559: Building sensitivity to climatic fluctuations and user's actions: a challenge for high-tech buildings

M.Palme, A.Isalgué, H.Coch, R.Serra

Architecture, energy and environment. School of Architecture. Technical University of Catalonia (UPC) Barcelona, Spain. Corresponding author: massimopalme@hotmail.com

Building sensitivity to climatic fluctuations and users' actions: a challenge for high-tech buildings

Due to the current concern about energy consumption and CO_2 emissions, buildings are increasingly insulated and equipped with controlling machinery. However, the effective energy consumption of high-tech buildings is often higher than expected, and users' sensation of temperature comfort is not as good as it should be. One reason for the poor performance of these new buildings could be the high sensitivity to changes in weather and user-dependent variables. A sensitivity analysis can be conducted using thermal equations or a software simulation, or by directly analyzing real measurements. Sensitivity analyses show that the zone performance of high-tech buildings often varies in different spaces. This variation can be found in the Planes de Son centre located in the Catalan Pyrenees, which was built with low-energy strategies in mind. The performance of the different spaces depends very strongly on the orientation of the different zones that make up the building. This work analyzes data measured in 2006 and 2007 and shows that extreme sensitivity to changes is the factor that most contributes to the imperfect performance of the building. The results show that the south-facing glass façade does not perform as well as expected, despite abundant solar radiation. The dimensions of the building and the thermal systems are also analyzed to determine their influence on sensitivity. Potential ways of increasing the efficiency of the building are discussed, and a generic case is analyzed. In conclusion, the consumption and emissions of high-tech buildings could be further reduced if they respond appropriately to variations in weather and user actions.

Keywords: energy consumption, sensitivity, users, climatic fluctuations

1. Introduction

Due to the current concern about energy consumption and CO_2 emissions, buildings are increasingly insulated and equipped with controlling machinery. However, the effective energy consumption of high-tech buildings is often higher than expected and, importantly, they are not as comfortable for users as they should be. One reason for the poor performance of these new buildings might be their high sensitivity to changes in weather and user-dependent variables. Recently, some studies centred on the sensitivity of the building's thermal performance to changes in the various parameters that appear in the thermal exchanges of the building [1].

In this work, we analyse the thermal sensitivity of well-insulated buildings in an elemental way. We use the Planes de Son centre in the Pyrenees as a case study and analyze measurements taken in this building and simulations of it. Finally, some conclusions are drawn.

2. Elementary thermal sensitivity analysis

This section analyses buildings' sensitivity to fluctuations in the variables that influence thermal performance. A general sensitivity analysis can be performed by differentiating the balance equation:

$$T_i = T_e + \frac{I+D}{G};$$

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

where T_i is the internal temperature, T_e is the external temperature, I is the solar radiation contribution (W/m^3), D is the internal contribution (people and systems, W/m^3), and G is the volumetric loss coefficient of the entire building (transmission and ventilation, in W/m^{3}ºC). The equation shows that I and D fluctuations have a greater effect on internal temperature variation when the loss coefficient G is small. The loss coefficient varies, particularly when users carry out different activities in the building. The G^2 term in the equation shows that a G fluctuation is greater when the G coefficient is small, and can easily be more significant than the I and D changes.

For instance, assume a building is in a cold climate, Te= 2ºC; if the building is well insulated, G can be 0.35. If we have I= 3.5 W/m^3; and D = 3.5 W/m^3, then Ti = 22ºC, which is a good result. But if G changes by 30% due to an increase in ventilation on a windy day (here G is low and the contribution of ventilation to G is relatively high), then Ti is nearer to 16ºC. Similarly, with the same initial G conditions on a cloudy day, the solar contribution becomes negligible, and the indoor temperature is nearly Ti = 12ºC.

3. A case study of sensitivity

3.1 Introduction

An analysis of thermal sensitivity is important, even if it is not exhaustive. The following factors must be considered: the accumulation in thermal mass, the spatial distribution of the internal temperature and the time-dependent displacement of the thermal wave in the walls. Therefore, it is important to perform a simulation in the design phase, and to analyse real data when the building is in use.

