THERMAL MODELIZATION OF A SIMPLE BUILDING

Cours of Energy Management in Buildings
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Introduction

This report contains all the results obtained by analyzing the thermical behavour of a simple building. The aim of this work was to use an effective virtual model in order to represent the building in a more simplified way and to develop some thermical simulations that faithfully reproduce the real case.

After describing the building in its geometry and the technical solutions chosen for the enveloppe, we have defined the hypothesis and the boundary conditions, such as local weather, internal gains (occupants, lighting, electronic devices…) and heating and ventilation system.

Secondly, we have created a R/C model considering both the hypothesis and the characteristics of materials. In this way, we've obtained a graph wich schematize the thermical functioning of the building. Knowing the difference of temperature between the nodes, we have also noted the heating flows with their directions .Depending on this scheme, we have defined the terms of the matrices needed for the thermodynamic simulations.

All the information has been entered in a MATLAB model, that has been used for simulating the thermical behavour of the building. Depending on the aim of each simulation, we have changed some settings of the model, like, for example, the time range considered.

Finally, after discussing about the results, we have searched some strategies to improve the thermical performance of the building. We have made some optimizations like changing the wall's thickness or the materials.

1. Description of the building

The following image represents the building that has been studied.

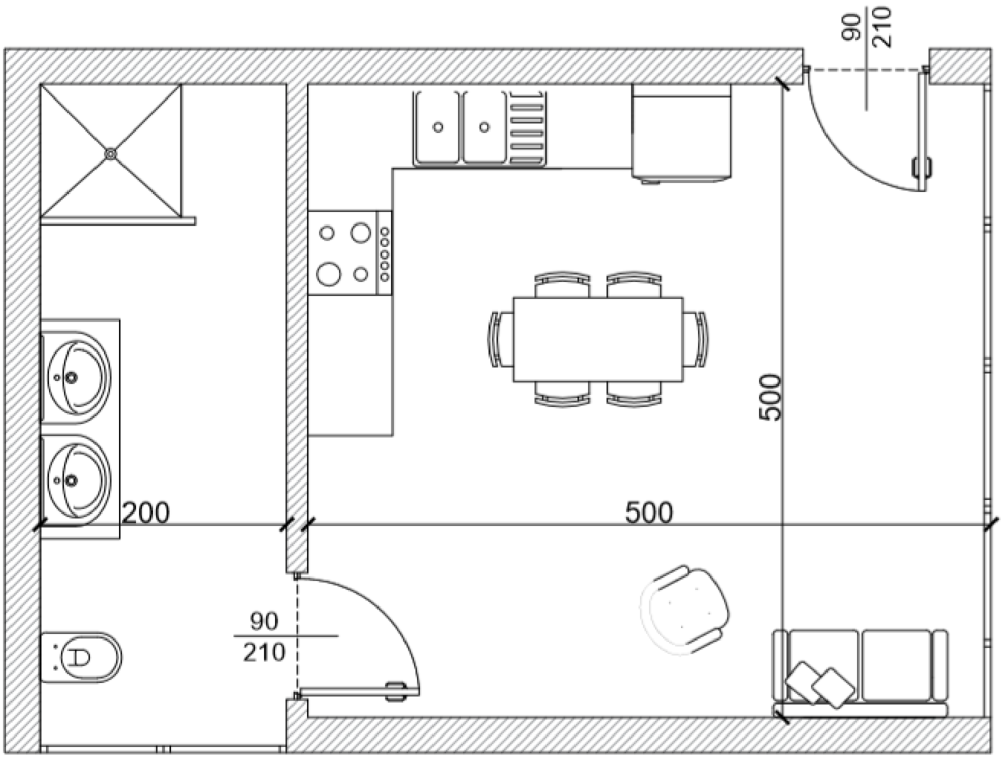


Figure 1 – Characteristics of the building

The apartment is a loft. It's a T1 composed of an open space with the kitchen and the living/bedroom and a bathroom for a total surface of 35 m². The main room is around 25 m² and the bathroom is around 10 m² for the bathroom.

All the walls are made of concrete, but only the external ones are isolated. The external walls are composed of 20 cm of concrete and 8 cm of insulation; the wall between livingroom and bathroom is composed of 10 cm of concrete without insulation. The living room is lit up thanks to a fully-windowed wall, so as the toilet. The window thickness is 1 cm. We made simulations about different transmittance's coefficient of those windows, in order to improve the system.

Both the floor and the roof are made of concrete and insulation, with the same thickness and characteristics used for the external walls. This is possible thanks to the stilts under our building, because it doesn't touch the ground directly. This means that we consider the same temperature all around the apartment.

2. Hypothesis for modelling

To modelize the building, we made some hypothesis :

- We only have 1D thermal Exchange, because the thickness of the wall is small compared to the height and the width.
- The diffused solar flow is placed on every surface of the building.
- All the external walls have the same composition and same characteristics, including the roof and the floor.
- We consider the building as settled on stilts, so that the ground and the walls are in contact with the same air temperature.
- There is no reflected radiative flow between walls and glass.
- There is no conduction at the junction between walls and glass, because the variation is negligible.
- The density and the capacity of the air are identical in each room.
- We neglected the capacity of the door.
- The flow absorbed by the window is neglected.
- We consider the internal walls as white surfaces.
- A direct radiation flow is added in some simulations. In those ones, the direct flow is applied on some surfaces only: the roof, one of the side walls of the living room and the living room glass.
- The initial inside temperature is always 20°C.

3. Model

To modelize our system we have used the fundamental principles of thermodynamics (figure 2).

0th principle : temperature scales ($e_1 = \theta_0 - \theta_1 + b$)
1st principle : energy conservation ($q_1 - q_2 = -f$)
2nd principle and constitutive laws: direction / value of heat ($q_1 = G_1 e_1$)

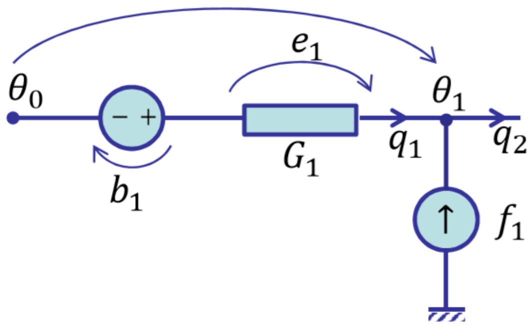


Figure 2 – Schéma of fundamental principles of thermodynamics

b_1 means we inject energy without changing the temperature. For example the temperature outside is independent of the wall during our simulation.

f_1 means we inject energy without changing the flow (for example a radiator).

The resistance e_1 correspond to the convection or conduction depending on the case.

Thanks to this figure, we can modelize our system and create the thermal model of the full building by adding the capacity of the air inside.

