ENERGY CONSUMPTION AND ROBUSTNESS OF BUILDINGS

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Summary

Building energy performance depends on various parameters, which may be classified as: climatic, constructive, systems-dependent and users-dependent. The users-dependent parameters are relevant determining the building consumption. Especially in extreme climates, wrong actions of the users can generate pernicious effects that can be regarded as bifurcations in the physical dynamical system representing the building.

In this work a new concept is proposed: the energy robustness of the building. An energy-robust building means a building which has the ability to mitigate the unpredictable variations caused by users or by external factors (for instance, malfunctions of systems, changes in meteorological conditions). Depending on construction typology, materials selection, control system functioning, a building can have a very different robustness: in some constructions a user action (for instance, let a door open) generates an important consumption variation, and in others this would not happen. A robustness indicator is searched from the sensitivity vector and the thermal global effusivity. Tree phases of analysis (heuristic evaluation, software simulation, monitoring) of a case study are presented as confirmation of the hypothesis.

Case study building locates in the Catalan Pyrenees, in a mountain climate characterized by low external temperature in winter and high solar radiation levels. Building was projected and constructed with energy-saving concepts and strategies. Otherwise, real consumption and sensation of comfort are not the expected ones, and the cause is the relevance of the user-dependent variations that continuously move the building performance far away from the working projected values.

Keywords: energy, robustness, sensitivity

1 Introduction

Energy evaluation of buildings is normally conducted by heuristic evaluation, software simulation and monitoring. In the tree phases appears sensitivity as a problem in the dates interpretation. In the heuristic evaluation sensitivity appears in the selection of the parameters values to insert in the equations representing the method of work. In simulation, sensitivity is related to the high number of parameters presents in the building editor. Finally, in monitoring can be estimated the sensitivity of the building to real changes in the operative conditions, due to user's attitude, climatic scenario, or system functioning. In this work a three phase sensitivity study over a reference building is done.

Building locates in the Catalan Pyrenees, in a mountain climate, and was constructed with low-energy techniques and methodologies. At the end of the paper robustness concept is proposed as a new evaluation and certification methodology, taking in account sensitivity.

2 Case study

The reference building is a Nature Centre, located in the Son town. Quote is 1500 meters on the sea, and environment is a mountain South oriented. Figure 1 and 2 shows the localization of the building.

Fig. 1 Planes de Son location

Fig. 2 Catalan Pyrenees

2.1 Climate

The climate definition according to the Köppen classification is difficult to obtain exactly. Building locates at the division line between two important climate zones: the Mediterranean and the Oceanic. The South orientation of the mountain suggest the classification in the Mediterranean zone. However, the high of the mountain suggest a mountain climate. In simulation the selection will be a Mediterranean file with the correction of the air density corresponding to the high of 1500 m.

Figure 3 shows the average temperatures registered by the meteorological stations of Pardines and Molló, located near the Son town. Figure 4 shows the solar radiation on a horizontal plane in the building emplacement.

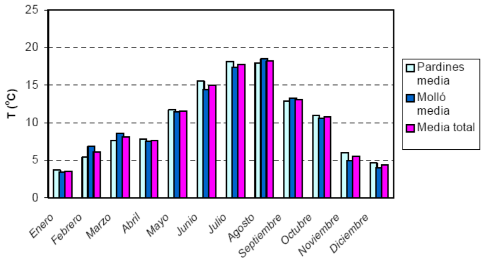

Fig. 3 Average temperature

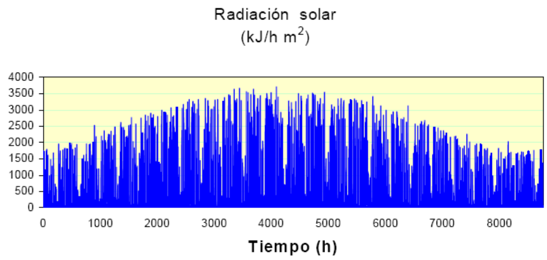

Fig. 4 Horizontal solar radiation

Radiation levels are very high, for this reason buildings was South oriented and systems of solar energy caption (direct and indirect) were projected and integrate on the building. Building was covered by a vegetal roof and north zones result to stay under the ground.

