Final Project

Energy Management in Buildings

Part 1: Modelling, implementation, simulation

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I. Description of the building

The considered building is a cubic ventilated room with an HVAC control system acting as a proportional controller. The edge length of the cube is 3 m.

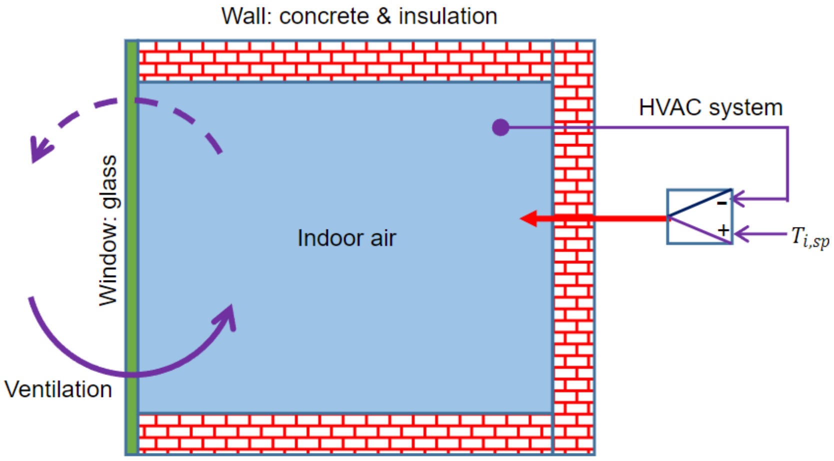


Figure 1 : Simple ventilated room equipped with an HVAC control system which acts as a proportional controller.

The room is composed of five two-layer walls. For the initial model, the concrete layer is placed outside, and the insulation is placed inside.
The thermophysical properties and the geometry are presented in Table 1.

Table 1: Thermophysical properties of materials and geometry

	Conductivity (W/(m·K))	Density (kg/m³)	Specific heat (J/(kg·K))	Width (m)	Surface (m²)
Concrete	1,400	2300,0	880	0,20	45
Insulation	0,027	55,0	1210	0,08	45
Glass	1,400	2500,0	1210	0,04	9
Air		1,2	1000		

II. Hypothesis used in the modelling.

i. Occupancy

We suppose that we are in a small office, where there is lighting, a computer and one person. According to the EnergiePlus website[1], we can consider a mean auxiliary heat sources of 30 W/m^2. In this case, the surface is 9 m^2 so $Q_a = 270\ W$. As it is an office, the auxiliary sources are only active during office hours, which will be considered between 9am and 5pm. Outside of those hours, the internal sources will be 0W. Our datas are spread across a week, between Tuesday, August 1st and Monday, August 7th. The office will be considered open only between Tuesday and Friday, and on Monday.

[1] EnergiePlus Le site. Charges thermiques internes pour les bureaux [online]. Available on : https://energieplus-lesite.be/theories/bilan-thermique44/charges-thermiques-internes-pour-les-bureaux/ (accessed 05/03/2024)

ii. Convective and conductive heat exchanges

The walls and the glass are in contact with the outside air, so they exchange heat with it through conduction and convection. The convection and conduction coefficients are constant and homogeneous in the insulation, glass, and concrete. The thickness of the walls and glass is small compared to the surface area of the facades, so the problem is treated linearly and edge effects as well as thermal bridges are neglected. The temperature of the interior air of the cube is homogeneous.

The wall consists of two layers of concrete and insulation with different convection and conduction properties. Both layers store heat thanks to their specific heat capacity $c\ (J.kg^{-1}K^{-1})$.
From Fourier's laws, $\phi_{12} = -\lambda\frac{dT}{dx} = \lambda(\theta_1 - \theta_2)$ for the conduction and from Newton $\phi = h(\theta_s - \theta_{int})$ for the convection, which both depend linearly on temperature, the wall can be modelled by the following thermal circuits:

The walls:

