Improving thermal comfort using cost-effective passive strategies
Lessons from a single-floor detached dwelling in Nicaragua

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Abstract
About 40\% of the world population lives in the tropics. This region represents the highest urban growing potential few decades from now; therefore, building energy efficiency would be a key strategy from a global energy perspective. Building techniques used today in most developing countries situated in this region are associated with high-energy consumption and lack of thermal comfort due to the absence of energy policy framework for buildings. In this context, this study intends to improve thermal comfort of dwellings in Nicaragua using cost-effective passive strategies. To achieve this goal, a representative house of Nicaragua is studied through a parametric analysis using Energy plus V8.2 and MatlabR2014. Solar absorptance and thermal transmittance of the opaque envelope, as well as the solar heat gain coefficient are the variables selected to be analyzed. Discomfort hours based on the adaptive comfort model are used as performance indicator. Results indicate that the main variables affecting thermal comfort are associated with the roof and glazed areas. The solely implementation of a roof solar absorptance equal to 0.3, a Roof U-value equal or less than 2W/m\textsuperscript{2}-K and a solar heat gain coefficient equal or less than 0.4, allows reaching comfort 80\% of the time within 80\% Acceptability limits. This work is a step towards wider researches and may significantly contribute to guidelines and regulations, particularly in developing countries with cooling dominated climates.

Keywords: Parametric analysis, thermal comfort, adaptive model.

1 Introduction
Building techniques used today in developing countries are associated with high-energy consumption and lack of thermal comfort due to the absence of energy policy framework for buildings (Liu et al. 2010; Janda 2009). Those countries area mainly situated in the tropical region, that plays a critical role in the global energy panorama due to its rapid population growth (PNUD 2012). Giving this situation, the definition of cost-effective passive strategies for hot climates becomes crucial; however, it is a complex task due to the interaction between several independent variables influencing thermal behaviour of buildings.

In such a context, building energy simulation tools help understanding the complex interrelation between design decisions and performance parameters allowing the identification of potential problems and the appropriate design solutions in a reduce time and cost (Clarke 2001). Those tools have continuously evolved and matured during the last 50 years (Clarke 1989; Malkawi, Ali;Augenbroe 2003; Crawley et al. 2008). In spite of that, their potential have rarely been harnessed because their use have been mostly restricted for code compliance checking and thermal load calculations for sizing HVAC equipment (Hensen 2004).
In order to overcome this situation, new approaches combining computer programming and parametric simulation methods have emerged in the last decades (Nguyen et al. 2014). Those methods allow the analysis of several parameters simultaneously through numerical sequences achieving solutions near the optimum according to pre-established criteria. The application of those methods has proven great potential in order to define predictive-based and performance-based requirements for building energy efficiency programs (Crawley 2008; ADEREE UNEP/GEF 2011).

In Latin-American countries, there are also efforts to find suitable solutions for thermal performance enhancement using parametric simulation (Westphal et al. 2011; Silveira & Labaki 2012). However, any of those studies are conducted in the context of Central America, where prevails a lack of building thermal regulations.

Against this background, this paper intends to apply robust and proven methods of thermal analysis based on simulation and automation in order to enhance the thermal performance of residential typologies in Nicaragua, taking into account different climatic conditions.

The context

Nicaragua is the biggest country of Central America and one of the poorest of the continent, classified as Lower middle income (World Bank 2015). It is situated in the tropics, between 12° and 15° North Latitude and 86° and 87° West Longitude. Its prevailing climate conditions are classified as savannah climate, monsoon climate, and tropical rainforest according to Koppen-García (García 2004; INETER 2001).

The Country is divided into three geographical regions, the Pacific, Central and Atlantic Region. The first one agglomerates 61% of the total population and its exposed to the highest levels of solar radiation in the country (MEM 2013). See (figure 1).

![Figure 1 Geographical distribution and solar radiation map of Nicaragua](image)

The single-family detached dwelling is the dominant housing typology of this country, due to, among other factors, its extensive history of earthquake activity. This fact has influenced people’s preference for low-rise buildings.

Most of those single-family detached dwellings are built without any thermal comfort criteria, due to the lack of National thermal regulations. Sample of this is the use of prevailing materials for the building envelope having a poor thermal performance, since at least two-thirds of the existing houses have a Zinc corrugated roofing without any ceiling and at least...
one-third of the houses have concrete blocks walls (INEC, 2001) (See fig.2). As a result overheating often occurs affecting the health and thermal comfort of most of the population.