2.2 Zones

Building has different zones, that can be classified by orientation or by use. By orientation: zones in the north of the building under the ground, zones in the south of the building on the ground floor and zones in the south of the building on the first floor. By use: bedrooms, kitchen, baths, auditorium, laboratory, entrance and multiple use rooms. On the north locates the kitchen, the auditorium, the laboratory and the baths. On the south locates the bedrooms (first floor), the entrance and the multiple use rooms (ground floor). Figures 5 and 6 shows the zone distribution.

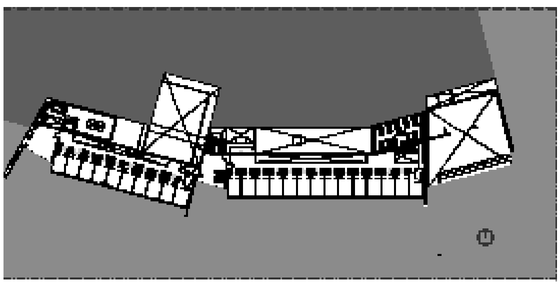

Fig. 5 First floor

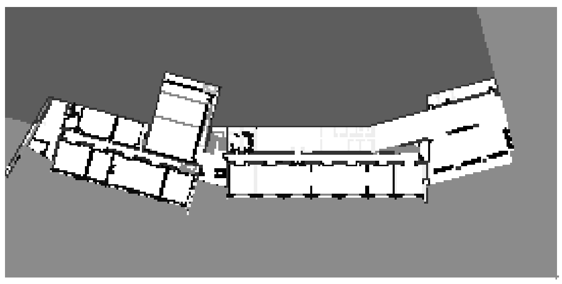

Fig.6 Ground floor

Figures 7 and 8 show the cross section, the incoming radiation in winter and the functioning of the solar protection in summer.

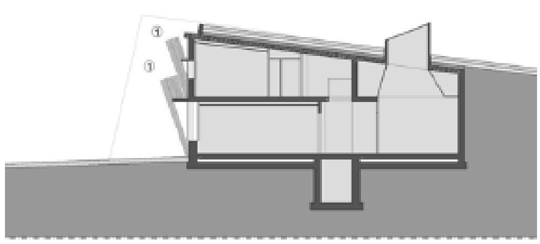

Fig. 7 Summer cross section

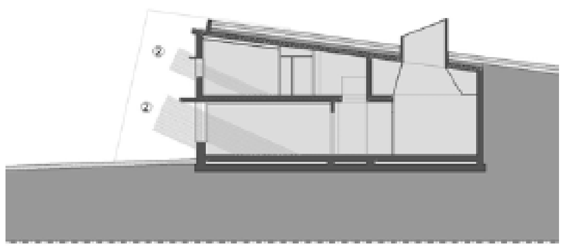

Fig. 8 Winter cross section

2.3 Materials

Building has been constructed using ecological and energy-saving concepts. For this reason, materials used in the construction were principally materials of the zone, traditionally used in the Catalan architecture. In details, walls and windows composed as follow:

- External walls are composed by internal plasterboard (13 mm), insulation of rock wool (70 mm), concrete (200 mm) and granite (200 mm).
- Walls touching ground are concrete walls (400 mm). Transmittance value is calculated tacking in account the average profundity of the walls touching ground.
- Floor is composed by internal wood, cement mortar, rock wool (50 mm), air gap (180 mm) and concrete (280 mm). Transmittance value is calculated considering the 3 m profundity of the floor.
- Roof is a green roof well insulated composed by plasterboard, concrete (260 mm), mortar (10 mm), rock wool (80 mm), polyethylene (2 mm), expanded polystyrene (30 mm), vegetal ground (460 mm).
- Windows are double glass with low heat conductivity, aluminium marks without thermal bridges.
- Internal panels for energy adsorption (behind windows) are composed by plasterboard (13 mm), rock wool (50 mm), plasterboard (13 mm).

Table 1 resume the transmittance values of walls and windows.

Tab. 1 Transmittance values of walls and windows

	External walls	Walls touching ground	Floor	Roof	Windows	Internal panel
U (W/m^2K)	0.48	0.38	0.00	0.28	1.70	0.34

Figure 9 shows the South façade of the building. Figure 10 shows a detail of the window and the internal absorption panel.

