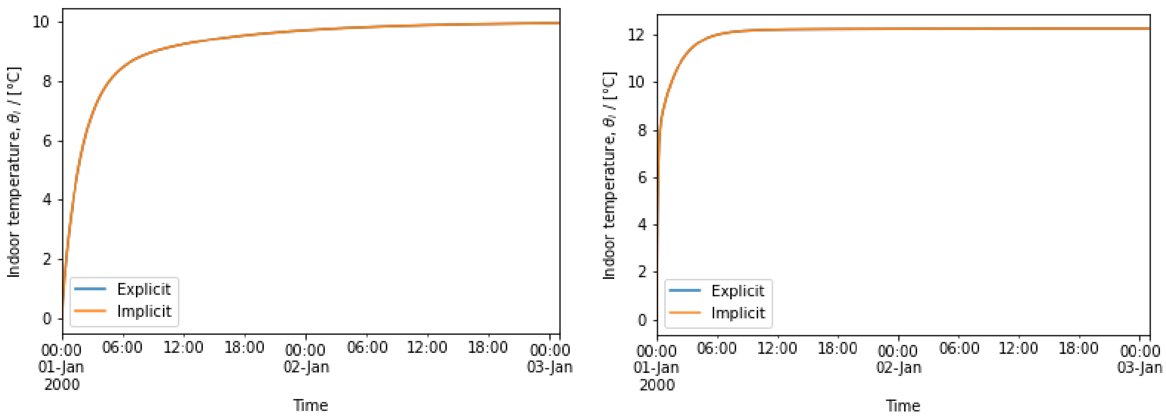
Figure 3 : thermal circuit of the building

There are two types of sources : temperature sources (the outdoor air temperature T_0 and the indoor temperature setpoint $T_{i,sp}$) and the flow rate sources (the radiative heat flow absorbed by the glass Φ_a, the outdoor radiative heat flow on the concrete wall Φ_o, the indoor radiative heat flow Φ_i, and the auxiliary heat gains Q_a).

III. Results

Initial model

The initial model, whose parameters are described in the code V0, gives the following results for the evolution of indoor temperature :

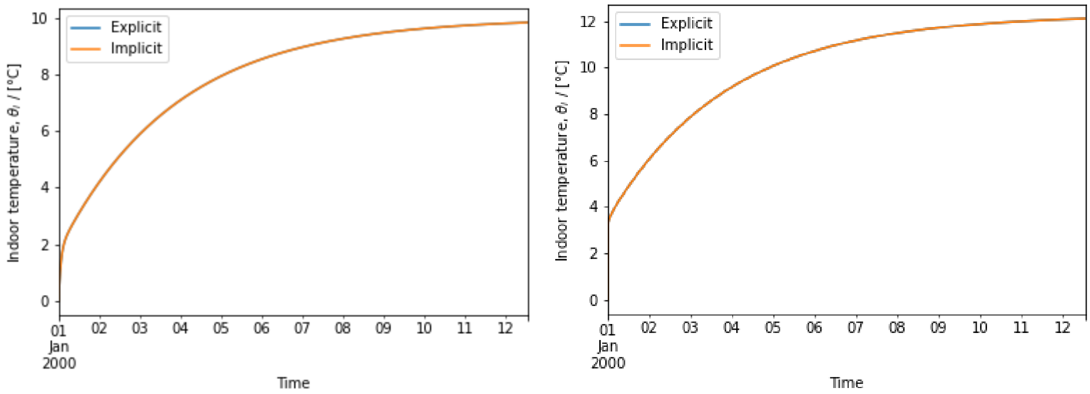


Graphs : Evolution of indoor temperature without and with internal loads

Settling time : 2.04 days
duration = 49.0 h

Variation 1 : External insulation

For this first variation, we chose to replace the internal insulation by an external insulation. We obtain the following results :



