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# Building Energy Simulation to Assess Unconditioned Buildings in Equatorial Latitude and High Altitude Regions

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***Abstract:*** *Energy efficiency in buildings, as well as the indoor thermal behaviour of buildings, have been largely studied in recent years. However, the research has been focused on the performance of conditioned buildings in order to reduce the building energy consumption. Little research has been conducted in the study of the thermal performance of unconditioned buildings and even less in buildings located in equatorial high-altitude regions. In this context, this work aims to assess the influence of the principal building variables on the thermal comfort of unconditioned residential buildings in high-altitude equatorial regions. Quito was chosen as a case study and multiple simulations (17280 building configurations) in EnergyPlus were conducted in order to evaluate the percentage of annual discomfort. Results suggest that the roof is a key parameter to improve the thermal comfort of residential buildings and the use of insulation in the roof is advisable. Infiltrations, thermal mass and window orientation are other important parameters to be considered for the passive design of residential buildings.*

***Keywords:*** *thermal building behavior, equatorial high-altitude regions, parametric study*

## INTRODUCTION

In recent decades, efforts to improve building design have been increased on the aim of reducing energy consumption, mainly related to indoor conditioning. Most of these efforts have been focused in conditioned buildings located in urban areas and in countries with seasonal climates. This has allowed the development of standards and guidelines with minimal requirements to ensure the efficient use of energy in buildings. However, regarding the thermal behavior and thermal comfort in unconditioned buildings there is little information, and even less in equatorial high altitude regions. Commonly, the equatorial region is related to a hot and humid climate (Rosenlund, 2000). This is particularly true in low altitude areas. However, as the altitude increases (above 1000 masl), the daily ambient temperature oscillation increases, which means a climate with hot days (high solar radiation) and cold nights. Moreover, in this type of climate, there is little or no seasonal variability (I. Miño-Rodríguez, Naranjo-Mendoza, & Korolija, 2016). This type of climate is characteristic in high regions of Central Africa, South Asia and South America. On this, the passive design of buildings is a challenge since it is very common that there are heating demands at night and cooling demands in hours of high solar radiation (Gonçalves & Fernández, 2015).

Most of the studies conducted in unconditioned buildings have been focused in cooling dominated climates. These studies have concluded that the use of shading devices (Ahsanullah & Van Zandt, 2014), vaulted roofs (Tang, Meir, & Wu, 2006) or a combination of both (Arumugam et al., 2014; Barbaresi, Dallacasa, Torreggiani, & Tassinari, 2017; Kumar, Garg, & Kaushik, 2005) might lead in the increase of thermal comfort in buildings. On the other hand, regarding unconditioned buildings in equatorial high-altitude regions, the information is even more limited in spite of the fact that several important cities (with more than 2 million inhabitants) such as Bogotá, Addis Ababa or Quito are in this characteristic climatology. This fact highlights the necessity to increase research in energy efficiency and thermal comfort in buildings located in this climatic zone. Some clues can be noted from the available literature. For instance, Gonçalves and Fernández (2015) studied the thermal behaviour of unconditioned office buildings in Bogota. The authors conclude that in this type of buildings, it is very important that the occupants have control over the openings to reduce the indoor thermal variation and thus expand the thermal comfort ranges. Likewise, Wang et al. (Wang, Yoshino, Liu, & Yang, 2017) studied the thermal performance of residential buildings in the Tibetan Plateau. The results show the importance of the use of materials with high thermal mass on the exposed


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surfaces, mainly in the floor. This type of material helps in maintaining a more stable behaviour and avoiding excessive heat gains in the hours of high solar radiation, as well as heat losses at night. Miño-Rodriguez et al. (2016) also concluded in their study of high-altitude residential buildings (Equatorial Andes) that the use of high thermal mass materials in the roof, contribute to improving the indoor environmental conditions throughout the year.

