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The impact of increasing the building envelope insulation upon the risk of overheating in summer and an increased energy consumption

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This work describes a study aiming to establish the impact of the increase of the building envelope insulation upon the thermal performance of buildings. A particular emphasis is placed upon the consequences in terms of higher temperatures in summer, potentially leading to increased needs for installation of air-conditioning. This study also describes the coupled influence of other parameters that can reduce overheating, like solar shading and ventilation. The methodology is based on parametric studies obtained through simulations. The comfort analysis methodology is based on the adaptive approach. The results show that, with added insulation, it is necessary to control solar and internal gains more closely to avoid overheating in summer. Results also include the requirements to avoid air-conditioning, in terms of window shading for each level of insulation and internal gains.

Keywords: building envelope insulation; adaptive comfort; building simulation; air-conditioning avoidance

1. Introduction

Thermal regulations for buildings in the European countries were recently revised to comply with the European Directive on the Energy Performance of Buildings (EU Official Journal 2003). One of the consequences was the general adoption of stricter requirements for insulation of the building envelope in the European legislations. There was a strong pressure from industry (Ecofys 2004) and from the European Commission itself (EC 2005) to move towards higher insulation levels in all types of buildings everywhere in Europe. As an example, the Portuguese thermal regulations for residential buildings were recently modified (2006) and insulation requirements increased by about 50\% and a similar tendency was visible in most EC countries (Maldonado 2005a,b; DGE 2006).

The benefits of increasing the insulation thickness are evident in a typical winter situation, when a lower U-value directly reduces heating needs. In countries that have long heating periods and short and mild summers, e.g. northern European countries, the energy consumption can be considerably reduced with the adoption of highly insulated envelopes.

However, the consequences during the summer period are not so evident. In certain conditions, when solar and internal gains are not adequately controlled, a highly insulated envelope may cause a rise in the indoor temperature, possibly above acceptable comfort limits. This problem can be found more frequently in countries where summers have long periods with high outdoor temperatures and high solar radiation exposure, which is the case of the southern European countries.

In traditional southern European residential buildings, air-conditioning is not usually needed. Architectural solutions are well adapted to such climates, taking advantage of high thermal inertia, good solar protection and night ventilation. However, if there are changes in the way that buildings are designed, and if the degree of discomfort becomes too important, overheating in summer can lead building occupants to adopt air-conditioning, thereby increasing the total energy consumption of the building, possibly offsetting any savings obtained from increased insulation during the heating season. The sales of air-conditioning in Europe have been growing very fast in the last two decades (Dupont and Adnot 2005), at a rate averaging 10\% or more per year, and this rate can become even higher by adding more insulation to the building envelopes without taking additional measures to limit summer overheating.

It thus seems wise to investigate the influence of increasing the building envelope insulation upon its global thermal performance, in terms of the consequences of promoting overheating in summer. It is necessary to determine the limit until such time it

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becomes desirable to increase the insulation of the envelope without causing summer overheating that could offset the significance of any savings in energy heating during winter.

To achieve this objective, it was decided to analyse the thermal behaviour of the envelope through parametric studies obtained via computational simulations. Distinct building models with varying envelope insulation levels were studied, together with other parameters that can reduce overheating, like solar shading and ventilation. High thermal inertia solutions were preserved. The adaptive comfort approach was used to evaluate the acceptability of the resulting indoor environments.

2. Parametric studies

2.1. First phase of simulations

In this phase, the simulations were carried out for three types of buildings (Figure 1), each one used either as a residence or as a small office:

- A one-storey building (Building A).
- Two intermediate flats in multi-storey buildings (Buildings B and C).

All three typologies are quite current in southern European construction and they all have a high thermal inertia. Reasonable ranges of window
shading, pattern of use of the building as a residence or as an office, ventilation rates, envelope insulation and climate were considered for each of them. The simulations were performed both in free-float conditions and with heating and cooling systems (thermodynamic conditions). Figure 2 shows an overall scheme of the studied combinations and Table 1 lists the detailed input data for all the parametric studies. Table 2 presents the U-values for the external envelope of the simulated buildings and Table 3 describes the average climatic data for the selected locations (Figure 3).

The simulations of the thermal behaviour of the buildings were carried out with TRNSYS software (Solar Energy Laboratory 2002). Because of the large amount of simulations (3780 individual cases), a program, named PARAM and written in C++, was prepared to automatically run TRNSYS for all the cases and to treat the outputs (post-data processing) (Chvatal et al. 2003, 2005).

