Estimating the indoor thermal comfort deficit in the social housing built in Ecuador by integrating Building Information Modelling and Geographical Information Systems

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Abstract

This study aims to estimate the thermal comfort deficit that exists inside of the social housing dwellings that are built in Ecuador. For this, building energy simulations of the social housing model were carried out considering the climatic conditions of all parishes of the continental part of the country. From simulation results, thermal comfort was evaluated using the adaptive comfort model included in CEN Standard EN15251. Based on the Category III acceptability limits of the standard, the adaptive thermal discomfort hours inside social housing were calculated. Finally, the adaptive thermal discomfort hours were mapped using a Geographic Information Systems software, in order to identify areas of the country where there is a high thermal comfort deficit inside social housing. The obtained results show areas in the Andean Highlands, where there is a significant thermal comfort deficit. For this reason, it is recommended that the political proposals involving public investment in building refurbishment focus on the regeneration of dwellings that are located in these areas of the country.

Introduction

Latin America is facing evident problems regarding the deficit and the poor quality of social housing. The policies implemented in the region mainly focus on the provision of new housing units, though the main problem is qualitative (Simioni and Szalachman (2007)). In the case of Ecuador, 2,033,878 households (48.9%) are in housing deficit. From a total of 4,157,113 households nationwide, 632,488 (15.2%) have quantitative housing deficit while 1,401,390 (33.7%) have qualitative deficit (Ministerio Coordinador de Desarrollo Social (2016)).

With the aim of reducing the quantitative housing deficit nationwide, the government of Ecuador through the Ministry of Urban Development and Housing (MIDUVI), has implemented over the last decade several social housing projects along the country. In these projects, MIDUVI has used a single social housing model, consisting of houses built of concrete floors and walls, and zinc roofs without insulation. This model does not take into account the differences in climate of every region of Ecuador, which has caused discomfort among people who live in those residences. This mainly happens because social housing built in Ecuador does not include HVAC systems, which may cause temperatures registered inside dwellings to fall outside the thermal comfort zone established by standards such as CEN Standard EN15251 (2007), for prolonged periods.

Considering that users of social housing belong mainly to the segment of very low economic capacity (Ministerio de Desarrollo Urbano y Vivienda (2016)), they are unable to bear the financial cost that would represent keeping the house in thermal comfort conditions. This could represent a serious risk as many studies already identified that physical, mental and social health are affected by living conditions (Novoa et al. (2017)). The quality issue directly affects the users thermal comfort, which indicates the need for improving housing from the design stage. Taking this into consideration, the analysis of weather conditions should be the starting point for the design of bioclimatic architecture with two main objectives: first, to maximize comfort conditions and second, to minimize energy consumption.

Considering that climate plays a vital role in the energy and thermal performance of buildings, it is important to identify locations of the country where climate could lead into excessive thermal stress inside social housing and could represent a serious health risk to their inhabitants. By integrating Building Information Modelling (BIM) and Geographical Information Systems (GIS), areas of the country where this type of housing does not ensure adequate thermal comfort conditions were identified.

Building performance simulations and geospatial modelling techniques have already been used in several studies (Mastrucci et al. (2014); Ascione et al. (2013); Caputo et al. (2013)) to determine building sector energy consumption profiles and for estimating energy savings, as a supporting method for defining energy strategies at urban scale. These techniques have also been used in the development of maps that delineate the extents of thermal comfort requirements of a region, which are called Architectural Climate Zones, Building Climate zones, or Bioclimatic Zones. These maps and zoning criteria are published in many climatically diverse countries including but not limited to China (Wan et al. (2010)), USA (Briggs et al. (2003)), Brazil (Roriz et al. (1999); ABNT (2005)). Despite that the map obtained from this study could be considered a Building Climate Zone map, the main aim of this study is to identify regions of the country where climate could lead into excessive thermal stress inside social housing. An understanding of the spatial temperature variability and human thermal comfort can provide timely warning to groups under high risk.

From this perspective, the results of this study can be a valuable support tool to promote and prioritize the retrofit of the social housing stock at national scale, based mainly on indoor thermal comfort criteria and therefore on human health.

Methodology

Location and climate

Ecuador has a total area of 283,520 km^2 (109,468 sq mi), including the Galapagos Islands. It is located northwest of South America (lies between latitudes 2°N and 5°S), bounded on the west by the Pacific Ocean, with Colombia in the north border and Peru in the east and south border (Figure 1).