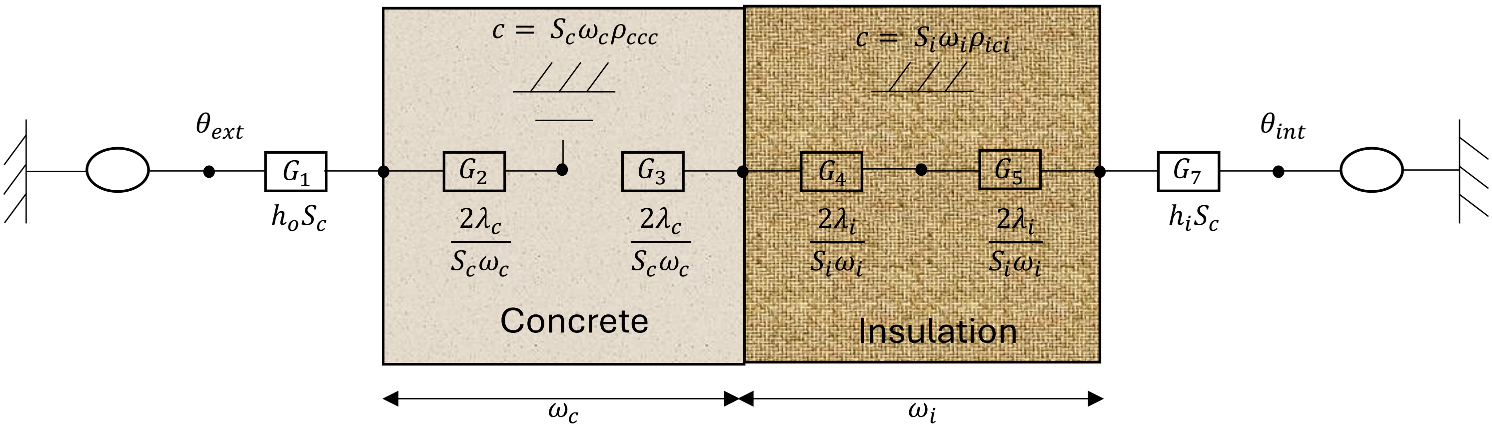


Figure 2 : scheme of the wall's model

The windows:

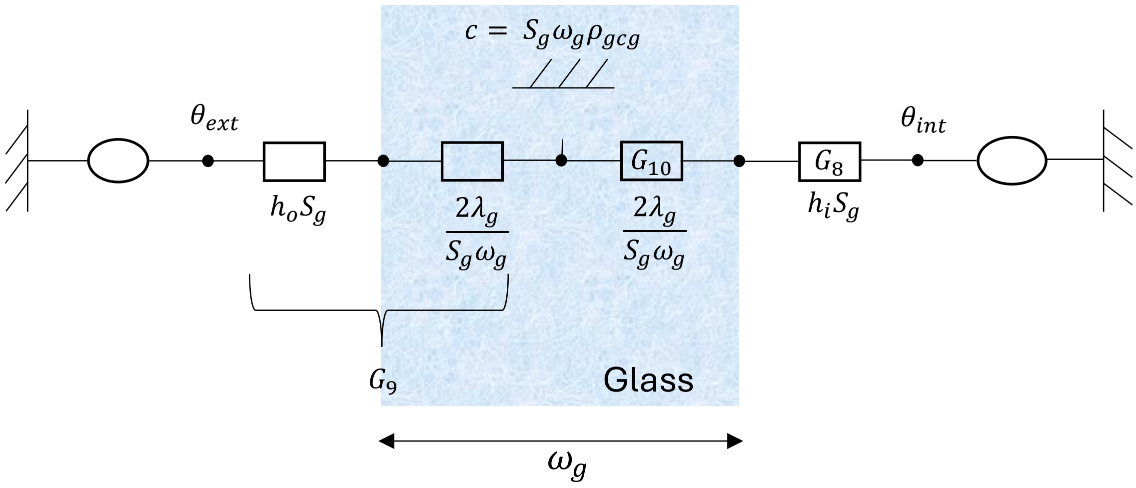


Figure 3: scheme of the glass' model

iii. Radiative balance of exterior and interior facades

Assumptions :

- Multiple reflections of short wavelengths inside the cube are neglected.
- Rays emitted by the sky vault are neglected.
- The glass and interior and exterior facades are considered grey bodies, with characteristics provided in the introduction.

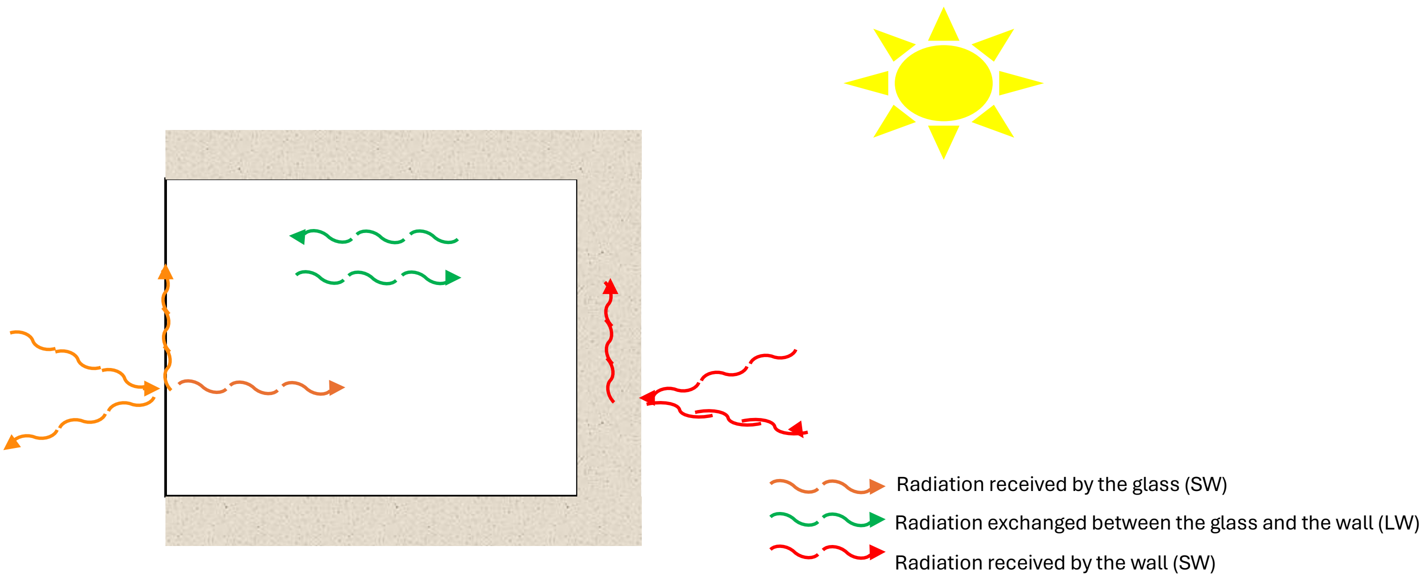
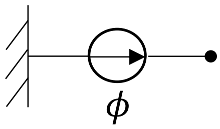


Figure 4 : scheme of the radiation received on the cube

The cube is thus solely subjected to sunlight and its reflections on the surrounding environment.