Fig. 9 South façade

Fig. 10 Absorption panels

2.4 Systems

Systems provided to the building are heating system, air conditioning, hot water solar production, photovoltaic electricity production. Boiler is a biomass boiler of 150 kW, with an efficiency of 85%. Hot water production has a solar contribution of 50%. Ventilation is guarantee by air conditioning system. Efficiency of cooling is assumed as 220%, considering heat pump efficiency and energy recovery system. The final unit of heating is a radiant floor. Thermostats are placed in the middle of the building, on the corridor. A secondary natural gas boiler is functioning for kitchen and used when the principal boiled failed. Direct energy absorption of the panels has not secondary distribution inside the building. Bedrooms windows are provided of transmission protection (wood of 150 mm thickness). No solar mobile protection is provided. Windows of the first floor are fixed.

3 Methodology

As described in the introduction, a tree phases analysis was conducted over this building. Tree phases are: heuristic evaluation, simulation and monitoring.

3.1 Heuristic evaluation

Heuristic evaluation of sensitivity was conducted by the balance equation (1) and its time variation (2) proposed by Serra [1]:

$$(T_i - T_e) \times G = I + D \tag{1}$$

$$\delta T_i = \delta T_e + \frac{\delta (I+D)}{G} - \frac{I+D}{G^2} \delta G \tag{2}$$

Where T_i and T_e are the internal and external temperatures, G is the loss coefficient (including transmission and ventilation losses) per unit volume, I and D are respectively the solar and internal gains per unit volume. The I, D and G variations are considered separately, and were estimated as the 30% for I and D and 100% for the ventilation. G value is divided in transmission and ventilation parts and is calculated by (3):

$$G = G_t + G_v = \frac{\sum U_i \times S_i}{V} + 0.29ach \tag{3}$$

Where U_i and S_i are the transmittances and the surfaces of the walls, V is the building volume, and ach is the air renewal coefficient (1/h). Sensitivity vector is obtained by the relation between the internal temperature variation and the maximum comfortable variation of the same temperature (4). Indication over the maximum comfort acceptable variation of temperature was obtained by Carrier [2] as 4ºC.

$$S = \frac{\delta T_i}{\Delta T} \tag{4}$$

3.2 Simulation

Simulation was conducted with Ecotect tool. Sensitivity analysis was a discrete sensitivity analysis over five parameter variation: insulation thickness, windows transmittance, solar protection factor, air renewal coefficient, air permeability of windows. Selection of the parameters was made by literature review, especially by indication of Clevenger [3] and De Wit [4]. Discrete cases considered were a base case, a better case and two poor cases.

Table 2 shows the discrete values of the parameters selected.

Tab. 2 Discrete values used in sensitivity analysis

Cases	1	2	3	4
Insulation (mm)	70	60	50	40
U window (W/m^2K)	1.6	2.8	3	3.3
Solar factor (no dimension)	0.1	0.2	0.6	1
Air renewal (1/h)	0.2	0.4	0.8	1.2
Air permeability (1/h)	0.0	0.1	0.2	0.4

