Robust design: a way to control energy use from the human behaviour in architectural spaces

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ABSTRACT: Human behaviour is an important factor to consider in making an accurate assessment of the thermal exchanges between a building and its surroundings. The actions of a building's users, such as opening windows or doors, resetting the default temperatures of heating or cooling systems, or turning on electrical lights or appliances, can have a significant effect on energy consumption and the subsequent sensation of comfort. Basing our work on schemes for classifying these actions, in this study we determine which ones are to have precedence over the others. The effects of these actions can then be computed based on energy transfer equations for different types of buildings. An analysis of the changes caused by users to thermal parameters shows that different design solutions lead to different sensitivities. The stability of the thermal transfer in the building is analysed in part. From the results, it seems reasonable to limit what actions users can carry out by making appropriate design choices. The system is thus "robust" in its response to users' actions while it continues to provide them with the feeling that they are in control. This work emphasises the importance of the concept of "robustness" of energy efficiency and comfort in building design. Robust design here refers to the design process as a whole, carried out in such a way that it is difficult for users to make inappropriate decisions. This is accomplished by permanently sealing windows, or installing mechanisms to control lighting, heating, cooling or ventilation systems.

Keywords: energy, comfort, users, robustness

1. INTRODUCTION

The actions that the users of a building can undertake are a very important factor for the good thermal performance of the building. This paper shows as, simply considering a quasi-static condition, the various actions that a user can do determine the real sensation of comfort inside of the building and have an important influence on the energy consumption. We have considered, as a first approach only a static condition, in order to simplify the assessment of the consumption and temperature index.

With these considerations two buildings are compared: the Planes de Son building, a recent construction in the Pyrenees, and a building of 8x8 m^2 in the same climatic conditions, which complies the thermal norms for Spain [1, 2].

The results and the discussion show that the concept of energetic "robustness" of the buildings has a great importance when the users are free (always?) to make actions and to take decisions on the building.

2. METODOLOGY

Energy consumption and the sensation of comfort are two very different terms, but both are very important for evaluating the energy efficiency and performance of buildings. As has been shown in other studies [1, 3], a preliminary criterion for assessing comfort and energy consumption can be obtained from the heat transfer equation. This equation may be written per unit of floor area as:

$$\frac{dm}{dt} = i + d - U\,(T_i - T_e)$$

or, in an equivalent way, per unit volume [1]:

$$\frac{dM}{dt} = I + D - G\,(T_i - T_e)$$

Eventually, some norms re defined with equivalent parameters (the Spanish one [2] is defined with K as losses through unit surface of skin).

It is simple change the parameters for utilize one or other equations, and these are perfectly equivalent.

In the above equations, Ti is a representative internal temperature, Te is the external temperature, I and i are terms for radiation gains, D and d stand for internal gains, U and G are loss coefficients, which include thermal transport though the walls (Gt – Ut) and air exchanges (Gv - Uv), and M and m are terms representative of the thermal mass. It is typical for the terms in the above equation to be expressed as specific terms. We have selected the terms per unit volume for our tables and graphics.

A general sensitivity analysis will show that the lower the term U or G (it is low when buildings are very well insulated), the higher the sensitivity. A change in climatic conditions or users' actions causes a considerable perturbation to the behaviour of the building.

This may be understood in correlation to thermal balance equations [4]:

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

where Ti is the internal temperature. By differentiating this equation, one obtains the following:

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

where dTi is the internal temperature change induced by changes to Te, I, D and G.

If Te is constant, we get the following:

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

If we further consider that I and D are constant, we get:

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

This equation clearly shows that variations in G have a high repercussion when G is low, because of the presence of a quadratic term on the denominator.

If the terms I or D change, the effect is very nearly the same: the quadratic term G^2 is critical when assessing the significance of the climatic variation to thermal performance.

To employ a numerical example, we consider a variation in the solar contribution, I, of 1.5 W/m³ (7 W/m²). Assuming a Gt value of 0.17 W/(m³ ºC) and Ut value of 0.8 W/(m² ºC), the variation in Ti is then 9 ºC. If the Gt value is 0.8 W/(m³ ºC) and Ut value is 3.8 W/(m² ºC), the variation in Ti is 2 ºC. While a 2 ºC variation in the internal temperature might be acceptable or relatively easy to compensate for, a variation of 9 ºC is very difficult to accept in ordinary conditions, and will inevitably entail a need for comprehensive measures to be taken.