Exterior Surfaces:

The exterior surfaces of the glass and walls are heated by the sunlight they absorb. These heat fluxes, which depend only on the external illumination, can be represented by sources of heat flux.

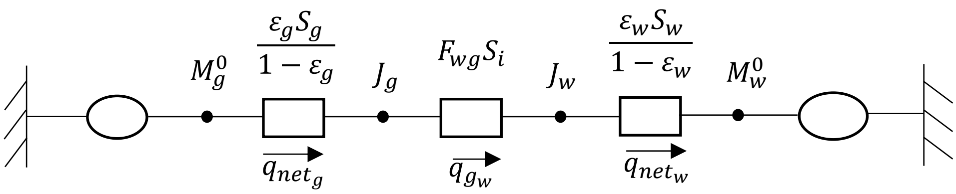


Radiation on the exterior walls: $\phi_{wo} = \alpha_{w,SW}\, S_c E_{tot}$
Radiation on the interior walls: $\phi_{wi} = \alpha_{w,SW}\, \tau_{g,SW} S_i E_{tot}$
Radiation on the exterior glass $\phi_g = \alpha_{g,SW}\, S_g E_{tot}$

Interior Surfaces:

Conversely, the interior surfaces of the glass and walls are heated by the radiation emitted towards each other. They are therefore interdependent on the temperature of the other interior surface. We must therefore construct a circuit considering the radiosity of each surface.

$$radiosity:\ J_i = \frac{\phi_{net,i}}{S_i} + \sum_{j=i}^{n} F_{ij} + J_j$$



$F_{wg} = \frac{1}{5}$: The view factor between the glass and the 5 interior walls (each face of the cube has the same surface)
ε_g : Emissivity of the glass
ε_w : Emissivity of the interior walls
$M_g^0 = \varepsilon_g \sigma T^4$: Emittance of the glass
$M_w^0 = \varepsilon_w \sigma T^4$: Emittance of the interior walls
J_g : Radiosity of the glass
J_w : Radiosity of the interior walls

So :

$$q_{net_g} = \frac{\varepsilon_g S_g}{1-\varepsilon_g}\left(M_g^0 - J_g\right) = G'_{LW,1}\left(M_g^0 - J_g\right)$$
$$q_{net_w} = \frac{\varepsilon_w S_w}{1-\varepsilon_w}\left(M_w^0 - J_w\right) = G'_{LW,3}\left(M_w^0 - J_w\right)$$

$$q_{net_{gw}} = F_{wg} S_i\left(J_g - J_w\right) = G'_{LW,2}\left(J_g - J_w\right)$$
$$q_{net_{gw}} = \left(G'_{LW,1} + G'_{LW,3} + G'_{LW,2}\right)\left(M_g^0 - M_w^0\right) = \left(G'_{LW,1} + G'_{LW,3} + G'_{LW,2}\right)\sigma\left({T_g^0}^4 - {T_w^0}^4\right)$$

To introduce these equations into our thermal circuit, we are seeking relationships that linearly involve temperatures. Therefore, we need to linearize $\left({T_g^0}^4 - {T_w^0}^4\right)$:

$$\left(T_g^{0^4} - T_w^{0^4}\right) = \left(T_g^{0^2} + T_w^{0^2}\right)\left(T_g^{0^2} - T_w^{0^2}\right) = \left(T_g^{0^2} + T_w^{0^2}\right)(T_g^0 + T_w^0)(T_g^0 - T_w^0)$$

$$= 4\bar{T}^3(T_g^0 - T_w^0) \quad \text{with } \bar{T} = \sqrt[3]{\frac{\left(T_g^{0^2} + T_w^{0^2}\right)(T_g^0 + T_w^0)}{4}}$$

We want a mean temperature equal to 20°C => $T_g^0 = T_w^0 = 20°\text{C}$
We get $\bar{T} = 20$

$$G_{LW,1} = 4\sigma\bar{T}^3 \frac{\varepsilon_g S_g}{1 - \varepsilon_g}$$
$$G_{LW,2} = 4\sigma\bar{T}^3 F_{wg} S_i$$
$$G_{LW,3} = 4\sigma\bar{T}^3 \frac{\varepsilon_w S_w}{1 - \varepsilon_w}$$

III. Mathematical model

iv. Formulas and justification based on the hypothesis of modelling.

