The importance of users' actions for the sensation of comfort in buildings

A. Isalgue, M. Palme, H. Coch, R. Serra

AiEM. School of Architecture UPC, Av. Diagonal 649, 08028 Barcelona (Spain)
Tel.+34934016422 Fax.+34934016426 antonio.isalgue@upc.edu

ABSTRACT: The sensation of comfort one feels inside a building is difficult to assess due to the number of parameters involved, such as internal temperature, thermal exchanges with the external atmosphere (air, radiation, heat), the presence of electrical appliances and – in particular – the behaviour of its users. The ability to make choices and control the environment is critical to the satisfaction of users, and psychological and sociological effects are a determining factor in the comfort they feel. However, a regular user of a building may make decisions that are inconsistent from an energy efficiency point of view, and the addition of more users to a building may indeed worsen the situation. This work focuses on determining the significance of the actions that users can undertake, such as opening windows, turning on lights or other appliances, opening or closing shutters or blinds, and changing the décor. Furthermore, we compare different buildings that have different designs, in order to show that users' control over their actions and choices determines whether they will experience comfort in these buildings. Scenarios are compared that posit simultaneous, yet distinct actions, due to the importance of comfort in buildings designed for use en masse. The aim of this study is to underline the fundamental role played by design solutions, and to emphasize the need for appropriate design choices, in particular when mechanical appliances cannot completely solve the problems that users generate.

Keywords: comfort, human behaviour, users

1. INTRODUCTION

The ability to make choices and control the environment is critical to the satisfaction of users, and psychological and sociological effects are a determining factor in the comfort they feel. Therefore, being able to determine the relevance of different decisions and actions is of primary importance in drafting policies regarding energy efficiency and comfort.

The first possibility is to have two distinct schemes for classification, the first one ranking buildings based on how well they reduce energy consumption and the second ranking buildings based on the sensation of comfort perceived inside them. Though classification schemes related to energy consumption might be easier to codify, comfort-based schemes should distinguish the relevance of factors and actions that might be not as important in determining energy consumption, such as users changing their décor to keep up with new trends, and ones that might be relevant to both comfort and energy consumption, such as using shutters and blinds.

Uncomfortable environments may be remedied by the use of mechanical appliances, or alternately by changing criteria for design and construction. Comfort solutions achieved via design and construction decisions may include appropriate solar orientation, the arrangement and protection of windows, and the selection of materials.

Energy efficiency will always be relevant in architecture. As a large part of the total energy bill in any building system comes from the building use, designers must understand the physical behaviour of buildings in order to produce efficient solutions to issues of comfort and energy efficiency.

This study discusses the topic of comfort and the relationship between comfort and energy consumption, in order to correlate good thermal and energy behaviour with the real sensation felt by users. Furthermore, we present a preliminary analytical method that might be expanded and completed in the future. Moreover, we discuss the ramifications of these preliminary results for design, and we lastly underline why architects must produce designs that are "robust" when faced with the sorts of actions taken by the users of buildings.

2. A PRELIMINARY CLASSIFICATION

In order to assess the influence of a number of factors on comfort and energy consumption, we first postulated that the buildings we studied would have a simplified geometry and materials, and we also simplified the climatic data.

All the evaluations are conducted, in a first approach with a simple thermal balance equation.

We express all the terms in the balance equations as specific terms per unit volume of the building, in order to permit the translation of the results to buildings with shapes or volumes very different. The same concepts can be expressed as specific terms per unit of floor area, or even per unit skin of the building area [1, 2]. We have used as a basis the climatic data of a temperate place at 41º latitude (Barcelona), and some possible extensions are indicated.

The general approach is differentiating the balance equation supposing that only one or two terms change, the others are considered constant.