Graphs : Evolution of indoor temperature without and with internal loads

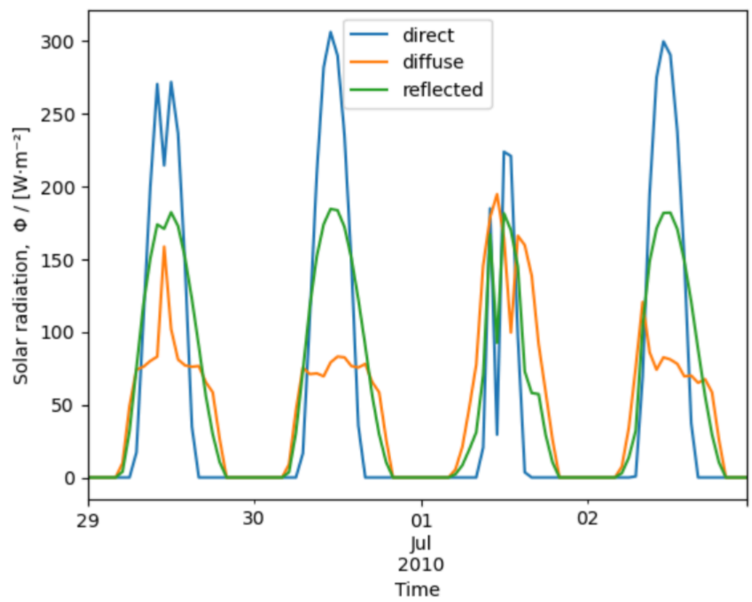
Settling time : 11.52 days
duration = 277.0 h

We can observe that compared to the initial model, the settling time is much longer : the steady-state with the internal insulation is reached after 2,04 days, whereas it is reached after 11,52 days with the external insulation.
The duration is also longer : 49h compared to 277h.

GitHub link :
https://github.com/dm4bem/thermal-model-steady-state-step-response-group-5/blob/main/Results_Variant1.ipynb

Variation 2 : Influence of solar radiation

We are taking into account the solar radiation : ie. The absorption coefficients, the reflectivity and transmission of sun rays through the zone-toy house model. We split the radiation into 3 categories and we see that the part that has an impact on the zone is the direct radiation.



Graph : Solar radiation as a function of time

GitHub link :
https://github.com/dm4bem/thermal-model-steady-state-step-response-group-5/blob/main/Results_Variant2.ipynb

Variation 3 : Modification of the width of some materials

To conduct the influence of the construction width onto the settling time, several modifications have been made. Firstly, the width of the concrete has been changed from 0,20 m to 0,25 m. In the following steps the insulation and glass width was duplicated to 0,16 m and 0,08 m and reversed.

Scenario	Settling time	Difference
0,20 m concrete 0,08 m insulation 0,04 m glass	48,93 h	21,62
0,25 m concrete 0,08 m insulation 0,04 m glass	70,55 h	1,38
0,20 m concrete 0,16 m insulation 0,04 m glass	71,93 h	0,07
0,25 m concrete 0,16 m insulation 0,08 m glass	72,00 h	21,98
0,20 m concrete 0,16 m insulation 0,08 m glass	50,02 h	0,99

0,20 m concrete 0,08 m insulation 0,08 m glass	49,03 h	

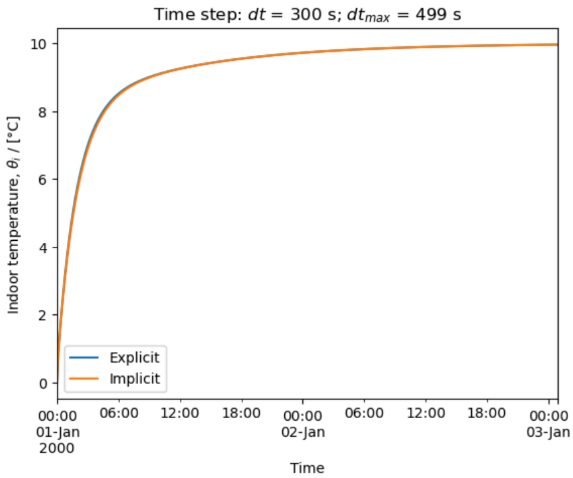
Table : Width of each layer with setting times

As visible in the table above, the change of the width of the concrete wall made the greatest difference in the settling time of the construction. The impact of the insulation and glass can be, in comparison to the concrete, neglected.