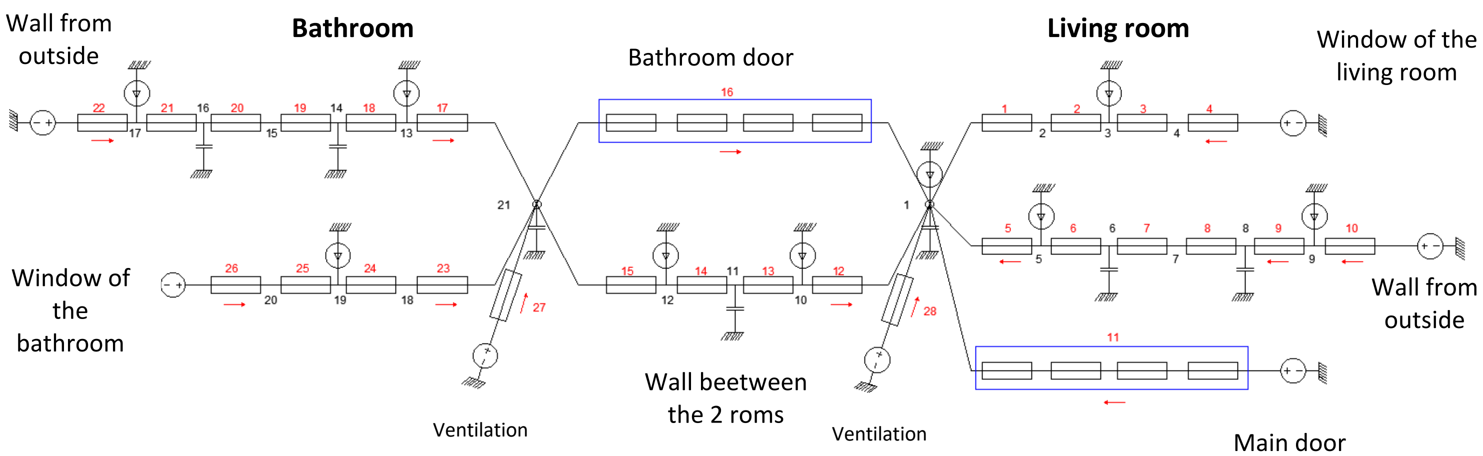


Figure 3 – Schéma of the thermal model

The nodes and the resistances were numbered appropriately and used to determine the matrices for the model.

The living room is connected with the window, the main door, the bathroom door, the wall between the bathroom and the living room and an external wall. We consider that the roof, the floor and the 2 others walls from outside have the same characteritiscts as the one represented in the model, so we can report them as an equivalent big wall (named "Wall" from outside in the figure 3).

In the thermal model, a wall is divided into 2 parts : the concrete thikness and the insulation thickness.

If we take into account the modelisation of the external wall for the living room, we can explain all the resistances, capacities etc... We obtain the following figure (figure 6).

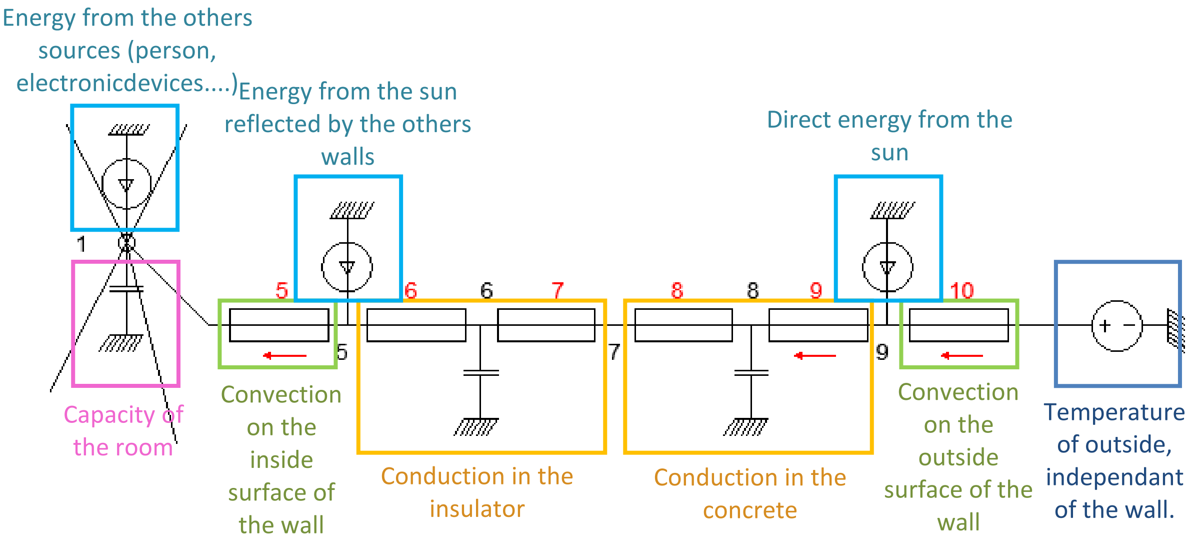


Figure 4 – Details of the thermal model for the wall from outside

To obtain the system of linear equation for the whole model, we have to :

- Obtain all the potential differences.
- Obtain consecutive laws.
- Perform balance sheet.

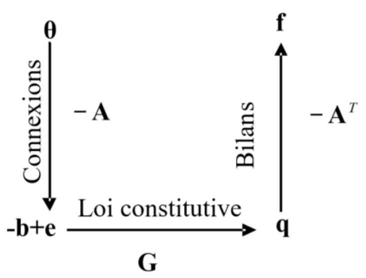


Figure 5 – Pattern of the equations

This can be expressed in the pattern of figure 5, naming θ the temperature of the nodes, e the temperature differences over resistances, q the heat flow through resistances and f the external fluxes.

To solve the system, we had to solve the following equativo, which can be linked whith the previous pattern.

$$\mathbf{C}\dot{\boldsymbol{\theta}} = -\mathbf{A}^T\mathbf{G}\mathbf{A}\boldsymbol{\theta} + \mathbf{A}^T\mathbf{G}\mathbf{b} + \mathbf{f}$$

The C-matrix respresents the capacity of the different surfaces. This matrice is defined depending on our choices of dimensions and materials.

The A-matrix represents how a flow is connected to nodes. The number of lines is equal to the number of flows and the number of columns is equal to the number of nodes. Beforehand we've decided the direction of each flow from each branch (figure 3). If the path from the branch to the node is in the same direction as the flow, the corresponding coefficient in the A-matrix will be 1. If the flow is in the opposite direction, the coefficient will be -1.

The G-matrix represents the conductances of the surfaces (conduction or convection). The conductance is the reverse of the resistance for each surface. This matrice is also defined by our choices of dimensions and materials.

The b-matrix respresents the temperatures imposed in the system. We have put a value of temperature for the branchs which are connected to a temperature (outside temperature for example).

The f-matrix represents the sources imposed in the system. We have put a value for the nodes where there is a source (radiator in a room for example).

Matrix are written in appendix.

The building is divided in two different areas:

Area	**Surface (m^2)**
Zone A (living room+kitchen)	25
Zone B (bathroom)	10

Table 1-Room's areas.

The building is made of shuttering panel filled with concrete. At first, we have put a layer of rockwool insulation on this concrete. The wall between the two rooms is made only of concrete. We can also find a window in each room and doors, one for the main entrance and the second to go from A to B.
The characteristics of the materials are shown in the table below (Table 2).

Material	Thermal conductivity (W/m.K)	Specific heat capacity (J/kg/K)	Density (kg/m^3)
Air	0.026	1000	1.2
Glass	1.2	720	2500
Concrete	2	1000	2500
Insulation	0.04	840	157
Door	0.36	neglected	500

Table 2 - Material's characteristics.