To classify the significance of the actions carried out by users for the sensation of comfort, we referred to a temperature index. Here, our base temperature was the internal temperature first sensed by the users, and we came to the following conclusions:

- any action that increases or decreases the internal temperature by 0-1 ºC has a relatively low repercussion on comfort
- any action that increases or decreases the internal temperature by 1-2 ºC has a medium repercussion on comfort
- any action that increases or decreases the internal temperature by 2-4 ºC has a high repercussion on comfort
- an action that increases or decreases the internal temperature by more than 4 ºC has a very high repercussion on comfort

Also, to classify the importance of actions for energy consumption, we referred directly to a consumption variation index and, after looking at various possibilities, we decided to look for a specific consumption, as power per unit volume of building (which can be converted to power or magnitudes per unit surface with the help of the design of the building), and in an initial approach we assumed that:

- any action that increases or decreases the energy consumption by 0-0.5 W/m³ has a very low repercussion on consumption
- any action that increases or decreases the energy consumption by 0.5-2 W/m³ has a low repercussion on consumption
- any action that increases or decreases the energy consumption by 2-4 W/m³ has a medium repercussion on consumption
- an action that increases or decreases the energy consumption by 4-10 W/m³ has a high repercussion on consumption
- any action that increases or decreases the consumption by more than 10 W/m³ has a very high repercussion on consumption

The importance of an action such as "forgetting to close the shutters" may also be assessed using simple energy balance equations. For instance, the influence of the solar radiation that gets inside because someone "forgot to close the shutter" may be assessed using an average energy balance equation [1]:

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

Where Te is the external temperature, I is the term for radiation transfer, D stands for internal dissipation, and G is a loss coefficient (which includes thermal conductivity Gt and air exchanges Gv). Forgetting to close a shutter changes the effective value of I, and changes in the interior temperature will then come about if no mechanical appliance is turned on at the time to monitor the interior temperature. Alternately, if a mechanical appliance controlling interior temperature is turned on, either the heating will be turned down, or the cooling needs will be greater.

The graph in Figure 1 shows the increase in this "perceived" interior temperature in the presence of different increases due to solar radiation and using different coefficients of ventilation (expressed as air changes per hour, *rh*) in a flat of 8 x 8 m² situated in a temperate climate. No mechanical appliances or internal dissipations are assumed to have contributed to these internal temperature changes.

The ventilation contribution to the loss factor, Gv, is calculated as follows:

$$G_v = \rho\ c\ rh$$

Where ρ and c are respectively the density and the specific heat of the air, and *rh* stands for a term of air exchange dependent on the velocity of the air.

For architectural purposes, this formula is typically reduced to:

$$G_v = 0{,}30\,\mathrm{rh}$$

Where rh is the total air renovation of the building's volume (the Gv variation is also proportional to the rh variation). In the above equation for architectural evaluations, the ventilation coefficient rh is expressed as the total air changes in one hour (1/h).

The case considered is natural ventilation, or a mechanical air ventilation system without recuperation of heat. The numerical results change if we consider this recuperation, but the general trends and the significance of the discussion remain.

As the repercussion on comfort of a 2-3 ºC increase in temperature is relevant, an action such as "forgetting to close a shutter" must be classified as having "high" repercussions on comfort.

A similar assessment for other actions leads us to the results in Table 1, in which the relevant energy consumption has been calculated using the same average balance equation, and the relevance to comfort is correlated with the corresponding changes in internal temperature based on free thermal evolution.

As the consumption relevance is expressed using a cooling/heating index D, we separate the heating/cooling contributions Dc and the other contributions Do (dissipations inside a building, such as from the human body Db, or electrical lamps and appliances, Dl).

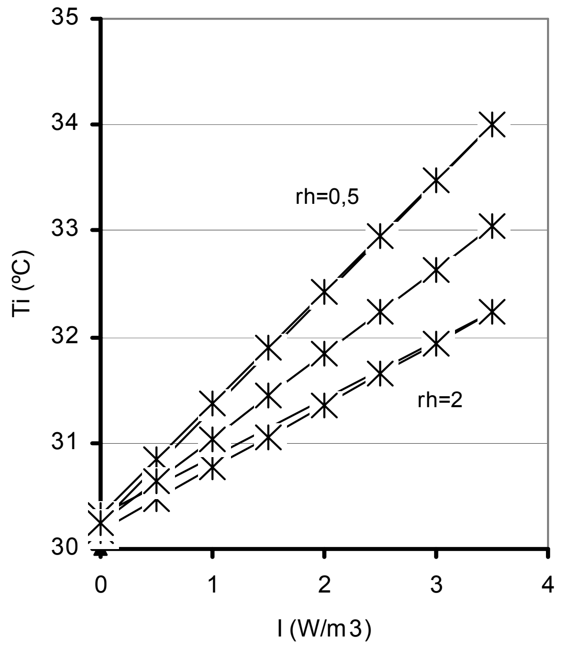

Figure 1: increase in internal temperature due to incoming solar radiation for different air renewal rates (0,5; 1; 2 h^{-1} as ventilation coefficient rh). Incoming solar radiation is given as specific contributions, in power per unit volume (W/m^3)

