STUDY ON THE IMPACT OF THE BUILDING FORM ON THE ENERGY CONSUMPTION

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ABSTRACT

The strategy to minimize the energy demand stands in several improvements of the building shape form, its thermal mass or envelope insulation. To minimize the heat losses of a building a compact shape is wanted, knowing that the most compact orthogonal building would then be a cube. This design, however, may place a large area of the floor far from the perimeter of daylighting. A compact shape is desirable to minimize the costs and the thermal energy consumption of the building; however a hyper-compact building is not desirable from architectural and daylight-use with high impact on the electrical consumption especially for office buildings.

In this article thermal and lighting simulations were conducted for different building shapes, glazing areas and meteo files in order to establish their impact on the electrical and thermal consumption. The study is orientated towards office buildings, were the electric energy has the highest rate of all consumptions. It was found a difference between a cubical shape and a rectangular one on the lighting visual comfort of more than 30\%. In the same time the heating demand is reduced by 6-10 \% if a more compact shape, so optimal parameters must be found. This article gives guidelines for architects and engineers to better understand the problem and energy correlation curves are established.

INTRODUCTION

In France, the building industry contributes to 25\% of greenhouse emission gases and 43\% of total energy consumption, making it the biggest consumer of energy across all of the economy sectors. The energy spent to heat the occupied spaces in the residential sector represents more than 40\% from the total energy demand that includes electricity, hot-water and air-conditioning.

Heating, ventilating and air conditioning (HVAC) systems, which consume large quantities of energy, have become a necessity for almost all the buildings (ASHRAE, 1992) to provide a comfortable indoor environment. This environment is not only related to thermal conditions but goes much further, because it also involves air quality, lighting and acoustics. All these aspects of the indoor environment interact with each other and may have consequences on the overall indoor comfort and building energy consumption. When talking about attaining a certain indoor conditions it must be mentioned what are the costs in terms of energy and parametric studies must be realized to find an optimal solution. Four main aspects of the indoor environment may be considered: thermal comfort, air quality, lighting and acoustics. The indoor conditions are influenced by numerous elements, like HVAC systems, building envelope, occupant’s behavior or air infiltration.

SIMULATIONS APPROACH

Building relative compactness

Building morphology is an important factor that could influence an increase/decrease of energy required to heat or cool the occupied space. The shape of a building has also an important impact on the construction costs but most important on the energy consumption and implicitly on the costs.

Based on a literature review it was found a pertinent solution to define the building geometry and implicitly the heat loss surfaces, by using the building shape factor ($L_b$) (also called building characteristic length) which is defined as the ratio between the heated volume of the building ($V_b$) and the sum of all heat loss surfaces that are in contact with the exterior, ground or adjacent non-heated spaces ($\sum S_i$) (see Eq.1). Another indicator of the form is the building relative compactness ($R_c$). The $R_c$ of a shape is derived in that its volume to surface ratio is compared to that of the most compact shape with the same volume.

\begin{equation}
L_b = V_b / \sum_{i=1}^{n} S_i \quad \text{and} \quad L_b = R_c \cdot V_b^{0.66} \cdot 6^{-1},
\end{equation}

\begin{equation}
R_c = 6 \times V_b^{0.66} \times \sum_{i=1}^{n} S_i^{-1}
\end{equation}

Optimizing the shape and functional structure of energy-savings buildings has been the research work of (Jedrzejuk & Marks, 2007). (Werner et al., 2003) found that the association between the values of such indicators and simulated heating loads of buildings...
with various shapes, orientation, glazing percentage and glazing distribution was found to be significant. Accordingly, the use of such indicators in energy standards (for heating load prediction and evaluation purposes) may be justified. Their study extended for several shapes where the glazing area and orientation was modified (see Figure 1).

The research work consisted to analyze like the previous authors the influence of building shape on the energy consumption with a variation of glazing area and orientation. In our case, several building morphologies from L of 0.73 to 1.22 m have been studied.

**Equivalent glazing surface**

The glazing area is important due to its influence on the natural lighting of the building and its potential on reducing the heating demand in mid-season especially. (Persson et al., 2006) showed that by using energy-efficient windows it would be even better than having a highly insulated wall without windows. Talking about thermal comfort is equivalent to obtain certain indoor conditions that may influence the occupant’s thermal state. These conditions are achieved by using a certain amount of energy for the heating or cooling the space. The glazing area does not directly influence the thermal comfort but the energy consumption which is connected with the indoor conditions. (Bojic and Yic, 2007) compared different types of glazing and found that the cooling consumption may be reduced by 6.6% if using double-pane glazing (low-e). Other research studies were only orientated towards the impact of glazing on the energy consumption and thermal comfort (Stegou-Sagia et al, 2007). The input of the proposed regression models is the South equivalent glazing surface ($S_{es}$). The importance of this parameter is especially high due to its potential on reducing the heating demand in mid-season and for the natural lighting. In certain cases, the use of energy-efficient windows can be a better solution than an insulated wall and this is due from the fact that the windows can collect and use the solar energy to heat the indoor spaces during shiny days.