Figure 11 Shows the Ecotect model of the building

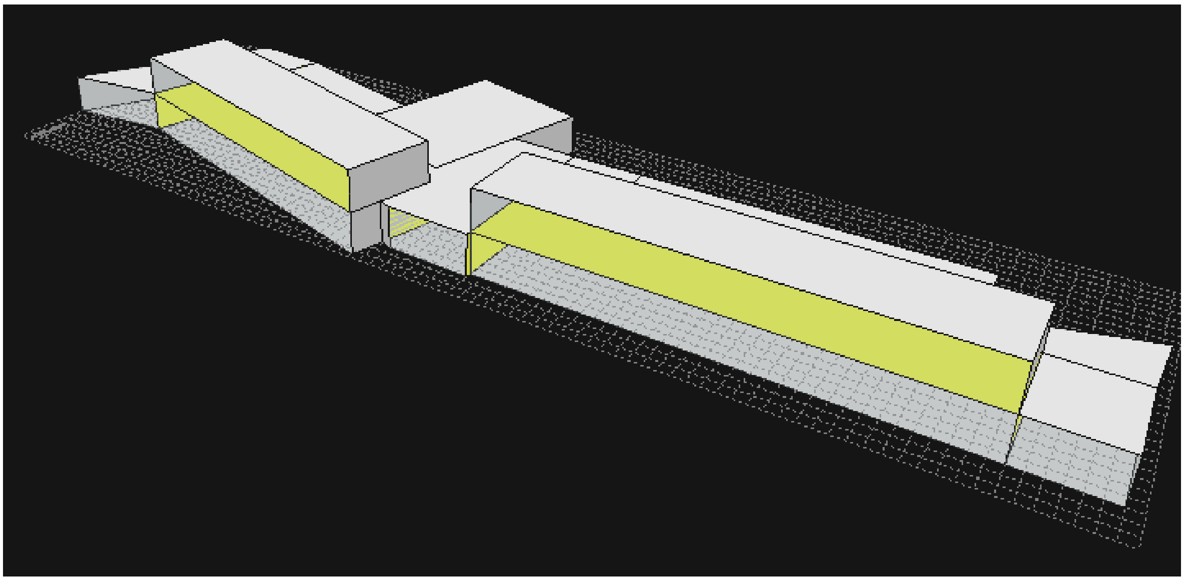

Fig. 11 Building Ecotect model

3.3 Monitoring

Monitoring of the building was conducted during years 2006 and 2007. Dates obtained were hourly temperature of all the zones, of the radiant floor impulsion for each zone, and the external temperature evolution. In march 2007 surface and radiant temperature of the walls (especially of the absorption panels) were recognized during two days. Consumption dates was obtained directly from the gas and biomass invoices, and indicate a heating final energy consumption of 45 kWh/m^2 per year. Ecotect simulation base case has a heating final energy consumption of 37.5 kWh/m^2 and a cooling final energy consumption of 15.5 kWh/m^2. Simulated heating consumption is also a little lower than the real.

4 Results

Results are searched by obtaining a sensitivity vector for heuristic evaluation and for simulations. Monitoring is used to confirm the sensitivity analysis results.

4.1 Heuristic evaluation

Building has a volume of 7000 m^3 for a floor area of 2400 m^2. Project values of the coefficients are resumed in Table 3.

Tab. 3 Values of the coefficients

U (W/m^2K)	G_t (W/m^3K)	G_v (W/m^3K)	I (W/m^3)	D (W/m^3)
0.4	0.14	0.12	1.5	2

Sensitivity vector has the form of equation (5):

$$S = (dT_i\,(dG);\ dT_i\,(dI);\ dT_i\,(dD)) \tag{5}$$

Values obtained are shown in equation (6):

$$S = (-6{,}2;\ 1{,}7;\ 2{,}3) \tag{6}$$

Percent values are expressed in equation (7):

$$S = (155\%;\ 43\%;\ 58\%) \tag{7}$$

Global sensitivity of the building can be searched by equation (8):

$$S = \frac{\sum_i S_i f_i}{n} \tag{8}$$

Where S_i are the sensitivities to one change, f_i are the estimated frequency of the change correspondent, and n is the total number of changes considered. If changes are equally probable, the final sensitivity of the building is 85%.

4.2 Simulation

Simulation results were obtained by discrete parameters variation, as exposed in the methodology. Sensitivity result was obtained by comparing the consumption project evaluation with the bigger consumption obtained with the variations. Sensitivity vector has the form expressed in Table 4.

Tab. 4 Sensitivity simulation results

	U window	Insulation	Air renewal	Air permeability	Solar factor
Sensitivity (%)	21.6	1.0	78.4	32.8	0.2

Simulation confirm the air renewal as the most sensitive parameter of the building. However, estimation of global sensitivity is lower that the heuristic evaluation (27%).

Figure 12 shows the Ecotect simulation and sensitivity results. Reference values of the four cases are the values of Table 2.