Table 1: Classification of actions by relevance on energy consumption and sensation of comfort (approximate repercussions)

Action	Energy repercussion	Comfort repercussion
Opening an ordinary window (1.5 m²)	high	high (3 ºC)
Opening an internal door	very low	low (1 ºC)
Turning artificial lights on	low to medium	medium to high (2 ºC)
Turning electrical appliances on/off (not the heating system)	medium	low (1ºC)
Opening or closing shutters/blinds	medium	high (3 ºC)
Resetting base temperature for heating system	high to very high	medium to high (2 ºC)
Resetting base temperature for cooling system (air conditioning)	very high	high (4 ºC)

The actions analysed here are those that are most typical for an ordinary flat and the way in which it is used. Actions such as change dressing are not included here because of the relatively low relevance they have to the energy balance, though they may in fact be significant for the sensation of comfort.

In the following graph (Figure 2), we show the increase in the internal temperature when one turns on the light, which totals 60 W of power: a dissipated 60 W entails a specific dissipation (power per unit volume of space) of 0.3 W/m³ in a space of 200 m³. We started at an average of 1 W/m³ due to the presence of other appliances and residents. Turning on a light raises the internal temperature by 0.25 ºC; thus, turning on five light bulbs increases the temperature by 1.2 ºC. Of course, especially bright lighting can sometimes use even more power.

Turning on the lights is classified as “highly relevant to comfort”, as an analysis of comfort cannot be based solely on the internal average temperature.

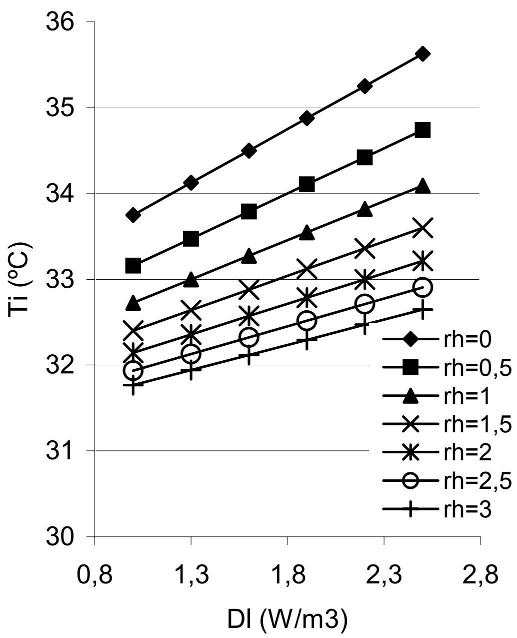

Figure 2: Increase in energy consumption and internal temperature when a user turns on one to five 60 W light bulbs for different air changes (*rh*) in the space and as a function of specific dissipation in the space (DI, consumption of the lights).

To obtain more satisfactory results, we must move on to a zone study on the influence of this particular action: for example, turning on a 60 W light bulb increases the average internal temperature by 0.25ºC (a low repercussion), though near the light the comfort sensation may be highly affected (due to the presence of lighting), and there will also be temperature gradients in the room.

3. DISCUSSION OF DESIGN RELEVANCE

The figure in the first example shows that different configurations entail different behaviours: equal amounts of power or energy input (as lights or radiation) have a larger effect in buildings in which there is less ventilation.

Generally, a good configuration has to be versatile and robust, which means that the users must be able to change the configuration. However, users' actions might not come in time, might not be carried out at an appropriate scale, or could even simply be wrong. Thus, there should be some way of filtering the way in which these users control their actions. While filters are a traditional means of controlling the actions of mechanical appliances, we posit architecture itself as a way to limit possible wrong actions taken by users.

For example, if a user forgets to close a shutter, it is preferable that the building should not be overly sensitive to this change. If one user desires heating and another desires cooling in adjacent locations in a building, the building must limit the possibility of there being a simultaneous use of heating and cooling systems in a single place.