We begin by examining a winter scenario for two different buildings. Furthermore, we start with the average values, which are more significant when the term of accumulation in the mass is small. We then go on to discuss the more complex summer scenario.

3. RESULTS

The real-life example referred to herein is the Planes de Son building located in the Alt Aneu region of Catalonia, in the Pyrenees (Figures 1 and 2).

The external temperature is relatively low (see Table 1). The thermal results are shown in tables 2 and 3. The levels of solar radiation are high (Table 4).

The building is very well insulated from a thermal point of view; the K coefficient is 0.99 W/m² ºC (losses through the skin) and the Gt (t = thermal) coefficient is 0.17 W/(m² ºC), Ut is also 0.8 W/(m² ºC).

With this G coefficient value, the building is very sensitive to small changes in the *ach* coefficient (air renewals per hour, rh in the Spanish norms [2]) (Ti-Te=15 ºC), as shown in Table 2.

In Table 2, one can see that energy consumption may increase by 260% when users open the windows in order to ventilate the building in the absence of solar radiation.

Figure1: Planes de Son, south façade

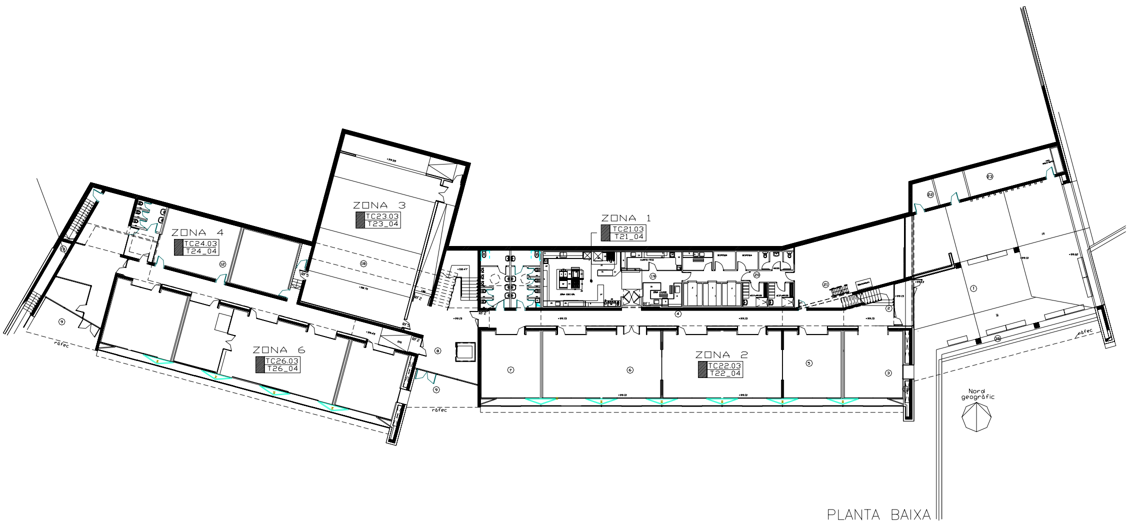

Figure 2: Planes de Son, ground plan

Table 1: External average temperature near Planes de Son in 1996-1998 and average [5]

Month	T (ºC) 1996	T (ºC) 1997	T(ºC) 1998	T (ºC) average
January	3,6	3,0	4,5	3,7
February	2,0	6,5	7,7	5,4
March	4,9	9,6	8,3	7,6
April	7,6	9,3	6,5	7,8
May	10,9	12,4	11,8	11,7
June	15,8	14,3	16,5	15,5
July	18,3	16,5	19,6	18,1
August	16,7	17,8	19,3	17,9
September	11,0	15,3	12,3	12,9
October	10,1	12,3	10,4	10,9
November	6,0	6,8	5,4	6,1
December	3,9	5,2	4,9	4,7

The values of G are assed with the sum of the terms Gt (thermal) and Gv (ventilation), which depends on the air velocity and may be expressed as 0.30 *ach.*

Table 2: changes in consumption in the absence of solar radiation and with a low ventilation term