The main objective of this study is to compare a general sensitivity analysis with data measured in a real building that was designed with low-energy strategies in mind by the architect Francesc Rius. The building is the Planes de Son Nature Centre. The data were collected in 2006 and 2007, as part of the EULEB project of the Intelligent Energy Europe Programme in collaboration with TramaTecnoambiental SA.

3.2 Location

The Planes de Son Nature Centre is located in the Catalan Pyrenees at 1350 m. above sea level. The *"Fundació territori i paisatge"* of the *Caixa de Catalunya* savings bank financed this building, which was designed and constructed to be sustainable. The architect Frances Rius was commissioned to achieve this objective. The final result was a south-oriented and semi-buried building that improves solar radiation income and avoids day-night fluctuations. The insulation values are also higher than average in this zone.

Table 1. Average external temperature, solar radiation (horizontal plane) and relative humidity of the location

	External average temperature (ºC)	Solar radiation (horizontal plane) (kJ/m2)	Relative humidity (%)
January	4.8	7478	75.5
February	3.4	10889	60.4
March	3.6	15200	56.4
April	8.7	18489	68.8
May	11.5	21811	72.7
June	14.1	23233	77.7
July	19.5	23100	71.0
August	16	20378	70.6
September	10.3	16122	75.6
October	12.2	12567	68.8
November	8	8433	71.4
December	3.4	7033	63.9

The building is used as a nature centre where groups or individual users can be in close contact with nature for a period of time. Courses last from one day to two weeks and a lot of activities are arranged. The centre functions as an isolated hotel in the mountains, so all the facilities are provided in the main building.

The location is 42ºN, 1ºE, 1350 m. The external temperature, the relative humidity and the radiation values are shown in Table 1 [2].

3.3 The zones of the building

The building is divided into different zones with different uses and occupancies. These include:

- The laboratory, located in the north, on the lower floor below ground level.
- The auditorium, located in the north, on the lower floor below ground level.
- The kitchen, located in the north, on the lower floor below ground level.
- The living rooms, located in the south-west on the lower floor
- The reception and the dining room, located in the south-east on the lower floor
- The bathrooms, located in the north, on the lower floor below ground level.
- The bedrooms, located in the south-east and south-west on the upper floor