Thanks to the Matlab program and to the characteristics of each materials, we have studied this building, considering the following conductances (Table 3).

Material	Conductance (W/m²/K)
Exteriorconcretewall	6
Interiorconcretewall	12
Insulation	0.5
Doors	7.2

Table 3 - Conductance's value for each material of our building.

In order to thermally improve our building, we've tried to change the type of window. For doing this, we have had to change the value of their conductance and transmittanc on Matlab.

Windows	Conductance (W/m²/K)	Transmittance SW
Simple	5.8	0,8
Double	2.8	0,7
Triple	1.9	0,5

Table 4 - Conductance and transmittance coefficients for each type of window

4. Simulation

With the goal to thermally optimise this building, we've made many analysis, both in winter and in summer, in order to compare the results obtained in the two seasons.

For this reason, we've tried to create a dynamic model thanks to which it is possible to monitor the evolution of the weather in function of time.

We started from the solution of the thermal analysis, which is the following differential equation :

$$\mathbf{C}\dot{\boldsymbol{\theta}} = -\mathbf{A}^T\mathbf{G}\mathbf{A}\boldsymbol{\theta} + \mathbf{A}^T\mathbf{G}\mathbf{b} + \mathbf{f}$$

The matrix A gives us the description of how the flows are connected with nodes. It has a number of lines equal to the number of flows and a number of columns equal to the number of nodes. If the node "receives" the flow, the coefficient will be 1 and if it not, the coefficient will be -1.
The matrix B corresponds to the description of the external sources. This column-matrix has a number of lines equal to the number of flows. If the flow comes from an external source, the coefficient will be 1. If it doesn't, the coefficient will be 0.
The matrix C corresponds to the description of all the capacities of the system. They will help us to model the response of the air temperature by not changing his value very quickly. This diagonal matrix has a number of lines and columns equal to the number of nodes. If the node has a capacity its value will be dependant of the material they are putted in. If the node doesn't have a capacity the value will be 0.
The matrix G corresponds to the description of the resistances of all the materials (conduction and convection). This diagonal matrix has the number of lines and columns equal to the number of flows and its value depends on the material.
The matrix f corresponds to the description of external flows, like the sun. It has a number of lines equal to the number of nodes and its values depends on the flow. If the node does not have an external flow the value will be 0.
The matrix y corresponds to the temperatures that we need to calculate. This matrix has a number of lines equal to the number of nodes. In our case, we are looking for the temperatures of the nodes 1 and 21 that corresponds to the inside temperature in both zones.

All of these matrix were treated with the function fTC2SS and we obtained different matrix As,Bs,Cs and Ds. We were able to build the dynamic model as below :

$$\begin{cases} \dot{\boldsymbol{\theta}}_C = \mathbf{A}_S\boldsymbol{\theta}_C + \mathbf{B}_S\mathbf{u} \\ \boldsymbol{\theta}_0 = \mathbf{C}_S\boldsymbol{\theta}_C + \mathbf{D}_S\mathbf{u} \end{cases}$$

It gives us a state-space representation of our walls and windows.

Finally, the matrix u describes the external sources and flows as below.

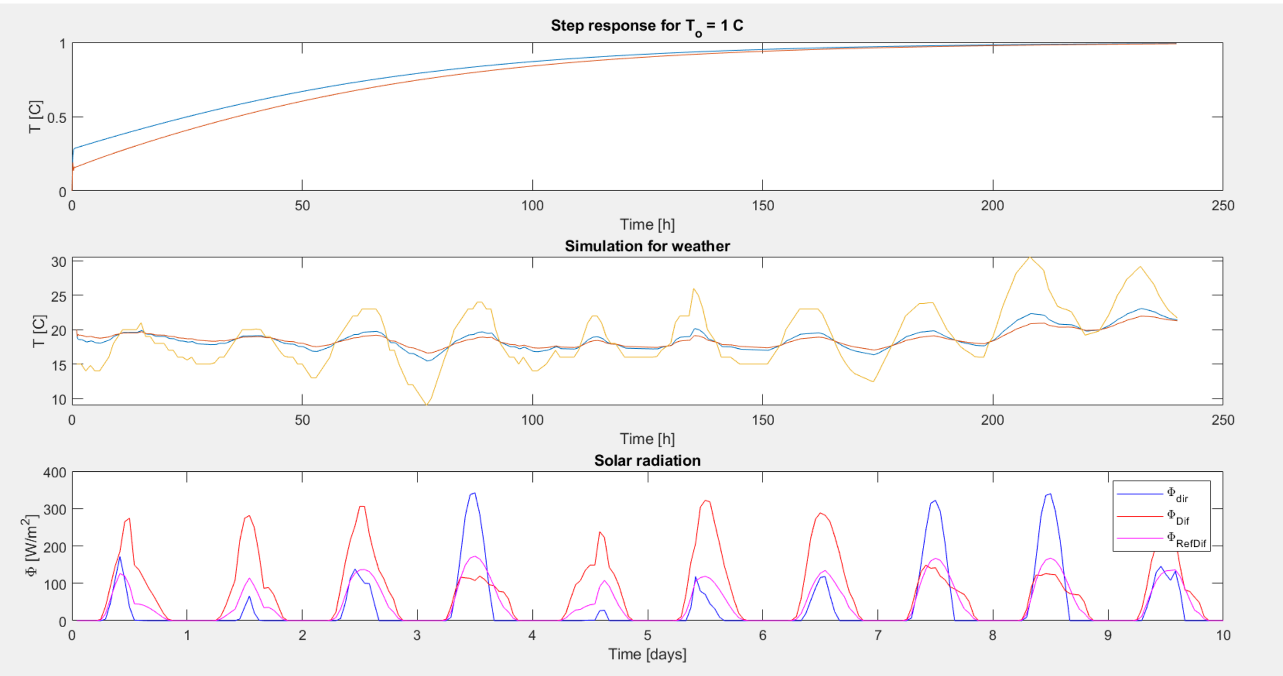
```
u = [Temp Temp Temp Temp Temp Temp Temp...
Qa phiaga phiia phi0a phiiaba phiiabb phiib phi0b phiagb]';
```

```
% Inputs
PhiTot = PhiRef+PhiDif;
phiaga=alphagSW*(Sga)*PhiTot*0;
phiagb=alphagSW*(Sgb)*PhiTot*0;
phiia= alphacSW*4*Fwg*taugSW*(Sga)*(PhiTot+PhiDir);
phiib= alphacSW*4*Fwg*taugSW*(Sgb)*(PhiTot);
phi0a=epswSW*(Sca-25)*PhiTot+epswSW*(Sca-25-15)*PhiDir;
phi0b=epswSW*(Scb-10)*PhiTot+epswSW*(10)*PhiDir;
phiiaba= alphacSW*Fwg*taugSW*(Sga)*(PhiTot+PhiDir);
phiiabb= alphacSW*Fwg*taugSW*(Sgb)*(PhiTot);
```

Temp corresponds to the outside temperature, Qa to the auxiliaries sources and all of the phi to the flow coming from the sun. PhiTot corresponds only to the flow reflected and diffused from the sun. We decided to put a direct flow only in some of the surfaces (the roof, one of the side walls of the living room and the living room glass).