This study was performed only in the continental part of the country, which excludes the Galapagos Islands. The continental Ecuador has three main geographic regions: The Coastal region, the Andean Highlands and the Amazon rainforest. Each region presents different climatic conditions determined by altitude, location, and the influence of the Andean Cordillera and the Pacific Ocean. Generally, the Pacific coastal area has a tropical climate with a rainy and a dry season; the Andean highlands have two seasons, a rainy cold season and a temperate dry season; and the Amazon rainforest has a humid subtropical climate with rains throughout the year.

In order to perform building simulations of the social housing in all the regions of the continental Ecuador, weather data of each parish of this part of the country (1024 parishes) was generated using the software Meteonorm, which is a meteorological database. Weather data files are generated for a point located in the centroid of each parish. The validation of these weather data would be considered as a future work.

Thermal simulation of social housing

The thermal behavior of social housing was simulated in dynamic state using the software DesignBuilder v.4.7. Simulations were run on an ENSIMS X3200 Simulation server with 64 GB of RAM and two Intel Xeon processors. In addition, Mouse Recorder pro was used to automate and rapidly run a large number of simulations. Indoor operative temperatures and running average outdoor air temperatures (T_{rm})

Figure 1: Map of Ecuador.

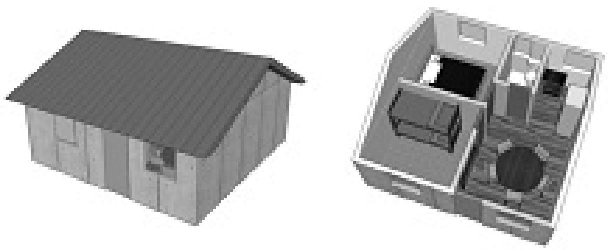

Figure 2: Model of social housing developed by MIDUVI.

were output hourly. Data collation was performed using a python script which ran through the simulation results, calculating adaptive thermal discomfort metrics for social housing dwellings.

Considering that the model of social housing built in Ecuador has the same design and uses the same construction materials regardless the climatic conditions in which it is located, building simulations were performed on a single model of social housing using the weather data of each parish of the continental Ecuador. The typology and construction materials of the social housing have been defined based on information provided by MIDUVI (Ministerio de Desarrollo Urbano y Vivienda (2012)). The housing has two bedrooms, a bathroom and a kitchen - dining - living room in a single environment, contained in an area of 36m^2, as shown in Figure 2. Social housing construction materials are presented in Table 1. Default values of thermal and surface properties of construction materials included in the DesignBuilder Component Library were used in the simulations. For simplicity in thermal calculations, the social housing was modelled as one single zone.

Information such as the use of lighting and the number of electrical appliances that provide thermal loads

Table 1: *Details of building materials of social housing built in Ecuador.*

	Material	Thk (mm)	K (W/mK)	Cp (J/kgK)	d (kg/m^3)	U-value (W/m^2)	E	S.A	S.T	S.R	SHGC
Reference exterior wall/ internal partition	Concrete block	150	0.62	840	1040	2.315	0.90	0.60	-	-	-
Reference roof	Asbestos-Cement sheet	5.00	0.36	1050	1500	6.498	0.90	0.70	-	-	-
	Galvalume roof panel	3.00	50.0	896	7800	7.143	0.25	0.35	-	-	-
Reference floor	Stone pavement	100	3.49	840	2880	3.240	0.90	0.60	-	-	-
	Sand	20.0	1.83	712	2200		0.90	0.60	-	-	-
	Polyethylene	0.40	0.33	2200	920		0.90	0.70	-	-	-
	Concrete slab	50.0	1.35	1000	1800		0.90	0.60	-	-	-
Reference windows	Single clear glazing	3.00	0.90	-	-	5.894	0.85	-	0.83	0.075	0.861

Thk - Thickness
K - Thermal conductivity
Cp - Specific heat capacity
d - Density
U-value - Thermal transmittance
E - Emissivity
S.A - Solar absorptance
S.T - Solar transmittance
S.R - Solar reflectance
SHGC - Solar heat gain coefficient

was defined based on information from the Survey of Living Conditions performed by the National Institute of Statistics and Censuses (Ministerio Coordinador de Desarrollo Social (2016)). To analyze the thermal comfort of the occupants of social housing, occupancy of four people was taken into consideration, which is the average number of occupants in such type of dwellings. In addition, the typical housing occupancy periods of Ecuadorian families was considered, which is as follows: From 7 to 12 a.m. there is 25% occupancy, from 12 a.m. to 5:30 p.m. there is 75% occupancy, and from 5:30 p.m. onwards there is 100% occupancy. In total, 1024 simulations were performed.