GitHub links :
https://github.com/dm4bem/thermal-model-steady-state-step-response-group-5/blob/main/Variant_3.1.py
https://github.com/dm4bem/thermal-model-steady-state-step-response-group-5/blob/main/Variant_3.2.py
https://github.com/dm4bem/thermal-model-steady-state-step-response-group-5/blob/main/Variant_3.3.py
https://github.com/dm4bem/thermal-model-steady-state-step-response-group-5/blob/main/Variant_3.4.py
https://github.com/dm4bem/thermal-model-steady-state-step-response-group-5/blob/main/Variant_3.5.py

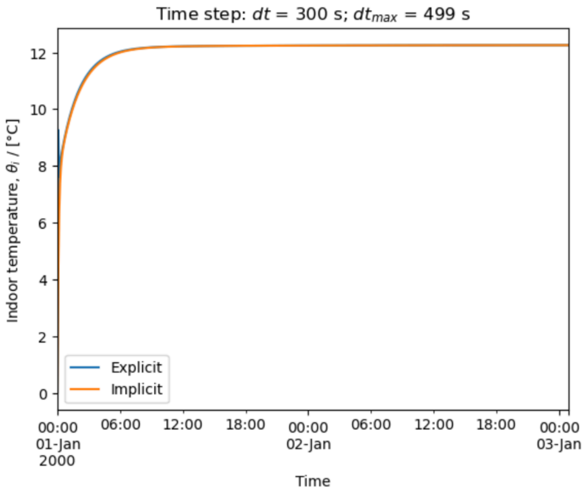
Variant 4 : No imposed time-step

The initial graphs are the following :



Graph : Indoor temperature as a function of time (without internal load)

and with internal load, it changes to :



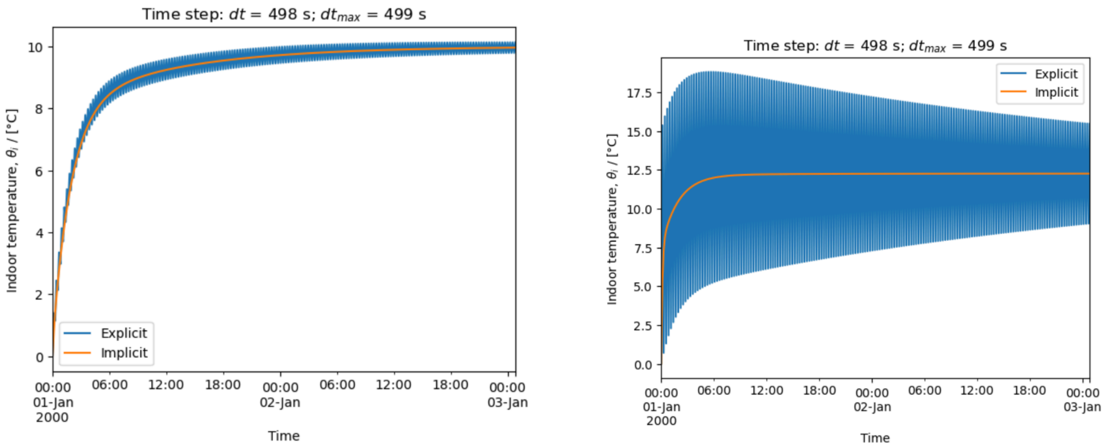
Graph : Indoor temperature as a function of time (with internal load)

We can see that the explicit and implicit curves are almost superposed, with only a very small error (at the order of 10e-15). This means that when the system is being let free, it naturally goes to the set-point temperature with a time-step dt=300 seconds.

GitHub link :
https://github.com/dm4bem/thermal-model-steady-state-step-response-group-5/blob/main/Results_Variant4-5-6.ipynb

Variant 5 : Imposed time-step

In this version, we impose the time-step. Thus, by putting "True" in the time-set code line, we obtain the following graphs :



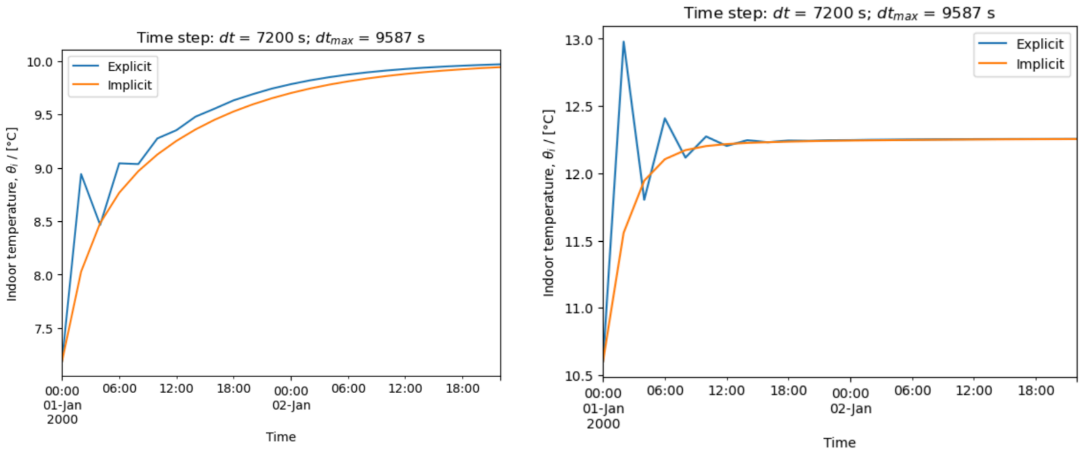
Graphs : Indoor temperatures as a function of time (imposed time steps)