Figure 4 shows a simplified scheme of the whole process. The first step consists of manually creating the TRNSYS input files for the base cases that are to be analysed. The base case corresponds to a combination of building and type of use (Figure 2). In these simulations, nine base cases were studied. These TRNSYS input files for each base case contain all the information regarding geometrical characteristics, orientation and type of use (internal gains). These parameters are fixed and do not change during the simulation process.

In the second step, the input files for the program PARAM are created. These files contain all needed data to perform the parametric studies: climates,

![Diagram](image_url)  
**Figure 2.** Overall schemes of the parametric studies combinations for the first phase of simulations.
Table 1. Input data for the first phase of simulations.

**Simulated buildings A, B and C (Figure 1)**

**External envelope**  
Double external walls (Buildings A, B and C)  
- (a) Render (2 cm)  
- (b) External ceramic hollow bricks (15 cm)  
- (c) Intermediate air layer (2 cm)  
- (d) Insulation (e)  
- (e) Internal ceramic hollow bricks (11 cm)  
- (f) Render (2 cm)  

Solar absorptance coefficient, exterior surface: 0.6, interior surface: 0.3

**Internal elements**  
Internal walls (Buildings A, B and C), ceramic hollow bricks masonry (11 cm)

**External envelope insulation**  
Five envelope insulation levels: [0/2], [2/4], [4/6], [6/10] and [15/22] cm [wall insulation/roof insulation thicknesses]  
Thermal conductivity of the insulation material: 0.04 W/m. °C

**Percentage of window area**  
Window/floor area: 12.9% (building A), 11.6% (building B), 10.2% (building C)

**Window shading**  
- **Summer**  
  Seven possibilities of shading \(^{c}\) (corresponding solar factors): 0.75 / 0.60 / 0.45 / 0.37 / 0.30 / 0.22 / 0.15  
- **Winter**  
  No shading, corresponding solar factor = 0.75

**Types of use**  
- Housing (the original purpose of the buildings or apartments)  
- Services (a small office, for example – this type of adaptation is common in the Portuguese reality. Two patterns of internal gains were considered.)

**Occupation schedule**  
- **Use: housing**  
  Between 18:00 and 09:00 h, on weekdays 24 h on weekends  
- **Occupied zones**  
  - Building A: zones 1, 3, 4 and 5  
  - Building B: zones 1, 3, 4 and 5  
  - Building C: zones 1, 2 and 3  

**Internal gains**  
- Use: housing, pattern 1  
  3.3 W/m\(^2\) – average over 24 h, in the occupied zones

**Ventilation**  
Two possibilities of ventilation: with minimum and night ventilation

**Minimum ventilation**  
Constant rate of 0.6 air changes/h

**With night ventilation\(^{d}\)**  
- **Use: housing**  
  Night ventilation between 18:00 and 24:00 h (3 air changes/h), every day.  
  During the night: no night ventilation due to noise constraints.

**Floor (Building A)**  
- (a) Gravel (5 cm)  
- (b) DPM (1 cm)  
- (c) Insulation (a)  
- (d) Concrete (10 cm)  
- (e) Concrete flat roof (13 cm)  
- (f) Render (2 cm)  

Solar absorptance coefficient, exterior surface: 0.6 / interior surface: 0.3

**Slab (Buildings B and C), concrete slab (18 cm)**  
- (a) Wood (0.5 cm)  
- (b) Mortar (2 cm)  
- (c) Concrete (12 cm)  
- (d) Gravel (15 cm)  
- (e) Insulation (5 cm)
ventilation characteristics (number of air changes per hour and period of ventilation), window shading factor and envelope insulation levels, as well the heating and cooling system characteristics (set point temperature, period of use, etc.).

After the input files are completed, the third step simply consists of running PARAM. The program automatically creates the TRNSYS input files for each individual case to be simulated, runs TRNSYS and then performs the post processing of the results, i.e. hourly values of the indoor temperature for each zone, for the whole year, as well as the heating and cooling loads. Post processing treats these data to obtain summarized results and to show the differences between each case. It includes the comfort analysis described in detail in Section 3.

Table 1. (Continued).