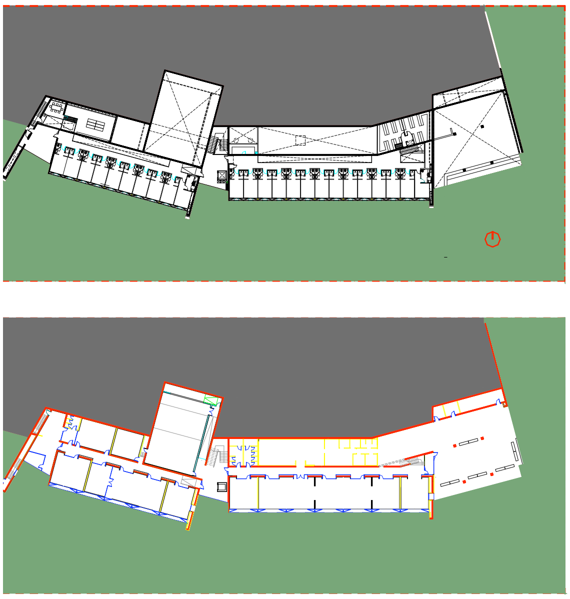

Figure 1. Planes de Son first and lower floor

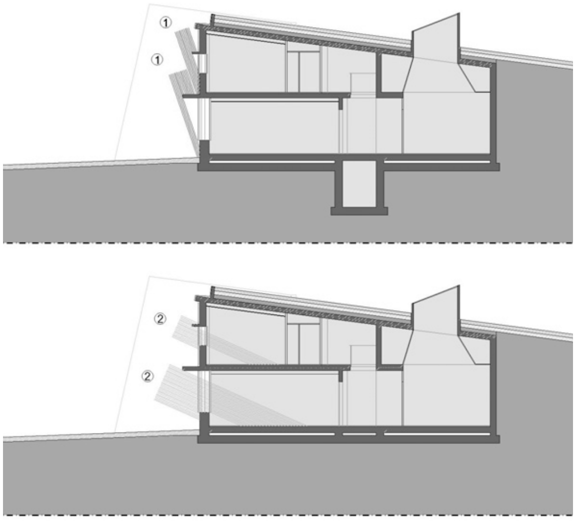

Figure 2. South-north section of the Planes de Son Centre

3.4 Materials

The building was constructed using typical regional materials as far as possible. The north zone is completely below ground level and the roof is green and 1.5 m thick. The east façade is composed of 0.2 m thick concrete and 0,01 m wood insulation. The west façade is composed of 0.2 m thick concrete without insulation. . The south façade is a light façade, made entirely of glass. Water and photovoltaic solar panels are located on the upper floor. Behind some of the glass on the lower floor and part of the upper floor is a high absorption panel, to increase the solar energy gain.

After a year of occupancy, uncomfortable internal temperatures have been reported. The Nature Centre's management was surprised when informed of the overheating problem in winter, leading to windows being opened during hours of solar radiation. Though the energy consumption was not far from the expected results, which indicates that the indoor temperature comfort was good, this does not tally with the users' perceptions.

To explain this behaviour, it is necessary to analyze the performance of the different zones throughout the year.

3.5 Analyzed data

Temperature sensors were placed at different points of the building to obtain measurements of its performance. Data were registered hourly from July 2006 to June 2007. In March 2007, both the superficial and radiant temperatures were recorded in different places and at different times. The daily minimum, maximum and average temperatures were obtained from data for various points. Then, the monthly absolute minimum, the absolute maximum, the average daily maximum and minimum and the monthly average temperatures were obtained. These data were used to undertake a zone analysis, in which the temperature of the different zones, the correspondence with the impulsion temperature of the heating system (a radiant floor) and the daily evolution of the supposed temperature comfort were compared. The data showed that variations in the performance of the different zones were very high. Therefore, a surface temperature analysis was undertaken for the most interesting places. Finally, the data were used to find an explanation for the claims of the centres' staff and users.

4. Results

4.1 Sensitivity analysis

The transmission and ventilation coefficients per unit volume can be calculated by [3]:

$$G_T = \frac{\sum U.S}{V}$$

And

$$G_V = 0,29 \ \frac{V(airperhour)}{V(building)}$$

Table 2 shows the transmission coefficients per unit surface of the walls and the corresponding surfaces.

Table 2. Transmission coefficients of the walls

Wall	U (W/m2ºC)	S(m2)	U.S (W/ºC)
ext. east	2.9	23	66.7
ext. west	4	60	240
ext. south	0.48	192	92.1
ext. north (buried)	0.38	478	181
windows	1.7	267	453.9
green roof	0.28	1200	336

The floor is 4 meters under the ground. Consequently, it does not contribute to the transmission.

With these values and the total volume of the building (7000 m2), the G coefficient is 0.2 W/(m^{3o}C).

The ventilation coefficient depends on the volume of air per person needed to guarantee comfort. It varies from 0.29 to 0.87 W/(m^{3o}C) in normal use conditions, depending on the occupation density of the zones. Users can open lower floor windows and open or close a thermal protection system in the upper floor bedrooms. Therefore, the users' actions can change the ventilation coefficient values considerably.

The radiation term I depends strongly on the absorption panels. An absorption coefficient of 0.8 can be considered very high. Data measured on site demonstrate that the absorption level is very good.

With equation [4]:

$$I = S_{windowsouth} R_{verticalsouth}$$

and considering the values in Table 1 (to convert data from the horizontal plane to the vertical southern plane, a coefficient of 1.67 can be used in winter and a coefficient of 0.45 in summer), I assumes the values shown in Table 3.