What we can say is that in this case, the explicit method is not accurate. Indeed, instead of creating a line, the points are all scattered, even though the global shape we obtain is alright. We also see that the time-step indeed changed from 300 to 498 seconds, as it was set. The fact that the time-step is bigger here "forces" the system to be less precise and that is why we observe these kinds of results.

GitHub link :
https://github.com/dm4bem/thermal-model-steady-state-step-response-group-5/blob/main/Results_Variant4-5-6.ipynb

Variant 6 : Neglecting air & glass capacities

When neglecting both the air and glass capacities, we obtain the following graphs :

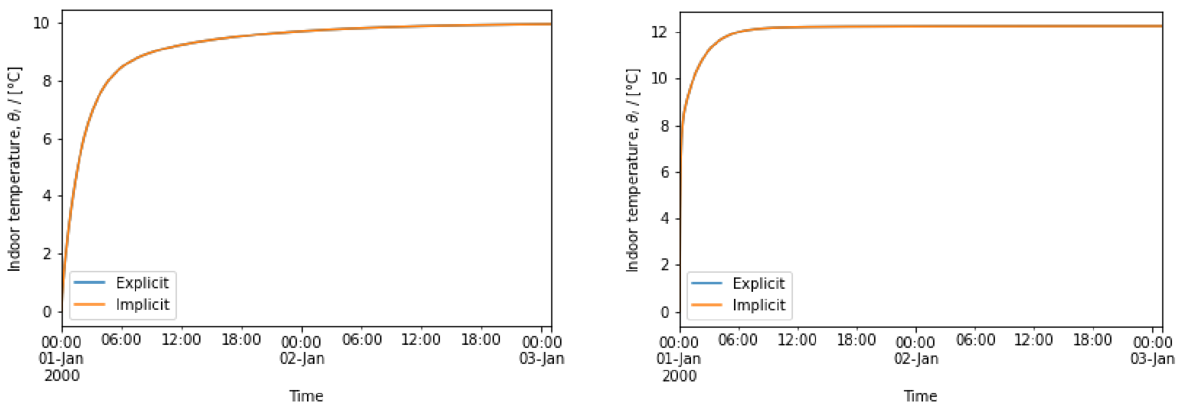


<u>Graphs : Indoor temperatures as a function of time (without any capacities)</u>

We can observe that the time-step has become really huge and the curves are more rounded, meaning that the system is struggling to reach the set-point temperatures. The explicit model is once again more scattered than the implicit model, which has a smoother curve. The stabilization thus depends on the capacities that we use for modeling the toy model house (here of air and glass). What this means is that it is easier to work without neglecting the capacities that surround the model house because the units change in order for the temperature in the model to set are being made by implementing all the parameters.

GitHub link :
https://github.com/dm4bem/thermal-model-steady-state-step-response-group-5/blob/main/Results_Variant4-5-6.ipynb

Variant 7 : Controller ineffective (0)