Gt (W/(m^3 ºC)) Ut ((W/m^2 ºC))	ach (1/h)	G (W/(m^3 ºC)) U (W/(m^2 ºC))	D(W/m^3) d(W/m^2)	dD (%)
0.17 (0.8)	0.00	0.17 (0.8)	2.5 (12.1)	0
0.17 (0.8)	0.50	0.32 (1.5)	4.8 (22.5)	86
0.17 (0.8)	1.00	0.47 (2.2)	7.0 (33.0)	172
0.17 (0.8)	1.50	0.62 (2.9)	9.3 (43.5)	260

If we consider a radiation of 2 W/m^3 (9.5 W/m^2) and a *ach* variation of 1 (ranging from 1.5 to 2.5), the energy consumption increases by 66%, as shown in Table 3.

These examples apply to the current climatic conditions, in which the average horizontal radiation in winter is approximately 115 W/m^2 (10 MJ/m^{2}day: see Table 4).

Table 3: Changes to energy consumption given the real conditions at the Planes de Son building

Ach(1/h)	G (W/(m^3 ºC)) U (W/(m^2 ºC))	I (W/m^3) i (W/m^2)	D (W/m^3) d (W/m^2)	dD(%)
1.50	0.62 (2.9)	2 (9.5)	7.30 (34.0)	0
2.00	0.77 (3.7)	2 (9.5)	9.55 (46.0)	35
2.50	0.92 (4.4)	2 (9.5)	11.8 (56.5)	66
3.00	1.07 (5.0)	2 (9.5)	14.0 (65.5)	93

The *ach* factor of 1.5 is, according to [2], the value required for an acceptable internal air quality in the presence of occupants, though a value of 2.5 is more likely if the windows are to be opened.

Table 4: Global radiation in horizontal plane near Planes de Son in 1996-1998 and the average [5]

Month	KJ/m^2 day 1996	KJ/m^2 day 1997	KJ/m^2 day 1998	KJ/m^2 day average
January	6400	7300	8000	7233
February	9400	14500	12600	12167
March	17200	17600	17400	17400
April	17600	19900	17600	18367
May	24800	20700	19100	21533
June	22300	20800	23800	22300
July	22100	22400	24800	23100
August	21800	19500	19400	20233
September	15800	17500	13400	15567
October	12300	14200	14300	13600
November	7200	7900	10700	8600
December	6800	7000	7800	7200

Comparing this with another example shows that a building with a lower G value exhibits a very different behaviour: for instance, if we consider an 8 x 8 x 3 m^3 building with a Gt value of 0.8 W/(m³ ºC) and a Ut value of 2.4 W/(m² ºC), the values given the guidelines [2] for this location, with windows placed so as to maximise incoming solar radiation in order to achieve appropriate conditions.

The energy consumption in this case may change by 56% in the absence of solar radiation. In the presence of solar radiation, the consumption clearly decreases. More remarkably, the effect of ventilation is also lower: the energy consumption changes only by 20%. The sensitivity is thus much lower.

If we evaluate the increase in consumption caused by an increase of 1 *ach* over the consumption present in a normal scenario (at 1.5 *ach*) and calculate the sensitivity, we obtain a result of 0.6 for the Planes de Son building, and 0.2 in the other scenario (see Table 5, we have not considered the changes in solar radiation term). The sensitivity to changes in ventilation of the Planes de Son building is higher (more than double).

The graphs (Figures 3 and 4) show the respective scenarios.

Table 5: sensitivity to *ach* variation

G(W/(m³ ºC)) U(W/(m² ºC))	*ach* (1/h)	d*ach* (1/h)	D (W/m³) d (W/m²)	dd (W/m³) dD (W/m²)	dD/ D
0.17 (0.8)	1.5	1	5.3 (25.2)	2.5(11.9)	0.6
0.80 (2.4)	1.5	1	14.2 (42.6)	3.0 (9.0)	0.2