The French thermal directive propose a 16.5% of window/floor area ratio as a reference but this value can be increased to higher values, but with the advice of using solar blinds and energy efficient glazing. To calculate the south equivalent glazing surface ($S_{es}$), an older version of French thermal directive was used and in which this parameter is defined as follows:

$$S_{es} = \sum_{i=1}^{n} S_i \cdot S_{fsi} \cdot C_i,$$

$$S_{fs} = S_{fs1} \cdot S_{fs2},$$

where $S_i$ is the surface of the glazing $i$, $S_{fsi}$ is the solar transmission factor, $S_{ti}$ is the sunshine factor and $C_i$ are the declination/orientation coefficients (see Table 1). The sunshine factor translates the reduction of solar energy due to shading masks or different obstacles. It is calculated as in Eq.3 and 4. The $S_{fs1}$ is the reduction coefficient due to loggias, balconies or building morphology (ex. L-shape geometry) and $S_{fs2}$ is related to the environment reduction (ex. shading from other buildings).

**Table 1**

<table>
<thead>
<tr>
<th>Slope (degree)</th>
<th>SSE-SSO</th>
<th>SSE-ESE and SSO-OSO</th>
<th>ESE-ENE and OSO-ONO</th>
<th>ENE-NNE and ONO-NNO</th>
<th>NNE-NNE</th>
</tr>
</thead>
<tbody>
<tr>
<td>85° to 90°</td>
<td>1.00</td>
<td>0.85</td>
<td>0.35</td>
<td>0.30</td>
<td>0.20</td>
</tr>
<tr>
<td>70° to 84°</td>
<td>1.15</td>
<td>0.95</td>
<td>0.60</td>
<td>0.35</td>
<td>0.20</td>
</tr>
<tr>
<td>55° to 69°</td>
<td>1.20</td>
<td>1.05</td>
<td>0.65</td>
<td>0.35</td>
<td>0.25</td>
</tr>
<tr>
<td>40° to 54°</td>
<td>1.20</td>
<td>1.05</td>
<td>0.75</td>
<td>0.40</td>
<td>0.30</td>
</tr>
<tr>
<td>25° to 39°</td>
<td>1.15</td>
<td>1.00</td>
<td>0.75</td>
<td>0.50</td>
<td>0.40</td>
</tr>
<tr>
<td>10° to 24°</td>
<td>1.00</td>
<td>0.95</td>
<td>0.80</td>
<td>0.65</td>
<td>0.55</td>
</tr>
<tr>
<td>0° to 9°</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
</tr>
</tbody>
</table>

For the parametric study a high number of south equivalent glazing surfaces ($S_{es}$) were analyzed by a variation of the windows surfaces and for different percentage of the glazing (5%, 15%, 25%, 40% from the useful floor area) on the orientations (North, South, East, West). Other inputs on the prediction models are the sol-air temperature ($T_{sol-air}$), building thermal inertia defined by the building time constant and the building average U-value. As outputs is considered the total annual heating demand (kWh/year).

**REGRESSION ANALYSIS**

The objective of multiple regression analysis is to predict the single dependent variable (mean illuminance level, heating specific consumption) by a set of independent variables (windows to floor area...
ratio, climate coefficient, south equivalent surface, building average U-value, building time constant). In order to predict the building heating demand as a function of the 5 selected parameters, different models have been studied. Based on the relationship between the input parameters a clear inter-connection is observed. These interdependences may be modeled by adding interaction terms to a pure quadratic function obtaining thus an interaction model (see Eq.5).

\[ Y = \alpha + \sum_{i=1}^{5} \beta_i X_i + \sum_{i=1}^{5} \delta_{ij} X_i X_j + \sum_{i=1}^{5} \varepsilon_i X_i^2 \]  

(5)

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Value</th>
<th>Coefficients</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha)</td>
<td>-16.5</td>
<td>(\delta_{2,4})</td>
<td>-7.65E-02</td>
</tr>
<tr>
<td>(\beta_1)</td>
<td>29.8</td>
<td>(\delta_{2,5})</td>
<td>3.5698</td>
</tr>
<tr>
<td>(\beta_2)</td>
<td>125.2</td>
<td>(\delta_{3,4})</td>
<td>2.67E-04</td>
</tr>
<tr>
<td>(\beta_3)</td>
<td>-1.98E-02</td>
<td>(\delta_{3,5})</td>
<td>-3.36E-04</td>
</tr>
<tr>
<td>(\beta_4)</td>
<td>-2.31</td>
<td>(\varepsilon_1)</td>
<td>-6.9433</td>
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<tr>
<td>(\beta_5)</td>
<td>2.4</td>
<td>(\varepsilon_2)</td>
<td>-9.8835</td>
</tr>
<tr>
<td>(\delta_{1,2})</td>
<td>-55.7</td>
<td>(\varepsilon_3)</td>
<td>2.56E-04</td>
</tr>
<tr>
<td>(\delta_{1,3})</td>
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<td>(\varepsilon_4)</td>
<td>9.73E-03</td>
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<tr>
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<td>1.2</td>
<td>(\varepsilon_5)</td>
<td>0.1181</td>
</tr>
<tr>
<td>(\delta_{2,3})</td>
<td>-0.087</td>
<td>(R^2)</td>
<td>0.9935</td>
</tr>
</tbody>
</table>

