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Assessment and Proposal to Improve Hygrothermal Comfort and IAQ in Housing in Bogotá: Four Case Studies

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Abstract

Low-income housing is that which is developed to guarantee the right to housing for low-income households, the value of which does not exceed 135 minimum wages. This study was conducted as part of eEvaluation and sustainable proposal for improvement of the integral habitability of low-income housing (VIS) project in Bogota, Colombia. It provides a diagnostic and assessment plan for improving indoor air quality (IAQ) and hygrothermal comfort in terms of CO2 concentrations in four residences in Bogotá. The assessment considers the city's climate, occupancy patterns, and schedules of use within the buildings. The study confirmed results using six-month monitoring data, modeling and simulation of dwellings using Sketchup, EnergyPlus and OpenStudio plugin. These methods provided accurate modeling of relative humidity and temperature behavior. Indoor air quality (IAQ) is closely tied to hygrothermal behavior, particularly in cold weather when closed windows lead to increases humidity, and CO2 buildup. To enhance comfort levels, avoiding air infiltration and implementing hygienic ventilation practices are recommended. However, it was noted in several cases that the hygrothermal comfort standards outlined by ASHRAE were not met. As a result, passive improvements based on simulation were suggested, including the use of thermal stucco, double-glazed windows, and insulating floors, all of which improved internal comfort conditions.

1.0 INTRODUCTION

Law 46 (1918), which addressed public health issues with sanitary housing, is where the idea of habitability in social interest housing (VIS) in Colombia first emerged. Then, in accordance with the scale of the city in which it is situated, the VIS and the idea of habitability are subjugated to their economic worth connected to minimum monthly earnings under Law 9 of 1989 on Urban Reform. The Housing Policy and the National VIS System (SINAVIS), which defines the housing solution in terms of the current legal minimum salary, were established with the new Political Constitution of 1991. Another factor at play has been Law 142 of 1994, a socioeconomic stratification system that uses property observations to divide Bogotá's population's income level into six strata. Among these, strata 2 and 3 correspond to the state interventions in VIS that have remained constant over time.

The main purpose of buildings, especially housing, is to provide adequate habitability conditions. Despite human’s efforts to improve environmental conditions through various technologies, there are still many shortcomings in bioclimatic and habitability aspects. These include the inappropriate use of materials, building orientation, spaciousness, among other aspects that have generated dissatisfaction with housing and a diminished quality of life (Rodríguez et al., 2019), (Mewomo et al., 2023).

Habitability in a home is an architectural concept that encompasses both the physical space and the living environment, aiming to guarantee minimal conditions of health and comfort. Comfort and indoor environmental quality (IEQ) are connected. Comfort comprises the total indoor environmental elements (i.e., ventilation, thermal comfort, noise, and lighting) within that building, while indoor air quality (IAQ) primarily focuses on the quality of air circulating within a building (Dimitroulopoulou et al., 2023).

Because of human activity, the IAQ inside the buildings might not be sufficient. Adequate ventilation is crucial for the residents' comfort and health; with natural ventilation playing a significant hygienic role. This type of ventilation, known as hygienic ventilation or winter ventilation, is required permanently, particularly in colder seasons or predominantly cold areas where windows tend to remain closed to maintain thermal comfort. Therefore, hygienic ventilation becomes essential for ensuring air quality (Scherer & Grigoletti, 2023). It is vital to guarantee that ventilation occurs at a level higher than occupants to sanitize these environments effectively (Russi & Rocha, 2014).

The most significant risk factor in homes is poor indoor air quality, often caused by inadequate ventilation (Wimalasena et al., 2021). Elevated indoor CO2 levels serve as a reference for assessing IAQ, with concentrations adversely affecting the attention and productivity of the occupants (Cao & Deng, 2019). Additionally, exposure to acute high concentrations of CO2 can cause mucosal and respiratory diseases, blood acidosis, neurophysiological consequences, and impaired decision-making in those affected (Huimin Yao et al., 2024).

Hygroythermal comfort depends on factors such as air temperature and humidity, thermal radiation, and ventilation. This is directly related to the climate of the place, occupancy patterns, and house characteristics (Espinosa Cancino & Cortés Fuentes, 2015). According to the American Society of Heating, Refrigerating and Air-Condition Engineers (ASHRAE) standards, thermal comfort "is a mental condition in which satisfaction with the environment is expressed." It is said that to reach this sensation of comfort, you must be in thermal equilibrium (Ming et al., 2023), that is, where individuals experience neither excessive heat nor cold (American Society of Heating, 2017).

High humidity in the air and "low temperatures" inside buildings can cause water condensation on surfaces, and possible deterioration of construction materials, as well as the proliferation of mold and other microbial agents (World Health Organization, 2009), (Smith & Gorse, 2021) which can cause serious structural and health problems (Pipiriate, 2017).

In Colombia, the application of thermal comfort standards regulating in the design of buildings is advised but not mandatory within sustainable architecture policies. Regulatory frameworks are limited, and policies are relatively new compared to other countries (Medina et al., 2021). Some studies have shown that comfort levels in houses that have been built and are still being built, particularly in Bogotá, often fall below acceptable thresholds of temperature and relative humidity (Rodriguez et al., 2019), (Calderon Uribe, 2019). The situation regarding regulations for air quality is not significantly different, since it remains challenging to find standards specifically tailoredto homes.

Bogotá has a bimodal climate with two rainy periods and two dry periods annually, each of approximately three months (Cuellar & Perez, 2023). During the rainy season, there's a notable increase in cold sensations due to greater cloudiness and less solar radiation on surfaces. According to (Agudelo Varón, 2014), in at least six of the twelve months of the year, houses in Bogotá fall short of thermal comfort standards because parameters such as spatial distribution, lighting, ventilation, and materials are not ideal.

These issues stem partly from a focus on quantity over quality in housing, driven by government policies aiming for broader coverage, as well as construction companies seeking higher profits by repeating models regardless of the specific characteristics of each place, saving in costs of designs, materials and other expenses (García Ramírez, 2020). This situation generates a problem, given the city's cold weather conditions, with an average temperature of 14°C and relative humidity of 80% (Rodríguez et al., 2019), resulting in cold stress. Therefore, when inhabiting these cold and humid spaces, it can generate deterioration in health and low satisfaction, especially in social housing, where the cost of maintaining comfort attributes or making adjustments can exceed the economic capacity of residents (Rodriguez et al., 2019).

Computational modeling offers a valuable tool for evaluating buildings and propose constructive solutions. These models analyze thermo-energy behavior and its relationship with thermal comfort and air quality. While most bioclimatic and air quality analyses have been carried out with CFD-based programs, other methods like zonal and network models in software such as EnergyPlus, DesindBuilder, DOE, Transys, Esp-r, Domus Procel Edifica, among others are also common and applicable to both commercial buildings and housing (Al Ka'bi, 2020).

Notably, the U.S. Department of Energy (U.S Department of Energy (DOE), 2021) produced EnergyPlus, one of the most popular open source energy and bioclimatic simulation systems for buildings globally (Guerra García et al., 2022).