The Matlab code is in the appendix.

At first, we have studied the building without adding any special equipement, such as HVAC system for example. With these settings we have obtained the results below.



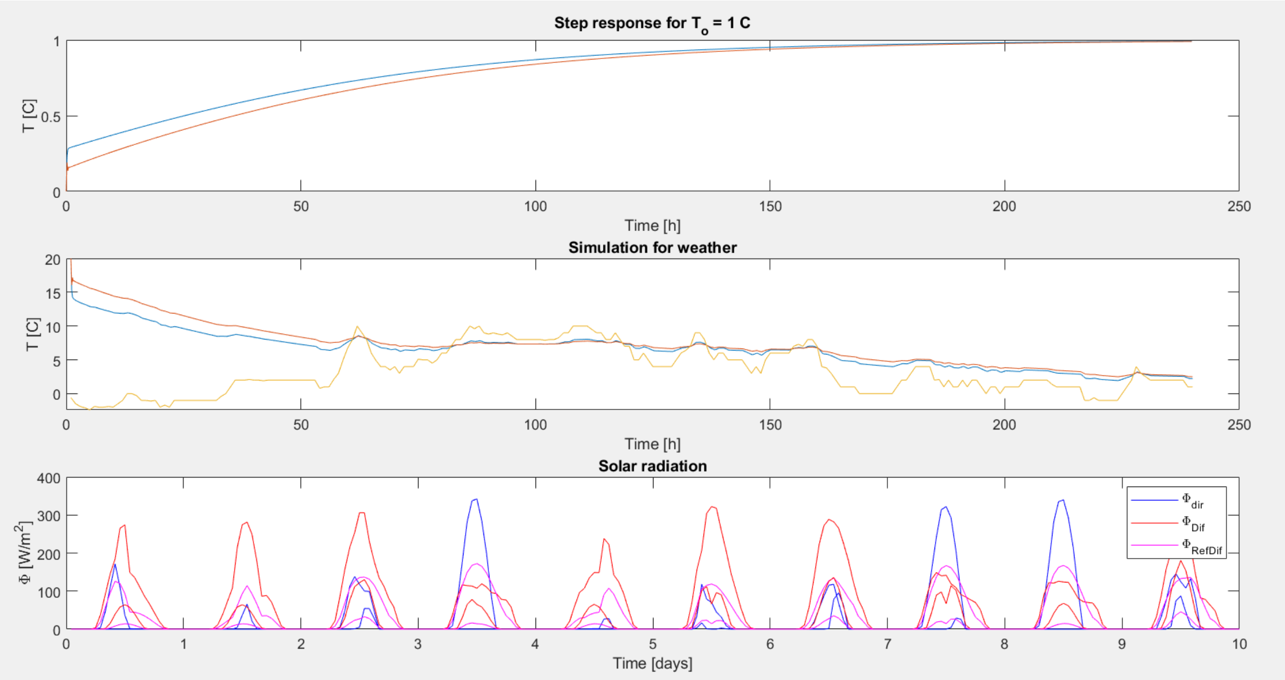


Figure 6 – First modelization without speciality in Summer (on top) and in Winter (below)

We have a response time similar in both cases. It takes about 225 hours to attempt the 1 degree Temperature. The variation is about 0,8 degree. Reaching this temperature shows us that we don't have an error in the way we modelized our building. We can see that the inside temperatures (orange and blue lines for the 2 rooms) have a lot of pics and vary constantly. In Winter after 10 days we reach an inside temperature of 5°C which is very low. That's why we had to add a heater and a cooler.
In order to stabilize those temperatures we can add a controller.

To make our model more realistic, we have chosen to add some ventilation. Thit represents the renewal air, whose values are imposed by the reglementation: at least of 15 m3/h in the bathroom and 30 m3/h in the living room. In our case, we've chosen to set the following air renewal rate:

Room	Air renewal rate [m^3/h]
Bathroom	15
Living Room	37

Table 5 – Air renewal rate

To add this air renewal in the code, we've modelised them as flows getting inside the internal nodes. Indeed, we've calculated the value of equivalent conductances as :

Gva = Vpa*rhoa*ca; The conductance due to the air renewal in the living-room
Gvb = Vpb*rhob*cb; The conductance due to the air renewal in the bathroom

With :

→ rhoa, rhob, ca, cb : the characteristics of the inside air considered equals for both rooms.

→ Vpa and Vpb : the air renewal rates

Then, we've added a heat controller to represent a heater and a cooler that trie to set the temperature at an imposed value. In our case, we've chosen to set this temperature at Tc=20[°C]. After taking the controller into account in the code, we have added the following loop:

```
187  for k = 1:n-1
188      th(:,k+1) = (eye(nth) + dt*As)*th(:,k) + dt*Bs*u(:,k);
189      Qhvac(k+1) = Kp*(Tc-th(1,k));
190          if Qhvac(k+1) < 0
191              Qcool(k+1)= Qhvac(k+1);
192          else Qheat(k+1)=Qhvac(k+1);
193          end
194      u(8,k+1)= u(8,k+1)+Qheat(k+1)+Qcool(k+1);
195  end
```

In this loop we have :

Line 189 : Qhvac represents the necessary flow to reach the temperature Tc.

Line 191 : Qcool represents the necessary cooling flow to reach the temperature Tc.

Line 192 : Qheat represents the necessary heating flow to reach the temperature Tc.

Line 194 : We add the value of Qheat and Qcool in the u vector.

It is important to notice that this is a simplified model of controller, that isn't perfect. Indeed, the set point temperature is 20°C no matter the season, which implies an energy consumption when it is not necessary for comfort. For example, in summer, an inside temperature of 23°C wouldn't need to be cooled down.

Once the controller was added into the code, we had to use/find the best K coefficient, so we tested many values to find the better one. We began with a value of K= 300 and we had an important instability in our numerical modelisation (figure 8). An instability can be observed at the end of the experimentation if we found an extreme inside temperature (around 10246 °C) or at the beginning if we observe a lot of variations as an oscillation of the temperature in a short amount of time.

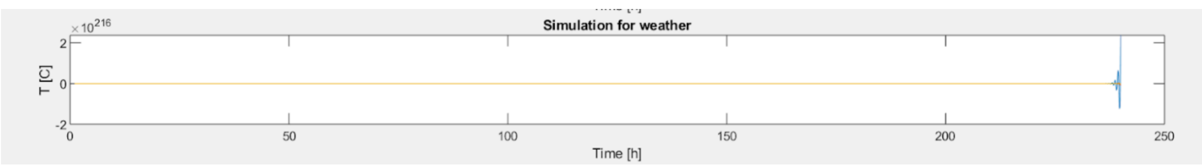


Figure 8 – Results for K=300

Then, we have done this with other values as K=150 in a first time and K=100 in another time. For K=150, we had an important oscillation of the temperature in the good interval (figure 9). So, we were unable to use this simulation with this kind of instabilities because we could not quantify the consumption or determine the inside temperature.

