Informes de la Construcción
Vol. 71, 555, e305
julio-septiembre 2019
ISSN-L: 0020-0883
https://doi.org/10.3989/ic.61006

A post-occupancy strategy to improve thermal comfort in social housing in a tropical highland climate: A case study in Bogotá, Colombia

Estrategia pos-ocupación para mejorar el confort térmico en vivienda social en climas tropicales de montaña: un caso de estudio en Bogotá, Colombia

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ABSTRACT

This study exposes substantial thermal comfort deficiencies present in social housing projects in Bogotá, which are believed to result from a generalised lack of policy, research and knowledge. This problem might be widespread in most residential buildings; however, there is very little information available. Thermal comfort deficiencies are linked to low occupant's satisfaction, poor health and wellbeing, as well as, increases in the building's energy consumption and CO2-e. This article contributes towards the documentation, assessment and treatment of these deficiencies using a multi-phase and solution-orientated approach, which includes a case study, dynamic thermal simulations and fieldwork. This approach can be replicated and adapted for other contexts within tropical highland climates. The fieldwork focused on improving the existing facade thermal mass, and the performance of external windows through two retrofit interventions. These showed to be cost-effective, feasible and practical with a view to being implemented directly by the occupants.

Keywords: Thermal comfort, social housing, occupant's satisfaction, housing policy.

RESUMEN

Este estudio expone deficiencias en el confort térmico en vivienda social en Bogotá. Se presume que estas son el resultado de la falta de políticas, investigación y conocimiento sobre el tema. Este problema puede ser generalizado en edificios residenciales y repercutir en problemas de salud y baja satisfacción de los ocupantes, así como aumentos en el consumo de energía y la emisión de CO2. Sin embargo, hay muy poca información disponible. Este artículo contribuye al estudio, evaluación y búsqueda de soluciones a través de un caso de estudio, simulaciones térmicas dinámicas y trabajo de campo. Este enfoque puede ser replicado y adaptado para otros contextos con climas tropicales de montaña. El trabajo de campo se centró en mejorar la masa térmica de la fachada y el rendimiento de las ventanas a través de dos intervenciones. Estas demostraron ser rentables y prácticas con miras a ser implementadas directamente por los ocupantes.

Palabras clave: *Confort térmico, vivienda social, satisfacción del ocupante, política de vivienda.*

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Cómo citar este artículo/*Citation*: Rodríguez, C.M.; Medina, J.M.; Pinzón, A.; García, A. (2019). A post-occupancy strategy to improve thermal comfort in social housing in a tropical highland climate: A case study in Bogotá, Colombia. *Informes de la Construcción*, 71(555): e305. https://doi.org/10.3989/ic.61006.

Recibido/*Received*: 10/11/2017
Aceptado/*Accepted*: 29/11/2018
Publicado on-line/*Published on-line*: 17/09/2019

1. INTRODUCTION

Thermal-comfort is an essential requirement of habitable indoor environments and a crucial factor for the post-occupancy evaluation of buildings. Climate change is currently driving new approaches within contemporary thermal comfort research. A significant paradigm shift is claimed to be moving away from the physically-based determinism of the Fanger's comfort model (1), toward an adaptive model that considers the active involvement of occupants (2). Unfortunately, thermal comfort research in many parts of the world is still in its infancy, and there is much work to be done before this paradigm shift is widespread (3). This article discusses a complex thermal comfort problem in the context of social housing in Bogotá, the capital of Colombia. It is argued here that many of Bogotá's residential buildings feature poor thermal performance due to a series of interrelated factors; however, there are very few efforts being undertaken to identify, assess and treat this problem. The general aim of this study is to contribute precisely towards the documentation, assessment and treatment of thermal comfort problems in social housing. This is accomplished via a three-phase methodology that analyses the problem within a case study and assesses potential solutions by employing dynamic thermal simulations. Chosen solutions are then tested and studied on site.

1.1. The problem and background

The problem of thermal comfort in Bogotá's social housing has been linked to uncontrolled urban growth and housing deficits. Cost restrictions set by the existing policy and the lack of precision, clarity and enforcement regarding sustainable construction standards have had a negative impact on the thermal performance of social housing buildings. This problem is not widely documented or discussed partly because there is a lack of research to expose it, measure it and explore potential solutions. There is also a general erroneous assumption that Bogotá enjoys pleasant warm weather throughout the year, as it is located within the tropics. The consequences of thermally inadequate housing include low occupant's comfort and satisfaction, negative impacts on health and wellbeing, increments in energy consumption and CO_2-e and costly post-occupancy adaptations. There are also missed-opportunities for improvement and investment due to the lack of research regarding this problem.