In light of these challenges, the goal of this study was to analyze hygrothermal comfort and IAQ (CO2) using EnergyPlus simulations and to propose improvements based on passive strategies for four houses in Bogotá.

2.0 METHODOLOGY

Four case studies were selected, representing houses from different historical periods of social housing in Bogotá: Antonio Nariño Urban Center Case (CUAN) (1958), Paulo VI Case (1966), Sauzalito Case (1987), and Alcalá Case (2010). The first three cases are considered Social Interest Housing (VIS) in the city (socioeconomic strata 2 and 3), while the Alcalá Case belongs to a higher socioeconomic stratum (socioeconomic strata 5). This selection provided a contrast reference, thus expanding the research framework. In Figure 1 the location and orientation of the selected dwellings is shown.

Figure 1. Location of case study homes in the city of Bogotá.

(Source: the authors)

Visits were conducted to verify planimetric data and gather input for simulations through surveys on house routines, natural ventilation, equipment usage, and lighting.

To analyze the study cases regarding their materials and configuration concerning hygrothermal comfort, simulations were carried out using the free-access program EnergyPlus and the OpenStudio plugin. These simulations were validated using data collected every 20 minutes over a period of 6 months, resulting in a total of 12,960 data collected for each variable. Data were collected using Wöhler 210 dataloggers, which recorded variables of temperature, relative humidity, and CO2 within the ranges and precision shown in Table 1.

Table 1. Wöhler 210 Parameter Ranges and Accuracy.
(Source: adapted from the team manual.)

Parameter	Measuring range	Precision
CO2	0 _ 6000 ppm	± 5%
Temperature	-10 °C _ 60°C	± 0.6 °C
Relative Humidity	5% _ 95%	±3%

For each case study, 3D geometry was modelled using the Sketch up program and the Open Studio Plugin to generate an IDF-type file. The geometries created thermal zones for spaces, added boundary conditions such as sun protection, contact with the ground, and thermal zone connections, among others, and assigned names to spaces and surfaces. The model was oriented according to the corresponding case for easy recognition.

For the CUAN Case, the apparatus (data logger) was positioned at a height of 1.0 m in the study room. The geometry for the case was set up with nine thermal zones (Figure 2-A). Additionally, sun shields were incorporated into the modelling to simulate the shadows cast by the upper floor (Figure 2-B).

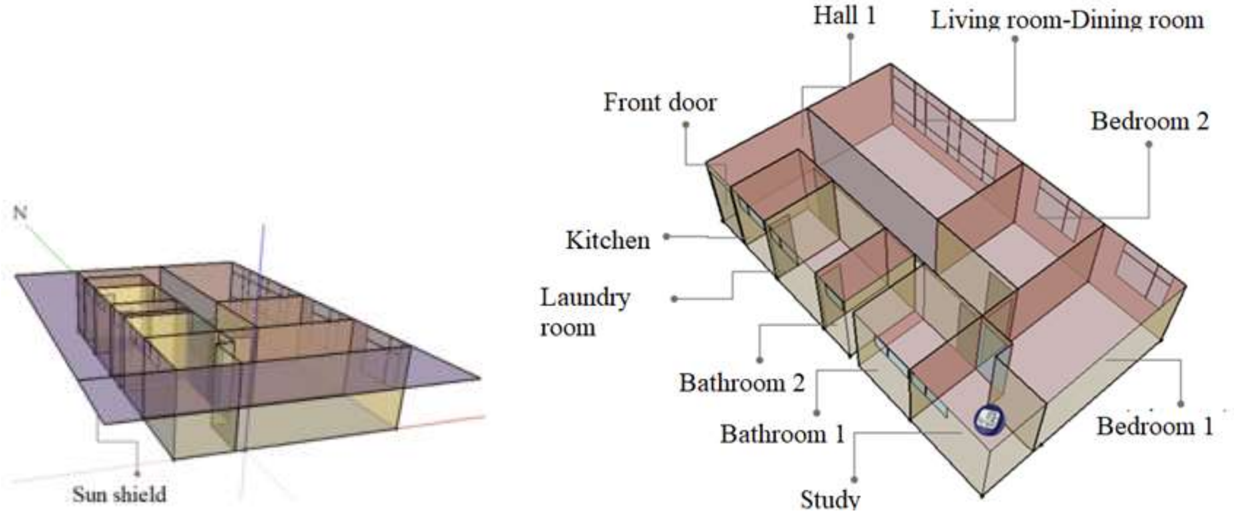

Figure 2. 3D geometry CUAN case: A. Spaces corresponding to thermal zones. B. Sun shields.
(Source: the authors)

The Paulo VI Case is a house with 2 floors, with 14 thermal zones (Figure 3). In this case, two Wöhler units were installed, one on the first floor, in the bedroom 3, and the other in the living-dining room on the second floor. A sun shield was used that recreates the parking lot door located on the first floor.

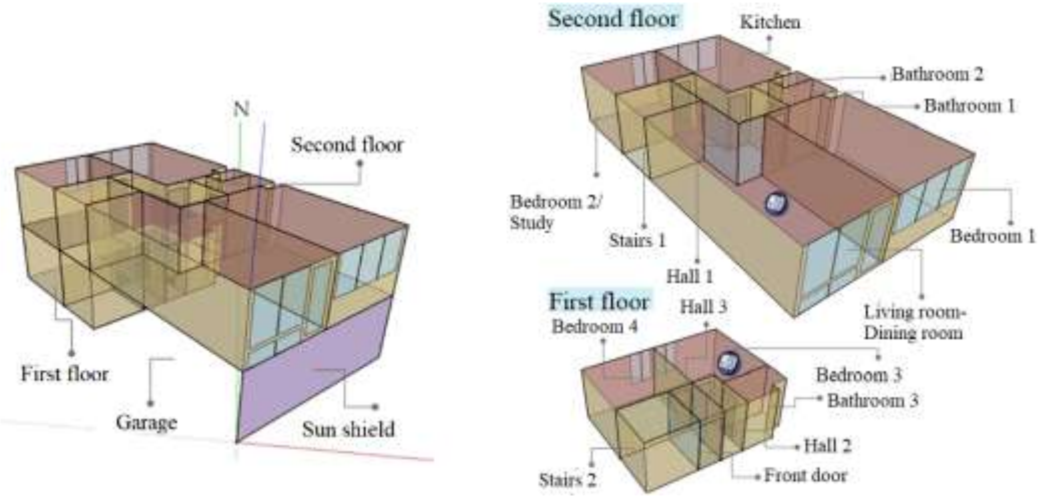

Figure 3. 3D geometry Paulo VI case.
(Source: the authors)

Additionally, the Sauzalito Case was divided into 8 thermal zones (Figure 4) and the data logger was installed in the living-dining room.