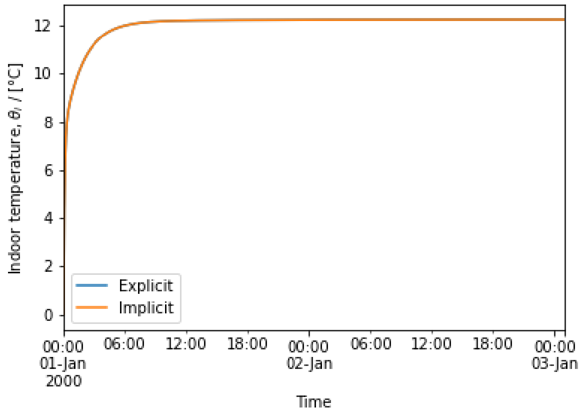


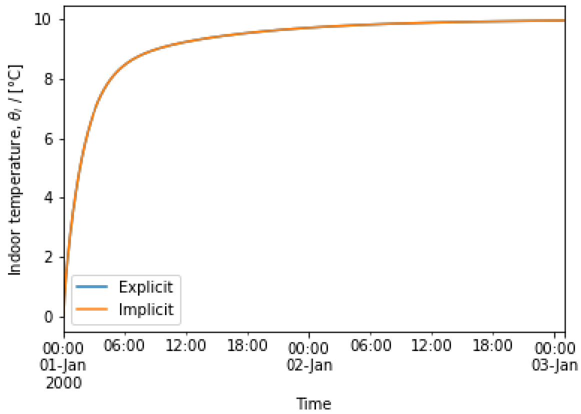
We are using no controller (Kp=0) which leads to a maximum time step of 8,31 minutes with a dt of 8 minutes. The settling time is 2,04 days (48,9 h) which leads to a duration time of 49 h. The output of the state-space representation (yss) is 10,0 °C. The error of the steady-state values obtained from the system of DAE settles around 8,88e-15°C. The value of the output of the state-space representation with an input of Q (yssQ) is 12,26°C.

GitHub link :
https://github.com/dm4bem/thermal-model-steady-state-step-response-group-5/blob/main/Results_Variant7-8.ipynb

Variant 8 : Perfect controller (infinity)

We changed the controller gain to the perfect controller (Kp=1e4). There we could see that the maximum time step changed to 0,11 minutes with a dt of 6,0 seconds. Even though the settling time changed to 2,02 days (48,6 h), the duration stayed at 49 h. In comparison to the version without a controller gain, the output of the state-space representation (yss) is 19,92°C. Also the error of the steady-state values obtained from the system of DAE changes, when the perfect controller is applied. Instead of the value of 8,88e-15°C from before, it switched to 3,55e-15°C. After the change to the perfect controller the value of the output of the state-space representation with an input of Q (yssQ) decreases to 0,10°C.





GitHub link :
https://github.com/dm4bem/thermal-model-steady-state-step-response-group-5/blob/main/Results_Variant7-8.ipynb

IV. Inputs and simulation

Variant : Changing the inputs

The start- and end-date were changed to study potential result variances. The original dates were in february and were changed to the summertime, more precisely the month of july. Despite these modifications and also the prolongation of the simulation time no changes could be seen.

GitHub link :
https://github.com/dm4bem/thermal-model-steady-state-step-response-group-5/blob/main/Results_Variant-Changing%20the%20inputs.ipynb

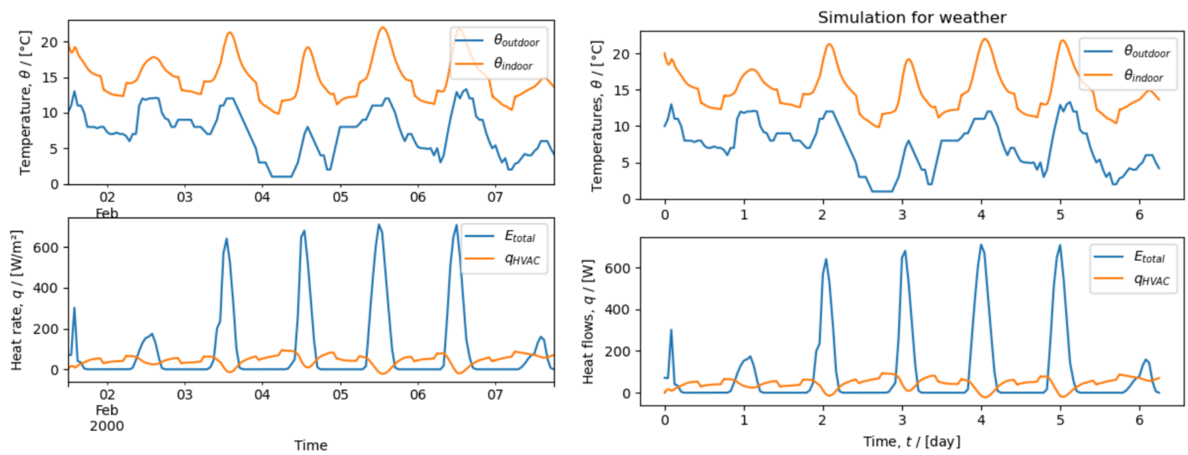
Variant : Changing the values of the controller