As shown in the preceding section, a gap in knowledge in passive design or best construction practices in unconditioned buildings in equatorial high-altitude regions is evident. It is important to add that an adequate study that seeks to help the building sector in the decisions making related to the passive design, should cover most of the cases that may arise in actual constructions. For example, in the design of buildings, the residences that have the roof exposed (top-storey apartment) will have a different behavior to buildings that have the adiabatic roof (mid-storey apartments). Likewise, in conventional buildings, there are residences that have all their walls exposed to the environment, while others will forcefully have adjacent walls to other residences or buildings. In addition, builders often cannot freely vary the orientation of buildings due to space constraints or urban patterns. Therefore, this type of variables should be studied and the best practices for different types of buildings should be proposed in order to improve the indoor environmental conditions. In this context, this paper aims to study the impact of different variables on the thermal behavior of unconditioned residential buildings in high-altitude equatorial regions in order to maximize the thermal comfort of the occupants. The study is focused on analyzing the configurations of buildings that have the lowest annual discomfort in order to determine the best passive design practices in dwellings located in this particular of climatology.

# METHODOLOGY

In order to achieve the objective of this study, a parametric analysis of the main variables that affect thermal comfort in a residential building was carried out. For this, multiple annual simulations that focus on determining the percentage of discomfort of the dwellings for each case study were conducted. In the following sections, the input data of the study are detailed.

## Location

The case study focuses on single-family residential buildings under the climatic conditions of Quito, Ecuador. Quito (2.5 million inhabitants) is a city located on the equatorial line at 2800 MASL. A number of cities in the Andean region (Bogotá Cuzco, La Paz, Cuenca, etc.), as well as certain regions of South Asia and Africa, have similar climate characteristics. In such cities the sun exposure is very high, while the average temperature is predominant cold with variations from moderate values during the day to low values during the night. Figure 1 shows the average solar radiation and temperatures for Quito.

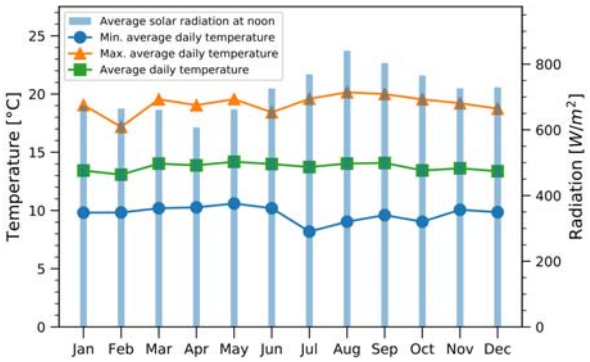


*Figure 1: Monthly weather conditions of Quito*

This range of temperatures differs largely from cities with seasonal variability. For instance, the maximum and minimum average yearly temperatures of Quito varies from ~8◦C min. to ~22◦C max. Additionally, the aforementioned temperatures range occurs daily.

## Building configurations

Since the temperatures range in Quito is not extreme, most of the population do not utilize air-condition equipment. Also, it is a common practice do not utilize any insulation on the walls or on the roofs. Moreover, the actual building practices do not include any energy criteria. As consequence, a huge number of buildings are not thermally comfortable. Even the mentioned common characteristics, there is not an unique configuration of building. Size, materials and design may differ significantly between different buildings. To have a uniform point of view of the problem, a simplified model was proposed. The building fabrics studied here were the materials commonly used in buildings in Quito. These are concrete blocks and bricks according to the last national housing census (INEC, 2012). The urban configuration of the city includes small familiar houses, as well as multi-familiar buildings. The major simplification consists in to model those small familiar houses, as well as single units in multi-familiar buildings, as an unique volume of 36 $m^2$ of surface. This typology was selected according to the typical social housing surface. This type of housing is small enough to be evaluated as a single thermal zone model. Since larger residential buildings have similar internal heat gains, it is assumed that these buildings will have a similar trend in their thermal behavior.


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Accordingly with that, 8 different configurations were chosen based on 3 different boundary conditions (**¡Error! No se encuentra el origen de la referencia.**). In this way, most of the dwellings configurations typically found in Quito were covered, whether they are isolated or integrated into larger buildings. The shape factor was not taken into account, instead, a square surface was defined for all the configurations. According to Givoni (1992) n temperate climates where winter and summer are not extreme, the shape of the building is irrelevant.