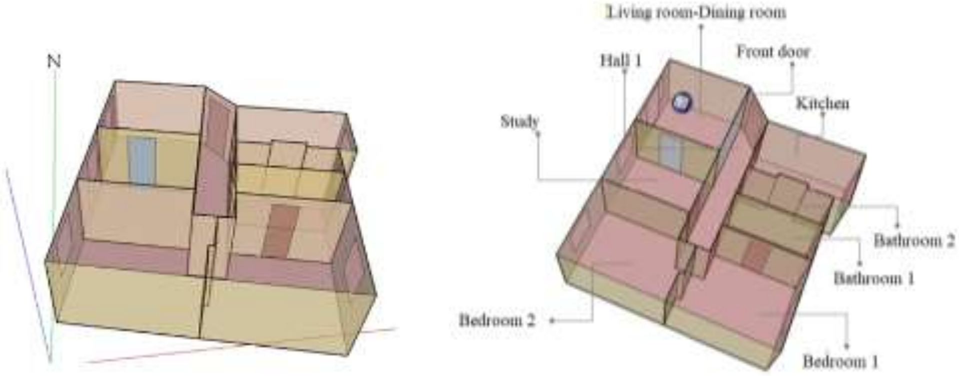

Figure 4. 3D geometry Sauzalito case.
(Source: the authors)

Finally, the Alcalá Case (second floor) was divided into 13 thermal zones (Figure 5-A). Sun shields were used in this instance to simulate the shadows cast by the cantilever on the upper floor (Figure 5-B). It is worth noting that, in this house, the first floor corresponds to the parking area.

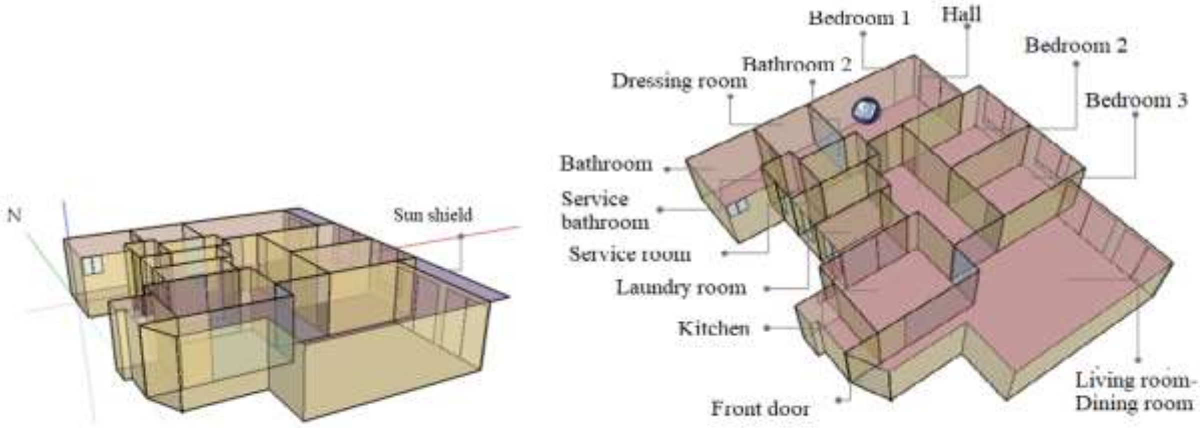

Figure 5. 3D geometry Alcalá case: A. Spaces corresponding to thermal zones, B. Sun shields.
(Source: authors)

Subsequently, the IDF file was imported into the EnergyPlus software, where the thermal properties of the materials, the power of internal equipment such as lighting fixtures and appliances, the metabolic heat of people, routines or patterns of use, among others, were assigned. Likewise, the free climate file called Santa Fé de Bogotá, available in the EnegyPlus Weather Data, was imported (U.S. Department of Energy’s (DOE) Building Technologies Office (BTO), 2021).

Table 2 shows the usage patterns of the four case studies, obtained in various surveys. Based on the values established by the ASHRAE standards, the metabolic rate of the occupants according to the activity carried out was established: eating (60 W/m2), cooking (115 W/m2), sleeping (40 W/m2), teleworking (70 W/m2), lying down (45 W/m2), and exercising (200 W/m2).

Table 2. Schedules and power of electrical equipment in the 4 models.
(Source: the authors)

Thermal zone	**Monday to Friday**				**Weekend**			
	P	**Sch**	**MR (W/m2)**	**PW (W)**	**P**	**Sch**	**MR (W/m2)**	**PW (W)**
CUAN case								
Living-Dining room	1	9:00-9:30	60		1	15:30-17:00	60	
	1	9:30-10:00	200					
	1	10:00-12:00	60					
	1	13:00-14:00	60					
Kitchen	1	8:30-9:00	115	1000				
	1	12:00-13:00	115	1000				
Bedroom 1	1	0:00-8:00	40		1	0:00-7:00	40	
	1	8:20-8:30	70		1	13:20-15:00	40	
	1	23:00-24:00	45	120	1	19:00-24:00	45	120
Bathroom 1	1	8:00-8:20	70		1	13:00-13:20	70	
Study	1	14:00-23:00	70	200	1	7:00-13:00	70	200
Clothes cleaning area					1	15:00-15:30	70	
Paulo VI case								
Living-Dining room	1	12:00-13:00	60		1	9:30- 11:00	60	
	1	14:00-15:00	60		3	12:00-15:00	60	
Kitchen	1	6:00-6:20	115	1000	1	6:00-6:20	115	1000
	1	11:00-12:00	115	1000	1	11:00-12:00	115	1000
	1	18:00-19:00	115	1000	1	18:00-19:00	115	1000
Bedroom 1	1	0:00-5:00	40		1	0:00-5:00	40	
	1	5:00-6:00	45		1	5:00-6:00	45	
	1	9:00-9:30	70		1	9:00-9:30	70	
	1	19:00-21:20	70		1	19:00-21:20	70	
	1	21:40-24:00	40		1	21:40-24:00	40	
Bathroom 1	1	8:30-9:00	70		1	8:30-9:00	70	
	1	21:20-21:40	70		1	21:20-21:40	70	120
Bedroom 2/Study	1	9:30-11:00	70	120	1	15:00-18:00	70	120
	1	15:00-18:00	70	120				
Sauzalito case								
Living-Dining room	1	14:00-14:30	60		1	7:30-10:00	60	
Kitchen	1	12:30-14:00	115	1000				
	1	19:30-20:00	115	1000				
Bedroom 1	1	0:00-6:30	40		1	0:00-7:00	40	
	1	14:30-17:30	45	120	1	19:30-00:00	40	
	1	22:00-0:00	40					
Bathroom 1	1	06:30-07:00	70		1	7:00-7:30	70	
Study	1	7:00-12:30	70	200				

Alcalá case								
Living-Dining room	1	7:30-8:00	60		1	8:30-9:00	60	
Kitchen	1	8:00-8:30	115	500	1	9:00-9:30	115	500
					1	19:30-20:00	115	500
Bedroom 1	1	0:00-7:00	40		1	0:00-8:30	40	
	1	7:00-7:30	45		1	8:30-9:00	45	
	1	19:30-24:00	40	120	1	21:30-22:00	45	120
					1	22:00-0:00	40	
Bathroom 1	1	8:30-9:00	70		1	9:30-10:00	70	

P: Number of people, Sch: schedules, MR: metabolic rate, PW: power. (Source: The Authors)

Table 3 shows the usage patterns corresponding to switching on lights, ventilation, and opening curtains.