The model accuracy was evaluated by the mean of coefficient of determination (\(R^2\)), the sum of residuals and the standard error of the estimate.

**RESULTS**

To observe the impact of the building shape factor on the building heating demand, two diagrams were traced. In Figure 2 the energy consumption for different months according to two data climates (Nice – hot and humid and Lyon – temperate) are plotted.

In order to trace the charts based on the prediction models the assumed hypotheses were that the building time constant is 50 hours, the building average envelope insulation is 0.62 W/m²K and the ratio glazing area/floor area to be 17 %. The results illustrate a reduction with the increase of the Sf that is higher for Nice climate, due to the fact that the building receives a larger quantity of solar gains while for Lyon climate this reduction is the range of 6% to 10%. It can be concluded that the impact of building shape factor is more important for hot climates with solar radiation and outdoor temperature values higher.

![Figure 2a Impact of building shape on the heating demand (Nice - hot and humid climate)](image)

In order to compare the two cases, two simulations were conducted using Dialux software and the chart of the illuminance values was studied (see Figure 3). The illuminance \(E\) is the total amount of visible light illuminating (incident upon) a point on a surface from all directions above the surface. This "surface" can be a physical surface or an imaginary plane (our case the working plane situated at 0.8m). A mean \(E_{an}\) value of 366 lux was obtained for the rectangle shape compared to 244 lux for the second one. The illuminance level is reduced with more than 30% which is a considerable value that could influence the visual comfort, lighting system use, etc, especially

![Figure 3 Daylighting representation of the two shapes (rectangle and cube)](image)
during the last part of the day, when the need for extra artificial lighting will be desired.

A regression model was obtained with the horizontal solar radiation \( H_g \) and \( S_{es} \) as inputs and the output \( E_m \) (lux).

\[
E_m = 30.35 \cdot H_g^{0.34} \cdot 1.06^{S_{es}},
\]

(6)

The Coefficient of Multiple Determination for this model is \( R^2=0.922 \). The number of analyzed points was 96 and the average residual error of 0.49.

STUDIED CASES

The sensitivity analysis case study consisted of investigating several cases corresponding to the shape 1, 2 and 3 (see Figure 4).

![Figure 4 Plans and detail data for the building shapes 1, 2 and 3](image)

For shape 1 the building heated volume was set to 175 m\(^3\) and a total heat loss area of 220 m\(^2\). With these data the building shape factor (characteristic length) can be calculated and the obtained value is 0.795 m. For the second validation the volume was of 250 m\(^3\) and the heat loss area of 220 m\(^2\) which gave a \( L_b \) equal to 1 m. For the last scenario, shape 3 has a volume of 375 m\(^3\), a heat loss area of 340 m\(^2\) so a \( L_b \) of 1.1 m. For each of these building shapes an important number of tests were conducted: different scenarios were investigated where the building thermal inertia and building envelope were varied from 7 to 155 h and respectively 1.18 W/m\(^2\)K to 0.30 W/mK (V1 correspond to 1.18, V2 to 0.54, V3 to 0.3 and V4 to 0.55 W/mK).

Table 3

<table>
<thead>
<tr>
<th>Lyon</th>
<th>Heating demand comparison (simulation vs models)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Case</td>
</tr>
<tr>
<td>Shape 3-V1</td>
<td>15301</td>
</tr>
<tr>
<td>Shape 3-V2</td>
<td>10062</td>
</tr>
<tr>
<td>Shape 3-V3</td>
<td>15301</td>
</tr>
</tbody>
</table>

CONCLUSION

The presented work showed that the building morphology is an important design parameter in the process of finding energy efficiently project with a non-negligible impact on the daylighting and heating consumption. Based on dynamic simulations of three climates (hot and humid, temperate and cold) a number of correlations and regression models have been developed. It is shown that the building shape can reduce or increase the workplane illuminance level. The glazing area and its distribution are also essential parameters when sketching the future project. It can be concluded that the proposed prediction models showed promising features to be easy and efficient forecast tools for comparing heating demand of residential buildings and the daylighting levels potential with direct impact on reducing the electrical energy demand.

ACKNOWLEDGEMENT

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