The thermal circuit for the cubic building is shown in Figure 5.
Here is the signification of the colours used in the model:

- Red: concrete and insulation wall
- Green: glass window
- Magenta: ventilation
- Blue: indoor air volume: (conductance 6 & 7 for convection; conductance 5 for long wave radiation between the walls and the glass window)
- Black: HVAC system

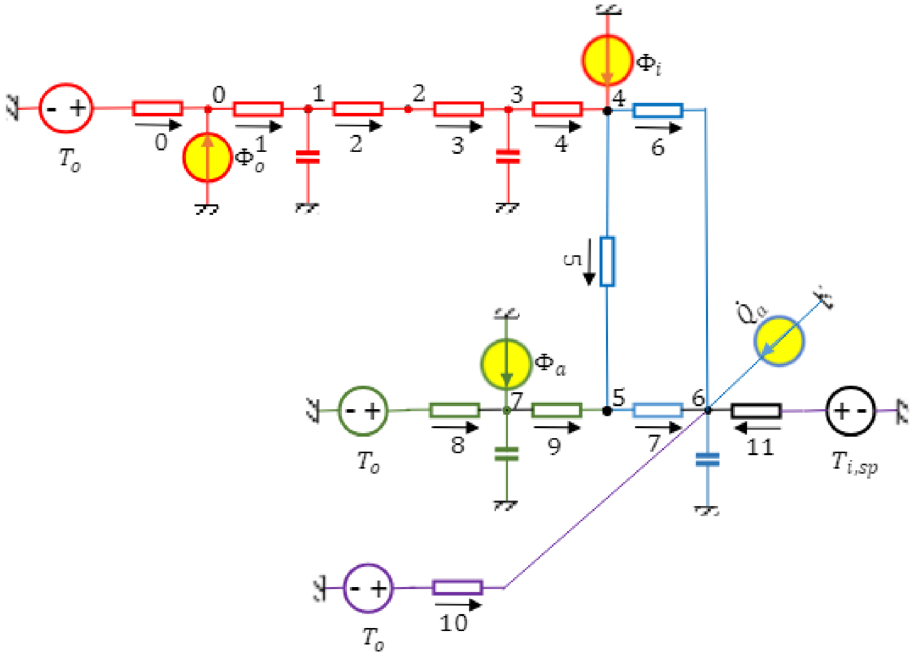


Figure 5: Thermal circuit for the building

IV. Software implementation of the mathematical model

i. Thermal model, steady-state and step response

The aim is to understand how the system works by varying different parameters such as the geometry or materials properties.
The software implementation with further details and the codes used are on our Github repository, available on this link:
https://github.com/dm4bem/thermal-model-steady-state-step-response-group-4

For this first part, we wrote 5 codes: [2]

- WeatherData.py, that compile with the weather data of a specific place (in a .epw file) and allows you to obtain the direct radiation, diffuse radiation and solar radiation diffused by the ground.
- Thermal model.py, the main code that combines the thermal mode, the steady-state and step response.
- Insulation out.ipynb, that study the influence of the position of the insulation (either on the inside or on the outside of the walls) on the time step.
- Conductivity_insulation.ipynb, that study the influence of the insulation's conductivity on the time step and settling time.
- Glass_capacity.ipynb, that study the influence of neglecting the capacity of the glass on the behavior of the thermal system.

ii. Inputs and simulations

In this second part, we used different codes to try the effects of different things.

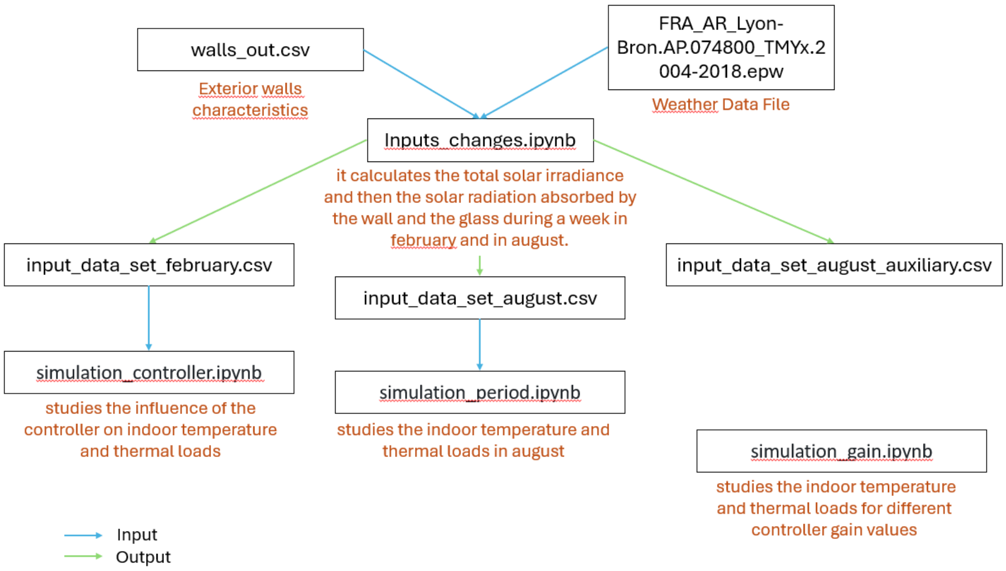


Figure 6: Scheme of the links between the different codes

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[2] These codes are directly inspired by the dm4_bem book "Dynamic Models for Energy Management" written by Christian Ghiaus (2024). Available on: https://cghiaus.github.io/dm4bem_book/intro.html (accessed throughout February 2024)