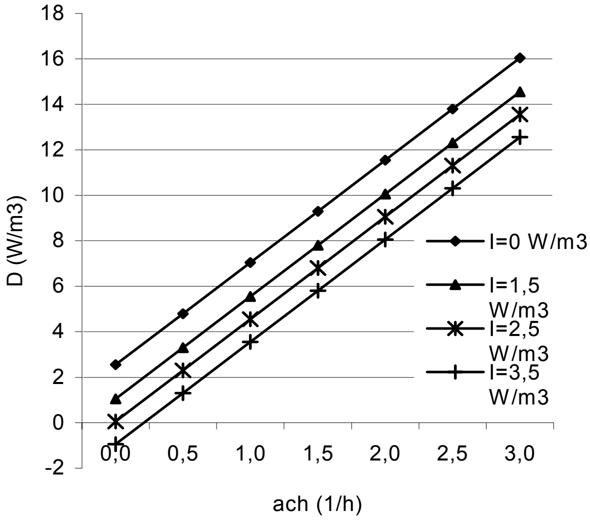

Figure 3: Changes in energy needs for the building at Planes de Son, based on different levels of incoming solar radiation and ventilation (see text).

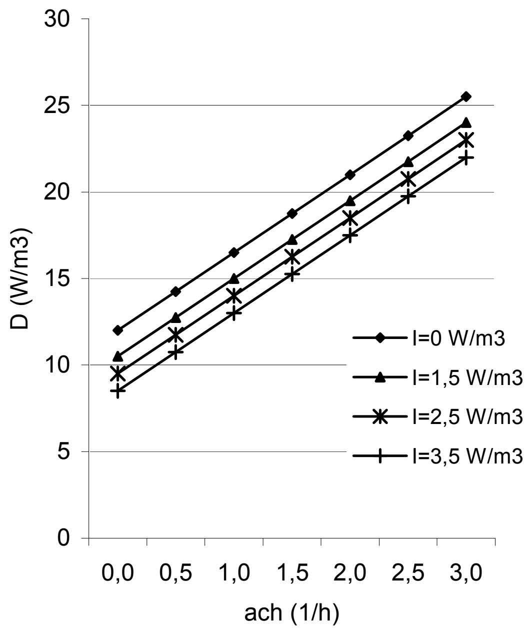

Figure 4: Changes in energy needs for the 8 x 8 x 3 m^3 building, based on different levels of incoming solar radiation and ventilation (see text).

4. DISCUSSION

Energy and sensitivity to changes in conditions are not the only significant points in this discussion. The sensation of comfort, as discussed in [6], may also be strongly affected even when the results of the equation analysis indicate it to be of little relevance. This depends on the spatial distribution of the internal temperature, which may generate a very uncomfortable sensation in areas adjacent to windows, for example.

This is the case of the Planes de Son building, in which the south-facing windows can generate a large energy gain in the area adjacent to them, yet only in this area. The sensation of comfort may thus be strongly affected in the area adjacent to the windows while at the other side of the building the sensation may be very different. In conditions like these, one user may wish to turn on the air conditioning while another simultaneously desires heating. The increase in consumption might be high and the actions undertaken by the users might end up driving a feedback loop.

Clearly, if a building is sensitive to temperature changes, the sensation of comfort one perceives in it is more difficult to assess, as it can change rapidly with time and space, but the building will always be less comfortable than a building that is not highly sensitive.

The iconic modern buildings clad entirely in glass – the buildings that use the most advanced materials known to science in order to keep themselves properly insulated – are very sensitive to heat fluctuations. The sensation of space and the satisfaction derived from the buildings' glazed façades do not counteract the fact that the spaces inside them may have significant thermal gradients, and the sensation inside is often one of discomfort.

The sensation of control is another highly significant factor: the more a building is insulated and its indoor atmosphere controlled by mechanical appliances, the more the user forgets that he or she is actually in control. This can lead to an uncomfortable sensation of helplessness if one cannot attain "perfect" conditions for one's work or dwelling space, or can lead to residents engaging in actions that call the utility of the whole into question.

Extreme scenarios can come into play when different individuals feel opposite sensations and consequently carry out opposing actions. In such cases, a highly sensitive building may easily cause some sort of feedback loop to arise and the situation will only be exacerbated. For example, in winter a user near a large, southerly window may wish to lower the ambient temperature. However, if opening the window is not possible or does not remedy the situation, the user may decide to turn on the air conditioning. Nevertheless, a colleague sitting a few metres away and outside the reach of direct sunlight could just as easily feel that the temperature is too cold. He or she then turns on the heating, only to have the first user sense the room getting hotter and try to turn the air conditioning up further.