Internal heat gains by lighting, occupancy and equipment, as well as the natural ventilation rates were based on the residential patterns of the study of Miño-Rodríguez et al. (2016) and are shown in Table 1. Special attention should be done on the infiltration parameter. The model considers that during the 08h00-17h00, openings may be operated by users. When opened, an interchange of air with the ambient by natural ventilation is done. The aperture of the windows occurs when the indoor temperature reaches the low limit temperature of the comfort range (19.6◦C). Below this value, windows will remain closed and above they will be opened. On the other hand, during the night openings remain closed, and the infiltration is due to the seals, etc., which was varied as one of the studied parameters

*Table 1: Schedule of internal heat gains for the studied buildings*

| Sched | Occupancy (people) | Lighting (W) | Equipment (W) | Natrl Vent (% open window) |
|---|---|---|---|---|
| 00-06 | 4 | 0 | 50 | 0 |
| 06-08 | 1 | 45 | 130 | 0 |
| 08-17 | 1 | 0 | 260 | 30% |
| 17-22 | 4 | 180 | 520 | 0 |
| 22-00 | 4 | 90 | 50 | 0 |

## Studied variables and model set up

For each configuration, five variables were analyzed parametrically as shown in Table 2. The studied variables are those that the builders or designers can modify without restriction. Additionally, because buildings in this city do not have wall or roof insulation nor active equipment to control indoor temperatures, they seem to be the most influencing parameters on the indoor temperature. Further studies should be conducted to analyze the advantage to use insulation. The approach is to analyze as many cases as possible and from the results determine the best practices to reduce the thermal discomfort. It is worth mentioning that the window to wall ratio (WWR) is defined as the ratio of the window surface to the total wall surfaces. For that reason, since the model considers that the maximum number of glazed walls is two, the WWR may vary until the 40%. Regarding the thermal mass, only the mass on the walls were varied, while the mass on the floor and roof was imposed as constant.

*Table 2: Studied variables for the parametric analysis*

| Variable | Range of study |
|---|---|
| Window to wall ratio (WWR) | 5-10-15-20-30-40 (%) |
| Main window orientation | N-NE-E-SE-E-SW-W-NW |
| Glazing type | Single-Double |
| Infiltration | 0.3-1-2 (ach) |
| Wall thickness | Concrete block (10-15-20 cm)<br>Brick (10-15-20 cm) |

Following this methodology, a total of 17280 annual simulations were performed through jEPlus (Zhang & Korolija, 2010), a software which allows multiple simulations using EnergyPlus (US Department of Energy, 2010) as a calculation engine. The EnergyPlus 2010 version was used. EnergyPlus is one of the most accepted software available for building energy simulations.

## Thermal comfort ranges and objective variable

Due to the mild ambient temperature and human adaptation in Quito, building occupants prefer to dispense with the use of air-conditioning systems. Therefore, the use of adaptive thermal comfort models is preferable. For this reason, the ASHRAE 55 adaptive model (2004) was used to define the thermal comfort ranges for this study. According to this standard, the adaptive thermal comfort range for the climatic conditions of Quito does not vary significantly from month to month. Hence, the annual average is considered for this study (from 19.6 to 24.6 C for an 90% of acceptance). In this context, the objective variable for this study is the percentage of annual discomfort, which is defined according to Equation 1.

$$discomfort\ (\%) = \frac{hours\ out\ of\ comfort\ range}{total\ occupation\ hours} \times 100 \qquad (1)$$