Simulated buildings A, B and C (Figure 1)

| Climate | Three climates: Porto, Lisbon and Évora
| Typical of the three Portuguese summer climatic zones, according to building Regulations (DGE 2006) Table 3 and Figure 3.
| The hourly climate data for these three cities were generated by the Meteonorm program (Meteotest 2000).

<table>
<thead>
<tr>
<th>Heating and Cooling</th>
<th>Summer setpoint temperature: 25°C</th>
<th>Winter setpoint temperature: 20°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>aThe external envelope is always the same, but the insulation thickness changes. Table 2 presents the U-values for the external envelope.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bBuildings B and C are located in intermediate floors and consequently have no slab insulation.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>cFixed external shading.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>dThere is night ventilation only during summer and if the outdoor temperature is lower than the indoor temperature.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>eThere is heating and cooling only in the occupied zones. When it is necessary, heating or cooling begin automatically. This is considered for the correspondent occupation period, during the whole year.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2. U-values (W/m² °C) for the external envelope of the simulated buildings.

<table>
<thead>
<tr>
<th>Envelope insulation level</th>
<th>1 2 3 4 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulation thickness (cm) [wall/slab]</td>
<td>[0/2] [2/4] [4/6] [6/10] [15/22]</td>
</tr>
<tr>
<td>Wall U-value</td>
<td>0.91 0.64 0.47 0.37 0.20</td>
</tr>
<tr>
<td>Roof U-value</td>
<td>0.80 0.50 0.38 0.27 0.14</td>
</tr>
</tbody>
</table>

ventilation characteristics (number of air changes per hour and period of ventilation), window shading factor and envelope insulation levels, as well the heating and cooling system characteristics (set point temperature, period of use, etc.).

After the input files are completed, the third step simply consists of running PARAM. The program automatically creates the TRNSYS input files for each individual case to be simulated, runs TRNSYS and then performs the post processing of the results, i.e. hourly values of the indoor temperature for each zone, for the whole year, as well as the heating and cooling loads. Post processing treats these data to obtain summarized results and to show the differences between each case. It includes the comfort analysis described in detail in Section 3.

2.2. Second phase of simulations

To analyse the influence of diurnal ventilation and to verify the validity of the obtained results for other southern European climates, another set of simulations was conducted (Figure 5), which corresponds to 1020 individual cases. The process was the same as the one described in the previous section. The input data are presented in Table 4. Table 3 describes the average climatic data.

3. Comfort analysis methodology

Finding an answer to the question that this study addresses rests on being able to set an objective criterion to define when an occupant feels enough discomfort, in terms of both intensity and length of exposure, to decide to install and use an air-conditioner. It is assumed that there are no economic constraints that would prevent occupants from installing and running AC equipment.

Comfort analyses of the indoor environments are covered by ISO 7730 (2005), based on the well-known Fanger theory. However, thermal comfort field studies have demonstrated some room for improvement in the predictions of the real mean vote (Nicol and Humphreys 2002). In these field surveys, the subjects demonstrated, with good statistical confidence, to accept a wider range of environmental conditions than those set by ISO 7730. One of the reasons for these differences is the capacity of adaptation of the subjects, e.g. the possibility that they have to make some changes in their thermal environment, like opening/closing windows, adjusting clothing, location, shading and ventilation conditions, etc. This would allow them to tolerate indoor conditions outside the narrow limits prescribed by the ISO standard, where no adaptation possibility is taken into account. The recent revision of the ASHRAE Standard 55 (De Dear and Brager 2002; ASHRAE 2004) also includes an adaptive model, which became an alternative to the deterministic method prescribed in its previous version. This approach can be used for naturally ventilated buildings that obey certain restrictions, on the basis of research carried out using an extensive worldwide database of thermal comfort field studies. The recent EN 15251 standard (Criteria for the Indoor Environment including thermal, indoor air quality, light and noise) (CEN 2007), linked to the implementation of the EPBD, also offers some room for adaptive...
considerations but they seem short when compared to the full potential identified by Humphreys and Nicol.

In the adaptive comfort theory, comfort temperature is closely related to the prevailing outdoor ambient temperature, as described by Equation (1) (McCartney and Nicol 2002):

\[ T_c = a \cdot T_{out} + b \]  

(1)

The adaptive comfort theory fits exactly into the traditional lifestyle of southern Europeans in their dwellings and unconditioned offices. It thus seems more realistic to use this approach rather than the more deterministic ISO 7730.