Considering that social housing that is built in Ecuador does not have HVAC systems, social housing was simulated taking into consideration only the modeling of natural ventilation and infiltrations. Social housing occupants tend to operate windows manually to control internal temperature or air quality, which will highly influence natural ventilation.

Based on the adaptive comfort theory, the manual operation of windows is one of the main adaptive strategies that the occupants of buildings use to regulate indoor operative or to control the quality of indoor air. For this reason, the main parameter of control for the operation of the windows of the dwelling is the indoor air temperature. As in previous studies (Mavrogianni et al. (2015); Nasir and Colbeck (2013); Mavrogianni et al. (2010)), window-opening was modelled to occur above a 25 °C threshold.

If the inside air temperature is greater than this set point temperature (and natural ventilation operation schedule is on) then natural ventilation can take place. The operation schedule specifies when window venting is available. A zero or negative schedule value means window venting is not allowed. A value greater than zero means venting can occur if other venting control conditions are satisfied. Considering that windows can only be operated when the dwelling is occupied, the natural ventilation operation schedule was set to be the same as the occupation schedule. This does not indicate that natural ventilation will take place whenever the dwelling is occupied, as windows of the social housing will only be opened when:

- The inside air temperature is above the natural ventilation cooling set point temperature (25 °C), and
- The inside air temperature is greater than the outside temperature, and
- The operation schedule allows ventilation.

Thus, if the dwelling is occupied and the indoor air temperature is above 25 °C, windows are considered to be opened to increase natural ventilation with the objective of reducing the indoor operative temperature. On the other hand, if the indoor air temperature falls below 25 °C, windows are considered to be closed to reduce the cooling effects of natural ventilation.

Natural ventilation modeling was carried out using the Calculated Natural Ventilation model option included in DesignBuilder. The ventilation rates are calculated using wind and buoyancy-driven pressure, opening sizes and operation of windows, crack sizes, etc. using the EnergyPlus Airflow Network model (AIRNET) (Gu (2007)) that has been validated using several sets of measured data. This fully integrated network model is able to predict airflow due to different natural ventilation controls, such as window or door openings, and their impact on building thermal performance. The AIRNET model calculations use pressure coefficients when calculating wind-induced pressure on each surface during simulations. The wind pressure coefficient is a function of wind direction, position on the building surface and side exposure. For the purpose of this study, typical approximate values of wind pressure coefficients were selected from the DesignBuilder database based on data given in a publication of the Air Infiltration and Ventilation Centre (AIVC) (Liddament et al. (1996)). It is important to note that even when windows and doors are closed, they still provide a small flow path through the crack between the opening and the surrounding surface, which is known as uncontrolled infiltration. The selected natural ventilation model option takes into consideration two main categories of uncontrolled infiltration airflow:

- Airflow through the surface itself which could be caused by cracks or by general fabric porosity.
- Cracks between windows, vents and doors and the main wall or roof surface.

To account for infiltration, DesignBuilder includes a single crack in each surface in the simulation. The size and properties of this crack depend on the setting of the crack template applied when setting crack properties. Considering that the dwelling analyzed in this study is a social housing dwelling built with a very limited budget, a poor crack template (corresponding to a high infiltration profile) was selected.

It should be mentioned that the simulation model was calibrated only with the average billed energy consumption of social housing in Ecuador. The calibration of the simulation model with measured data of environmental conditions inside the analyzed social housing model will be considered as future work.

Evaluation of adaptive thermal comfort

From the simulations, the indoor operative temperatures within social housing located in each parish of Ecuador were obtained. The adaptive approach included in CEN Standard EN15251 (2007) was then used to assess the indoor thermal environment. The decision of whether to use ASHRAE 55 or CEN Standard EN15251 to evaluate adaptive thermal comfort was mainly based on the index of outdoor temperature that each standard uses. The ASHRAE chart is expressed in terms of the monthly mean outdoor air temperature, while CEN Standard 15251 is expressed in terms of an exponentially weighted running mean of the outdoor air temperature. EN15251 is therefore able to handle varying weather conditions, which are not displayed in the historic monthly means that ASHRAE employs.