2 Methodology

The applied methodology is divided into four phases: 1) Selection of case studies, 2) Parametric variation, 3) Simulation using Energy plus V8.2 with the aid of Matlab R2014, and 4) Sensitivity analysis.

2.1 Selection of case studies

We analyzed one single-detached dwelling situated in the Pacific Region of Nicaragua. The selection of this model was based on its representativeness of Nicaraguan residential predominant type. The model information was obtained from databases of the Nicaraguan Urban and Rural Housing Institute (INVUR) and the Chamber of Nicaraguan Housing Developers (CADUR).

The overall floor area of the model is 56m$^2$ and its occupation is determined based on the standard average Nicaraguan family size with 6 people (PNUD 2002). Its envelope composition is described in figure 3.

Climate

Parametric simulation was done for five different climatic conditions (Figure4b). Three of them are locations from the Pacific region of Nicaragua, where live 61% of the national population (Managua, Chinandega and Rivas) (Figure4a) and two locations from the central region and Atlantic region of Honduras situated less than 50km from Nicaraguan border (Catacamas, Puerto Lempira). For each location, 500 simulations were performed. The final
results were compared and synthetized in order to extract the main results. Samples of one site location are used in order to illustrate those results.

Figure 4 a) Graphical representation of population density in Nicaragua, b) Geographical location of weather data files used in this study

2.2 Parametric variation
The thermal transmittance (U-Value) and solar absorptance of the building envelope opaque surfaces as well as the Solar heat gain coefficient (SHGC) of the glazed surfaces are the variables selected to be automatically modified during the simulations. Combinations of parameters were conducted simultaneously through a random choice based in the Multiplicative Congruential Method (Harris 2013).

Other passive strategies such as building and openings orientation, ventilation and solar shading systems are considered very important for tropical architecture, however they are not implemented in this study because they are more difficult to apply in existing buildings.

The base case thermal properties were established according to the real dwelling characteristics. Alternative solar absorptance and U-values were collected and calculated from constructions materials available in Nicaragua. Table 1. Summarizes those parameters.

<table>
<thead>
<tr>
<th>Input parameters</th>
<th>Base case energy model</th>
<th>Range of values for alternative energy models</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>U-Value [W/m²-K]</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>External walls</td>
<td>3.03</td>
<td>1.045-2.45</td>
</tr>
<tr>
<td>Internal partitions</td>
<td>2.135</td>
<td>1.045-3.877</td>
</tr>
<tr>
<td>Roof</td>
<td>2.52</td>
<td>1.042-3.01</td>
</tr>
<tr>
<td><strong>Solar absorptance</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>External walls</td>
<td>0.8</td>
<td>0.3-0.8</td>
</tr>
<tr>
<td>Roof</td>
<td>0.55</td>
<td>0.3-0.8</td>
</tr>
<tr>
<td><strong>SHGC</strong></td>
<td>0.8</td>
<td>0.2 - 0.8</td>
</tr>
</tbody>
</table>
2.3 Simulation using Energy V8.2 plus with the aid of Matlab R2014.
We executed 500 simulations for each location using Energy plus V8.2 (EERE 2009). The geometry of the base case was edited and imported from SketchupMake2015 to Energy plus V8.2 using Legacy1.6 Plug-in. To automatize the process of input and output data, we executed four routines in MatlabR2014 (MathWorks 2014) according to the following sequence:

- Automatic substitution of input values through a random choice based in the Multiplicative Congruential Method(Harris 2013), running simulations and storing outputs.
- Data extraction and generation of scatter plots of internal discomfort hours based on the ASHRAE 55 Adaptive model (80% acceptability status).
- Automatic extraction of indoor operative temperatures.
- Extraction of Resulting U-values.

2.4 Sensitivity analysis
We performed a global sensitivity analysis (Heiselberg et al. 2009; Tian 2013; Moore 2007) in order to identify the influence of each parameter in the thermal internal conditions as a result of several random combinations. For this, Pearson coefficient($r$) was used considering the strength of relationship among variables according to table 2.

<table>
<thead>
<tr>
<th>Absolute Value of $r$ (Pearson coefficient)</th>
<th>Strength of Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r &lt; 0.3$</td>
<td>None or very weak</td>
</tr>
<tr>
<td>$0.3 &lt; r &lt; 0.7$</td>
<td>Moderate</td>
</tr>
<tr>
<td>$r &gt; 0.7$</td>
<td>Strong</td>
</tr>
</tbody>
</table>

Comfort hours based on the adaptive comfort model ASHRAE Standard 55-2010, Thermal Environmental Conditions for Human Occupancy were used as performance indicator. In this model, comfort temperature is defined according to the monthly mean outdoor air temperature, calculated as the simple average of the previous thirty daily average outdoor air temperatures.