Table 3. Irradiation values (W/m^{3o}C)

month	Jan	Feb	March	April	May	June
I(W/m^3)	5.5	5.6	5.3	4.8	4.4	3.9
month	July	August	Sept	Oct	Nov	Dec
I(W/m^3)	3.8	3.9	4.2	4.6	5.2	5.3

These values were obtained from average values of radiation incoming in a horizontal plane. This means that the I fluctuation can be very high. The real values of I change range from 0 (no direct radiation incoming) to 10 or more watts per cubic meter.

The internal contributions can be estimated as 58 W per person, and 8 kW from the computers, lights and other electrical apparatus. For an average occupancy of 80 people, the D value is

1.8 W/m^3. Notice that the heating-cooling power was not considered in the D coefficient evaluation. The building is supposed to have zero energy performance.

With these values, it was possible to determine a sensitivity coefficient for each fluctuation. For example, the sensitivity to a change in the incoming solar radiation from 5 to 10 W/m^3 is:

$$\frac{\delta T_i}{T_i} = 0,4$$

for an external temperature of 10ºC and a ventilation term of 0.3 W/(m^{3}ºC). Changes due to users' actions, such as a fluctuation in the G ventilation term from 0.3 to 0.6 W/(m^{3}ºC), can be represented by:

$$\frac{\delta T_i}{T_i} = -0,35$$

The values of the changes in the internal temperature (40% for a fluctuation in the solar radiation and 35% for a fluctuation in the ventilation coefficient) are very high. In comparison, a traditional building, constructed using typical regional techniques and materials (granite walls, partial wood insulation, small windows with wood protections, low shape coefficient), has a G transmission coefficient near to 1, and an extremely high accumulation of heat in the thermal mass. Its sensitivity coefficient is 0.2 for a fluctuation in incoming solar radiation and 0.05 for a fluctuation in the ventilation term, in the same conditions as the Planes de Son evaluation.

4.2 Simulation

As the above sensitivity analysis is not exhaustive, to confirm the results an Ecotect software simulation was performed. The heating demand was small, but there was a cooling demand due to the incoming solar radiation. In fact, the solar radiation energy is not well distributed in the building and the accumulation in mass is lower than expected. A zone analysis shows that the south-facing zones have a highly different performance to the north-facing zones and to the zones protected from the incoming radiation. The south-facing zones require cooling, when only ventilation is available. The net result is that thermal energy which cannot be collected is simply dissipated without being used.

4.3 Measured data analysis

The sensitivity analysis and the Ecotect simulation suggest that the Planes de Son building has a bad distribution of the solar power incoming throughout the year. The data measured on site confirm this hypothesis. Figure 3 shows the monthly average temperature, and Figure 4 shows the absolute maximum temperature. The lower floor, south-facing zone has a very different performance to the other zones, including the upper floor zones that also face south. The reason for this difference in performance is the high incoming solar radiation. In fact, the incoming radiation depends on the orientation and, clearly, on the obstruction of the façade. On the upper floor, the thermal panels for warm water occupy nearly 60% of the surface. On the lower floor, the whole façade is occupied by windows, which are the cause of overheating in this zone. As explained by the Centre's staff, people always feel warm in the south-facing zone of the lower floor, especially in winter.