This kind of phenomenon that tends to snowball is very dangerous and it is very important that architects should focus on this problem and try to prevent it from happening. Resolving these issues once the building is finished may be impossible, very expensive, or at best highly inefficient.

The summer scenario is more difficult to evaluate. Generally speaking, solar orientation and ventilation are relevant factors. The cases analysed here have a good orientation: the windows face South or North. Thus, the solar radiation plays a significant role in winter, but not so much so in summer. The possibilities for ventilating these spaces are very different.

The Planes de Son building has windows on the south façade, but not on the north side, and proper ventilation in large buildings requires cross-ventilation (see plan in Figure 2). Furthermore, a change in the ventilation coefficient yields rapid changes in the internal temperature distribution, as well as some changes in the solar radiation conditions. In summer, users of the building may wish to turn on the air conditioning in one particular spot and the heating in another. Alternately, they may want heating now and cooling later. In short, these issues make the Planes de Son building relatively unstable in terms of its being able to ensure user comfort.

When faced with abrupt changes in temperature, the Planes de Son building's consumption of energy over time is clearly worse than that of other buildings: even if the building's baseline energy consumption is low, a climatic change or abrupt user action can cause all the building's internal parameters to shift.

The heating/air conditioning system will then immediately try to resolve this situation, which entails a significant expenditure of energy. The term of mass accumulation, which is not particularly relevant in the winter scenario, is more important in summer. Though a building such as the Planes de Son building seems to have a very relevant thermal inertia, this inertia is more apparent than real. A term of accumulation would not be particularly significant, as much of the thermal inertia of the building is concentrated in the north, which is the side that is less affected by solar radiation.

Furthermore, the presence of a large number of wooden tables increases the shadows cast over building components and raises the local internal air temperature. The relatively heavy construction materials, which entail a large contribution to thermal inertia, receive a reduced amount of solar radiation. As discussed in other works [6], the internal layout of the furniture is also significant and must be taken into consideration.

Unlike the Planes de Son building, more "traditional" buildings exhibit a moderate thermal inertia, though the filter effect on climatic changes and users' actions is relatively strong. The conditions that are generated inside may be much more comfortable.

The results show that careful attention to design is very important in the building process. Here, by design, we mean energy and comfort strategies. In particular, this paper underlines the fact that a good design may be "robust" even when coping with users' actions and climatic changes. “Robust” means not just highly sensitive to changes in climatic parameters, but also more stable. One, yet not the only, method for achieving “robustness” is to increase the mass of the building.

Furthermore, the possibilities for exchanging energy are great. The dimensions, orientation, proportions, materials, geometry, protection, and distribution of the spaces with respect to their use: all influence the results.

Natural ventilation, the presence of thermal mass adjacent to windows and the low resistance of glass to solar radiation are the most important problems at the Planes de Son building. Now that it is built, however, it is more difficult to indicate what may have been better solutions: it is the architectural design process that must work these natural phenomena in an intelligent manner. At the moment, we are working on further studies of the Planes de Son and other buildings, based on the real energy consumption figures and internal temperatures over the years. The users’ sensation of comfort must also be considered, and possible improvements for each scenario will be indicated in the future.

The behaviour of the Planes de Son building is not intended to be the main focus of this work – it is not a particularly bad building, and should actually be recognised for being an example of forward-minded design thinking regarding energy consumption. Our main purpose was to provide an overview of the relevance of the design process on the thermal and comfort behaviour of buildings, and we simply illustrated this with some examples. The significance of building sensitivity in response to changes carried out by users or climatic fluctuations could also be extended to address building irregularities or last-minute changes in the construction details.

In the future, due to the pending energy crisis the need to make a more intelligent use of natural resources will be ever more pressing. The concept of a “natural architecture” still needs to be formulated in terms of comfort, sustainability, and also the “robustness” of its energy efficiency and comfort.

Human behaviour and the actions undertaken by users are indeed highly significant, due to their effects on energy consumption and the sensation of comfort that human actions generate inside the buildings.

With this study we aim to underline the role of architectural design on the future use of the buildings. Thermal and comfort robustness should be taken into account in future designs.

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