In order to generate adaptive comfort output results in DesignBuilder, the option "Adaptive CEN Standard 15251" has to be selected on the Simulation Output Options − Comfort and Environmental category. By checking this option, the adaptive model running average outdoor air temperature is generated for each weather file, for each hour of the year. The adaptive model running average outdoor air temperature reports the weighted average of the outdoor air temperature of the previous five days, which is an input parameter for the CEN 15251 adaptive model. The reporting period for simulation comfort output results was set to "All periods", in order to generate data for all periods including times when the zones are unoccupied. In this way, the results obtained are not influenced by the established occupation schedule, which is generally very variable and difficult to estimate.

By applying the adaptive model, the number of hours of the year in which the indoor operative temperature within social housing is outside the range of thermal comfort (thermal discomfort hours) in the different parishes of Ecuador were obtained. Simulation results are generated in a standard .eso output file, which contains detailed results that must be viewed in the Results Viewer software as CEN Standard 15251 adaptive outputs are not available on the DesignBuilder Simulation screen. The Results Viewer is a separate DesignBuilder application which can be used to view EnergyPlus results stored in one or more .eso files. The total 1024 .eso files corresponding to the 1024 simulations were opened at a time, to generate hourly results of the following variables: Zone Operative Temperature; Zone Thermal Comfort CEN 15251 Adaptive Model Running Average Outdoor Air Temperature (T_{rm}). From these results, the adaptive thermal discomfort hours are calculated.

The adaptive thermal discomfort hours reports whether the hourly zone operative temperature falls into one of the Category acceptability limits of the adaptive comfort in the CEN Standard EN15251 (2007) during occupied or unoccupied periods. Category III acceptability limits were selected in this study to calculate the adaptive discomfort hours. After testing CEN Standard 15251 in a thermal comfort study in Ecuador (Gallardo et al. (2016)), this category was found to reflect appropriately the sensation and expectation of local people. The CEN Standard Category III acceptability limits are determined by Equation (1) and Equation (2).

$$T_{op,max} = 0.33T_{rm} + 18.8 + 4 \quad (1)$$

$$T_{op,min} = 0.33T_{rm} + 18.8 - 4 \quad (2)$$

Where $T_{op,max}$ is the upper limit value of indoor operative temperature (°C), $T_{op,min}$ is the lower limit value of indoor operative temperature (°C), and T_{rm} is the running mean outdoor temperature.

Classification of adaptive thermal discomfort hours

Adaptive thermal discomfort hours were classified into five different classes. Climate Consultant was used to establish the break values between each class of adaptive thermal discomfort hours. An analysis of the distribution of psychrometric data in sixteen different design strategy zones was performed to establish the boundaries where any change in thermal stresses (adaptive thermal discomfort hours) necessitates a corresponding change in building design strategies.

GIS for mapping thermal comfort

Results were finally aggregated and mapped across the country using a Geographic Information Systems software, in order to identify regions of the country hosting vulnerable populations, whose dwellings have a thermal comfort deficit.

The methodology for mapping thermal comfort consists in using a geostatistical tool to interpolate the thermal discomfort hours across the whole territory. First, a spatial prediction based on Kriging was applied. The prediction of values using Kriging alone does not reflect local variability, therefore the variogram was configured. The behavior of the sample was considered for the configuration of the variogram and a Gaussian model in conjunction with a nugget effect was assigned to adjust the values throughout the territory. Finally, a Kriging interpolation was applied. The results of the interpolation were averaged within the limits defined by each parish. As a result, an average of the adaptive thermal discomfort hours was obtained for each parish.