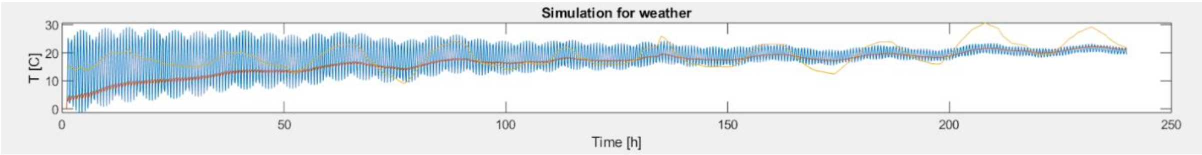


Figure 9 – Results for K=150

We finally used the K= 100 where there is just a little instability at the beginning but, after this, the results are exploitable (figure 10). It allows us to determine the right inside temperature and also the energy consumption.

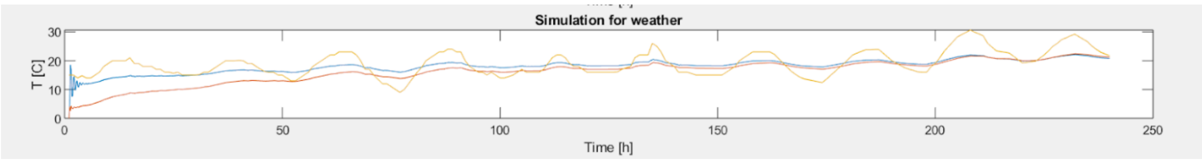


Figure 10 – Results for K=100

In order to see if K=100 is the best one we have done a last experiment with a K=1 (figure 11) and we conclude that, the more K has a high value the more the temperature is going to stabilize quickly. But, the higher K is the higher is the risk of numerical instability but a very low one involve a lot of variations. So, we had to find the one between those two extremes.

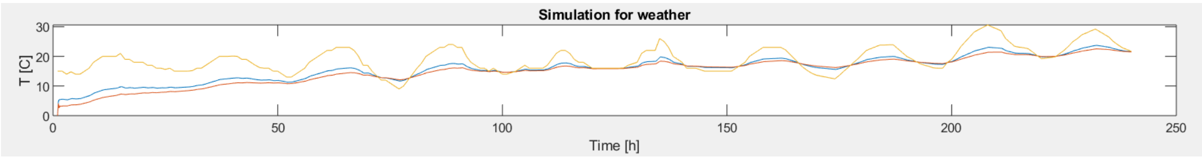


Figure 11 – Results for K=1

Otherwise, this problem of instability can be also solved with a different time-step value because it could be a source of error. So, we need to balance between those origins of instability.

Finally, for this project, we decided to use a time-step of dt= 100 (in seconds) and a K value of K=500. We obtained the results below with the controller (figure 7). We can see that in Winter we have only heating consumption and in Summer we have most of the time a cooling consumption.

We will use this model as a reference for all the modelizations.

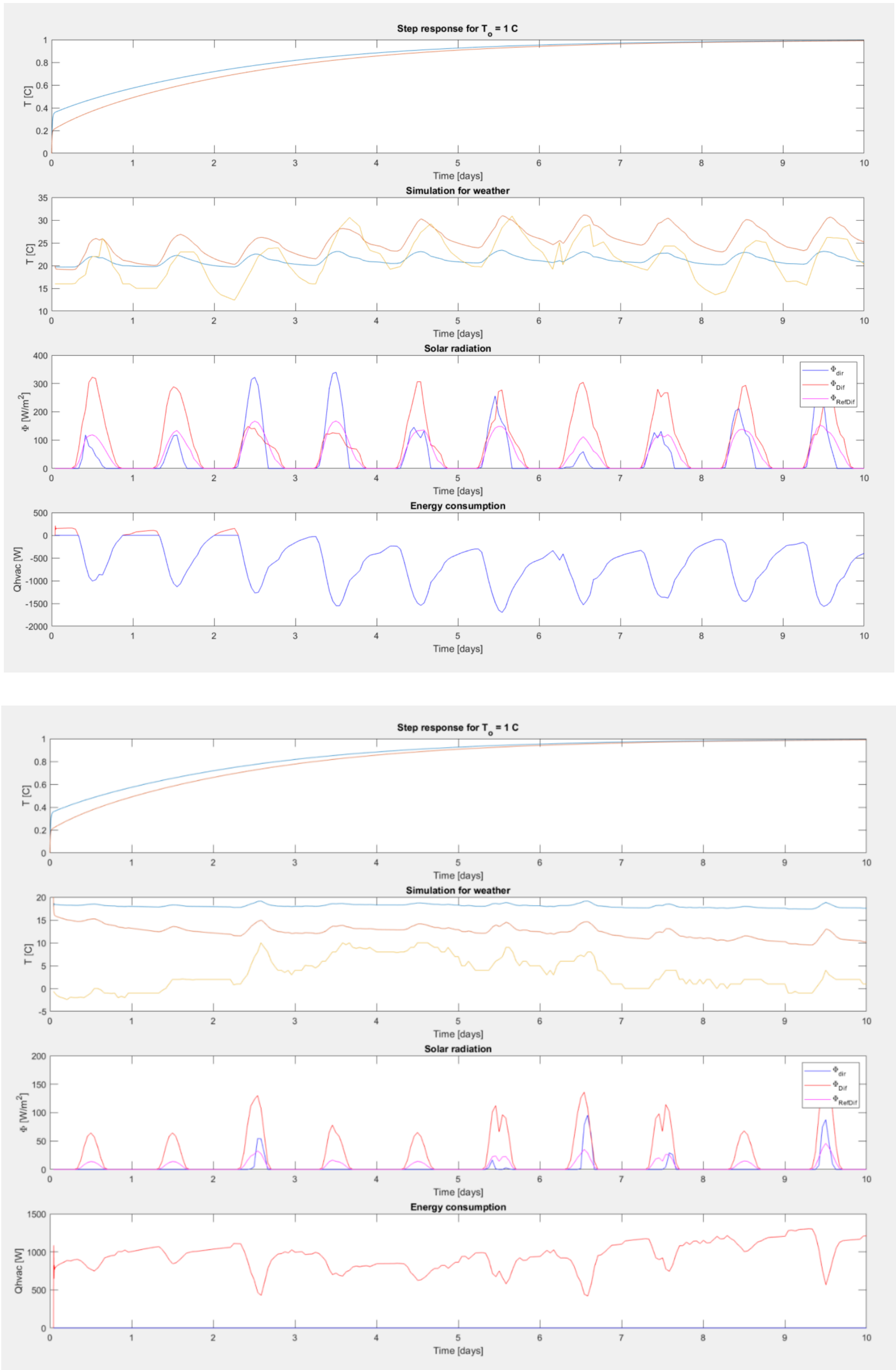


Figure 7 – Reference modelization with the controller in Summer (on top) and in Winter (below)

5. Optimisation

For every variations, differences were hard to locate and notice by just looking at the graph. So we decided to quantify by calculating the energy consumption over the time of the simulation. In addition, we calculated a price for this consumption and a price variation based on the references.The price is calculated with a unit price of 0,1546 [€/kWh]. In all tables, the light blue lines are those of the reference case. This case is the one explicit in our introduction with an inside insulation. We have made a comparison between summer and winter seasons, with a duration of ten days in all cases. The lines with a 1 in the column "PhiDir" are the simulations made with a direct radiation flow distributed as explained in the hypothesis. The lines with a 0 in the "PhiDir" column are made without direct radiation flow.