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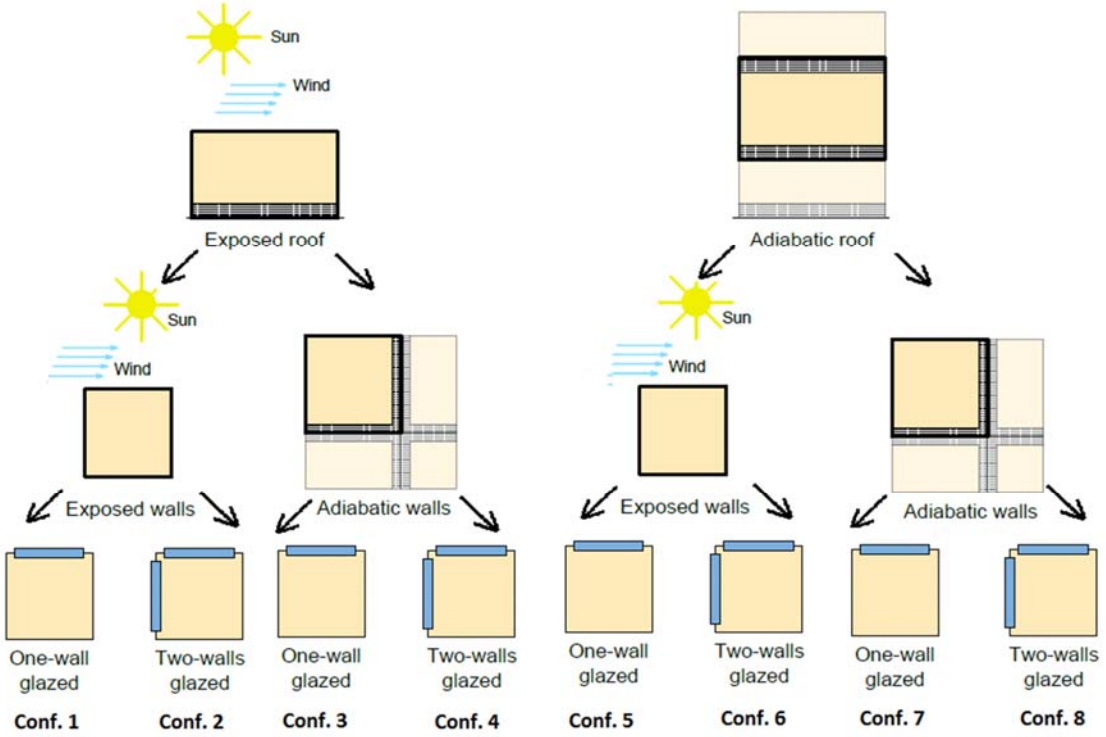


*Figure 2: Building configuration assessed.*

Combining the eight configuration proposed and the five parameters, 17280 simulations were carried out. The configurations in which the annual discomfort are less than or equal to 30% were selected for deeper analysis. This approach was selected in order to study only the configurations that maintain the best indoor environmental conditions. Through this, the idea is to determine the common points that have the best dwelling configurations and to obtain a guide to best practices for the passive design of residential buildings in equatorial high-altitude regions.

## RESULTS AND DISCUSSIONS

As previously mentioned, from all the simulations performed, the results in which the annual discomfort is less than or equal to 30% were filtered for deeper analysis. Hence, from the 17280 simulations, only 1386 belong to this category, that is, only 8% of all the study cases evaluated. In figure 3 the results of all simulations, expressed as discomfort vs. average operative temperature over a year, are presented. Note that simulations with annual discomfort lesser than 30% are those below the blue line.

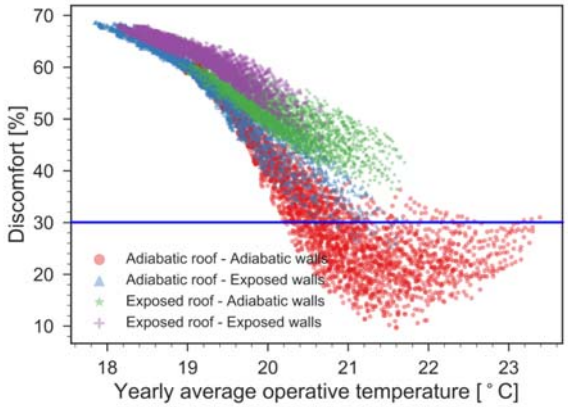


*Figure 3: Discomfort vs. yearly average operative temperature for all simulations conducted.*