Results

The results of implementing the methodology for mapping thermal comfort are presented in Figure 3. Each parish of the continental part of the country is assigned the average adaptive thermal discomfort hours of all the interpolated values within the parish. A colour symbology is assigned to each parish according to the class of adaptive thermal discomfort hours to which it belongs. The thermal comfort map shows the transition that exists between the Coastal, Andean Highlands and Amazon rainforest regions. As it can be seen in the thermal comfort map, the adaptive

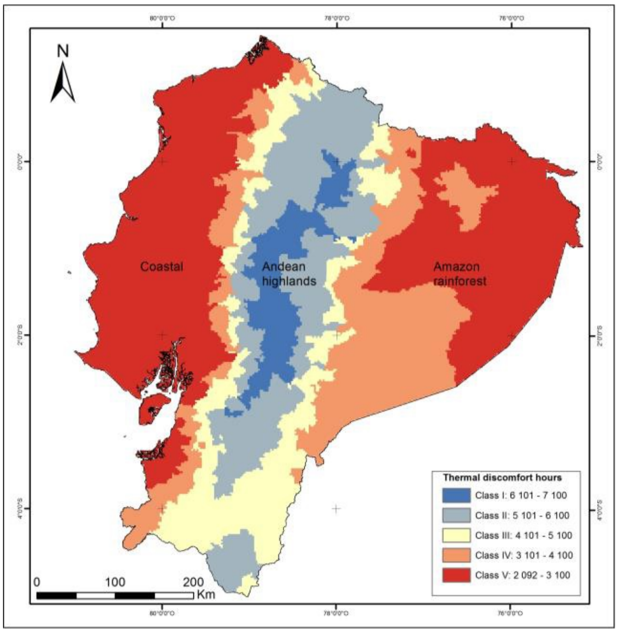

Figure 3: Map of adaptive thermal discomfort hours for the model of social housing built in Ecuador.

thermal discomfort hours were classified into five different classes using the software Climate Consultant. The first class of thermal discomfort hours (Class I: $6101 - 7100$ discomfort hours) is considered the most critical, which only includes some areas in the Andean Highlands. The thermal performance of dwellings located in these areas of the country is presented in Figure 4. Most of the parishes in these locations have an altitude above 3240 meters above sea level (MASL). According to the Census of population and housing 2010 performed by the National Institute of Statistics and Censuses of Ecuador INEC (2010), from a total of 3,748,919 occupied dwellings nationwide in 2010, approximately 107,000 dwellings (2.8 %) are located in this Class of thermal discomfort hours. Although this quantity includes all types of dwellings, the majority of them uses the same construction materials as the model of social housing and do not include wall or roof insulation. Social housing dwellings located in this area of the country have a significant thermal comfort deficit (up to 6754 hours of discomfort), as there are heating requirements of up to 4810 kWh/year that in most cases cannot be covered due to the lack of resources to acquire heating systems or to cover the associated energy costs (energy poverty). The use of wood for heating is common in these parts of the country, which has led to hypothesize the existence of associated respiratory diseases.

Based on these results, it is considered that this segment of the population is at high risk, since the thermal conditions inside their homes can even cause them health problems. A strong legislative tool based on these results will ensure that social housing dwellings and other buildings located in Class I locations are refurbished to comply with the most

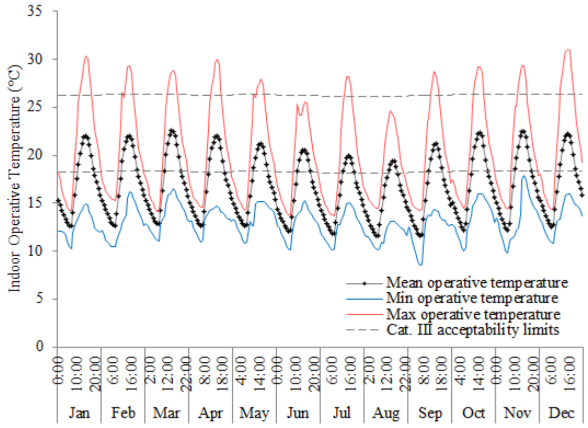

Figure 4: Time plot of indoor operative temperature for social housing dwellings located in Class I.

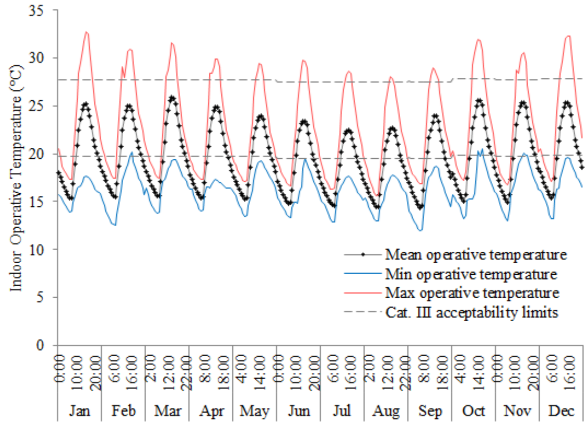

Figure 5: Time plot of indoor operative temperature for social housing dwellings located in Class II.