The software implementation with further details and the codes used are on our Github repository, available on this link:
https://github.com/dm4bem/inputs-simulation-group-4/tree/main

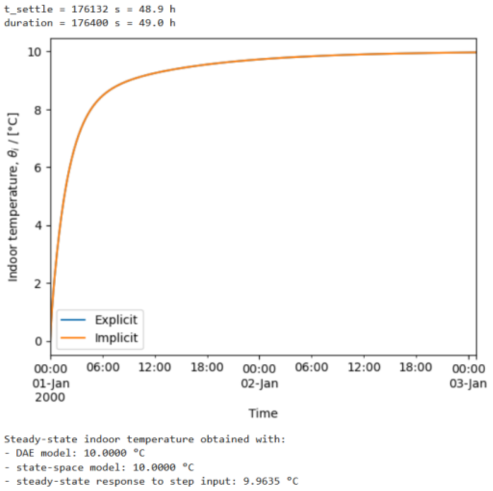
V. Results of running the software implementation

i. Comparison of insulation out and in

In future studies, we will focus on settling time. The settling time is the duration required for a system to reach a steady state. The indoor temperature achieved after the settling time is almost equal to the temperature reached in steady state.

A step response to outdoor temperature refers to the behaviour of the system when there is a sudden change in the outdoor temperature. It describes how quickly and how much the indoor temperature changes in response to the change in outdoor temperature.

Insulation in



Insulation out

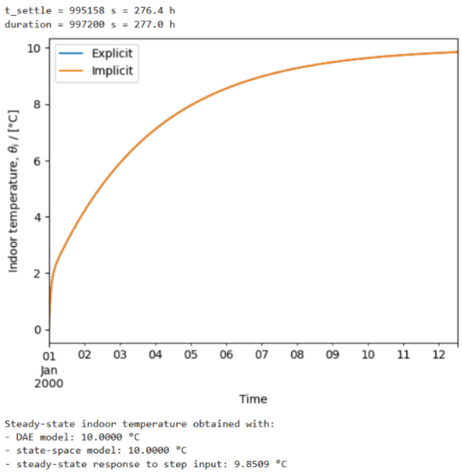


Figure 7 : : Comparison of settling time with insulation in and out

Observations:

We observe that reversing the order of insulation in the wall changes the time step. Indeed, the interior insulation will have a time step of 49 hours compared to 277 hours for the exterior insulation; thus, interior insulation allows for reaching the desired indoor temperature more quickly. In some cases, low thermal inertia may be preferable to allow for more precise control of indoor temperature, especially in buildings where changing thermal conditions are frequent, such as offices or meeting rooms. But in the contrary, exterior insulation can maintain or even increase the thermal inertia of the building, as it wraps the structural materials in a layer of insulation that helps to store the heat absorbed by the building during the day and release it slowly during the night. This can contribute to stabilizing indoor temperatures, reducing temperature fluctuations, and improving the thermal comfort of occupants. In tertiary buildings where a consistent level of comfort is important, such as hotels, schools, or shopping centers, greater thermal inertia can be beneficial in maintaining stable and pleasant indoor conditions.

ii. Conductivity modification

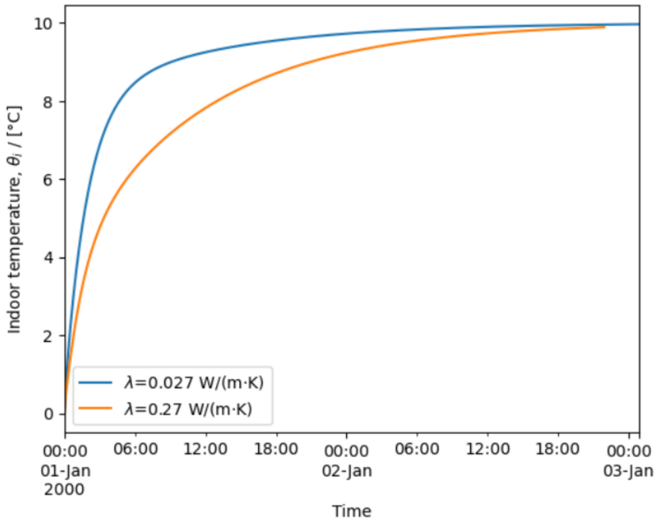


Figure 8: Comparison of a low conductivity and a high conductivity

We observe that an increase in the conductivity of insulation leads to a faster response to outdoor temperature changes (3h less). An insulation with a higher conductivity allows heat to transfer more quickly through the material.

Concerning the value of dt, it is higher when the settling time is higher. When more calculations are required, a larger time step is used to facilitate calculations.

A step response to outdoor temperature refers to the behaviour of the system when there is a sudden change in the outdoor temperature. It describes how quickly and how much the indoor temperature changes in response to the change in outdoor temperature.