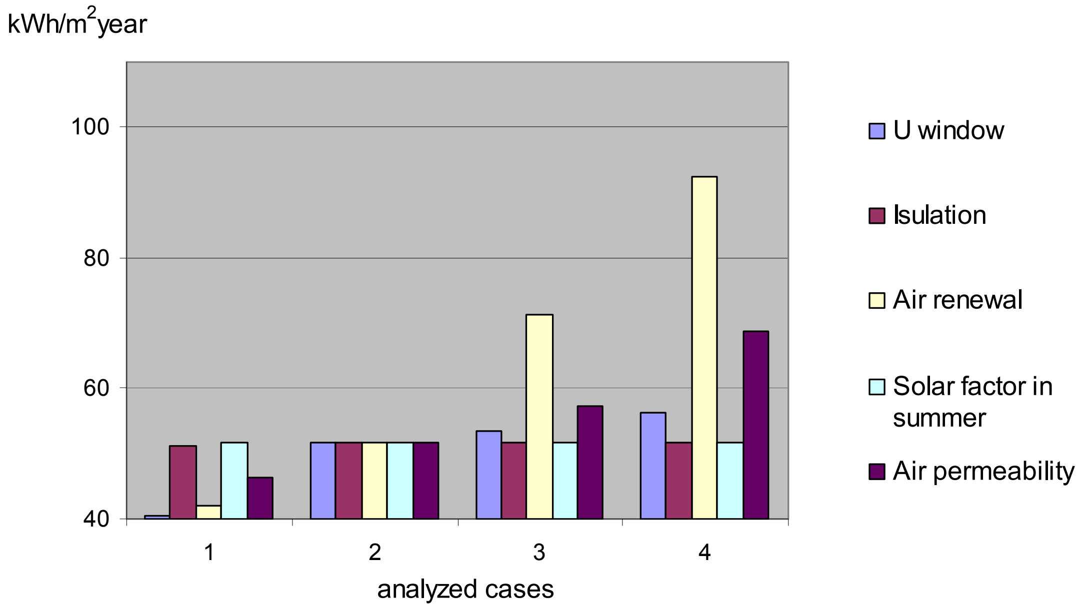

Fig. 12 Simulation and sensitivity results

4.3 Monitoring

Monitoring results can be visualized in Figures 13 and 14. North and South reference zones are analysed in details. Black line is the external temperature evolution between 6 January and 4 February 2007. Blue line is the internal temperature evolution. Red line is the heating system impulsion temperature.

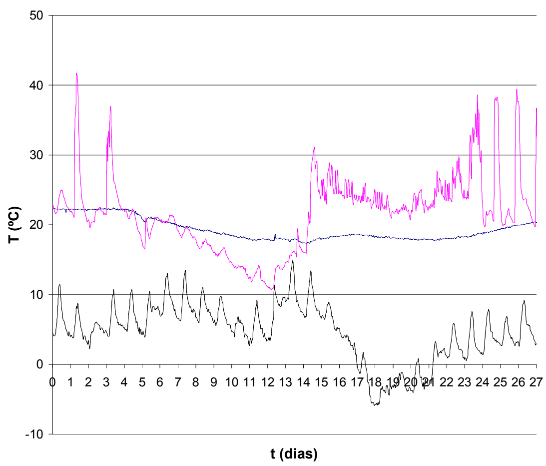

Fig. 13 Laboratory temperature

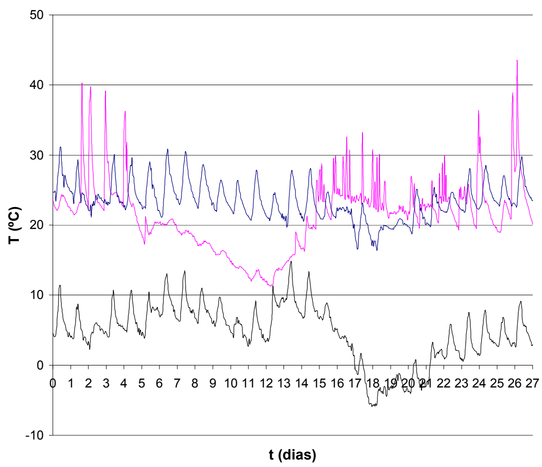

Fig. 14 Multiple use room temperature

In Figure 13 can be notice that the laboratory (north zone) has an internal temperature evolution constant with the change of the climatic condition (in the 3th week can be appreciated a cloud sky and a temperature lower than normal), but very dependent to the heating system (in the 2d week a malfunction in the radiant floor can be appreciated).

At the other hand, Figure 14 shows clearly that multi use room has a very climatic (and user – trough action as opening windows or close the solar protection) dependent behaviour. In the 2d week the zone doesn't change the temperature evolution, but in the

3th shows a temperature profile close to the external temperature profile. The reason of this behaviour is the solar radiation absorption, that concentrates the solar energy in the South façade, without distribute it trough the entire building. To confirm this fact, Table 5 resume the absorption panel temperatures.