stringency building code requirements, such as wall and roof insulation, to offer adequate housing conditions. According to Climate Consultant results, the best passive design solutions for maintaining indoor thermal comfort in these areas of the country are: retaining internal heat gains (minimize heat losses from the inside to the outside) and employing passive heating strategies (passive solar direct gain high mass and wind protection). In this area of the country where the adaptive thermal discomfort hours are the maximum, dwellings should have heating systems as in most of the occupation periods the indoor operative temperature is well below the Category III acceptability limits of thermal comfort.

The main difference between locations in Class I and locations in Class II is the heating requirements. The thermal performance of social housing dwellings located in the range of Class II adaptive thermal discomfort hours (Class II: 5101 − 6100) is presented in Figure 5. As can be seen in the figure, the indoor operative temperature is below the Category III acceptability limits of thermal comfort mainly in the early morning and late at night. Considering that these occupation periods correspond to the periods when people are asleep, the heating requirements are much less than locations in Class I. Assuming that people do not use heating systems during sleep time due to the use of heavy blankets (which is common in the Andean Highlands region), the estimated heating requirements for locations in Class II are 2611 kWh/year.

The third class of adaptive thermal discomfort hours corresponds to areas in which dwellings have a range of thermal discomfort hours between 4101 and 5100 hours. Areas located in this Class are mainly transition zones that exist in the boundaries between the Coastal region, the Andean Highlands and the Amazon rainforest. Dwellings located in this area have an acceptable thermal performance as can be seen in Figure 6, as most of the adaptive thermal discomfort

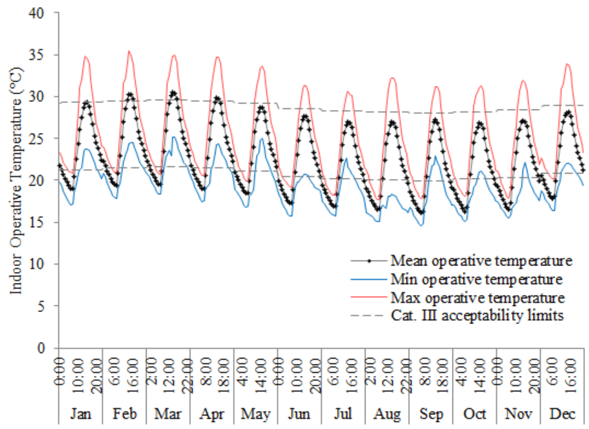

Figure 6: Time plot of indoor operative temperature for social housing dwellings located in Class III.

hours happen very late at night or at dawn, when people are normally asleep. According to Climate Consultant results, the best passive design solutions for maintaining indoor thermal comfort in these areas of the country are: taking advantage of internal heat gains, employing passive heating strategies (passive solar direct gain high mass) to take advantage of solar heat gains early in the morning, and sun shading of windows during midday and in the afternoon. In this area of the country, the heating requirements could be considered negligible, as heating is only required at dawn and very early in the morning when people are normally asleep wearing blankets. Social housing dwellings located in this Class of adaptive thermal discomfort hours would start to have some cooling requirements during midday and in the afternoon. Assuming that dwellings would be occupied at those times of the day, the estimated cooling requirements are 625.4 kWh/year.

The fourth class of adaptive thermal discomfort hours corresponds to areas in which dwellings have a range of thermal discomfort hours between 3101 − 4100 hours. The thermal performance of dwellings located

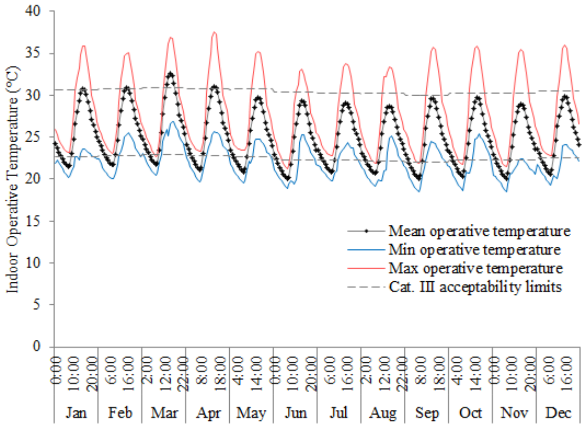

Figure 7: Time plot of indoor operative temperature for social housing dwellings located in Class IV.