The steady state is reached more rapidly with a higher conductivity, but the indoor temperature increases more slowly.

iii. Glass capacity modification

In this new model, we want to study the behaviour of the system when the capacities of the glass and the air are neglected.

	dt (s)	**Settling time (s)**
With C_{glass} and C_{air}	300.0	176132.233808
Without C_{glass} and C_{air}	7200.0	176057.968538

Figure 9: Comparison of time step and settling time

Neglecting the capacity of the glass and the air simplifies the system. A larger time step is therefore used in the simulation because the system is less complex and so faster to compute. The time step dt is multiplied by 24. We must ensure that the time step is not too large to prevent the calculated data from losing precision.

However, this change doesn't really affect the settling time. It's only reduced by just over a minute, which is negligible compared to the total time of 2 days. So, not considering the capacities of the glass and air is a valid assumption.

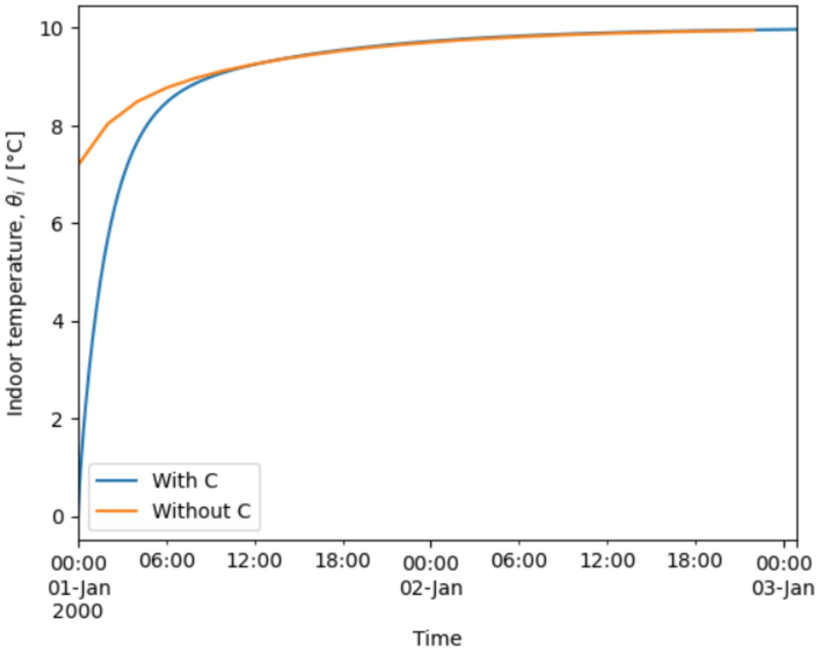


Figure 10: Comparison of step response to outdoor temperature

iv. Input changes

We modified the input_data files so that it can be used at every time of the year. We compared the results between a week in February and a week in august.

	Results in february (W/m²)	Results in august (W/m²)
Maximum total solar irradiance	444.465480	623.820985
Maximum solar radiation absorbed by the outdoor surface of the wall	6000.283977	8421.583297
Maximum solar radiation absorbed by the indoor surface of the wall	300.014199	421.079165
Maximum solar radiation absorbed by the glass	1520.071941	2133.467769

Figure 11: Comparison of the results between a week in February and a week in August.

As expected, the maximum total solar irradiance is higher in august as in February. It seems logical as the sun is stronger in the summer in France. As a result, the maximum solar radiation absorbed by the different materials (outdoor and indoor surface of the wall and the glass) is higher in august than in February. It is about 1.5 times higher in august.

Study in august

In this part, we study the system's behavior in summer, from August 1st to August 7th, using the input data file provided by the code in the Inputs_changes.ipynb file.

We focused on the indoor temperature and thermal loads during this period of time.