Table 3. Schedules and power lighting and ventilation, and schedules of curtain openings used in the 4 model. (Source: the authors)

Thermal zone	**Monday to Friday**				**Weekend**			
	LP (W)	**SchL**	**SchV**	**Cop**	**LP (W)**	**SchL**	**SchV**	**Cop**
CUAN case								
Living-Dining room			0:00-24:00	09:00-22:00			0:00-24:00	09:00-22:00
Bedroom 1	150	23:00-24:00	0:00-24:00	08:00-20:00	150	19:00-24:00	0:00-24:00	07:00-23:00
Bathroom 1	25	8:00-8:20			25	13:00-13:20		
Study	150	17:00-23:00			150	7:00-13:00		
Bedroom 2			0:00-24:00				0:00-24:00	
Paulo VI case								
Living -Dining room	35	14:00-15:00	6:00-12:00	7:00-20:00	35	14:00-15:00	6:00-12:00	7:00-20:00
Kitchen	35	6:00-6:20	10:00-12:00		35	6:00-6:20	10:00-12:00	
	35	18:00-19:00			35	18:00-19:00		
Bedroom 1	35	5:00-6:00	10:00-12:00	7:00-20:00	35	5:00-6:00	10:00-12:00	7:00-20:00
	35	19:00-21:20			35	19:00-21:20		
Bathroom 1	35	8:30-9:00			35	8:30-9:00		
	35	21:20-21:40			35	21:20-21:40		
Bedroom 2/Study	35	15:00-18:00	12:00-14:00		35	15:00-18:00	12:00-14:00	
Bedroom 3	35	18:00-20:00			35	18:00-20:00		
Bedroom 4	35	18:00-20:00			35	18:00-20:00		
Sauzalito case								
Living-Dining room	15	17:30-20:00		7:00-18:30	15	17:30-22:00		7:00-18:30

Kitchen	15	17:30-22:00	9:00-12:00		15	17:30-22:00	9:00-12:00	
Bedroom 1	15	17:30-22:00		7:00-18:30	15	17:30-22:00		7:00-18:30
Alcalá case								
Bedroom 1	50	19:30-24:00		8:00-19:30	50	19:30-24:00		8:00-19:30
Bathroom 1	50	8:30-9:00			50	8:30-9:00		

LP: luminaire power, SchL: schedules luminaires, SchV: schedules ventilation, Cop: curtain opening.

Regarding the construction materials of each zone, Table 4 presents each case study with its respective surface configuration, specifying material and thickness.

Table 4. Construction components of the four cases

Components	Description
CUAN case	
Exterior Wall	Wall of hollow brick partition, thickness of 18 cm.
Dry zone wall	Wall of hollow brick partition thickness of 18 cm..
Wet area wall	Wall with tile, thickness of 18.5 cm.
Dry zone floor	Brown carpet on tuned slab, thickness of 16 cm.
Wet area floor	Tile of 10x10 cm on tuned slab, thickness of 15 cm.
Windows	Aluminum frame and double glass with air chamber.
Interior doors	Wooden door and frame, 5 cm thick.
Front door	Metal door of 5 cm
Paulo VI case	
Exterior Wall Dry zone wall	Hollow block painted green, thickness of 15 cm.
Wet area wall	Brick wall, stuccoed and painted, 13 cm thick.
Dry zone floor	Wall of brick with tile, thickness of 13.5 cm.
Wet area floor	Black vinyl flooring on tuned slab, thickness of 15 cm.
Windows	Tile of 10x10 cm on tuned slab, thickness of 15 cm.
Interior doors	Aluminum frame and simple glass.
Front door	Frame and door leaf of wood, thickness of 5 cm.
Exterior Wall Dry zone wall	Metal door of 5 cm
Sauzalito case	
Exterior Wall Dry zone wall	Exposed structural brick, thickness of 16.5 cm.
Wet area wall	Brick wall with cement plaster, stuccoed and painted, 18 cm thick.
Dry zone floor	Brick wall with tile, thickness of 18.5 cm
Wet area floor	Tile on tuned slab, thickness of 16 cm.
Windows	Tile of 10x10 cm on tuned slab, thickness of 16 cm.
Interior doors	Aluminum frame and simple glass.
Front door	Frame and door leaf of wood, thickness of 5 cm.
Exterior Wall Dry zone wall	Metal door of 5 cm.
Alcalá case	
Exterior Wall Dry zone wall	Exposed structural brick with an air chamber, thickness of 13.5 cm.
Wet area wall	Brick wall with an air chamber, with cement plaster, stuccoed and painted, 15 cm thick.
Dry zone floor	Brick wall with an air chamber and tile, thickness of 15.5 cm.
Wet area floor	Laminated wood floors on lightened slab.
Windows	Tile of 10x10 cm on tuned slab, thickness of 16 cm.
Interior doors	Aluminum frame and simple glass.
Front door	Frame and door leaf of wood, thickness of 5 cm.
Exterior Wall Dry zone wall	Wood door of 5 cm.

Source: Adapted from (Proyecto i-COOP B20431-CSI, 2020)

Additionally, the thermal properties of the previously mentioned materials were determined (Table 5), including density (ρ), Conductivity (λ) and specific heat (C_p). These variables are essential for calculating energy transfer between the interior of homes and environmental conditions.

Table 5. Thermal properties of materials.

Material	**Thermal properties**		
	$\boldsymbol{\rho}$ **(Kg(m3)**	$\boldsymbol{\lambda}$ **(W/mK)**	$\boldsymbol{C_p}$ **(J/KgK)**
Stucco	1857	0.72	840
Cement Plaster	1860	0.72	840
Brick	2082	1.30	920
Tile	2300	1.5	850
Rug	910	0.12	1925
Concrete	2300	1.4	880
Ceramic adhesive cement	1920	1.4	800
Glass	2500	0.7	840
Wood	513	0.115	1380
Aluminum	2739	222	896
Tile	1470	0.1	840

Where: ρ: density, λ: thermal conductivity, and C_p: specific heat.

Source: Adapted from (NBR15220-2, 2005)

2.1. Data Analysis

CO2 concentration data recorded by the dataloggers for the four study cases were analyzed using scatter graphs to evaluate IAQ in the homes. Reference studies suggest that maximum recommended carbon dioxide (CO2) levels indoors range between 400 ppm and 800 ppm (Laurent & Frans, 2022), (Baselga et al., 2023).