### Table 3. Average climate data for the studied climates.

<table>
<thead>
<tr>
<th>Latitude ('north')</th>
<th>Temperature (°C)</th>
<th>Humidity (%)</th>
<th>Global horizontal radiation (kWh/m²)</th>
<th>Heating degree days (°C/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Summer</td>
<td>Winter</td>
<td>Summer</td>
<td>Winter</td>
</tr>
<tr>
<td>Porto</td>
<td>41.08</td>
<td>19.6</td>
<td>9.8</td>
<td>74.0</td>
</tr>
<tr>
<td>Lisbon</td>
<td>38.43</td>
<td>22.3</td>
<td>11.8</td>
<td>63.7</td>
</tr>
<tr>
<td>Évora</td>
<td>38.34</td>
<td>22.6</td>
<td>9.8</td>
<td>48.7</td>
</tr>
<tr>
<td>Athens</td>
<td>38.04</td>
<td>25.0</td>
<td>11.6</td>
<td>51.0</td>
</tr>
<tr>
<td>Nice</td>
<td>43.40</td>
<td>22.1</td>
<td>9.2</td>
<td>71.7</td>
</tr>
</tbody>
</table>

Temperature and humidity: average of monthly averages from July, August and September (summer) and from December, January and February (winter). The monthly averages are based on hourly data.

Global horizontal radiation: maximum of monthly averages and minimum of monthly averages.

Heating degree days: reference temperature: 15°C, during December, January and February. The differences were calculated using the hourly data.

### Figure 3. Climatic zones for summer, in Portugal and the selected cities for the parametric studies.

### Figure 4. Simplified scheme of the simulation process.

where, \( T_c \): comfort temperature, corresponding to the neutral comfort vote in the ASHRAE scale (ASHRAE 2004); \( T_{out} \): outdoor temperature index, for example, the average outdoor temperature; \( a, b \): constants obtained from regression analysis of measured data in field studies.
A recent European study, with the main purpose to develop an adaptive control algorithm fitting Equation (1), provided data for calculation of $a$ and $b$ constants fine-tuned to the southern European population. It included field studies in Portugal, France and Greece, as well as in other more northern climates (McCartney and Nicol 2002) and provided adaptive algorithms for each country. For Portugal, Greece and France, Equation (1) thus becomes:

Portugal:

$$T_c = 0.381 \cdot T_{RM} + 18.12 \, (^\circ C) \quad (2a)$$
Greece:

\[ T_c = 0.205 \cdot T_{\text{RM}} + 21.69 \, (^\circ \text{C}) \, (\text{for } T_{\text{RM}} > 10^\circ \text{C}) \, (2b) \]

\[ T_c = 22.88 \, (^\circ \text{C}) \, (\text{for } T_{\text{RM}} \leq 10^\circ \text{C}) \]

France:

\[ T_c = 0.206 \cdot T_{\text{RM}} + 21.42 \, (^\circ \text{C}) \, (\text{for } T_{\text{RM}} > 10^\circ \text{C}) \, (2c) \]

\[ T_c = 0.049 \cdot T_{\text{RM}} + 22.58 \, (^\circ \text{C}) \, (\text{for } T_{\text{RM}} \leq 10^\circ \text{C}) \, (2d) \]

In Equation (2a–d), \( T_{\text{RM}} \) is the running mean outdoor temperature. It is the outdoor temperature index that produces better accuracy and that can better reflect the time-dependency of the comfort temperature. It is similar to the half-life radioactive decay calculations, and it is calculated on a daily basis. In this case, it corresponds to a half-life of \( ~3.5 \) days, according to the following Equation (3):

\[ T_{\text{RM}}^n = 0.80 \cdot T_{\text{RM}}^{n-1} + 0.20 \cdot T_{\text{DM}}^{n-1} \, (^\circ \text{C}) \, (3) \]

where, \( T_{\text{RM}}^n \): running mean temperature on day ‘\( n \)’; \( T_{\text{RM}}^{n-1} \): running mean temperature on day ‘\( n-1 \)’; \( T_{\text{DM}}^{n-1} \): daily mean temperature on day ‘\( n-1 \)’.

At day 1, \( T_{\text{RM}}^1 \) is assumed to be the same as mean outdoor ambient temperature.