Bogotá, like many urban settlements in Latin America, has grown dramatically over the last five decades due to demographic changes and forced displacement. This city currently hosts approximately 8 million people (19% of the country's population), and its expansion is expected to continue in the near future, possibility reaching 12 million by 2050. In this context, reducing housing deficits has been one of the central governmental policies, focusing on the construction of social housing. In Colombia, social housing is divided into priority housing for victims of natural disasters (known as Vivienda de Interés Prioritario -VIP-) and other social housing for low-income inhabitants (known as Vivienda de Interés Social -VIS-). In Bogotá, records show that 42,767 new government housing units were built between 2012 and 2015, comprising 16,437 (VIP) and 26,330 (VIS) (4). VIP and VIS projects together represent more than half of the total housing stock in Colombia. Unfortunately, different studies have warned that the quality of the social housing built in recent years has been poor in aspects such as its relationship with the city, spatial distribution, flexibility, lighting, ventilation, thermal comfort, construction techniques and material quality (5)(6)(7). It has been argued that social housing projects have been constructed according to the criterion of quantity above quality because their focus has been on a price limit linked with the national minimum-monthly-wage (MMW). This limit is currently set to 70 MMW for VIP units and 135 MMW for VIS units, which in US dollars equates to approximately USD 15,600 and USD 30,000 respectively (8). It has been widely alleged that this policy is not supported on a structured system and lacks enforcement and quality control (9).

In 2015 the Ministry of Housing, City and Territory announced Resolution 0549 (10), which contained the minimum measures that new buildings had to meet from 2016 onwards regarding sustainable construction. These guidelines strongly highlight the need to ensure indoor environmental comfort through passive strategies such as orientation, solar gain and solar protection, thermal mass, insulation, ventilation and material selection. However, precise or mandatory requirements are not included; neither are recommendations for the adaptation of existing buildings, which raises concerns regarding the effectiveness of this legislation or their real impact on existing quality deficits. The lack of precision in Resolution 0549 is partly because there is very little information regarding aspects such as thermal comfort in the context of Colombia's different climates.

Field studies of thermal comfort (FSTC) or post-occupancy evaluation (POE) of buildings are very scarce in the country, even though they are generally regarded as a crucial tool for the improvement of buildings and the evaluation of what makes energy-efficient and sustainable buildings (11). This lack of knowledge could result in missing opportunities for improvement. For example, Bogotá is currently one of six cities in the world taking part in a 'Deep Dive' scheme for the Building Efficiency Initiative, launched in 2014 by the World Recourses Institute (WRI) and Johnson Controls (JCI). In this initiative, technical advisors are assigned to work with city officials and the private sector to support a multi-stakeholder planning process and expand the city's capacity to focus on building efficiency solutions. However, if the problem of thermal comfort is not well understood, there is very little that can be done to improve building efficiency in this area.

Bogotá is located at 04-70N latitude, 074-23W longitude and at a regular altitude of 2,600m above sea level, which contributes to creating cold climatic conditions, with little seasonal variation throughout the year in terms of average temperature (±14°C) and relative humidity (±73%). Its climate is regarded as a highland climate with uniform rainfall (Cfb) according to Köppen-Geiger's classification. This is a type of oceanic climate also found in the highlands of New South Wales and Victoria in Australia, South Carolina in the USA and other South American highlands in Ecuador, Peru, Venezuela and Brazil. Bogotá, however, has the heights altitude and is the largest urban settlement in the world with these climatic conditions, with an area of more than 300Km2.

A study on the applicability of the principles set by the Passivhaus Standard in the development of social housing in Colombia suggests that in Bogotá thermal comfort can be achieved with a relative-minor effort and initial investment (12). Another study analysed - through dynamic thermal simulations - the relation between urban density and thermal behaviour in selected social housing recently built in Bogotá and found that thermal performance could greatly improve with appropriate building orientation and densification (13). These studies are relevant for new constructions; however, approximately 89% of Bogotá's urban land is already built on, leaving only 11% for future developments (14). Therefore, densification might be the only way forward, with retrofits being the most cost-effective way to improve the building's energy performance and occupant's comfort.

In cold climates, successful retrofit approaches include improving insulation in facades and windows, increasing airtightness and promoting solar gains (15). Unfortunately, adapting an existing building to satisfy new requirements or standards often involves additional costs, time and resources, which are usually assumed by occupants or owners (16). Multi-dwelling units are particularly challenging to treat, due to the difficulty of raising and managing collective funds from different owners. On the other hand, the inability to adapt a building can bring high running or maintenance costs and ultimately can make the building fall out of use or become obsolete.

2. METHODOLOGY

A multiphase methodology, based on an approach by Budaiwi (17), was used for this research to identify and treat thermal-comfort problems in social housing in Bogotá. Budaiwi's approach was chosen due to its occupant satisfaction and solution-orientated focus and its clear structure. It consists of three phases: 1. Problem verification and mapping, 2. Preliminary assessment and 3. Detailed assessment. For this research, different adaptations to this approach were made to suit the existing conditions and available resources (Figure 1).

2.1. Problem verification and mapping – case study

This phase was conducted through a case study, which focused on a housing unit that is highly representative of the typology, distribution and materiality of the social housing currently built in Bogotá and surrounding areas. Figures indicate that approximately 42% of the total VIS projects built since 2012 in this region (approximately 20,000-25,000 units) are of a similar design and construction to the selected case study (4). Figure 2 shows the distribution and zoning of the chosen unit. These units are typically arranged to form building complexes of 6-15 storey towers.