1. Variation 1 : Invert concrete and insulation

In the first variation we decided to change the position of insulation. Instead of putting it inside, we put it outside to test if it is more efficient or not.
In the code, we had to change the characteristics of the concrete to the insulation characteristics and same for the others.

Interior/Exterior Insulation							
Variante	Season	Duration [days]	Cooling Energy [kWh]	Heating Energy [kWh]	Price [€]	Phi Dir	Price Variation
Interior Insulation	Winter	10	0	228,8405	35,3787	0	-
Exterior Insulation	Winter	10	0	208,8619	32,2901	0	-9%
Interior Insulation	Summer	10	125,1272	2,5228	19,7347	0	-
Exterior Insulation	Summer	10	103,3324	1,5638	16,2170	0	-18%
Interior Insulation	Summer	10	150,645	2,328	23,6496	1	-
Exterior Insulation	Summer	10	124,8125	1,3478	19,5044	1	-18%

Table 6 – Results for variation 1

In this first experiment of optimization we have seen that, for an apartment, to put the insulation in the exterior is a very good way to improve it thermally. In the table (table 6), we see a diminution of 18% of the price due to the consumption of energy and this, during the summer. In winter, the diminution is only of 9%. Even if this result isnot as good as for summer, it is still a good improvement. We can say that the exterior insulation seems to be a good solution to reduce the energy consumption.

2. Variation 2 : Modelization increasing only concrete's thickness

For the rest of modelizations, we still have used the first model as a reference to find the best one (insulation inside).
But this time, we tried to increase the thickness of the concrete and see the impact on the controller consumption. We finally obtain the results in the table below (table 7).

Concrete's Thickness							
Variante	Season	Duration [days]	Cooling Energy [kWh]	Heating Energy [kWh]	Price [€]	Phi Dir	Price Variation
Concrete 20 cm	Winter	10	0	228,8405	35,3787	0	-
Concrete 40 cm	Winter	10	0	214,4688	33,1569	0	-6%
Concrete 20 cm	Summer	10	125,1272	2,5228	19,7347	0	-
Concrete 40 cm	Summer	10	118,8093	2,9202	18,8194	0	-5%
Concrete 20 cm	Summer	10	150,6450	2,3280	23,6496	1	-
Concrete 40 cm	Summer	10	143,5912	2,6815	22,6138	1	-4%

Table 7 – Results for variation 2

We have seen that energies are not really varied if we increase the concrete's thickness because of the high value of its conductivity coefficient. That is why we only observed a diminution of few percents (between 4% and 5%) if we compare it to references. Given that, it would be more expensive and it would take more space to make a 40cm concrete wall, this solution might not be very profitable.

3. Variation 3 : Modelization increasing only the insulation's thickness

Once we have increased the concrete's thickness and analyzed its effects, we tried in this 3rd variation to increase the insulation. We kept a concrete wall of 20cm but we replaced the initial 8cm insulation by a 20cm one.
Then, after we modified the program to obtain this simulation we were able to compare the results with the last modelization for the same period and the amount of time. This is what we obtain in the table below (table 8).

Insulation's Thickness							
Variante	Season	Duration [days]	Cooling Energy [kWh]	Heating Energy [kWh]	Price [€]	Phi Dir	Price Variation
Insulation 8cm	Summer	10	150,645	2,328	23,6496	1	-
Insulation 20cm	Summer	10	136,3731	3,7968	21,6703	1	-8%
Insulation 8cm	Winter	10	0	227,1367	35,1153	1	
Insulation 20cm	Winter	10	0	183,882	28,4282	1	-19%

Table 8 – Results for variation 3

We observed a bigger difference than in the previous variation (table 8). So, with a bigger thickness of insulation, we have a price variation of 19% during the winter period. This percentage is something not negligible. But, we have just 8% for the summer. However, we can't make a conclusion about the efficiency of this solution because we didn't take the price of the insulation itself into account.

4. Variation 4 : Changing the transmittance coefficient of the window

For variation 4, we changed in our program the transmittance coefficient of the window, which was at the beginning Tsw = 0.8. In order to improve this characteristic, we found values for many kinds of windows listed previously. We have done the experiment with few of them and compared them.

Type of Glass							
Variante	Season	Duration [days]	Cooling Energy [kWh]	Heating Energy [kWh]	Price [€]	Phi Dir	Price Variation
Simple 5,8[W/m²K] / Ƭsw=0,8	Winter	10	0	227,1367	35,1153	1	-
Double 2,8[W/m²K] / Ƭsw=0,7	Winter	10	0	203,9454	31,53	1	-10%
Triple 1,9[W/m²K] / Ƭsw=0,5	Winter	10	0	194,2099	30,0249	1	-14%
Simple 5,8[W/m²K] / Ƭsw=0,8	Summer	10	150,645	2,328	23,6496	1	-
Double 2,8[W/m²K] / Ƭsw=0,7	Summer	10	137,8719	1,7679	21,5883	1	-9%
Triple 1,9[W/m²K] / Ƭsw=0,5	Summer	10	111,5727	1,8244	17,5312	1	-26%

Table 9 – Results for variation 4

Windows are often something unconsidered in building amenagement but, as you might see in the previous table (table 9), the difference between a simple and a triple window is quite huge. That is why, with a diminution of 14% in winter and 26% in summer, the triple window is the best option to choose thermally speaking. Once again, the cost of a triple glass would have to be taken into account to draw a conclusion about the profitability of that glass.

5. Variation 5 : Changing materials

Instead of changing the thickness of the wall, we change now the materials themselves. First we replaced glasswool by polyurethane and the concrete by terracotta brick. We had to change the materials characteristics in the program so we found them on internet (appendix) and put them in it to simulate thermally our apartment. We obtain results below.

Materials							
Variante	Season	Duration [days]	Cooling Energy [kWh]	Heating Energy [kWh]	Price [€]	Phi Dir	Price Variation
Glasswool 0,04[W/m²K]	Summer	10	150,645	2,328	23,6496	1	-
Polyurethane 0,025[W/m²K]	Summer	10	141,3119	3,0766	22,3225	1	-6%
Glasswool 0,04[W/m²K]	Winter	10	0	227,1367	35,1153	1	-
Polyurethane 0,025[W/m²K]	Winter	10	0	198,6868	30,717	1	-13%
Concrete 1,2 [W/m²K]	Summer	10	150,645	2,328	23,6496	1	-
Terracotta brick 0,3 [W/m²K]	Summer	10	132,1423	3,43	20,9595	1	-11%
Concrete 1,2 [W/m²K]	Winter	10	0	227,1367	35,1153	1	-
Terracotta brick 0,3 [W/m²K]	Winter	10	0	184,7527	28,5628	1	-19%

Table 10 – Results for variation 5

For the new insulation material, it is not a big variation compared to windows but it still is something important in our project to have the best thermal comfort and the smallest energy consumption as possible. For the brick instead of the concrete, the variation is bigger and it could be a great alternative to concrete to reach better thermal characteristics. The limits of this material could however be its strength that might reduce its range of application.

Conclusion

This project helped us to understand how to modelize a simple building using matlab in order to study its thermal behavior. During our coding, we faced different problems coming from various sources. Indeed, some errors in the code were due to syntax errors (like commas instead of dots or wrong naming of variables).