Using the above equations, daily comfort temperatures were obtained for the five cities for a whole typical year. The maximum values of the comfort temperature were found to be 26.7°C for Porto, 27.4°C for Lisbon, 27.7°C for Evora, 27.5°C for Athens and 26.6°C for Nice.

The comfort temperature corresponds to a neutral thermal sensation vote. The comfort zone was established as \( \pm 2^\circ \text{C} \) around the comfort temperature, according to Nicol and Humphreys (2005). Actually, there is not an exact limit between comfort and discomfort, but this is the recommended range to avoid an increased sense of discomfort and dissatisfaction with the ambient.

As a sample output from the simulations, Figure 6 shows the variation of the outdoor and indoor temperatures, as well as the upper limit of the comfort zone, during 6 days in summer for zone 1 of the building B, located in Porto, being used as an office, pattern 3 of internal gains, window solar factor of 0.30, 6 cm of wall insulation and with minimum ventilation.

The analysis of the results showed that parameters 2, 6 and 7 (percentage of discomfort hours, average maximum overheating and degree-hours of discomfort) were found to be the most representative for characterizing a building, as explained in the following section.

### 4. Results

#### 4.1. Housing

##### 4.1.1. Comfort analysis

(a) Insulation increase versus solar factor. Figure 7 shows the percentage of discomfort hours (parameter 2 of discomfort) per day of discomfort: temperature above the upper comfort limit.

Thus, in order to characterize the comfort conditions, the outputs from all simulated cases were post-processed to obtain the seven parameters described in Table 5. Each parameter was calculated for each of the occupied spaces and then averaged to obtain a ‘whole building’ indicator. All of these results refer to the occupied period only.

### Table 5. Defined parameters to characterize the comfort conditions.

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of discomfort days, during summer</td>
<td>( % )</td>
</tr>
<tr>
<td>Percentage of discomfort hours, during summer</td>
<td>( % )</td>
</tr>
<tr>
<td>Number of consecutive days of discomfort per year</td>
<td>( % )</td>
</tr>
<tr>
<td>Average overheating (°C of discomfort)</td>
<td>( % )</td>
</tr>
<tr>
<td>Average maximum overheating (°C of discomfort)</td>
<td>( % )</td>
</tr>
<tr>
<td>Degree-hours of discomfort, during summer</td>
<td>( % )</td>
</tr>
</tbody>
</table>

\(^a\) A day is considered uncomfortable when it has at least one uncomfortable hour.

\(^b\) Overheating (°C of discomfort): temperature above the upper comfort limit.
of Table 5) during summer, for the building B when used as a dwelling, with minimum ventilation, in Évora, which corresponds to the warmest summer zone of Portugal (Figure 3 and Table 3). The 'x' axis represents the insulation thickness used in the external envelope and each curve corresponds to one particular window solar factor (window shading). Depending on the solar factor, there are different patterns of behaviour as the insulation increases:

- When there is little shading (high solar factor, which means high solar gains), there is a tendency towards more discomfort as the insulation increases.
- However, when shading is more effective (lower solar factor and lower solar gains), the discomfort is low and it decreases even when the insulation increases.

This shows that the increase of the insulation of the envelope is favourable only when window solar gains are below certain limits. In this specific example, the cross-over point, i.e. the solar factor above which increased insulation results in worse building performance in summer is 0.32. This value was established by a specially refined running of the building model, to look for the precise value of the solar factor that produced different behaviours just below and above it.

(b) Selected comfort parameters. For the other comfort parameters of Table 5, the same type of result was observed (Figure 8a–f): there are clearly different patterns of behaviour depending on the solar factor. Well-insulated envelopes with insufficient shading (high solar factors and high solar gains) have a tendency for more discomfort, in all aspects (duration, maximum overheating, etc.). Because of the similarities of the observed patterns (or trends), it is not necessary to consider all these comfort parameters to characterize the level of summer discomfort in a building. Therefore, only some of them were selected.

The selection of the most representative parameters took into account the evaluation of the discomfort periods in terms of both intensity and length of exposure. The percentage of discomfort hours (Figure 7) was chosen to represent the duration of the discomfort period, and the average maximum daily overheating (Figure 8e), the highest intensity of this discomfort. The degree-hours (Figure 8f) complete the discomfort characterization, integrating the information from both the duration and the intensity in only one parameter.