In the case study, building occupant's perceptions were collected on-site via structured surveys and analysed in conjunction with simultaneous temperature and relative humidity (RH) measurements from 44 chosen apartments (a 14.6% sample). These apartments were chosen because they were all naturally ventilated, shared the same layout and percentage of exposed facades, had similar furniture and number and type of occupants (family-configuration and lifestyle). They were classified by orientation (northeast-facing, southwest-facing, southeast-facing and northwest-facing) and position within the building (ground floor, intermediate floors and top floor). Temperatures and RH% were logged at one-hour intervals during 24-hour periods using HOBO U12 data loggers placed at 70cm above the floor in the centre of each room. For this phase, only thermal zone TZ1 (comprising the living/dining room) was analysed, since it is typically the most used space in this type of apartment. A six-month period of study (between November 2015 and April 2016) was considered adequate for a relative comparison between indoor and outdoor conditions at any given time during the year, due to little seasonal variations.

Both the static and the adaptive model, suggested by the AN-SI/ASHRAE Standard 55 (18), were used to study levels of thermal comfort and satisfaction (Figure 3). The input

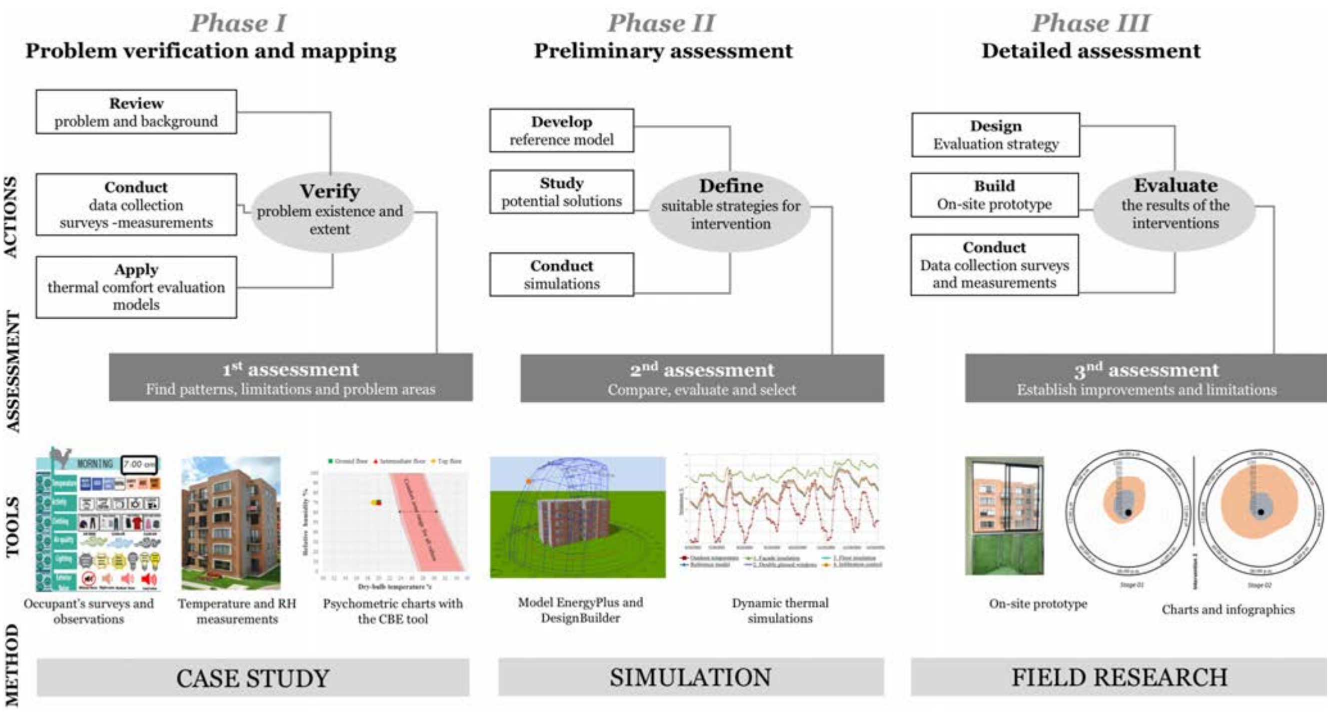

Figure 1. Methodology.