Results suggest that building with any energy criteria may result in high levels of discomfort. It is important to mention that of these 1386 simulations, no configuration has an exposed roof. Therefore, it is evident that the roof is, without a doubt, the most critical parameter in exposed-roof dwellings as it is the variable with the higher interaction with the external environment. In consequence, one of the main efficient passive design practices that must be adopted is the use of insulation in the roof of exposed-roof buildings. This opens a door for future research in which optimum materials and insulation thicknesses for


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exposed roofs can be determined. However, from Figure 3, note that buildings with adiabatic roof may also reach high discomfort values. It suggests that include insulation on the building envelope should necessarily be accompanied with improvements on the other parameters.

In that follows, to analyze the common parameters of the configurations that have a low annual discomfort, box plots with swarm plots were used. This kind of plots permit to visualize apart from the interquartile ranges, as well as the distribution of the data (dispersion). In Figure 4 is shown that most of the best configurations are those that, in addition to having an adiabatic roof, have two adiabatic walls, that is, dwellings integrated into buildings or dwellings with walls adjacent to neighboring buildings. This suggests that the biggest problem in typical residential buildings in Quito is the exposition of the envelope to the ambient conditions. However, from Figure 3, the adiabatic condition is not the only condition that reduce the thermal discomfort (discomfort for dwellings with adiabatic roof and walls may also achieve values as high as 60%). Given the climatic conditions of Quito, most of the hours of discomfort are due to over-cooling. Therefore, it is important for future studies to analyze how to minimize the heat losses from exterior surfaces using alternative materials or some level of insulation.

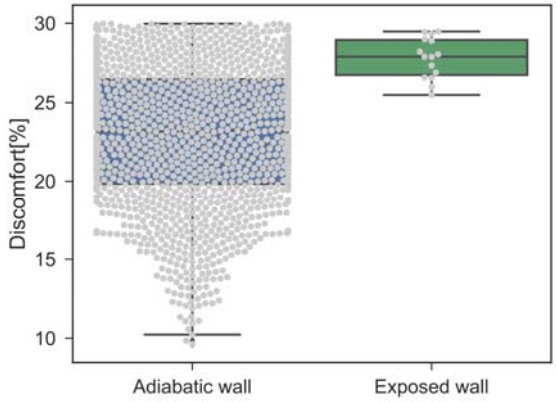


*Figure 4: Exposed-walls and adiabatic-walls buildings swarm plot.*

From the results, it can also be highlighted that, although buildings that have windows only on a single wall may reach discomfort of less than 20%, these are isolated cases. Most configurations with less than 30% of discomfort fit on configurations with windows on two glazed walls (Figure 5). A possible cause for this is the increase in solar gains on the daytime that would help to store heat in the walls and to decrease the discomfort due to over-cooling. This is particularly true in the morning when the solar radiation is high but the ambient temperature is low. This is confirmed if the window to wall ratio (WWR) is analyzed. Figure 6 shows that the best configurations are those with high WWR (between 20 and 30%). On the contrary, very few cases of houses with low WWR (less than 10%) fall within the configurations of low discomfort. Therefore, it is notorious that solar gains during the day should be maximized to reduce the global discomfort. However, it is important that future research focus on finding the optimal WWR for dwellings, as there are more cases with lower discomfort at a WWR of 30% that 40%. This might occur due to the reduction in thermal mass with the increase of WWR.