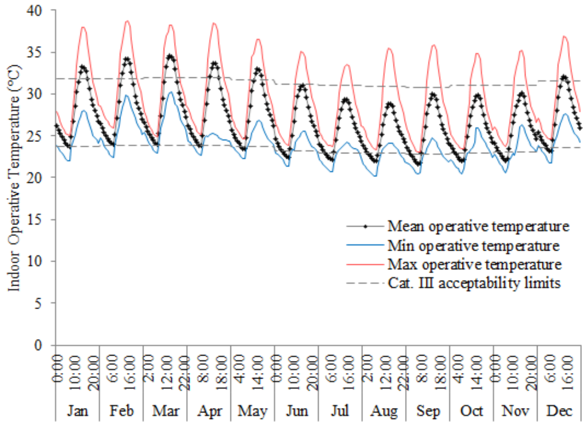

Figure 8: Time plot of indoor operative temperature for social housing dwellings located in Class V.

in these areas of the country is presented in Figure 7. Dwellings in this class are located mainly in the Amazon rainforest and in some parts of the Coastal region. Areas included in this Class are considered the most thermal comfortable, as social housing dwellings have the lowest energy requirements for achievement of thermal comfort. According to Climate Consultant results, the best passive design solutions for maintaining indoor thermal comfort in these areas of the country are the same as the solutions for the third class, with the differences that in this class dehumidification should be the main design strategy and cooling requirements during midday and in the afternoon are higher. Assuming that dwellings would be occupied at those times of the day, the estimated cooling requirements are 792 kWh/year. There are practically no heating requirements in these areas of the country.

The fifth class of adaptive thermal discomfort hours corresponds to areas in which dwellings have a range of thermal discomfort hours between 2092 and 3100 hours. The thermal performance of dwellings located in these areas of the country is presented in Figure 8. Dwellings in this Class are located only in the Coastal region and the Amazon rainforest. The main difference between locations in Class IV and locations in Class V are the cooling requirements. Dwellings in this class have the highest cooling (up to 1510 kWh/year) and dehumidification requirements. According to Climate Consultant results, the best passive design solutions for maintaining indoor thermal comfort in these areas of the country are: sun shading of windows and high thermal mass night flushed. Unlike the other Classes of adaptive thermal discomfort hours, any type of solar or internal heat gains should be avoided or reduced at all times because there are no heating requirements at any time. Although dwellings located in this thermal discomfort class currently do not present critical indoor overheating conditions, the exacerbation of urban heat island effect and climate change might further increase the risk of overheating and will be properly addressed in a future work.

Conclusions

The methodology that was implemented in this study has allowed identifying areas of the continental Ecuador where there is a high thermal comfort deficit inside of the social housing dwellings that are built in the country. The results show that there are areas in the Andean Highlands with very high thermal discomfort hours inside social housing. People located in these areas are considered to be at high risk, as the climatic and housing conditions may cause them health problems. For this reason, it is recommended that the political proposals involving public investment in building refurbishment, use the thermal map obtained in this study as a support tool to promote and prioritize the retrofit of the social housing stock at national scale. A strong legislative tool based on these results will ensure that social housing dwellings and other buildings located in Class I locations are refurbished to comply with the most stringency building code requirements, such as wall and roof insulation, to offer adequate housing conditions. On the other hand, dwellings located in all other Classes will have to comply with less stringent requirements and will not have to spend extra resources for achievement of thermal comfort.

To our knowledge, the results represent the first mapped estimates of thermal comfort metrics for social housing dwellings in Ecuador. In this way, the thermal comfort map could be a valuable support tool to the research on infectious diseases and its association with variables related to climatic and housing conditions in Ecuador. Future research in this field should focus on analyzing variables related to housing conditions mainly in the areas of the Andean Highlands where there is a high thermal comfort deficit inside social housing.

Although the thermal comfort map developed in this study did not have the intention of establishing Building Climate zones, the methodology to generate the map could be used to delineate the extents of thermal comfort requirements of a region. For this reason, it is considered that an important future step would be to validate the adopted methodology by performing post occupancy evaluations and field studies of thermal comfort.

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