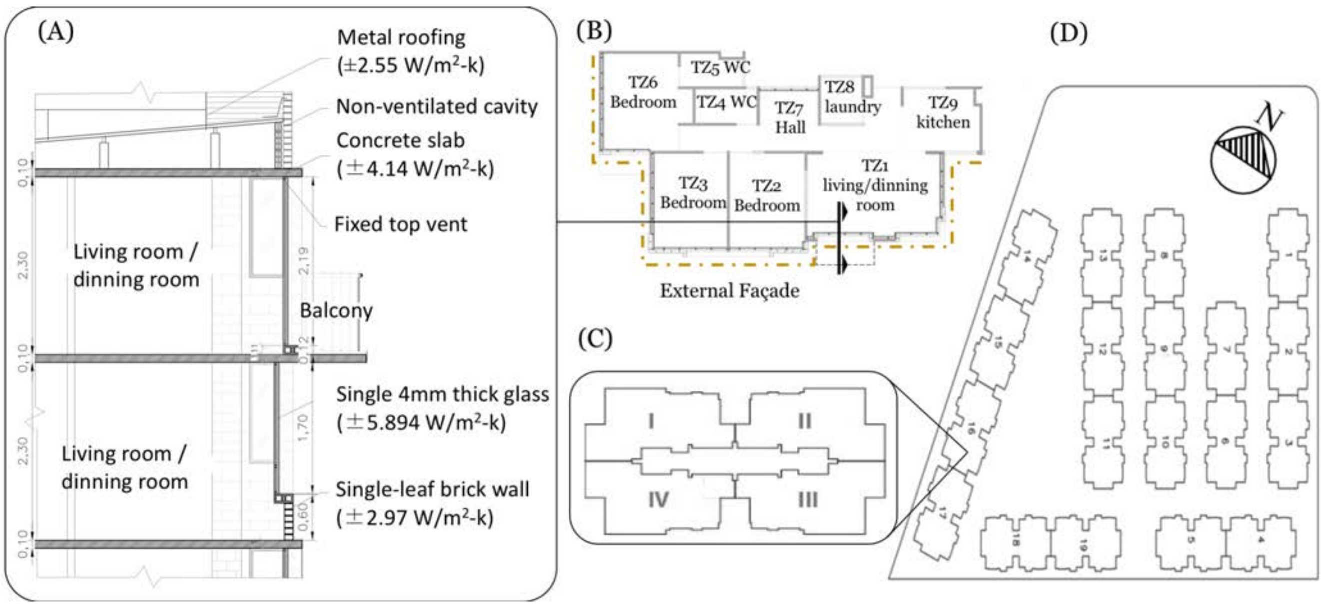

Figure 2. Psychometric charts using the static method (PMV) and adaptive method (using the CBE tool), according to apartment orientation and level.

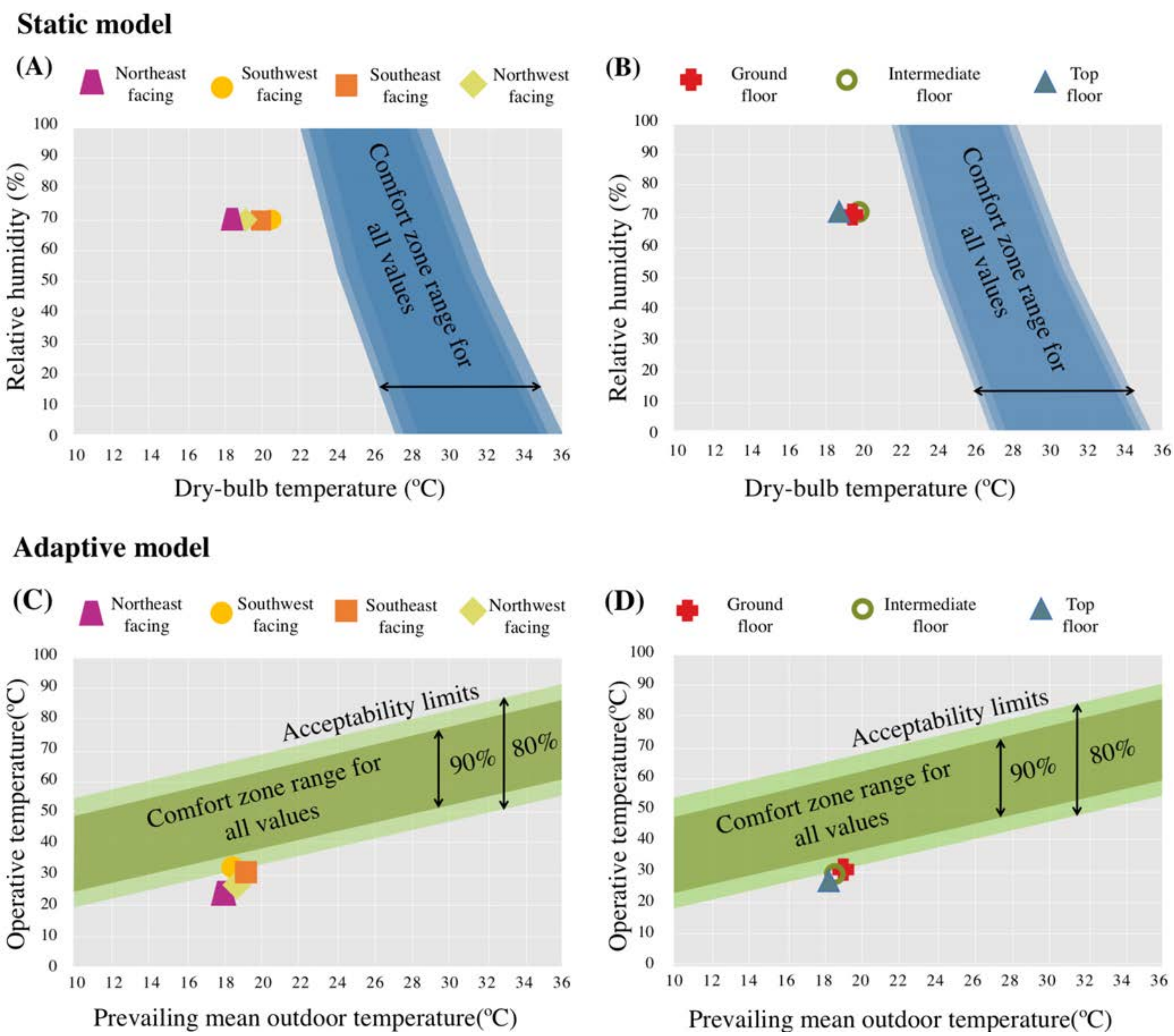

Figure 3. Case study. (A) Building section. (B) Apartment layout with thermal zones. (C) Apartment distribution on each floor. (D) Building distribution on the site.