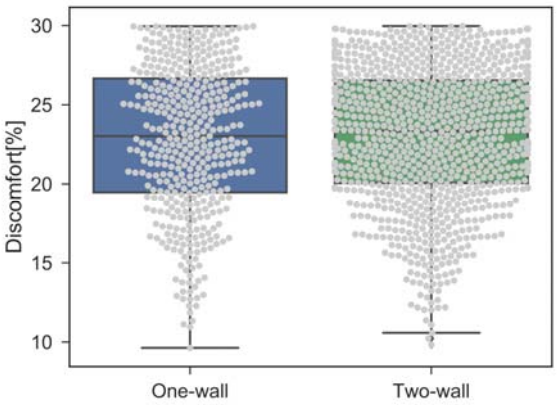


*Figure 5: One-wall and two-wall glazed building swarm plot*

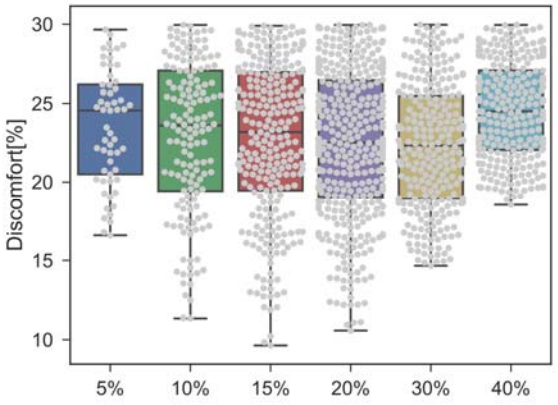


*Figure 6: WWR swarm plot*

Regarding the orientation, Figure 7 shows that there is no an optimal orientation for the main glazing. However, it can be noted that the less favorable orientations are the north, northeast and northwest. Most of the best configurations have a predominant orientation from east to west in the south direction. This behavior is quite particular in equatorial regions (latitudes lower than ±23◦) since the


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incidence of solar radiation comes from the south half part of the year, and from the north the other half. However, the angle of solar inclination (altitude) is high. Hence, annually, there is a greater solar incidence on the East and West facades. It is also seen that the use of single glazing can be as efficient as double-glazing (Figure 8). There is not enough evidence showing that the use of double-glazing is preferable. Although with double glazing there are cases of dwellings with an annual discomfort of less than 15%, these are very isolated cases, and the use of single glazing is as effective as double. Future research could focus on distinguishing the very particular cases where the use of double glazing is favorable.

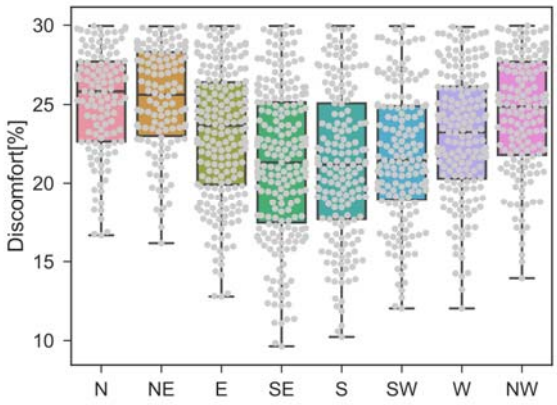


*Figure 7: Main glazing orientation swarm plot*

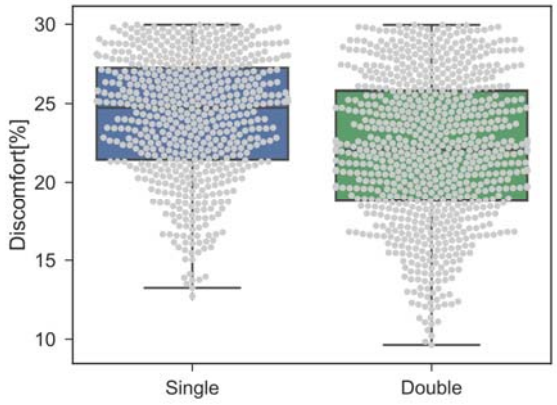


*Figure 8: Single and double-glazing swarm plot*

Figure 9 shows the impact of infiltration. As seen in the figure, the increase in the infiltration rate increases notoriously the discomfort. Most configurations with less discomfort have an infiltration of 0.3 air changes per hour (ach). Therefore, a guide to best practices of passive construction should suggest construction of good quality that minimizes the infiltration that typically occurs in windows-walls joints, doors-walls joints and electrical installations.