Furthermore, once the simulation models were completed and adjusted, they were validated. Normalized mean square error (NMSE) was used as a measure of comparison between real and simulated values, with values below 0.25 indicating an optimal level of agreement between simulation and field data, as per Equation 1 (ASTM, 2002).

$$NMSE = \frac{1}{n}\sum_{i=1}^{n}\frac{\left(Y_{pi}-Y_{mi}\right)^{2}}{Y_{pi}*Y_{mi}} \qquad \text{Eq.1 Normalized Mean Square Error (NMSE).}$$

Once the models were validated, the results were analyzed using box plots to compare the monitored data with the simulated values. This analysis considered the adaptive comfort intervals defined by ASHRAE 55-2010 standard, which set the temperature range between 20 and 24°C (Figure 6) and the relative humidity range between 30 and 60%. This regulation is applicable in spaces with natural ventilation and without centralized HVAC systems (air conditioning systems), where the thermal response is influenced by the external climate. This characteristic scenario applies to all four case studies.

2.2. Simulation Improvement Proposals

The Alcalá and Sauzalito cases were selected as the object of study in this section due to their shared issue of experiencing temperatures below 18.8 °C. Likewise, Alcalá is a stratum 5 home with the same cold stress problems as Sauzalito.

It is important to highlight that the primary objective of passive strategies is to retain internal heat gains within the home by increasing the thermal inertia of materials. The strategies recommended by the ASHRAE-55 adaptive comfort model for Bogotá (Figure 6) can improve comfort conditions by 55%. However, the implementation of these strategies is nearly nonexistent due to a lack of interest and technical ignorance among builders.

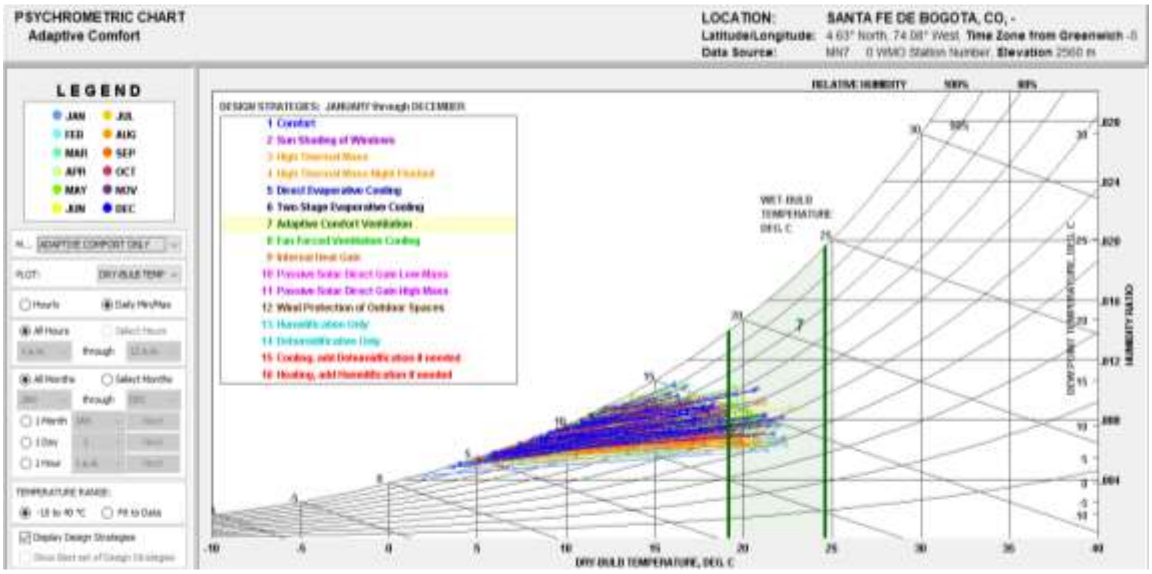

Figure 6. Adaptive comfort ASHRAE 55-2010 in Bogotá.
Source: Climate Consultant.

Considering the above, the ideal approach is to increase the internal gains of buildings through strategies like employing dark colors in the envelope, enhancing thermal inertia, and optimizing orientation, among others. However, d since these are constructed within horizontally-owned residential units, making significant changes to the facades is not possible. Therefore, strategies aimed at increasing thermal resistance are recommended.

Consequently, using double glass in windows (that has greater thermal resistance due to the air space inside) and insulating materials such as thermal stucco is selected as passive alternatives. Moreover, for the Alcalá case, an additional strategy involving insulation in the floor was included.

EnergyPlus simulations were conducted to assess the effectiveness of each choice in the case studies, comparing results to the original simulations. Box plots and mean analysis were used to determine the most effective technique.

The attributes of each strategy are outlined as follows:

- Thermal stucco with λ=0.18 W/mK, 2 cm thick: for Alcalá and Sauzalito cases.
- Duoble glases, 0.4 cm thick, with an air chamber of 2 cm: for Alcalá and Sauzalito cases.
- Thermal insulation in the floor with λ=0.18 W/mK: for the Alcalá case.

Furthermore, an analysis of variance (ANOVA) was conducted both between and within each sample set. This was accomplished using a F test with 99% confidence to determine whether the samples belong to the same population or to different populations. The higher the value of F, the higher the probability that the experiment will be considered significant, meaning that at least two pairs of socks differ (Fallas, 2012).

The Tukey test was used to determine the statistical difference between the mentioned passive strategies after confirming that at least one pair of means was statistically different.

3.0 RESULT

3.1. CO2 Analysis

Considering that carbon dioxide is one of the most common pollutants in IAQ and has significant implications for human health within buildings, it is important to control its presence to maintain health and comfort standards in homes.

Figure 7 shows three of the four cases primarily within the established range of CO2 concentration between 400 ppm and 800 ppm. However, the CUAN case stands out with approximately 50% of its values above 800 ppm. This is attributed to the small size of the space, inadequate ventilation, and prolonged occupancy by the user throughout the majority of the day.