Thus, the main conundrum is that users must be led to believe they have control, while in reality this is only partially true. A building with substantial thermal insulation whose component materials and protective features were subjected to strict monitoring in the design process should not leave a wide range of control to the users. In a building with a "robust" design, a greater degree of control can be given to the users without causing problems to arise due to the building's decreased sensitivity to any changes that might occur.

Let us consider a simple example: one building facing South and one facing West, whose remaining parameters are equal in every way to one another. In summer, the solar contribution (term 'I') is higher in the latter, which means that the action of forgetting to close the window or shutters may cause a substantial increase in the internal temperature. Thus, the first configuration appears more "robust" that the second.

The following examples, tables and discussions illustrate the aforementioned effects:

Table 2: Climatic situation (temperate), dissipation coefficients (Gt, Gv, G=Gt+Gv), consumption terms (D1, D2, D=D1+D2) and internal temperature of a building with a "robust" design, all in specific volume units

Te (ºC)	Gt (W/(m^3 ºC))	I (W/m^3)	D1(W/m^3)	Ti (ºC)
11	1	10	2	19
	Gv (W/(m^3 ºC))		D2 (W/m^3)	
CASE 1	1		4	
	G (W/(m^3 ºC))		D (W/m^3)	
	2		6	

Table 2 corresponds to a South-facing building receiving a significant amount of solar radiation that is not heavily insulated (thermal insulation is less necessary if there is a significant contribution from solar radiation) and has a ventilation coefficient (*rh*) of approximately 3-3.5. The D coefficients may correspond to different consumption contributions: for example, a person (D1) and the heating contribution (D2), which when added result in D (6 W/m^3).

Table 3: Climatic situation (temperate), dissipation coefficients (Gt, Gv, G=Gt+Gv), consumption terms (D1, D2, D=D1+D2) and internal temperature of a very well insulated building, all in specific volume units

Te (ºC)	Gt (W/(m^3 ºC))	I (W/m^3)	D1 (W/m^3)	Ti (ºC)
11	0.425	1	2	19
	Gv (W/(m^3 ºC))		D2 (W/m^3)	
CASE 2	0.45		4	
	G (W/(m^3 ºC))		D (W/m^3)	
	0.875		6	

Table 3 corresponds to a building in the same climate and possessing the same internal dissipation (D) as the building in Table 2. However, this building receives a lower amount of solar radiation, and it is well insulated. It therefore achieves the same results for energy consumption as the building in Table 2, and the air renewal coefficient is lower (1.5 *rh*).

In Tables 4 and 5, we compare the cases with that of a very well insulated building with low solar radiation (Gtot = 0.875 (W/(m^3 ºC)); I = 1 W/m³) and that of one with high radiation and ventilation (Gt = 1 (W/(m^3 ºC)), Gv = 1 (W/(m^3 ºC)), I = 10 W/m³) [2], when the ventilation coefficient Gv increases by 0.5 W/m³.

The values for insulation and ventilation have been selected according to the Spanish Official Guidelines [2] and to the guidelines published by ASHRAE [4] and Carrier [5].

Table 4: Change in the internal temperature caused by an increase in the ventilation coefficient (case 1 or Table 2). Compare the interior temperature (Ti) with the interior temperature in Table 5.

Te (ºC)	Gt (W/(m^3 ºC))	I (W/m^3)	D1 (W/m^3)	Ti (ºC)
11	1	10	2	17.4
	Gv (W/(m^3 ºC))		D2 (W/m^3)	
Change of G (W/(m^3 ºC))	1.5		4	
0,5	G (W/(m^3 ºC))		D (w/m^3)	
	2.5		6	

The results show that the second case (Table 5, related to Table 3) is more sensitive than the first (Table 4, related to Table 2): the same variation in G yields different variations in Ti. Thus, with an external temperature of 11ºC, we discover that by increasing the value of G by 0.5, the internal temperature of 19ºC drops to 16ºC in the second case and to 17.4ºC in the first.

Table 5: Change in the internal temperature, Ti, produced by an increase in the ventilation coefficient (Gv), in a very well insulated building (case 2 or Table 3).