Others were not visible or not reported in the code because they were due to a gap between what we wanted to model and what the code did. Finally the last source of problems has been the numerical instabilities that we explained previously.

Through the study of the different variations, we tested the efficiency of those alternatives to save energy and improve the thermal comfort inside the building. In a future project, it could be interesting to test the building under other conditions, in order to be closer to reality.

Appendix

Matlab code

```
% Cube with 2 walls and feed-back
clc, clear all, clf

%Physical values
%****************************
Kp = 1e0;              %P-controller gain: large for precision
Sca=(5+4.1)*3+5*5;  Sia=Sca;  Sga=5*3;  Sda=0.9*3;  Scab= 4.1*3;
Scb = (5+2)*3+5*2;  Sib = Scb;  Sgb=2*3;  Sdb = 3*0.9;  %surface [m2]: concrete,
insulation, glass
Va = 5*5*3;  Vb=5*2*3;          %air volume[m3]
rhoa = 1.2; ca = 1000;  rhob = rhoa ;  cb = ca;   %indoor air density; heat capacity
Vpa = 0.5*Va/3600;  Vpb = 0.5*Vb/3600;      %infiltration and ventilation air:
volume/hour

% c: concrete; i: insulation;  g: glass
lamc = 1.2;    lamcab=1.2;   lami = 0.04;    lamg = 1.2;   lamd = 0.36;%[W/m K]
gsimple=5.8; %[W/m K]
gdouble=2.8; %[W/m K]
gtriple=1.9; %[W/m K]
gtriplegaz=0.6; %[W/m K]

rhoccc = 2.0e6; rhoici = 2.5e6; rhogcg = 2.0e6; %[J/m3 K]
wc = 0.2;       wcab= 0.1;   wi = 0.08;     wd=0.05; %[m]
epswLW = 0.9;   %long wave wall emmisivity
epswSW = 0.8;   %short wave wall emmisivity

epsgLW = 0.9;   %long wave glass emmisivity
taugSW = 0.8;   %short wave glass transmitance
alphagSW = 0.2; %short wave glass absortivity

sigma = 5.67e-8;%[W/m2 K4]
Fwg = 1/5;      %view factor wall - glass
Tm = 20 + 273;  %mean temp for radiative exchange

% convection coefficients
ho = 10;    hi = 4;    %[W/m2 K]
%***************************

% Conductances and capacities
Gca = lamc/wc*Sca; Cca = Sca*wc*rhoccc; %concrete area A
Gcb = lamc/wc*Scb; Ccb = Scb*wc*rhoccc; %concrete area B
Gcab = lamcab/wcab*Scab; Ccab = Scab*wcab*rhoccc; %concrete separation
Gia = lami/wi*Sia; Cia = Sia*wi*rhoici; %insulation A
Gib = lami/wi*Sib; Cib = Sib*wi*rhoici; %insulation B
Gga = gsimple*Sga; %Cga= Sga*wg*rhogcg; %glass  A
Ggb = gsimple*Sgb; %Cgb = Sgb*wg*rhogcg; %glass  B
Gd = lamd/wd*Sda;
Ca = Va*rhoa*ca;
Cb = Vb*rhob*cb;

% Convection
Gwoa = ho*Sca; Gwia = hi*Sia;          %convection wall out; wall in A
Gwob = ho*Scb; Gwib = hi*Sib;         %convection wall out; wall in  B
Ggoa = ho*Sga; Ggia = hi*Sga;          %convection glass out; glass in A
Ggob = ho*Sgb; Ggib = hi*Sgb;          %convection glass out; glass in B
Gwiab = hi*Scab;            %convection wall in; Separation
Gda = 1/(1/(hi*Sda)+ 1/(ho*Sda)+1/Gd);
Gdb = 1/(2/(hi*Sdb)+1/Gd);
% Long wave radiative exchange
    %GLW1 = epswLW/(1-epswLW)*Si*4*sigma*Tm^3;
    %GLW2 = Fwg*Si*4*sigma*Tm^3;
```

```
    %GLW = 1/(1/GLW1 + 1/GLW2 +1/GLW3);  %long-wave exg. wall-glass
% ventilation & advection
Gva = Vpa*rhoa*ca;                  %air ventilation
Gvb = Vpb*rhob*cb;                  %air ventilation
% glass: convection outdoor & conduction
%Ggs = 1/(1/Ggo + 1/(2*Gg));         %cv+cd glass

% Thermal network
% ******************************************
A=[1    -1   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0    0
0    1   -1   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
0    0   1   -1   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
0    0   0   1    0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
1    0   0   0   -1   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
0    0   0   0   1   -1   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
0    0   0   0   0   1   -1   0   0   0   0   0   0   0   0   0   0   0   0   0   0
0    0   0   0   0   0   1   -1   0   0   0   0   0   0   0   0   0   0   0   0   0
0    0   0   0   0   0   0   1   -1   0   0   0   0   0   0   0   0   0   0   0   0
0    0   0   0   0   0   0   0   1    0   0   0   0   0   0   0   0   0   0   0   0
1    0   0   0   0   0   0   0   0    0   0   0   0   0   0   0   0   0   0   0   0
1    0   0   0   0   0   0   0   0   -1   0   0   0   0   0   0   0   0   0   0   0
0    0   0   0   0   0   0   0   0   -1   1   0   0   0   0   0   0   0   0   0   0
0    0   0   0   0   0   0   0   0   0   -1   1   0   0   0   0   0   0   0   0   0
0    0   0   0   0   0   0   0   0   0   0   -1   0   0   0   0   0   0   0   0   1
1    0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   -1
0    0   0   0   0   0   0   0   0   0   0   0   -1   0   0   0   0   0   0   0   1
0    0   0   0   0   0   0   0   0   0   0   0   1   -1   0   0   0   0   0   0   0
0    0   0   0   0   0   0   0   0   0   0   0   0   1   -1   0   0   0   0   0   0
0    0   0   0   0   0   0   0   0   0   0   0   0   0   1   -1   0   0   0   0   0
0    0   0   0   0   0   0   0   0   0   0   0   0   0   0   1   -1   0   0   0   0
0    0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1    0   0   0   0
0    0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   -1   0   0   1
0    0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1   -1   0   0
0    0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1   -1   0
0    0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1    0
0    0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0    1
1    0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0    0];


G = diag([Ggia 2*Gga 2*Gga Ggoa Gwia 2*Gia 2*Gia 2*Gca 2*Gca Gwoa Gda Gwiab 2*Gcab 2*Gcab
Gwiab Gdb Gwib 2*Gib 2*Gib 2*Gcb 2*Gcb Gwob Ggib 2*Ggb 2*Ggb Ggob Gvb Gva]');
b = zeros(28,1); b(4) = 1; b(10) = 1; b(11) = 1; b(22) = 1;  b(26) = 1;  b(27) = 1;
b(28) = 1;
C = diag([Ca 0 0 0 0 Cia 0 Cca 0 0 Ccab 0 0 Cib 0 Ccb 0 0 0 0 Cb]);
f = zeros(21,1); f(1) = 1; f(3) = 1; f(5) = 1; f(9) = 1; f(10) = 1;f(12) = 1; f(13) = 1;
f(17) = 1; f(19) = 1;
y = zeros(21,1);
y(1) = 1; y(21) = 1;

% Thermal circuit -> state-space
% ***********************************************************************
[As,Bs,Cs,Ds] = fTC2SS(A,G,b,C,f,y);

% Maximum time-step
dtmax = min(-2./eig(As));% [s]
dt = 100;                      % [s] time step

% Step response
% ***********************************************************************
duree = 10;
duration = 3600*24*duree;    % [s] time duration
n = floor(duration/dt); % no of time samples

Time = 0:dt:(n-1)*dt;    % time
nth = size(As,1);        % no of state variables
th = zeros(nth,n);       % zero initial conditions
```