(c) Influence of ventilation. Figure 9a–c shows the same type of results, both for the case above, with minimum ventilation, and for the cases with day and/or night ventilation. The presented window solar factors are 0.75 and 0.37. As was expected, when there is more ventilation, there is less discomfort. Ventilation gives an important contribution to remove the heat accumulated inside the building. Ventilation during the day and night showed to be more effective than during the night only, because exterior summer temperatures are below comfort level during many days. When insulation is added to the envelope, the discomfort does not increase as it increases for the case with minimum ventilation (in some cases, it does not even increase) and the cross-over point corresponds to a higher solar factor. In this case, the building can accept higher solar gains than with minimum ventilation and still be comfortable with higher insulation of the envelope. The cross-over points are presented in Figure 9d.

(d) Buildings A, B and C and other climates. Buildings A and C showed the same pattern of behaviour as the one described for building B. In building C (Figure 10), there was only a slight difference: in some cases, the discomfort increases as more insulation is added to the envelope, even when solar gains are low. Nevertheless, this increase is very small, compared to what is observed when the solar shading is inefficient. Building B presented the highest values of discomfort in all aspects, followed by C and A, respectively.

For the other southern European climates, namely Lisbon, Porto, Athens and Nice, the same pattern of behaviour presented for Évora was observed, regarding insulation increase versus shading.

4.1.2. Energy consumption

Figure 11a–c shows, respectively, the heating, cooling and heating plus cooling energy consumption for the building C, also located in Évora. The heating and cooling energy consumptions have the same
Figure 8. Results for the building B, used for housing, with minimum ventilation and various solar factors, in Évora. 
(a) Percentage of discomfort days, during summer. (b) Number of consecutive days of discomfort per year. (c) Percentage of the discomfort period per day, during summer. (d) Average overheating per day, during summer. (e) Average maximum overheating per day, during summer. (f) Degree-hours of discomfort, during summer.
conversion factors to primary energy, taking their respective efficiencies and the used systems into consideration (DGE 2006). Therefore, heating plus cooling energy consumption directly indicates the resultant primary energy.

The heating consumption always decreases as the insulation increases (Figure 11a), in opposition to the cooling consumption, which, in most of the cases, increases as more insulation is added to the envelope (Figure 11b). But the increase in the cooling consumption is not sufficient to offset the much larger energy savings produced by the added insulation during the winter. The consequence is that the heating + cooling energy consumption always decreases (Figure 11c), even when air conditioning is adopted and fully used during summer under thermostatic control mode. But Figure 11 clearly shows that an analysis based on heating needs alone can be totally misleading, as the impact of cooling energy consumption severely reduces the benefits of added insulation on a yearly basis. The same type of results was found for the other building types and climates.

4.1.3. Recommendations for the housing use

Summing up the results for the use of the building as a residential unit, the following was observed:

- Solar gains need to be carefully avoided in summer, especially when ventilation is low, coupled to enough thermal inertia indoors. If solar gains are too high, increases in insulation thickness will result in increasing the discomfort in summer. This could lead to higher AC energy consumption, reducing most of the benefits obtained during the heating season.
Offices, with higher internal gains, behave in a different way than when the same unit is used as a housing unit. Even with efficient shading, discomfort is clearly much higher, in all aspects. Results are shown in Figure 12, for building B, in Évora, with the lowest solar gains (solar factor equal to 0.15) and two different levels of internal gains (patterns 2 and 3). When the ventilation is at its lowest, there is always more discomfort as the insulation increases, even for the lowest solar gains (low solar factor). Discomfort occurs during nearly 100% of the occupied time in many cases, and the average maximum overheating reaches 13.2°C in the worst situation (building B, in Évora, higher internal gains, with no shading and highly insulated envelope). In this type of use, the use of air-conditioning is much more common than in dwellings.

With higher ventilation rates, the effects are similar to those observed for dwellings: the discomfort is always reduced, and day plus night ventilation showed to be more effective. When internal gains are reduced (from internal gains pattern 3 to 2), the discomfort also decreases, but not as much as it decreases with ventilation (Figure 12). Of course, the best results can be achieved when both strategies, i.e. ventilation and the reduction of internal gains are considered.