Tab. 5 External temperature, glass temperature and absorption panel temperature

Day time	2/3/07 16.00	2/3/07 17.00	2/3/07 18.30	2/3/07 21.00	3/3/07 8.00	3/3/07 10.00	3/3/07 13.00	3/3/07 22.00	4/3/07 8.00	4/3/07 9.30	4/3/07 12.00	4/3/07 13.00
T ext. (ºC)	20	18	16	8	9	12	13	9	9	15	18	20
T glass ext. (ºC)	30	24	18	12	10	14	15	8	8	18	28	38
T glass int (ºC)	40	32	22	18	15	30	28	10	10	24	33	54
T panel (ºC)	56	40	28	20	17	38	38	15	18	38	54	78

South facing zones have a extreme sensitivity to incoming solar radiation. This means that in winter this zone register temperature of more than 30 ºC. User's interviews confirm that in winter in the building they felt hot. For this reason the windows on the ground floor was done operable. Now the problem is the asymmetry of the energetic performance of the building. South zone absorption of solar radiation causes overheating in winter, so users open windows. This action causes a cooling effect in the north part of the building and the turn on of the heating system. A clear example of sensitive building, where a not perfectly dimension project lead to a inefficient performance. Figures 15 and 16 show the temperature on 13 January 2007 respectively in the laboratory and in the multi use room.

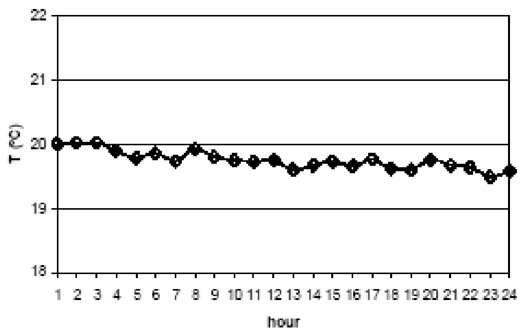

Fig. 15 Laboratory temperature

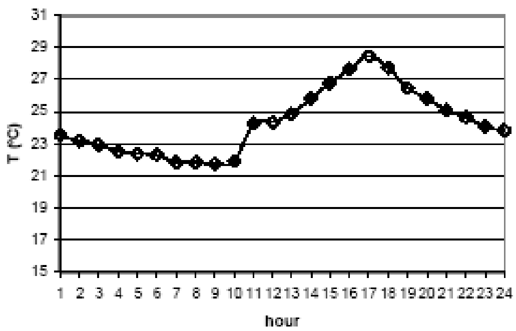

Fig. 16 Multi use room temperature

5 Conclusion

As a conclusion, it can be said that heuristic evaluation and simulation tools often offer a limited information over the thermal performance of buildings. Project values of parameters are always subjects to dynamic conditions, and in the majority of the cases this variations are totally unpredictable, depending on climate and users attitudes. It seems very important to integrate evaluations and simulation with sensitivity analysis, in order to obtain more information over the real performance of the building. Sensitivity vector or thermal effusivity can be indicators of the energy robustness of a building.

5.1 The sensitivity vector

As shown in the results, sensitivity vector said us how much the building is sensitive to changes in each parameter considered in evaluation or simulation. Final sensitivity depends on the frequency of the variations. It can be difficult to obtain this frequencies. User attitudes, so important in the sensitivity estimation, has not been estimate at the moment. Various researcher proposed the realization of a global user database, similar to the current climatic files, to use to predict the human behaviour inside a building. However, simple sensitivity analysis, as done in this paper, can be used to compare different architectural strategies.

For example, a building similar for shape and climatic location to the Planes de Son building, the Massia de Vallforners, but constructed with other strategies and materials, has a sensitivity vector very different, and the global sensitivity is 20%. Materials used in the Massia de Vallforners retrofit are principally stone and wood. The building has small windows and no direct solar radiation absorption. If the total consumption is something higher tan the Planes de Son consumption, sensitivity is also much lower. Figure 17 shows the Massia.

Fig. 17 Massia de Vallforners

Table 6 shows the values considered in the heuristic evaluation of the sensitivity. Final sensitivity vector, obtained as described in the methodology, was the equation (9):

$$S = (34\%;\ 14\%;\ 19\%) \tag{9}$$

Tab. 6 Values of the coefficients for the Massia

U (W/m^2K)	G_t (W/m^3K)	G_v (W/m^3K)	I (W/m^3)	D (W/m^3)
2	0.54	0.24	1.5	2

Global sensitivity result is 20%, when the Planes the Son has 85%.