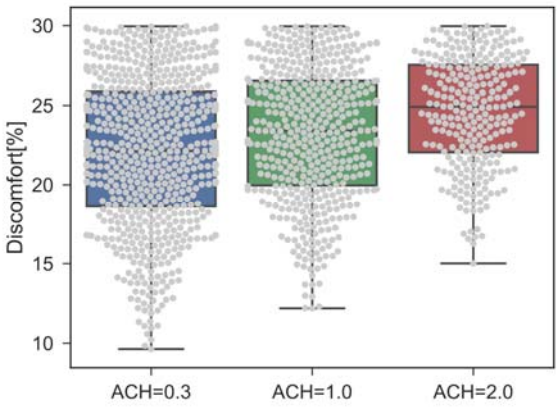


*Figure 9: Infiltration rate swarm plot.*

Finally, regarding building fabrics, Figure 10 shows that brick behaves better than concrete block. It is normal because of the better thermal properties of brick. It is worth mentioning that the thickness of the wall material has an impact on the discomfort. That is, increasing the thickness of the brick from 100 mm to 200 mm shows an improvement in the average thermal comfort. Consequently, residential buildings with low discomfort must be designed with the aim of maximize the thermal mass of the walls. This was also evidenced in the literature where it was highlighted that in climates with high diurnal thermal oscillation, high thermal mass materials are recommendable. Note that usually concrete block may increases its thermal conductivity when the space into the block increases. It is due to the convection into such a space. This phenomenon was not taken into account in this work, but it may reduce more the performances of such a material in buildings.

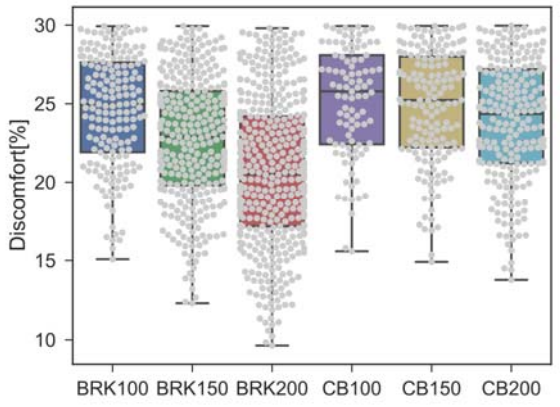


*Figure 10: Exterior wall fabric swarm plot*


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## CONCLUSIONS AND FUTURE WORK

In this study, the impact of the main building parameters on the thermal comfort in residential buildings located in equatorial high-altitude regions was evaluated. Quito has been chosen as a case study and the typical configurations of residential buildings in that region have been studied. The main results show that, although the equatorial high-altitude regions do not have an extreme climate, it is a challenge to guarantee comfort conditions for the occupants of unconditioned dwellings. However, due to the fact that the climate is not extreme, passive design plays an important. role in improving indoor environmental conditions. The first indications on best practices for efficient construction in Quito have been determined. For example, the use of insulating material on the roof and walls is essential to improve the comfort conditions in dwellings with exposed roofs and walls since the envelope is the most critical element. However, it is important to note that implement insulation in those buildings can not be the only implementation. Results showed that buildings with adiabatic roof and walls may also achieve high discomfort levels if the other parameters are not designed correctly. On the other hand, it was also evidenced that the use of brick on the exterior walls, a WWR in the ranges of 30% and glazing orientation from east to west in the south direction should be recommended as good practice for residential buildings in Quito. An important factor that is worth mentioning is the reduction of the infiltration through the improvement in the quality of the construction. It was shown that the reduction of the infiltration significantly improves the comfort of the dwellings

Future work suggests studying deeper about the use of insulating materials on the envelope of residential buildings. It is important that the research focus on minimizing the impact of the construction cost but aimed at maximizing thermal comfort. Likewise, it is advisable to deepen the research regarding the particular cases in which double-glazing is recommended. Also, as previously mentioned, future research is also suggested in finding optimal values for the WWR as a very high value might lead in the increase of discomfort by the reduction of the thermal mass of the dwellings. Finally, the thermal mass involved in a building may be studied. This work is very relevant for the building sector in Quito where there is very little information on passive housing design.

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