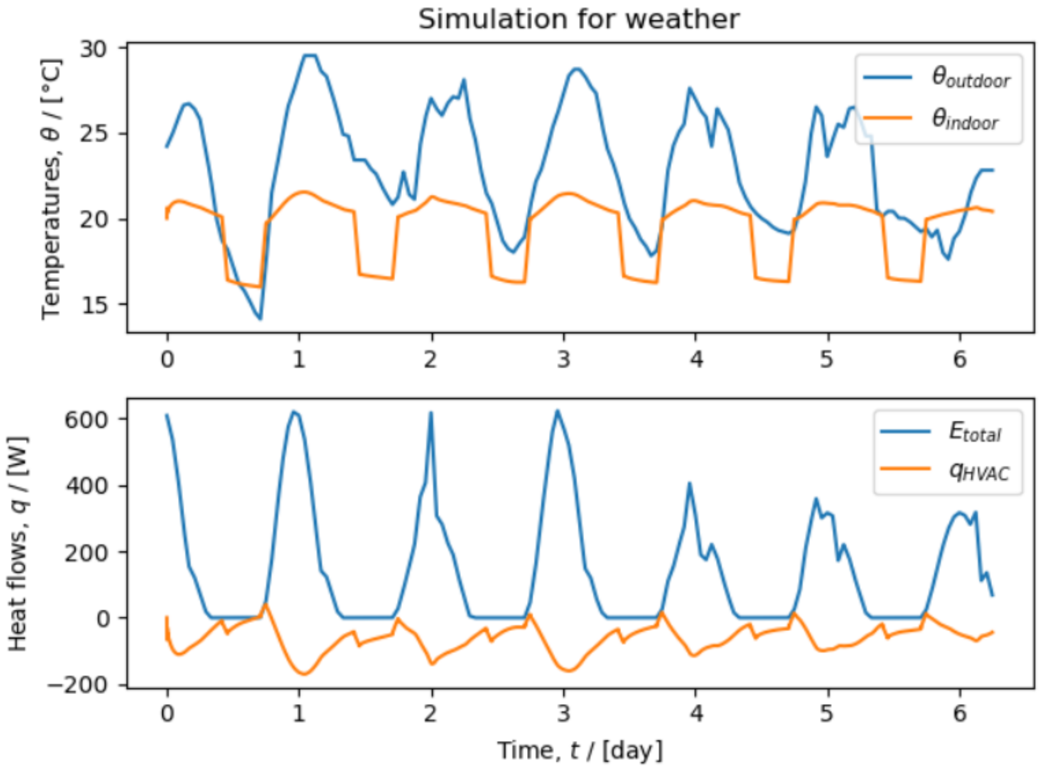


Figure 12 : Evolution of temperature and heat flows for 6 days in August

In summer, outdoor temperature is usually higher than indoor temperature, here set at 20°C. The first graph shows it. The outdoor temperature follows the variations of E_{tot}, the total solar radiation intensity on the wall. The more radiation there is, the higher the outdoor temperature will be. As outdoor temperature is bigger than 20°C, the power that the HVAC system needs to deliver to maintain the indoor air temperature at 20°C is negative.

The indoor air needs to be cooled, unlike in winter when heating is required to reach the desired temperature. According to the second graph, as radiation increases, the heat flow intensifies to lower the indoor temperature.

Utility of a controller

The behaviour of the system is studied when the controller is considered or not.
The weather data used are the February ones.

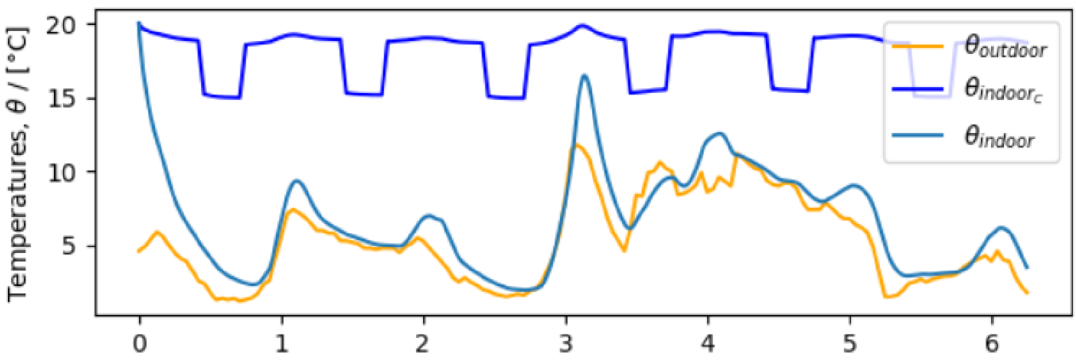


Figure 13 : Evolution of temperatures depending on the use of the controller

When the controller is not considered the indoor temperature follows the fluctuations of the outdoor temperature. Adding a controller allows us to control indoor temperature: according to the first graph, the controller gives the possibility to reduce indoor temperature during the night and increase it during the day. It allows people to do energy savings.

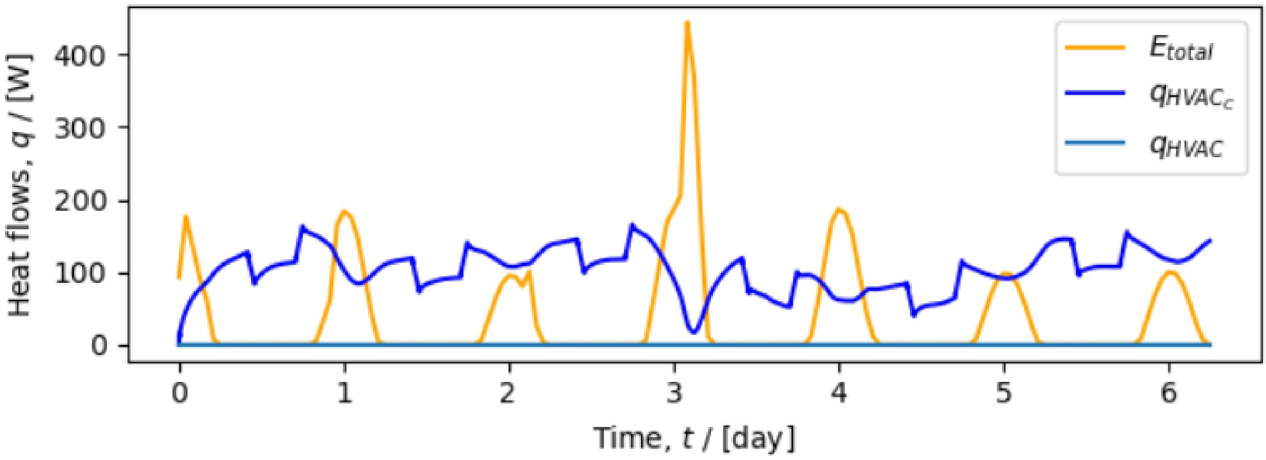


Figure 14 : Evolution of heat flows depending on the use of the controller

On the other hand, we can focus on the thermal load, q_{HVAC}, which is the power that the HVAC system needs to deliver in order to maintain the indoor air temperature at its set-point, $\theta_0 = 20°C$.
We are in February, so in winter, implying $q_{HVAC} > 0$. It means that we must produce heat in order to reach the desired indoor temperature.