Two comfort regions are defined, 80% Acceptability and 90% acceptability.

For this study, the 80% Acceptability status is considered, which means that upper and lower limits of the comfort region are calculated according to the next formula.

$$80\% \text{ Acceptability Limits: } \text{Tot} = 0.31 \times \text{To} + 17.8 \pm 3.5 \quad (1)$$

Where:

- $\text{Tot}$-operative temperature ($^\circ C$), calculated as the average of the indoor air dry-bulb temperature and the mean radiant temperature of zone inside surfaces.
- $\text{To}$ – monthly mean outdoor air dry-bulb temperature ($^\circ C$).

Comfort hours were calculated for 24 hours of the day in order to reach a wide group of the society with diverse occupational patterns. In Nicaragua, most of the children and elderly people stay at home most of the time.
2.5 Limitations
This study is performed for one model of dwelling in order to make a parametric analysis, which is appropriated for a specific case without taking into account other variables; though, further research is needed in order to generalize the results. However, the representativeness of Nicaraguan dwellings through this model is considered significant, because at least 68% of Nicaraguan houses have a zinc corrugated roof and almost 32% of houses are made of concrete blocks (INEC 2001).

3 Results
Summarised results for the five climates are presented through a comparison between the base case and the improved case thermal performance, indicating the thermal potential reduction due to the parametric variation for each climate.

In order to illustrate deeper analysis, samples of simulations for one site location (Managua) are presented, indicating correlations of input and output data, sensitivity analysis as well as the thermal behaviour of one of the main rooms of the dwelling.

3.1 Thermal comfort improvement potential
In Managua, the combined effect of parametrical variation achieves 85% reduction of discomfort hours. This potential reduction varies from 78% to 83% in other climates of the Pacific, Central and Atlantic Region of the study area (Figure 5).

![Figure 5](image)

Figure 5  a) Discomfort potential reduction in different climates, b) Climate location

![Figure 6](image)

Figure 6 Thermal comfort improvement potential in Managua
A sample of simulation results from Managua is shown in Figure 6 in order to illustrate a deeper analysis. As it can be noticed, the most efficient case encountered during simulation presents 2539 less annual discomfort hours than the base case. Such a reduction is equivalent in average to 7 hours per day. This reduction potential fluctuates through the year according to climate conditions and orientation of the building. An example of this behaviour can be observed in Figure 7, where the average daily discomfort hour reduction potential of the living room is illustrated for each month. As it can be seen, during the months of January and February, the discomfort reduction potential is lower than in the period of June, July and August due to climatic variations such as solar radiation affecting that room which is orientated to the southeast.

![Figure 7 Average daily potential reduction of discomfort hour’s in the living room](image)

Thermal oscillation inside the living room is clearly reduced as well as a result of the parametrical variation. Figure 8 shows a comparison between the base case and improved case relationship of indoor operative temperature in the living room and the mean outdoor temperature according to the adaptive comfort model.

![Figure 8 Relationship between indoor operative temperatures of the living room and mean outdoor temperatures according to the adaptive comfort model in Managua](image)

Considering one of the hottest days in the area of study, it is possible to observe a reduction of 4.6°C in the peak operative temperature of one of the main rooms of the dwelling (living room). This is equivalent to reducing the number of discomfort hours in almost 43%. (Figure 9).
3.2 Sensitivity analysis

As a result of 500 simulations, a correlation between the input variables and the amount of discomfort hours of the four main rooms of the dwelling is calculated. Comfort hours are based on the Adaptive model 80% acceptability status.

As it can be seen in figure 10, the roof solar absorptance is the most influencing parameter in our case study, having a positive moderate correlation of 0.64 with discomfort hours. This behaviour is persistent in the five climates simulated in this study. As much as the roof solar absorptance increases, the number of discomfort hours increases. A more detailed relation between this parameter and the thermal performance of the case study appears in Figure 11a. As it can be seen, the most efficient cases tend to have a lower solar absorptance value; however, that relation is not linear, because there are other factors that also have a moderate influence in thermal comfort such as the roof thermal transmittance and solar heat gain coefficient (SHGC).