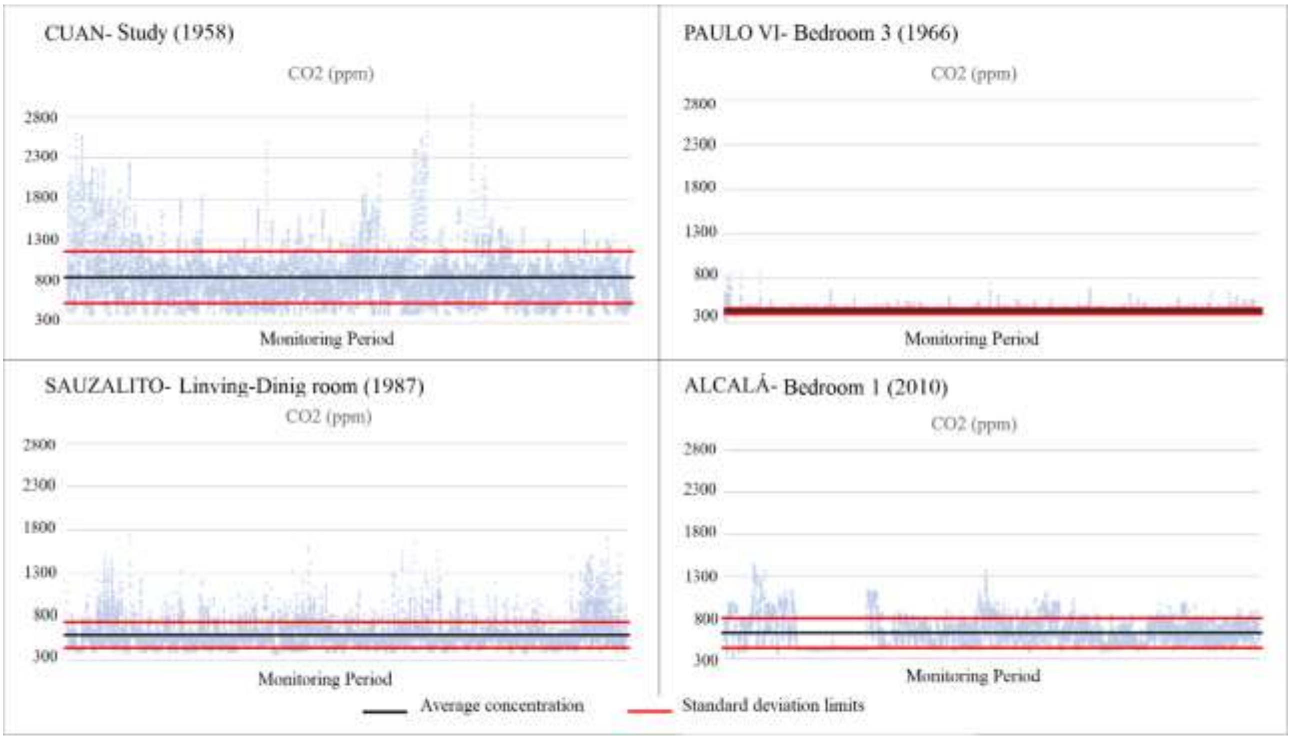

Figure 7. Diagrams of the dispersion of CO2 in the study cases.
Source: Own elaboration.

The graphics provide insights into the degree of space occupancy. It is evident that the Paulo VI case consistently maintains low CO2 levels, suggesting that there is greater air exchange facilitated by infiltration through windows and doors. Additionally, the presence large green spaces surrounding the structure contributes to this effect. Moreover, the property remains unoccupied most of the time, supporting the usage pattern data provided in Table 2.

In a complementary manner, Figure 8 displays the CO2 levels during an average day in the Alcalá Case. It is observed that CO2 levels remain above 700 ppm between 0:00 and 8:00 am, indicating that the space is occupied. It is clear that the person leaves the room after that hour, as the CO2 levels drop significantly until they reach the usual average atmospheric concentration of 414 ppm, indicative of significant air exchange and rapid equilibration of indoor air with outside air (Rae et al., 2021).

Ultimately, CO2 concentrations are seen to rise once more at 20:00, which is consistent with the space being used. Every house underwent this examination to confirm the occupation patterns found in the surveys.

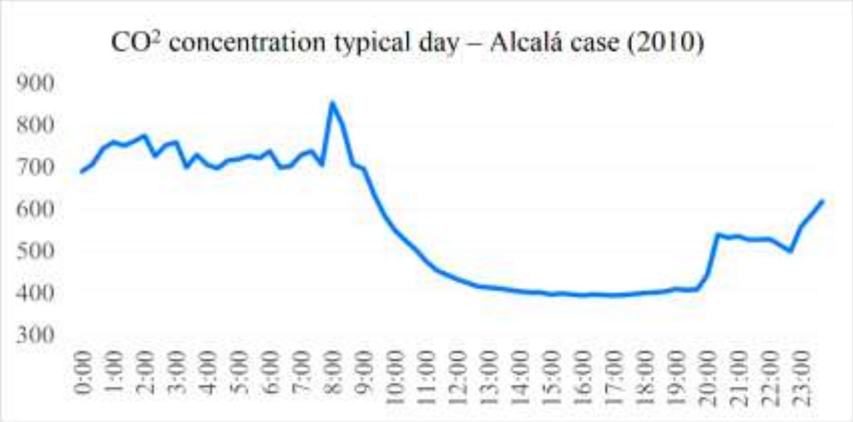

Figure 8. CO2 concentration typical day – Alcalá case.
Source: Own Elaboration

3.2. Simulation of current conditions

Following the simulation and monitoring of the four case studies, the Temperature box plots (Figure 9) and Relative Humidity (Figure 10) for the entire period of study are presented. Additionally, the NMSE values are displayed in the upper part of each graph corresponding to each case study. For temperature, NMSE ranges between 0.004 and 0.016 °C, and for relative humidity, it ranges between 0.021 and 0.036%. Taking into account that the acceptance value for model validation is below 0.25, despite some differences observed in certain months' differences, both variables show a high agreement between the simulation and the recorded data. Thus, the simulation models are considered suitable to represent the behavior of the case studies.

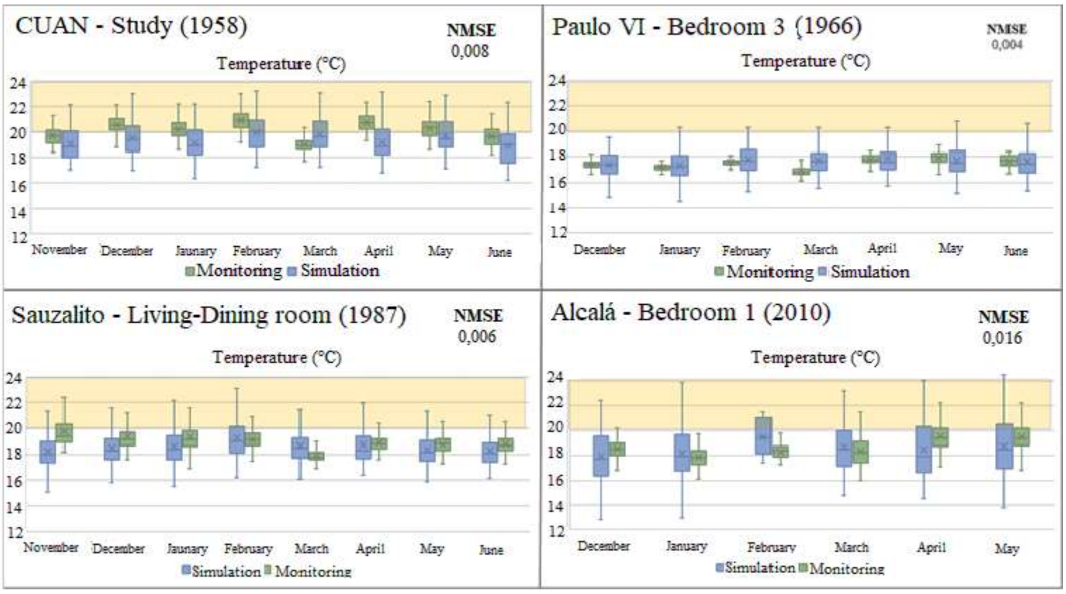

Figure 9. Box diagrams of simulation temperature data vs monitoring data for the study cases Source: Own Elaboration.