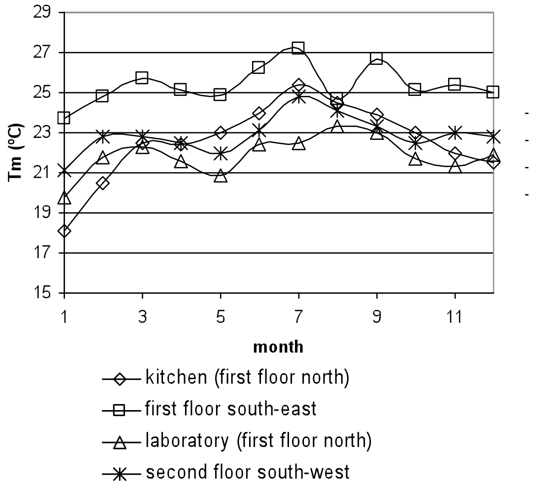

Figure 3. Monthly average temperature in various zones of the building

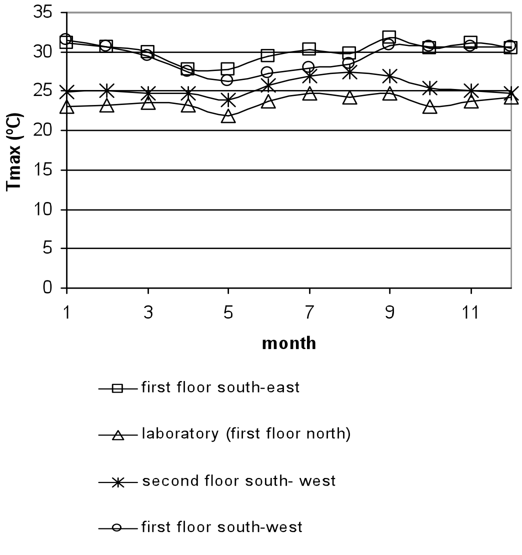

Figure 4. Monthly absolute maximum temperature in various zones of the building

Figures 5 and 6 show the temperature evolution on 13 January 2007 in the laboratory and in the dining room. The temperature in the dining room fluctuated from 22 to 29ºC, while in the laboratory it only varied from 19.5 to 20 ºC.

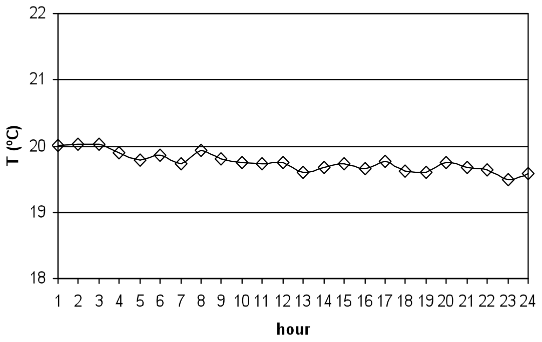

Figure 5. Temperature in the laboratory on 13 January 2007

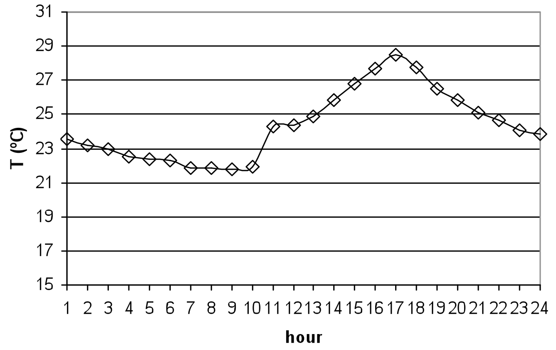

Figure 6. Temperature in the dining room on the 13 January 2007

The main cause of the building's performance problems seems to be the irregular distribution of absorbed energy. In March 2007, surface temperatures were measured to confirm this hypothesis. Figure 7 shows an absorption panel. It is located in the middle of the south façade on the ground floor. On the ground floor the panels are in function every time. On the first floor, users dispose of a wood insulated flap, but the instructions of use have a different meaning (there is an advice of close the flap during the night but not during the day). The panels directly heat their immediate spaces, but not the most internal parts or the massive part of the building, which are too far away. On the first floor the panels are smaller, because of the presence of the water panels in the façade. Table 4 shows the external temperature, the temperature of the glass (internal and external) and the absorption panel temperature in different conditions of incoming solar radiation. The temperatures of the absorption panel and of the glass increased very rapidly when the sun was out. On 4 March 2007, which was a sunny day, the temperature of the absorption panel changed from 18ºC at 8.00 am to 78ºC at 1 pm. The temperature on the inside of the glass increased from 10 to 54ºC in this time. These rapid changes mean that the energy is not correctly accumulated. The absorption zones communicate directly with the internal zones of the building, so the air moves towards the interior and generates the sensation of overheating. A significant part is immediately returned to the air between the panel and the glass. This generates an increase in the internal temperature in winter in the south-facing zones of the building, and discomfort to the users.