5.2 The thermal effusivity

Another way to evaluate robustness can be the thermal effusivity estimation. Thermal effusivity is a propriety of the materials, and is defined by (10):

$$\varepsilon = \frac{\lambda}{\sqrt{\alpha}} = \sqrt{\rho c \lambda} = \rho c \sqrt{\alpha} \tag{10}$$

Where ρ is the density (kg/m^3), c is the specific heat (J/kgK), λ is the linear conductivity (W/mK) and α is the diffusivity (m^2/s) of the material. It is an error very common to confuse the effusivity with the conductivity, because of the fact that the density-specific heat product is practically constant in the solid matter. However, in fluids things are very different and effusivity is the real parameter that indicate the velocity of the matter to respond to thermal solicitations. In buildings thermal exchanges depends by transmission and ventilation, so the conductivity is not the only parameter that has to be taken in account. We propose the definition of a global thermal effusivity as equation (11):

$$E = \sqrt{\varphi \xi GM} \tag{11}$$

Where G is the loss coefficient (W/m^3K), M is the thermal mass of the building (J/m^3K), φ and ξ are correction coefficient depending by distribution and orientation of the thermal mass. Global effusivity has the unit $W/(m^3 s^{0.5} K)$. This is a manner to evaluate rapidly the velocity of the building to respond to solicitation, including ventilation, transmission and solar adsorption phenomenon. Figure 18 shows the relation between the sensitivity to ventilation and the thermal effusivity.

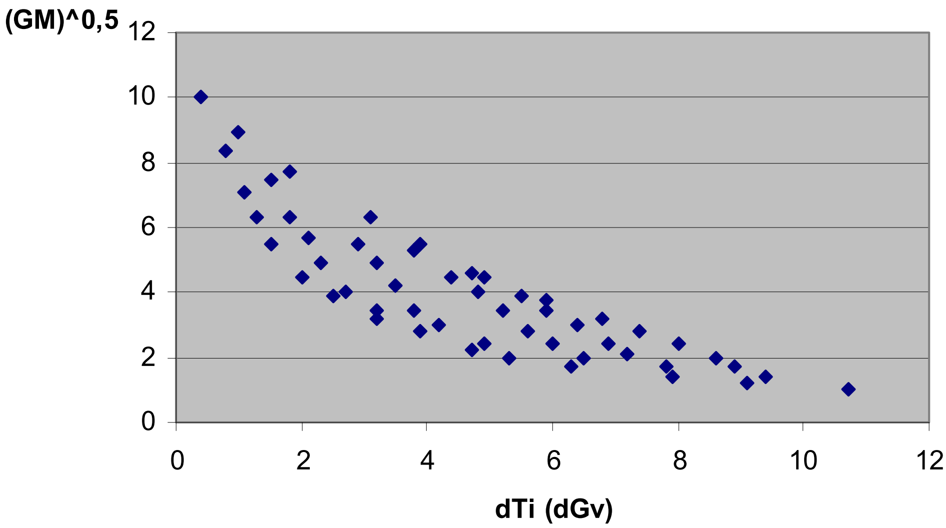

Fig. 18 Sensitivity to ventilation and thermal effusivity

Planes de Son values of thermal mass and loss coefficient (lower than the same coefficients of the Massia) locates the building in the high sensitivity zone (the right of the graph). Massia de Vallforners locates very close to the links zone of the graph, because the high loss coefficient and thermal mass values.

As a final conclusion, it can be said that:

- Robustness seems to be an important indicator of the real behavior of the building, because of the sensitivity that heuristic evaluation and simulations demonstrate.
- Sensitivity vectors and thermal effusivity are both manners to estimate the robustness. Both concepts could be introduced in the actual simulation and certification process.
- Robust solutions, as the old Massia de Vallforners, can respond better that new high-tech buildings as the Planes de Son to changes in the variables that regulates the energy interchanges between building and environment.
- Climatic change and other variables, that were not considered in this study, can do more important the robustness concept, because buildings will be probably strong forced away respect to the situation considered in the project.

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