We first make a few assumptions on the system :

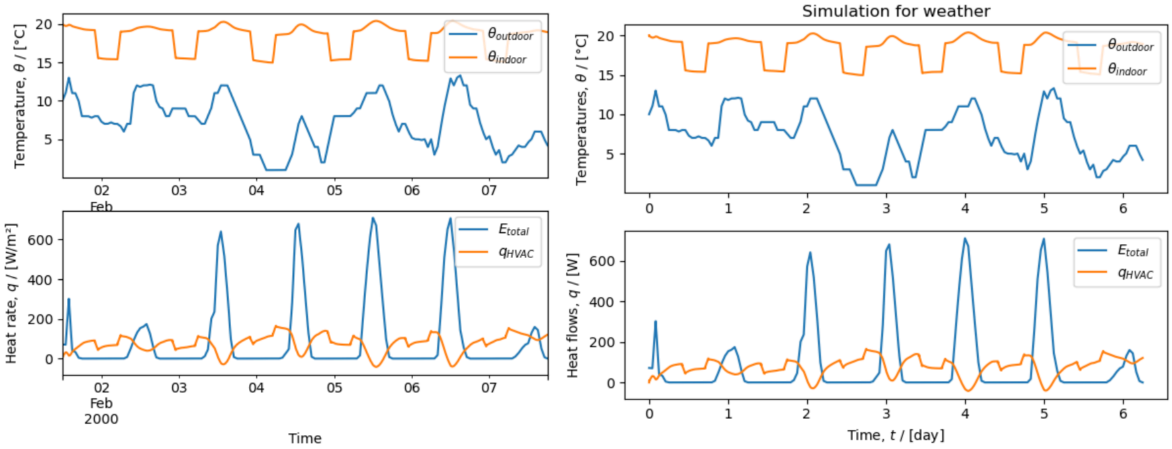
- The indoor air temperature is controlled or not (i.e., the building is in free running) by a P-controller having the gain Kp
- The time integration is done by using Euler explicit
- The time step is calculated from the eigenvalues of the state matrix

The changes made on the controller are : changing Kp to 1e2, 1e3 and 1e4 (almost perfect controller)

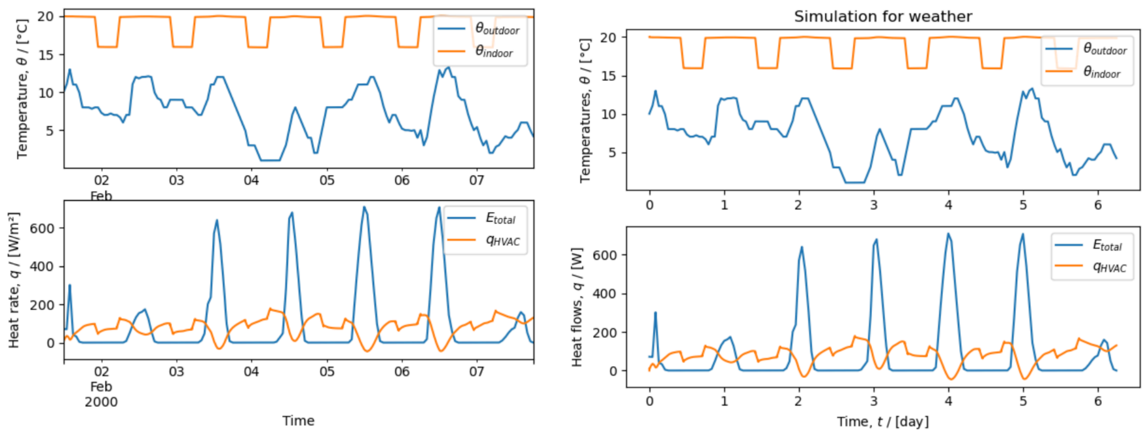
The following graphs show the differences for different values of the controller :



Graphs : Heat rates, flows and temperatures for Kp=1e2, as a function of time



Graphs : Heat rates, flows and temperatures for Kp=1e3, as a function of time



Graphs : Heat rates, flows and temperatures for Kp=1e4, as a function of time

We observe that, the higher the value of Kp, the more dampened the indoor temperature is. Indeed, we observe a few peaks for Kp=1e2 but for Kp=1e4, the curves are looking more like rectangles, the temperatures being constant during the day and then decreasing almost instantly so that they are constant during the night and vice versa.