Te (ºC)	Gt (W/(m^3 ºC))	I (W/m^3)	D1 (W/m^3)	Ti (ºC)
11	0.425	1	2	16.09
	Gv (W/(m^3 ºC))		D2 (W/m^3)	
Change in G (W/(m^3 ºC))	0.95		4	
0.5	G (W/(m^3 ºC))		D (W/m^3)	
	1.375		6	

The differences in the internal temperatures are 1.6ºC in the former case and 3ºC in the latter. A very well insulated building is nearly twice as sensitive as the other buildings, in which both solar radiation and ventilation are relevant. Thus, we can state that the building shown in Tables 2 and 4 has a "less sensitive design" in the sense that changes in ventilation produce only subtle changes in its internal temperature.

Clearly, the buildings that experience a relevant amount of solar radiation have other problems that affect the sensation of comfort. For example, in winter the thermal sensation near the windows may be very different from the thermal sensation in other parts of the building, and different users may desire different amounts of heating based on their location in the building.

The examples show that the project's preliminary design plays an important role in achieving the results: the solar orientation and selection of materials, the distribution of zones and local climatic conditions must all be considered in terms of how they each influence comfort.

Other important aspects to take into consideration include the electrical appliances, in particular the lights, the choice of which affects energy usage and perhaps even the sensation of comfort more than energy efficiency.

The graph in Figure 3 shows the importance of using low-wattage lighting, in particular in summer: the temperature increase caused by turning on the lights clearly decreases with the use of low, 15 or 30 W lights as compared to 60 W lights.

When one turns on five lights, the internal temperature increases by 0.3ºC, while for 60 W lights the increase is 1.2ºC.

This linear effect may be more important to obtaining a true sensation of comfort than simply reducing energy consumption, as was discussed in previous sections. Table 6 shows the summer values for 15, 30, 45 and 60 W lighting.

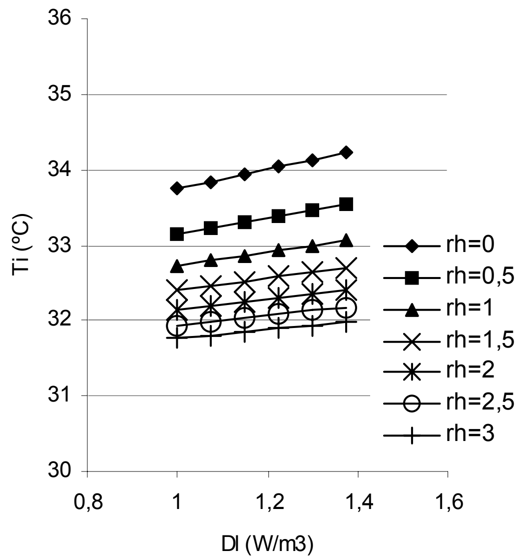

Figure 3: Increase in internal temperature and energy consumption when a user turns on one to five 15 W lights; internal temperature changes for different air renewal conditions.

Table 6: Effects of turning on 15, 30, 45 and 60 W lighting on energy consumption and on the perceived interior temperature.

light (W)	consumption (W/m^3)	interior temperature (ºC)
60	1.5	33.6
45	1.25	33.4
30	0.75	33
15	0.36	32.7
0	0	32.4

All these results are obtained in the above mentioned climatic conditions and considering natural ventilation. The use of an HVAC system, in particular with heat recuperation clearly may reduce the impact of all the actions, but the significance of the relevance of these on the energy savings and more, on the comfort sensation will not change strongly. Users' decisions are difficult to control, and the necessity of a project prevision on the possibility of these is a certain.

4. CONCLUSIONS

Analysing comfort may be more difficult than assessing energy consumption, in particular when human behaviour plays a relevant role. For this reason, a complete classification of the actions and decisions that users can carry out is needed.

Average thermal balance equations are clearly insufficient when one is making a full analysis of the summer scenario, because when changes in internal temperature are not mechanically controlled, there is typically an ample amount of ventilation with considerable incertitude on its value. Furthermore, changes in use over the course of the day and thermal mass are also significant when one is assessing the dynamic behaviour of the building.

One must also discuss the spaces of a typical building layout in order to provide a reference framework for analysing unique scenarios.