variables were: air temperature (from the data loggers); mean radiant temperature (MRT); prevailing mean outdoor temperature (taken from METAR-TAF at El Dorado airport in Bogotá, at 04-43N latitude, 074-09W longitude and 2547m altitude); airspeed of 0.3m/s (as advised by the ANSI/ASHRAE Standard 55 when operative temperatures are lower than 25°C); average values for 0.74 clo for clothing insulation and 1.1 Met for activity levels (taken from the surveys). MRT was assumed to be equal to air temperature as studies such as Kántor and Unger (19). The most problematic variable in the course of human-biometeorological comfort assessment of the mean radiant temperature. Studies have concluded that the differences are, in most cases, negligible (20).

The charts were produced using the Center of the Built Environment - CBE tool (21). Temperatures as low as 17-18 ºC combined with RH levels of 70% on average in all apartments contributed to the poor conditions of thermal comfort evidenced in the charts. It was noticed that indoor temperature fluctuations (of up to 4ºC) between maximum and minimum values throughout the day were directly related to outdoor fluctuations (of up to 11ºC), suggesting a poor building envelope performance. Thermal comfort conditions were the worst for top and lower floors, due to considerable thermal losses through the roof and the ground. Northeast-facing apartments were the most affected during the period studied and it is presumed that southwest-facing apartments have similar conditions between May and August due to sun path changes. The Predicted Percentage of Dissatisfied (PPD) calculated with the static model was as high as 60% in northeast-facing apartments, coinciding with the occupant's feedback which showed up to 80% of dissatisfaction the same apartments. The surveys showed that most occupants believed their thermal discomfort originated from elements comprising the apartment's envelope, such as draughts from windows and cold surrounding surfaces. 32.6% percentage of occupants considered installing heating systems, 23.9% modifying window/doors, and 10.9% contemplated changing surface materials.

2.2. Preliminary assessment - reference model and simulations

During this phase, dynamic thermal simulations were used to examine the research problem and develop potential solutions further. The first step in this process was to create a reference model, simulating the conditions present in the case study. EnergyPlus™ software, coupled with the DesignBuilder graphical interface, were used to recreate a typical building tower. The model was calibrated to ensure a minimum margin of error between the simulated conditions and the data recorded on site. Table 1 illustrates the thermal characteristics of the envelope components in the case study. The insulating property values were calculated using the DesignBuilder database due to the lack of information available from materials suppliers in Colombia. The table compares the estimated insulated properties with the government's recommendations (10).

Table 2 shows the characteristics of the thermal zones analysed for the reference model. The values for occupancy density and schedules and the values for artificial lighting usage were taken from observations recorded in the surveys. The metabolic rate values were based on data from the Chartered Institution of Building Services Engineers (22). Values equipment heat gains and usage were based on the SAP - the Standard Assessment Procedure for the Energy Rating of Dwellings - (23). Meteorological data was taken from the database: Bogotá 802220 International Weather for Energy Calculations (IWEC), ASHARE.

Potential passive and easy to implement strategies to improve levels of thermal comfort in the units were studied via dynamic thermal simulations, taking the reference model and the existing data of the conditions on-site as a base (Figure 4). The strategies considered four different scenarios: 1. Insulating the facade with 6cm thick fibreglass insulation. 2. Changing the existing single-glazed windows

Table 1. Thermal characteristics of the existing envelope components compared to the government's recommendations.

Component	Description (from the outside to inside layers)	Estimated insulating Properties (U Value)	Government's recommendation (Resolution 0549)
Windows	Translucent glass (4 mm thick) Total solar transmission (SHGC):0.768 Direct Solar Transmission: 0.741 Light transmission: 0.821	U= 3.835 W.m-2.K-1	No specification
	Aluminium frame with no thermal breaks or additional insulation		
Brick Facade	Single leaf brick wall (120 mm thick)	U= 3.174 W.m-2.K-1	No specification
	Stucco finish coat (3 mm thick)		
Concrete Facade	Single leaf concrete wall (100 mm thick)	U= 3.836 W.m-2.K-1	No specification
	Stucco finish coat (3 mm thick)		
Roof	Aluminium corrugated sheets	U= 2.55 W.m-2.K-1	No specification
	Non-ventilated cavity (700 mm thick at highest point)		
	Concrete slab (100 mm thick)		
Partition walls	Single leaf concrete wall (80 mm thick)	U=4.153 W.m-2.K-1	No specification
Floor slabs	Concrete slab (100 mm thick) Ceramic flooring (3mm thick)	U= 3.869 W.m-2.K-1	No specification
Overall envelope	Window-to-wall ratio (WWR)	32.9%	40% max.

Table 2. Data used for the reference model.