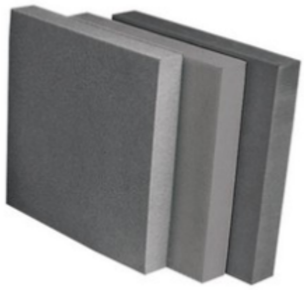
```
u = zeros(16,n);          % u = [To To To Tsp Phio Phii Qaux Phia]
u(1:7,:) = ones(7,n) ;  % To = step variation

for k = 1:n-1
 th(:,k+1) = (eye(nth) + dt*As)*th(:,k) + dt*Bs*u(:,k);

end
y = Cs*th + Ds*u;
subplot(4,1,1)
plot(Time/(24*3600),y)
xlabel('Time [days]'),ylabel('T [C]')
title('Step response for T_o = 1 C'),

% Simulation with weather data
% Load weather data
fileName = 'FRA_Lyon.csv';
from = 24*30*6 + 24*30;   % start time: from 30 July at 1:00 AM.
period = duree*24; % simulation period: for 10 days

[Time,Temp,RadNDir,RadHDif,WDir,WSpeed,month,day,hour,minute]...
    = fReadWeather(fileName,from,period);

B = 90; Z = 0; L = 45; albedo = 0.2;
[PhiDir, PhiDif, PhiRef] = fSolRadTiltSurf(month, day, hour, minute, ...
  RadNDir, RadHDif, B, Z, L, albedo);

% interpolate weather data for time step dt
Temp = interp1(Time, Temp, [Time(1):dt:Time(end)]');
PhiDir = interp1(Time, PhiDir, [Time(1):dt:Time(end)]');
PhiDif = interp1(Time, PhiDif, [Time(1):dt:Time(end)]');
PhiRef = interp1(Time, PhiRef, [Time(1):dt:Time(end)]');
Time = [Time(1):dt:Time(end)]';

n = size(Time,1);
th = zeros(nth,n);
Qa = zeros(n,1);  %auxiliary sources (electrical, persons, etc.)
TintSP = 20*ones(n,1);

alphacSW=0.26;

% Inputs
PhiTot = PhiRef+PhiDif;
phiaga=alphagSW*(Sga)*PhiTot*0;
phiagb=alphagSW*(Sgb)*PhiTot*0;
phiia= alphacSW*4*Fwg*taugSW*(Sga)*(PhiTot+PhiDir);
phiib= alphacSW*4*Fwg*taugSW*(Sgb)*(PhiTot);
phi0a=epswSW*(Sca-25)*PhiTot+epswSW*(Sca-25-15)*PhiDir;
phi0b=epswSW*(Scb-10)*PhiTot+epswSW*(10)*PhiDir;
phiiaba= alphacSW*Fwg*taugSW*(Sga)*(PhiTot+PhiDir);
phiiabb= alphacSW*Fwg*taugSW*(Sgb)*(PhiTot);

Kp=500;
Tc=20;

u = [Temp Temp Temp Temp Temp Temp Temp...
    Qa phiaga phiia phi0a phiiaba phiiabb phiib phi0b phiagb]';
% Memory alocation and initial value
n = size(u,2);
Qhvac=zeros(1, n);
Qcool=zeros(1,n);
Qheat=zeros(1,n);
th = 20*ones(size(As,2), n);

for k = 1:n-1
 th(:,k+1) = (eye(nth) + dt*As)*th(:,k) + dt*Bs*u(:,k);
```

```
 Qhvac(k+1) = Kp*(Tc-th(1,k));
    if Qhvac(k+1) < 0
        Qcool(k+1)= Qhvac(k+1);
    else Qheat(k+1)=Qhvac(k+1);
    end
 u(8,k+1)= u(8,k+1)+Qheat(k+1)+Qcool(k+1);
end
CoolingEnergy = sum(abs(Qcool*dt))/(1000*3600)  %[kWh]
HeatingEnergy = sum(Qheat*dt)/(1000*3600)  %[kWh]
Prix=0.1546*(CoolingEnergy+HeatingEnergy)  %[€]
y = Cs*th + Ds*u;
subplot(4,1,2)
plot(Time/(24*3600),y,Time/(24*3600),Temp)
xlabel('Time [days]'),ylabel('T [C]')
title('Simulation for weather')

subplot(4,1,4)
plot(Time/(24*3600),Qhvac,'r'), hold on
plot(Time/(24*3600),Qcool,'b')
xlabel('Time [days]'),ylabel('Qhvac [W]')
title('Energy consumption')

% Solar radiation
subplot(4,1,3)
plot(Time/(24*3600), PhiDir,'b'), hold on %direct on surface
plot(Time/(24*3600), PhiDif,'r')  % diffusif on surface
plot(Time/(24*3600), PhiRef,'m')  % reflected on surface
xlabel('Time [days]'), ylabel('\Phi [W/m^2]')
legend('\Phi_d_i_r','\Phi_D_i_f', '\Phi_R_e_f_D_i_f')
title('Solar radiation')
```

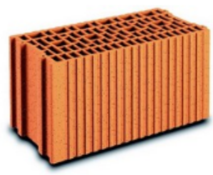
Characteristics of the materials

Polyuréthane :

Les isolants en polyuréthane sont fabriqués à partir d'un moussage de polyols, de méthylène diisocyanate, d'agents gonflants et d'additifs. Son très fort pouvoir isolant fait que le polyuréthane est parfois qualifié de « meilleur isolant thermique ».

Pouvoir isolant (W/m.K)	0,022 à 0,028	
Avantages	Résistance mécanique élevée Bonne résistance à l'humidité	
Inconvénients	Longévité assez faible Irritation en cas de contact prolongé Dégagement de gaz toxique en cas d'incendie	
Environnement	Energie grise : 974 kWh/m^3 Production : issu du pétrole Recyclabilité : non	
Prix	De 20 à 50€/m^2 pour R = 6 m^2.K/W 7,39€/m^2 pour R = 1 m^2.K/W	
Consultez notre fiche isolant dédiée au polyuréthane pour en savoir plus		

Brique de terre cuite :

Pouvoir isolant (W/m.K)	0,17 à 0,8	
Avantages	Naturellement ininflammable Naturellement insensible aux rongeurs Longévité élevée Facile à mettre en place (habitude des maçons)	
Inconvénients	Imperméable à l'humidité (ne laisse pas le mur respirer)	
Environnement	Energie grise : 450 kWh/m^3 Production : terre cuite Recyclabilité : oui	
Prix	Tout comme la conductivité thermique, le prix des briques de terre cuite peut varier énormément	