According to the model that takes the controller into account, we observe that we need more power to maintain the indoor temperature constant, when the total solar irradiance is low. The more solar irradiance there is, the less heating we will need in winter.

Without a controller, the thermal load equals 0. It's logical since the indoor temperature is not controlled.

Concerning time steps, Figure 15 shows us that not considering the controller implies that the time step is larger. On the contrary, adding a temperature controller adds complexity to the initial model. Therefore, calculations must be done at shorter intervals, implying the use of a little time step.

	dt (s)
With perfect controller	50.0
Without perfect controller	300.0

Figure 15 : Time steps obtained for the two cases: with and without a controller

Influence of the controller gain

Here we study the behaviour of the system when the gain of the controller changes.
The weather data used are the February ones.
As before, the indoor temperature and heat flows are studied.

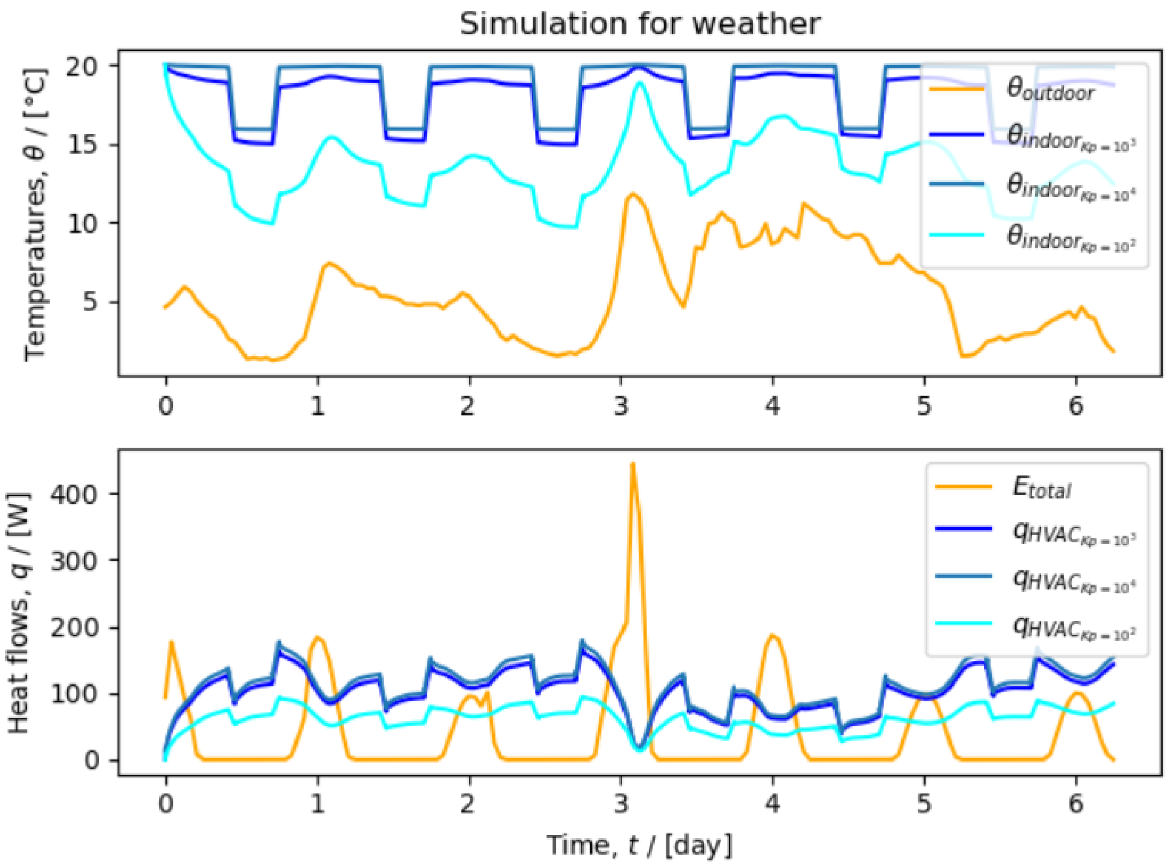


Figure 16 : Evolution of temperatures for different values of gain

The value of the controller's gain has a major effect on the temperature inside a building. The larger K_p is and the closer it is to infinity, the closer the indoor temperature will be to the desired comfort values. Conversely, the smaller K_p is and the closer it is to zero, the less effective the temperature controller will be, and the indoor temperature will follow the fluctuations of the outdoor temperature. However, with a high K_p, the calculation time will be longer, which can be a disadvantage. Calculation time is therefore longer.

	dt (s)
$Kp = 10^2$ **W/K**	240.0
$Kp = 10^3$ **W/K**	50.0
$Kp = 10^4$ **W/K**	6.0

Figure 17 : Time steps used for different values of gain

As the controller gain increases, it gets closer and closer to a perfect controller.
According to these results, we understand that the time step must be small for the calculations to run smoothly.