<table>
<tr><th>Thermal zone</th><th>Occupancy Density (people/m²)</th><th>Occupancy schedule</th><th>Metabolic rate (W/person)</th><th>Equipment heat gain (W/m²)</th><th>Equipment usage</th><th>Artificial lighting heat gains (W/m²)</th><th>Artificial lighting usage (W/m²)</th></tr>
<tr><td>Living room TZ1</td><td>0.36
(4 people per room)</td><td>00:00-06:00 = 0%
06:00-07:00 = 25%
07:00-09:00 = 100%
09:00-10:00 = 25%
10:00-18:00 = 0%
18:00-19:00 = 50%
19:00-21:00 = 75%
21:00-22:00 =30%
22:00-24:00 = 0%</td><td>110</td><td>3.06</td><td>00:00-06:00 = 8%
06:00-07:00 = 31%
07:00-09:00 = 100%
09:00-10:00 = 31%
10:00-18:00 = 8%
18:00-19:00 = 54%
19:00-21:00 = 100%
21:00-22:00 =36%
22:00-24:00 = 8%</td><td>4.05</td><td>00:00-06:00 = 0%
06:00-07:00 = 50%
07:00-18:00 = 0%
18:00-22:00 = 75%
22:00-24:00 = 0%</td></tr>
<tr><td>Main bedroom TZ6</td><td>0.28
(2 people per room)</td><td rowspan="2">00:00-06:00 = 100%
06:00-08:00 = 50%
08:00-09:00 = 25%
09:00-19:00 = 0%
19:00-22:00 = 50%
22:00-24:00 = 75%</td><td>90</td><td>3.58</td><td rowspan="2">00:00-07:00 = 7%
07:00-08:00 = 53%
08:00-09:00 = 100%
09:00-10:00 = 53%
10:00-17:00 = 7%
17:00-18:00 30%
18:00-19:00 = 53%
19:00-20:00 = 77%
20:00-22:00 =100%
22:00-23:00 = 77%
23:00-24:00 = 30%</td><td>2.82</td><td rowspan="2">00:00-05:00 = 0%
00:05-06:00 = 50%
06:00-07:00 = 25%
07:00-18:00 = 0%
18:00-19:00 = 50%
19:00-20:00 = 75%
20:00-22:00 = 100%
22:00-24:00 = 0%</td></tr>
<tr><td>Bedrooms TZ2 -TZ3</td><td>0.15
(1 person per room)</td><td>90</td><td>3.58</td><td>3.19</td></tr>
<tr><td>Bathrom TZ8</td><td>0.02</td><td>00:00-07:00 = 0%
07:00-10:00 = 100%
10:00-19:00 = 0%
19:00-23:00 = 20%
23:00-24:00 = 0%</td><td>120</td><td>1.67</td><td>00:00-06:00 = 6%
06:00-07:00 = 29%
07:00-09:00 = 100%
09:00-10:00 = 29%
10:00-18:00 = 6%
18:00-19:00 = 53%
19:00-21:00 = 100%
21:00-22:00 = 34%
22:00-24:00 = 6%</td><td>8.5</td><td>00:00-05:00 = 0%
05:00-06:00 = 75%
06:00-19:00 = 0%
19:00-21:00 = 50%
21:00-24:00 = 0%</td></tr>
<tr><td>Kitchen TZ9</td><td>0.03</td><td>00:00-07:00 = 0%
07:00-10:00 = 100%
10:00-19:00 = 0%
19:00-23:00 = 20%
23:00-24:00 = 0%</td><td>160</td><td>30.28</td><td>00:00-07:00 = 7%
07:00-10:00 = 100%
10:00-19:00 = 7%
19:00-23:00 = 25%
23:00-24:00 = 7%</td><td>3.95</td><td>00:00-05:00 = 0%
00:05-06:00 = 50%
06:00-07:00 = 25%
07:00-17:00 = 0%
17:00-18:00 = 50%
18:00-19:00 = 75%
19:00-20:00 = 100%
20:00-21:00 = 50%
21:00-24:00 = 0%</td></tr>
<tr><td>Hallway TZ10</td><td>0.02</td><td>00:00-07:00 = 0%
07:00-10:00 = 100%
10:00-19:00 = 0%
19:00-23:00 = 20%
23:00-24:00 = 0%</td><td>180</td><td>1.57</td><td>00:00-07:00 = 6%
07:00-08:00 = 53%
08:00-09:00 = 100%
09:00-10:00 = 53%
10:00-17:00 = 6%
17:00-18:00 = 30%
18:00-19:00 = 53%
19:00-20:00 = 77%
20:00-22:00 = 100%
22:00-23:00 = 77%
23:00-24:00 = 30%</td><td>5.11</td><td>00:00-05:00 = 0%
00:05-06:00 = 50%
06:00-07:00 = 25%
07:00-17:00 = 0%
17:00-18:00 = 50%
18:00-20:00 = 75%
20:00-23:00 = 25%
23:00-24:00 = 0%</td></tr>
</table>

for double-glazed windows. 3. Insulating the floor with a 3cm thick polyurethane layer. 4. Minimising infiltrations by sealing window and door-frames. The behaviour was evaluated and compared using the coldest week of an average year in Bogotá (6-13 October). It was observed that for the case study, the most efficient strategy to increase indoor temperatures was scenario 1, which entailed the insulation of the facade from the inside of the units. The simulations showed an average temperature increase of 0.5ºC in TZ1, 1.4ºC in TZ3 and 0.8ºC in TZ6 between this scenario and the reference model. The other scenarios (2-4) resulted in more moderate increases between 0.1ºC and 0.3ºC (Table 3).