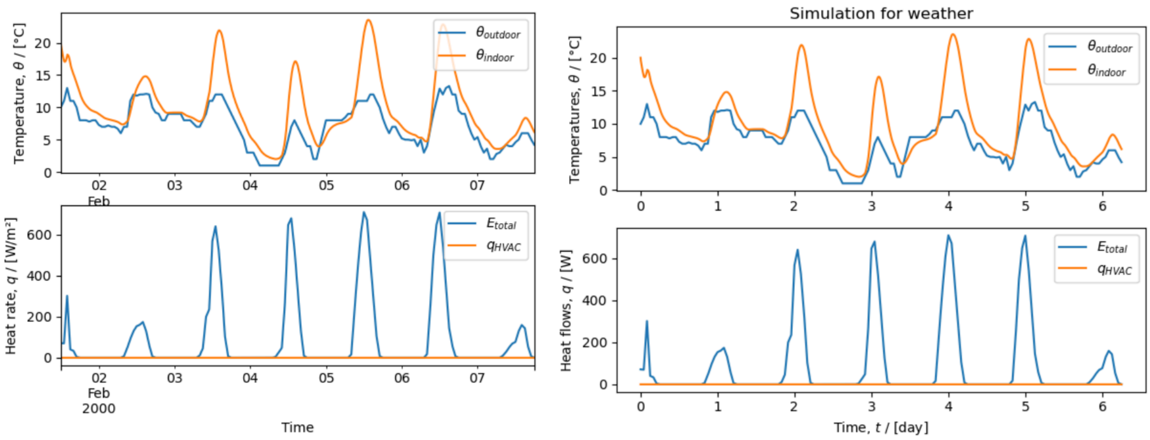
This shows us that the value of Kp has a direct influence on the system. The higher the value of Kp, the higher the effect of the controller is and thus the closer the system is to the set-point temperature that was fixed.

What's more, we observe that when Kp increases the thermal load q of the system increases as well. Because the degree of control that is being put on the system to maintain it exactly at a set-point temperature is higher, the system will use more energy/power to maintain itself to this set-point, thus this explains the corresponding increase in thermal load.

GitHub link :
https://github.com/dm4bem/inputs-simulation-group-5/blob/main/Results_Variant-Changing%20values%20of%20Kp.ipynb

Variant : Setting the controller to zero

The changes made on the controller are : Setting Kp to 0 (the controller is thus supposed to be ineffective).
The building is free-running, meaning that the flows and temperatures are not controlled anymore. It will set when it “feels” like setting.
The corresponding graphs are obtained below.



Graphs : Heat rates, flows and temperatures for Kp=0, as a function of time

We observe that there are no evolutions in the heat flows and rates q inside the toy house. Moreover, these are constant and stay put to the value of 0. Indeed, since that q is the power that the HVAC system needs to deliver in order to maintain the indoor air temperature at its set-point, and since there are no more set-points in this configuration, we understand why the thermal load is thus non-existent.

What’s more, compared to the curves for the indoor temperatures previously obtained (for values of Kp that are not nil), we observe that the curves look like Gaussian curves, and that there are no threshold/limits to them. Indeed, the curves go higher and their peaks are not dampened as they were in the graphs of the previous variation.

Finally, the indoor temperatures and outdoor temperatures curves are almost overlapped, meaning that their evolution is not exactly the same, but similar in free-running. The air, whatever its temperature, has the same behavior.

GitHub link :
https://github.com/dm4bem/inputs-simulation-group-5/blob/main/Results_Variant-Kp%3D0.ipynb

V. Conclusion

In conclusion, the goal of this project was to study a simple toy-model house. We tried different approaches and studied their effects : both steady-state and step-by-step response approaches. We observed differences in terms of set-point in the curves and in the forms of responses of the system. We tried to change the materials as well and play with their width, so as to obtain the most optimized configuration.
Finally, in the inputs and simulation part, we used the step-by-step approaches using different methods ; the explicit and implicit Euler approaches. We studied the effect of the controller gain on the system as well as the meaning of the thermal load q of the system.