Thermal transmittance of the roof is the second most important parameter on the thermal performance of the dwelling. This parameter has a positive moderate correlation coefficient of 0.47 with discomfort hours. As much as it increases, the number of discomfort hours also increases. Figure 11b shows a correlation between this variable and the discomfort hours.
SHGC is the third most important parameter on thermal comfort of this study with a positive moderate correlation coefficient of 0.43. Figure 12 presents its relationship with discomfort time.

Other parameters such as the walls solar absorptance and walls transmittance have small correlation coefficients (less than 0.3), indicating a weak influence on discomfort hours when compared with roof solar absorptance, roof transmittance and SHGC.

This behaviour was also observed in other climatic conditions analyzed in this study, having small variations in the correlation coefficient, but keeping the same pattern.

### 3.3 Thermal properties of the most efficient cases.

Giving that the most important parameters in terms of comfort analyzed in this study are associated with the roof and glazed surfaces, their values were identified for two groups. A first group of cases having less than 20% discomfort hours, and a group of cases having more than 30% discomfort hours (Figure 13). From this, it is possible to extract valuable information about the suitable values that can significantly contribute to a better thermal performance for housing in Nicaragua, as well as the values that should be avoided. A brief description of each parameter is presented below.
Around 76% of the cases presenting less than 20% discomfort hours have a roof solar absorptance equivalent to 0.3. In contrast, most of the cases presenting more than 30% discomfort hours have a solar absorptance of 0.7 to 0.8 (Figure 14).

Considering solar heat gain coefficient, most of the cases having less than 20% discomfort hours present values from 0.2 to 0.4 in a model with 7.43% glazed areas. On the other hand, the cases presenting more than 30% discomfort hours present values between 0.4 and 0.8. It is important to highlight that the influence of a lower solar heat gain coefficient has a similar impact than reducing the window-to-wall ratio, though the importance of this parameter is strongly influenced by the surface of glazed area and their orientation (Figure 14).

Roof solar transmittance tend to be lower than 2W/m²-K in the cases having less than 20% discomfort hours and higher than 2W/m²-K in the cases having more than 30% discomfort hours (Figure 15).
None of those parameters applied solely can warrant significant improvements on thermal performance of housing in such a context, but their combination may reduce significantly the number of discomfort hours. The use of low roof solar absorbance equal or less than 0.3, a Roof U-value of less than 2W/m²-K and a low solar heat gain coefficient equal or less than 0.4, are three cost effective measures having significant influence on thermal performance of the case study analyzed in this paper.

The solely implementation of those three measures can reach annual comfort 80% of the time within 80% Acceptability limits according to the adaptive comfort model. This occurs in the worst case scenarios simulated in Managua.

4 Conclusion
This paper has shown the potential of thermal improvement of a representative dwelling of Nicaragua, supported by robust and proven methods based on parametrical simulation using cost-effective passive strategies.

The sensitivity analysis showed that among the parameters analysed, the most important ones in terms of comfort are associated with the roof and glazed surfaces. The angle of incidence and high levels of solar radiation in tropical latitudes influence this fact.

In all the climates studied, solar absorptance presented a higher correlation coefficient with discomfort hours than the roof u-value. This fact has been largely discussed by the scientific community that support the implementation of cool roof systems in hot climates. Solar absorptance has the advantage of reducing solar heat gains without reducing heat dissipation.

None of those parameters applied solely can warrant significant improvements on thermal performance of housing in such a context, but the combination of them may reduce significantly the number of discomfort hours. An example of that is the potential reduction of 85% of discomfort hours achieved in Managua, which is equivalent in average to more than 7 hours of per day. Such a potential reduction varies from 78% to 83% in other climates of the Pacific, Central and Atlantic Region of the area in study. This reduction is considered significant and cost-effective.

The solely implementation of a low roof solar absorbance (equal or less than 0.3), a Roof U-value of less than 2W/m²-K and a low solar heat gain coefficient (equal or less than 0.4), are three cost-effective measures having significant influence on thermal performance of the case study analyzed in this paper. Those three measures can reach annual comfort 80% of the time within 80% Acceptability limits according to the adaptive comfort model. This occurs in the worst case scenarios simulated in Managua.

Most of the Building Energy Codes tend to consider that technical solutions for energy conservation have to be complex; however, this work shows through a simple case the huge potential of thermal improvement of housing in such a context by the simple variation of parameters involving the thermal properties of the envelope.

These statements are applicable for a specific geometry, without taking into account other variables not discussed in this paper; however, this is a step towards wider research. Similar improvements can be achieved and validated in other countries with cooling dominated climates, fact that transcends this study and should be confirmed with future researches.
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