Scenarios 1, 2 and 4 comprised alterations to the internal facade to improve thermal mass and fenestration performance, while scenario 3 entailed alterations to the floors. Based on the simulation results, it was decided to centre all the efforts only on the internal facade, as the aim was to stay within a budget limit of COP 10 million, which equates to approximately USD 3,477. This figure was taken from the case study surveys in which occupants were asked to estimate how much money they were willing to invest in improving the thermal conditions of their apartments.

Preference was given to scenario 1 as it showed a potentially higher temperature increase. However, it was presumed that

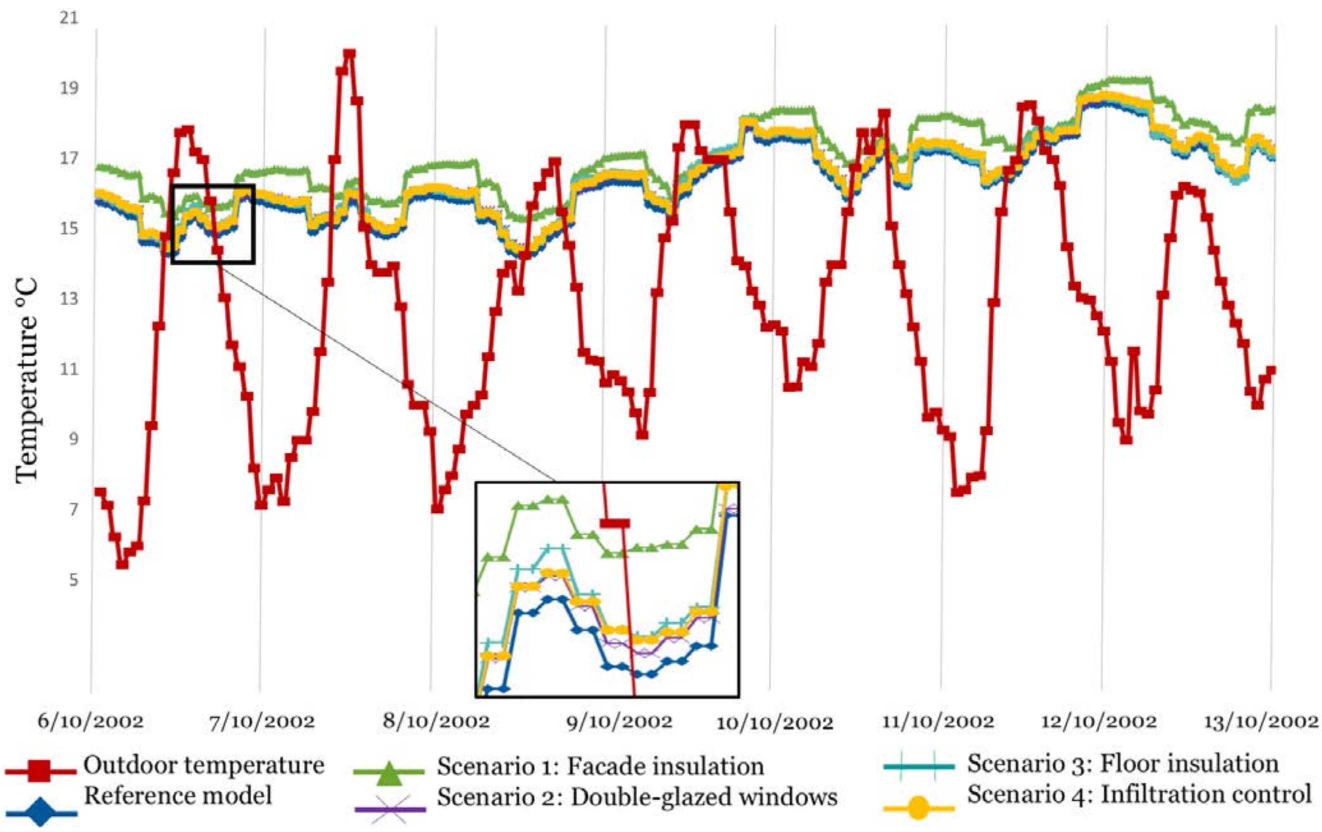

Figure 4. Dynamic thermal simulations of scenarios 1-4 compared to the reference model and the outdoor temperature, during the coldest week of an average year in Bogotá.

Table 3. Average temperature and relative humidity resulted from the simulations.