Similar results were obtained for buildings A and C and for the other climates, with obviously different values. The differences between the buildings and between the climates were the same as those observed for dwellings. Depending on the climate, the building typology, solar factor, the pattern of gains and the amount of ventilation, the discomfort can be low and the insulation can be increased without causing overheating or not. For example, for building B, in Évora,
Figure 11. Energy consumption for building C, used for housing, in Évora. (a) Heating consumption. (b) Cooling consumption. (c) Heating plus cooling consumption.

Figure 12. Percentage of discomfort hours for building B, with different patterns of ventilation, window solar factor: 0.15, used for housing and as an office (two patterns of internal gains: 2 and 3), in Évora.
Figure 13. Energy consumption for buildings A and B, used as offices, with internal gains pattern 3, in Lisbon. (a) Heating consumption for building A. (b) Heating consumption for building B. (c) Cooling consumption for building A. (d) Cooling consumption for building B. (e) Heating plus cooling consumption for building A. (f) Heating plus cooling consumption for building B.
with high insulation, the percentage of discomfort hours varies from 100% (services use pattern 3, minimum ventilation and solar factor equal to 0.75) to 9.8% (services use pattern 2, day ventilation and solar factor equal to 0.37).

4.2.2. Energy consumption

Unlike the pattern observed in residential buildings, the AC consumption increase is sufficiently high to offset the energy savings in winter in many cases, as is shown in Figure 13f, for building B, in Lisbon, with internal gains pattern 3. Figure 13b and d shows, respectively, the heating and cooling consumption for the same building.

This type of result was observed both for buildings B and C, in all cases with the highest values of internal gains (pattern 3). When the internal gains of these buildings are lower (pattern 2), the situation changes and the increase in cooling is not sufficient to undermine the heating energy savings. This last situation was also observed for all cases studied for building A, even for the higher internal gains, as is shown in Figure 13a, c and e.

The significance of internal gains is clear and it can be concluded that this type of buildings should not be highly insulated, when internal gains are high and cannot be reduced. For all situations, more shading has a positive effect in the heating + cooling consumption, showing the importance of solar gains control. Nevertheless, the same question about increased energy consumption for lighting, explained in the housing use, needs to be considered.

4.2.3. Recommendations for the office use

Summing up the results for the office use, the following was observed:

- Offices, with higher internal gains, should not be highly insulated. Solar and internal gains need to be carefully avoided and ventilation should be adopted to reduce the discomfort.
- Beyond the discomfort problem, the AC consumption increase can be sufficiently high to offset the heating savings and to contribute to increase the total energy consumption of the buildings as envelope insulation increases.

to determine the limit until which it is possible to increase the insulation of the envelope without causing summer overheating, which would lead to more air conditioning, thereby eliminating any energy heating savings gained during winter.

The methodology is based on parametric studies obtained through simulations. Distinct building models were studied. They had distinct envelope insulation levels, but a high level of thermal inertia has been ensured for all cases. The coupled influence of other parameters that can reduce the overheating, like solar shading and ventilation, has also been considered. The adaptive comfort approach has been used to evaluate the acceptability of the resulting indoor environments.

The main conclusions are as follows:

- When the gains (internal or solar) are not adequately controlled, there is a tendency towards more summer discomfort as the envelope insulation increases.
- If there is ventilation, the building remains comfortable during a higher proportion of the time (or, at least, the discomfort is reduced).
- In some cases, ventilation can be enough to practically eliminate the influence of the increase of insulation of the envelope.
- The level of envelope insulation should remain below the threshold that would lead to the probable installation of air-conditioning, to avoid increased investment and running costs.
- Indiscriminate conversion of buildings designed for housing to commercial purposes should be carefully evaluated. Adding insulation may be beneficial for housing units, but it may be undesirable for the same building used as a small office, resulting in increased overall energy consumption.

This research brings a new view regarding the study of the influence of the envelope insulation. It indicates that highly insulated envelopes, traditionally considered energy savers and the best option to provide comfort, cannot always bring benefits. Future works could analyse the coupled impact of reflectivity and emissivity of the walls and roofs, as well as perform simulations in a wider range of climates, namely colder places (where heating is used most of the time) and warmer climates (for example, the tropical ones).

5. Conclusions

This study aimed at evaluating the influence of the increase of the envelope insulation upon overall building performance. It clearly has a beneficial effect in winter, but not always in summer. It was necessary

References


European Committee for Standardization, CEN, 2007. EN 15251. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.