Temperature and lighting gradients and particularities of air movement, in addition to other factors, may have a large influence on energy savings and a very high repercussion on comfort.

Buildings with different designs have been analysed, and further examples have been discussed in other papers [3].

Figure 4 shows buildings respecting the Spanish norms, which may be a good example of "robust" buildings where the influence of the users' action has been considered.

We highlight the significance of a building's design with regard to its ability to effectively "resist" the actions of its users – that is, its ability to remain thermally stable in the light of inappropriate actions carried out by its users given its energy and/or comfort conditions. These actions could be due to erroneous judgement or other causes, such as simple omissions. When architects tackle issues concerning energy efficiency and comfort, all design solutions should aim to make it easy, or even "unavoidable", for users to inhabit these buildings in a correct fashion.

In conclusion, training users may not be enough to ensure that buildings are used in a suitable way. Design strategies and project solutions must be taken into serious consideration in order to minimise the possibilities of misusing energy and stifling comfort.

Furthermore, the sensations of users must be correlated to the actions and decisions they can actually carry out, as we should recall that cultural and sociological factors play a significant role in determining human behaviour.

Future investigations should consider all these factors. As we have pointed out, however, the current situation underscores the fundamental role played by design strategies on the sensation of comfort inside buildings. Suitable designs should not only be energy-efficient and comfortable, but also robust in order to make it difficult for incorrect actions to take place.

A way to realize this may be following the steps:

- first, a general design of the building
- second, evaluate the general thermal behaviour of the building, with balance equations and dynamic simulations
- third, evaluate the sensitivity to the actions of the users. Compute the building change of performance with the users' actions.
- finally, depending on the result of the previous steps, eventually reconsider the initial project and change it until good performance is achieved.

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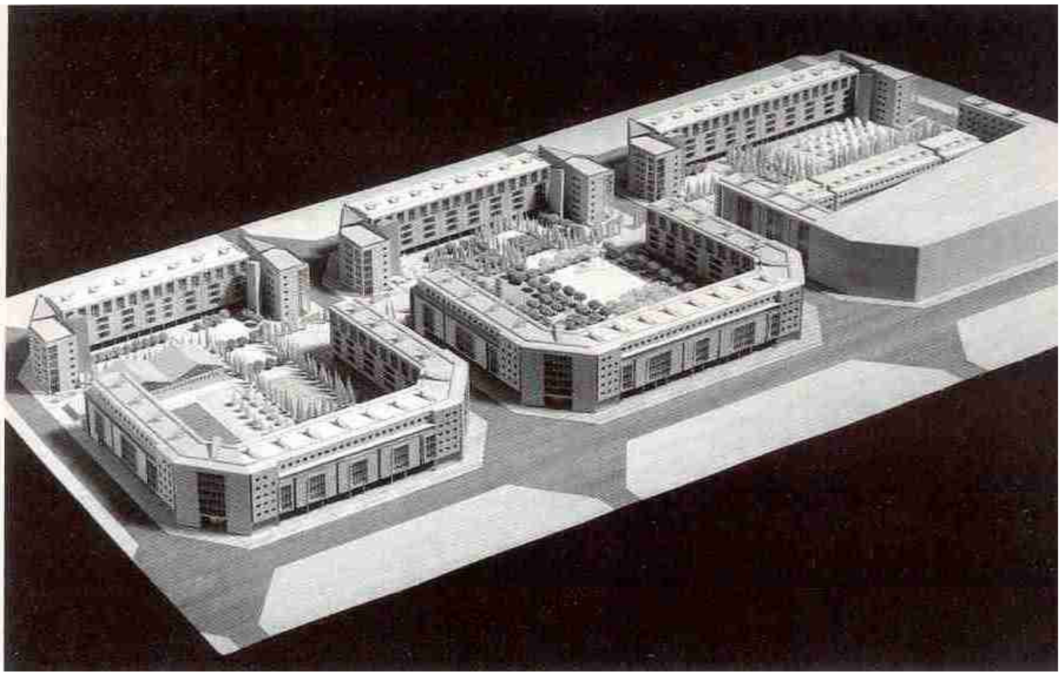

Figure 4: flat blocks in Villa Olímpica, Barcelona (Spain). Arch. Carlos Ferrater, 1992