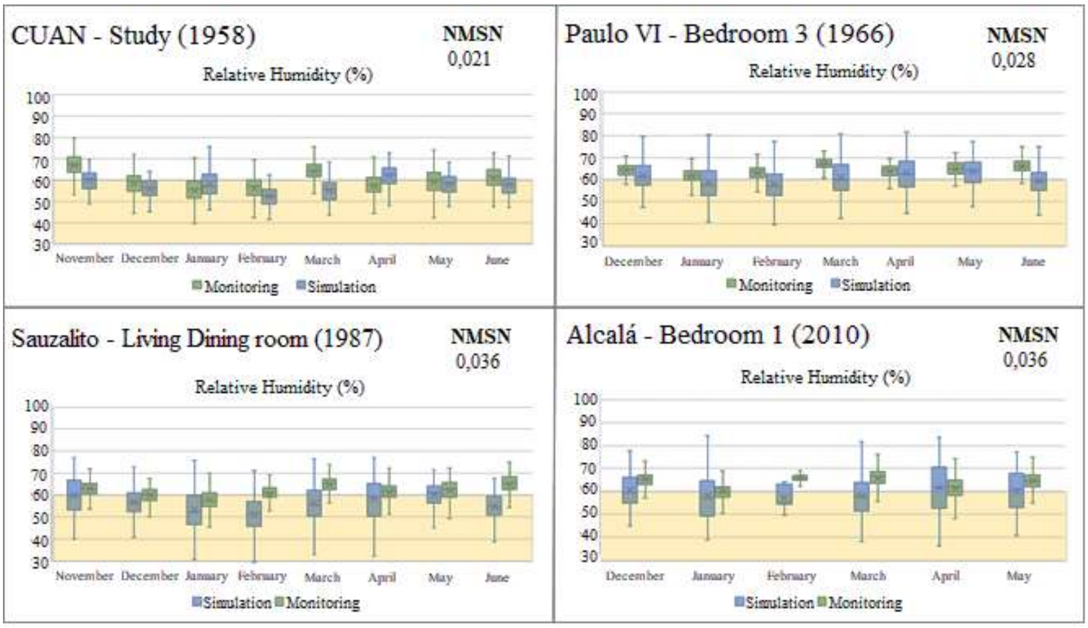

Figure 10. Box diagrams of simulation Relative humidity data vs monitoring data for the study cases. (Source: Own Elaboration.)

It is possible to observe that the CUAN case presents the most temperature data within the comfort range. This could be attributed to the windows configuration (double glass) and well-insulated walls with good thermal capacity. The double glass reduces abrupt temperature changes by providing greater thermal resistance in the facade, which creates a more comfortable environment for the user (García Navarro et al., 2017).

Conversely, greater wall thickness generates results in increased inertia and thermal resistance, which reduces energy losses from the outside.

In contrast, the Paulo VI, Sauzalito and Alcalá cases fall outside the comfort range most of the time, with temperatures below 20°C. Firstly, the Paul VI case, is a duplex apartment where the first floor is in direct contact with the ground and has air leaks that cool the space, as confirmed by CO2 concentration measurements. In addition, influenced by large green areas, the heat island effect is less pronounced in this area.

Similarly, the Sauzalito Case, situated on the first floor, is susceptible to heat loss from the ground. However, the Alcalá case, located on the top of an open parking lot, experiences constant wind currents that lead to a considerable decrease in temperature through the lighted plate that does not have any insulation. Furthermore, the three dwellings are not optimally oriented because they receive minimal direct sunlight throughout the day.

It is noteworthy to mention that the prolonged duration of La Niña's exceptional rain in March resulted in low temperatures and maximum relative humidity, causing variations in simulations due to the climate archive using average year data.

Regarding humidity, it can be observed that none of the residences remained within the established comfort range throughout the monitoring period, with the simulation exhibiting more significant variations compared to temperature.

The results indicate a direct correlation between the hygrothermal behavior and that of the IAQ of the cases studied, particularly concerning ventilation. It is clear that the concept of hygienic ventilation does not apply in any of the cases. This leads to users to close windows completely due to prevailing cold weather conditions, causing indoor relative humidity to increase and gases such as CO2 to accumulate. This was more evident in the CUAN case, where temperature elevation was also noted. While other cases were not as critical in terms of IAQ due to infiltrations, they still caused heat losses and a discomfort by creating cold air currents at the occupant level. To address these issues without compromising IAQ, controlling infiltrations and prioritizing hygienic ventilation are recommended (Roberto Rivero, 1988).

3.3. Simulation of Improvements

The adjustments mentioned earlier were implemented to enhance thermal comfort levels in the Sauzalito and Alcalá research instances.

3.3.1. Results of Improvements in Sauzalito Case

The results of each proposed technique are displayed in Figure 11. When two improvements are combined in the Sauzalito case, the temperature noticeably rises. This is because the windows now have double glass, and the thermal stucco coating has caused an average increase in temperature of 0.99°C throughout the course of the research period. Analyzing each strategy individually, it is observed that stucco contributes 25% to the total temperature increase, while double glass accounts for the remaining 75%, proving to be the most influential alternative.

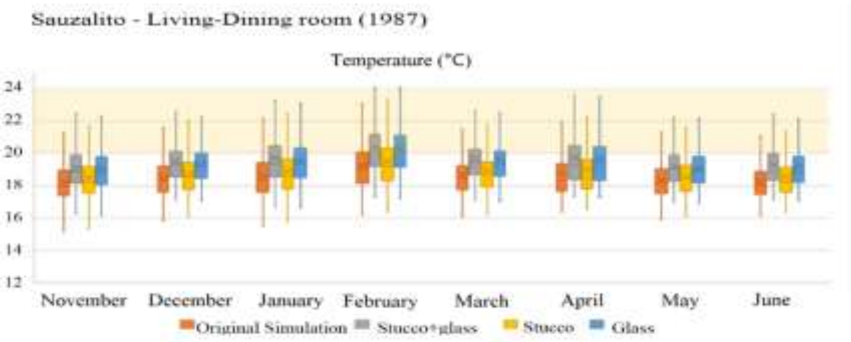

Figure 11. Simulation box plots of the original Sauzalito case vs simulation with improvement alternatives. (Source: Own Elaboration)

ANOVA analysis (Table 6) to identify the most influential passive strategy in improving temperature in the Sauzalito case shows that not all population averages are equal, rejecting the zero hypothesis and using the Tukey Test (HSD).