Table 4. External temperature, glass temperature and absorption panel temperature registered on site

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

Figure 7. Absorption panel on the south-oriented façade.

5. Conclusions

The sensitivity analysis, the ecotect software simulation and the analysis of the data measured on site explain the poor performance of the Planes de Son building. Ineffective distribution of the solar energy causes overheating on the south-facing lower floor. The zero energy heating performance obtained in the simulation is not real: the system is always functioning, and the north zones are not heated sufficiently with solar power. The thermal mass is also concentrated in the north of the building, where absorbed energy is not transferred. The dimensions of the building affect the function of the absorption: if the distance between the windows and the north walls were lower, the thermal mass would be able to accumulate. Below are some potential solutions:

- Close off part of the windows to obtain warm air between the glass and the absorption panel. This air has to circulate in tubs or plenums and heat the north zones of the building.
- Increase the number of water solar panels. Currently, the radiant floor is not the only energy source for the heating system. Increasing the number of solar panels could reduce the sensation of overheating on the lower floor.
- Transfer the solar energy to the building's north zone using a transition phase material, which conserves the latent energy in the phase transition.
- Protect the windows on the lower floor. This solution does not improve the performance of the building, but will make it more comfortable for users.

The following general conclusions can be drawn:

- The insulation of buildings is not always consistent with the solar energy absorption. This relationship depends on the geometrical arrangement of the thermal mass. Passive absorption systems must be designed accurately in terms of their dimensions and strategies.
- Increasing the insulation leads to higher sensitivity to climatic and user-dependent fluctuations. Users must be prepared to use the building control systems, which include windows and protection systems.
- In the design phase, when a real data analysis is not possible, a sensitivity analysis has to be considered as an instrument for assessing the performance of the construction. However, simulation programs do not always provide a realistic view of the situation.
- An appropriate orientation of the building is the most important factor for zero energy performance. However, the dimensions of the building and its zone divisions must also be considered to achieve zero energy.

An energy demand analysis is not sufficient to evaluate the performance of a building. The zonal distribution of temperature, climatic fluctuations and users' actions must also be considered. The case of the Planes de Son building demonstrates that imperfect temperature distribution generates user discomfort and a deviation from the calculated performance. A sensitivity analysis can be a rapid and simple instrument for assessing a design, and is associated with the current dynamic simulations.

Users play an essential role in obtaining real zero energy performance of the building. For an exhaustive evaluation of the relevance of the user's actions on the thermal performance of buildings in general, see [5]. Users' actions depend on their perceptions of whether the temperature in the rooms is comfortable. Therefore, a study of the definition of comfort in dynamic conditions is needed for future architecture. For a preliminary study of the dynamical comfort, see [6]. The definition of a dynamical comfort could lead to the project of buildings with a relative self-control over the zones that compound it. Alternatively, a control system that dynamically regulates all the elements of a building could be considered.

6. Acknowledgements

This study was made possible by the UPC research grant programme and TramaTecnoambiental, SA. We are also grateful for the use of the Planes de Son facilities and the help from this centre's management.

7. References

1. Saporito, A., Day, A.R., Karayannis T.G., Parand F.(2001) Multi-parameter building thermal analysis using the lattice method for global optimisation; Energy and buildings 33, p. 267-274,

2. Catalan Meteorology Service (2008) http://www.meteocat.com

3. Spain. *CTE Código Técnico de la Edificación (2008).* Ministerio de Vivienda, Spain

4. Serra, R.; Coch, H. (1995) Arquitectura y energía natural; Edicions UPC; Barcelona

5. Palme, M.; Isalgue, A.; Coch, H.; Serra, R. (2006) On the influence of users' actions on thermal performance of buildings; 4ª EPIC Conference proceedings, Lyon, France 29 November – 1 December 2006, p. 746-750

6. Palme, M.; Coch, H.; Isalgué, A.; Marincic, I.; Fanchiotti, A. and R. Serra (2007) Dynamic sensation of comfort in buildings: the temperature changes effects; 2ª PALENC Conference proceedings, Crete, Greece 27-29 September 2007, p. 13-18