Table 6. Variance analysis for strategies in the Sauzalito Case

Variance analysis for strategies in the Sauzalito Case					
Source of Variation	**DF**	**SS**	**MS**	**F**	**P**
Temperature					
Between groups	4	474036,216	118509,054	27865,977	<0.001
Residual	84555	359597,409	4,253		
Total	84559	833633,625			
Relative Humidity					
Between groups	4	6812096,66	1703024,17	24156,314	<0.001
Residual	84555	5961141,72	70,5		
Total	84559	12773238,4			

Source: Own Elaboration

It is important to note that, for the Tukey test, means that do not share the same letter are significantly different. Therefore, in the Sauzalito Case (**Error! Reference source not found.**), it is evident that thermal stucco does not significantly contribute to the current housing conditions regarding temperature increase. Moreover, it is also not evident that stucco contributes when combined with double glass, since glass, acting independently, falls into the same category (c).

Table 7. Average analysis for the Sauzalito Case.

Average analysis for the Sauzalito Case				
Strategy	**Temperature (°C)**		**Relative Humidity (%)**	
	Average	**St. D.**	**Average**	**St. D.**
External environment	13.25 a	3,545	82.07 a	13,916
Original simulation	18.57 b	1,378	56.50 b	8,519
Stucco + Glass	19.56 c	1,567	60.48 c	5,413
Stucco	18.82 b	1,511	63.34 d	5,581
Glass	19.427 c	1,435	60.93 c	5,081

Note: For all strategies N: 16913. Means followed by the same letters do not differ by Tukey test.
(Source: Own Elaboration.)

3.3.2. Results of improvements in Alcalá case:

Figure displays the results of each proposed strategy for the Alcalá case. This case benefits from a combination of passive improvements, including thermal stucco, the use of double glass, and additionally the floor insulation, resulting in an average temperature improvement of 1.15 °C compared to the simulation under current conditions. When comparing the strategies separately for this house, it is observed that the thermal stucco contributes the least to the increase in temperature, followed by floor insulation. However, evaluating potential strategy pairs reveals that combinations like thermal stucco + double glass (increase of 0.77°C) and floor insulation + double glazing (increment of 0.99°C) present a higher efficiency due to the presence of the double glass, which, as observed in the Sauzalito case, provides the best insulation.

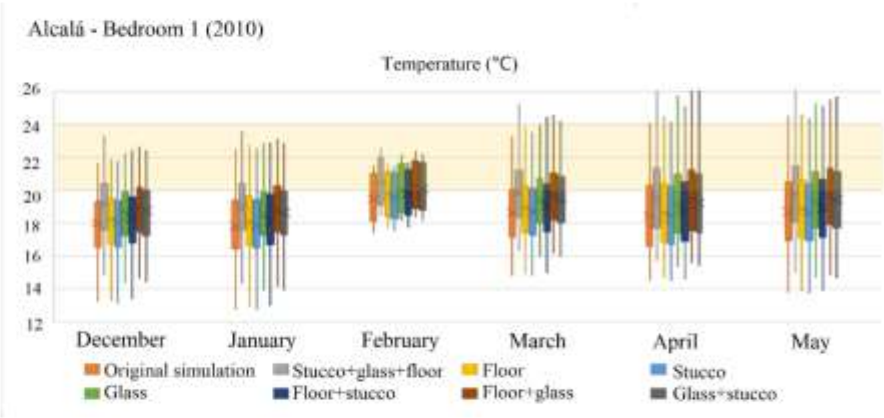

Figure 12. Simulation box plots of the original Alcalá case vs simulation with improvement alternatives. Source: Own Elaboration.

ANOVA analysis for the Alcalá case confirmed the contribution of passive methods to temperature improvement, rejecting the hypothesis due to differences among population averages and using the Tukey test (HSD) (Table).

Table 8. Analysis of variances for housing strategies in Alcalá case.

Analysis of variances for housing strategies in the Alcalá case					
Source of Variation	**DF**	**SS**	**MS**	**F**	**P**
Temperature					
Between groups	8	351000,87	43875,11	8597,14	<0.001
Residual	109611	559394,68	5,10		
Total	109619	910395,55			
Relative Humidity					
Between groups	8	6350062,34	793757,79	9395,248	<0.001
Residual	109611	9260488,44	84,49		
Total	109619	15610550,78			

Source: Own Elaboration.

In the Alcalá case (Table), it is observed that thermal stucco, when with the other strategies (floor and glass), falls into the same statistical category as when the floor and glass implemented independently. This suggests that it has no greater impact on improving the hygrothermal comfort of the house. It's also mentioned that the best way to improve the internal temperature and relative humidity of a house is to install double glazing, due to its higher thermal resistance (0.35 m2°k/w), compared to single glass (0.16 m2°k/w).

Table 9. Average analysis for the Alcalá case.

Average analysis for the Alcalá case				
Strategy	**Temperature (°C)**		**Relative Humidity (%)**	
	Average	**St. D.**	**Average**	**St. D.**
External environment	13.27 a	3,643	81.98 a	14,02
Original simulation	18.30 b	2,053	59.50 b	9,70
Stucco + Glass + Floor	19.45 c	2,043	56.36 c	7,46
Floor	18.52 d	2,032	59.77 b	7,94
Stucco	18.33 b	2,004	60.46 d	7,92
Glass	19.02 e	1,971	57.87 e	7,41
Floor + Stucco	18.59 d	2,05	59.52 b	7,97
Floor + Glass	19.29 f	2,014	55,97 f	9,23
Glass + Stucco	19.07 e	1,994	56.69 c	9,19

Note: For all strategies N: 12181. Means followed by the same letters do not differ by Tukey test.
Source: Own Elaboration.

Given that the analyzed houses have a larger window area compared to walls directly exposed to the outside environment, it is reasonable to assume that the thermal stucco has little effect, and that, double glazing is the simplest and most economical solution, without the need for changes design to the facades.

4.0 CONCLUSION

The construction of housing in Colombia must adhere to quality requirements outlined in regulations concerning the thermal performance of buildings. This ensures that occupants will have minimally comfortable and habitable surroundings. However, over the study period, only one of the four cases investigated consistently experienced ideal hygrothermal conditions.

The study reveals a strong correlation between indoor air quality (IAQ) and hygrothermal behavior. With windows closed due to cold weather, relative humidity increases, often exceeding ASHRAE-55 standards, and gases like CO2 accumulate, mainly in the CUAN case. While infiltrations in other cases do not significantly impact IAQ, they result in heat losses and discomfort due to cold air currents. For this reason, it is recommended to minimize unwanted air infiltrations without compromising air quality, that is, thereby improving both IAQ as hygrothermal comfort.

Passive strategies have improved the temperature conditions inside the studied houses by enhancing inertia and thermal insulation. In particular, the use of double glass in windows had an outstanding effect compared to the thermal stucco and floor insulation, with their combined effects contributing almost a third of the impact of double glass windows. In addition, double glazing is the simplest and most economical solution, as it does not require any modifications to the facades design.

When analyzing the indoor comfort of newly constructed dwellings and considering potential modifications or enhancements, bioclimatic simulation proves to be a dependable and cost-effective method. However, it's crucial to have high-quality input data, such as usage trends, material thermal qualities, construction features, and a reliable climate archive that covers the range of weather conditions the house might encounter.

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