Scenario	Temperature ºC			Relative Humidity %		
	Bedroom TZ6	Bedroom TZ3	Living/ dining TZ1	Bedroom TZ6	Bedroom TZ3	Living/ dining TZ1
Reference model	16.316	16.998	16.979	63.263	59.100	61.561
1	17.147	18.421	17.512	60.627	54.683	60.209
2	16.490	17.167	17.109	63.212	59.122	61.612
3	16.514	17.189	17.140	63.306	59.304	61.826
4	16.527	17.299	17.268	69.654	66.225	69.090
1+2	17.255	18.422	17.507	60.141	54.576	60.194

improving the window performance was also important as it could help to enhance this scenario and minimise drafts and air infiltrations, in a similar way to scenario 4. Both scenarios (1 and 2) were tested further to give occupants two solutions to choose from or to use together according to their means and preferences (Figure 5). Scenarios 1 and 2 combined showed a 1ºC average increase and a 10% decrease in relative humidity compared to the current conditions in the reference model. This correlates to previous studies, which demonstrate that insulation and airtightness effectively increase the mean indoor temperature by reducing the rate of heat loss through the building fabric (24).

Various configurations were studied, considering the local availability and affordability of materials. Two different interventions were selected using materials commonly available within the market. Intervention 1 consisted of adding a layer of internal insulation to the existing facades and intervention 2 entailed altering the existing windows.

2.3. Detailed assessment - field research

In this phase, field research was carried out using a comparative method where two units with similar conditions (unit A and unit B) were selected from the case study to be analysed further during three stages (one week for each stage). The chosen units were northeast-facing because those showed to have the worst thermal comfort conditions and lowest occupant's satisfaction in the overall sample. They were on intermediate floors within the same building tower; unit A was located on the third floor and unit B on the fifth floor. The ground floor and top floor were not considered, due to their higher exposure to energy losses through the floor slab and roof. The occupancy density and schedules, as well as, the occupant's metabolic rates, heat gains, equipment and lighting usage were also similar in both cases, as each unit was inhabited by an adult couple in their 40s. The units were naturally ventilated without any HVAC systems. For this phase, the thermal zones considered were TZ1, TZ3 and TZ6

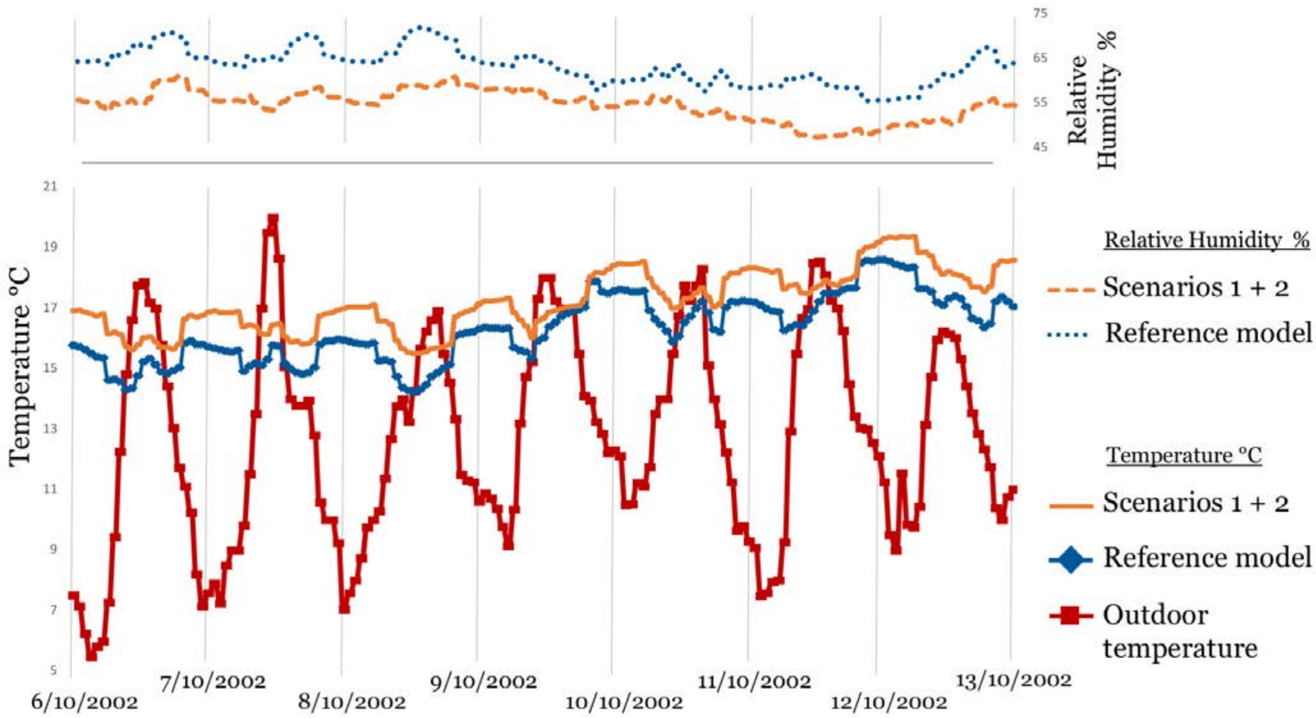

Figure 5. Dynamic thermal and relative humidity simulations of scenarios 1and 2 combined, compared to the reference model and the outdoor temperature, during the coldest week of an average year in Bogotá.

(Figure 6) because it was observed during the case study that they had the most active occupancy schedule. TZ9 was not considered due to the use of cooking equipment that could potentially alter the sample.

The sample aimed to monitor indoor conditions in parallel, as unit A was left untouched while unit B was intervened with two retrofits. This sample was considered adequate for a relative comparison between indoor and outdoor conditions.

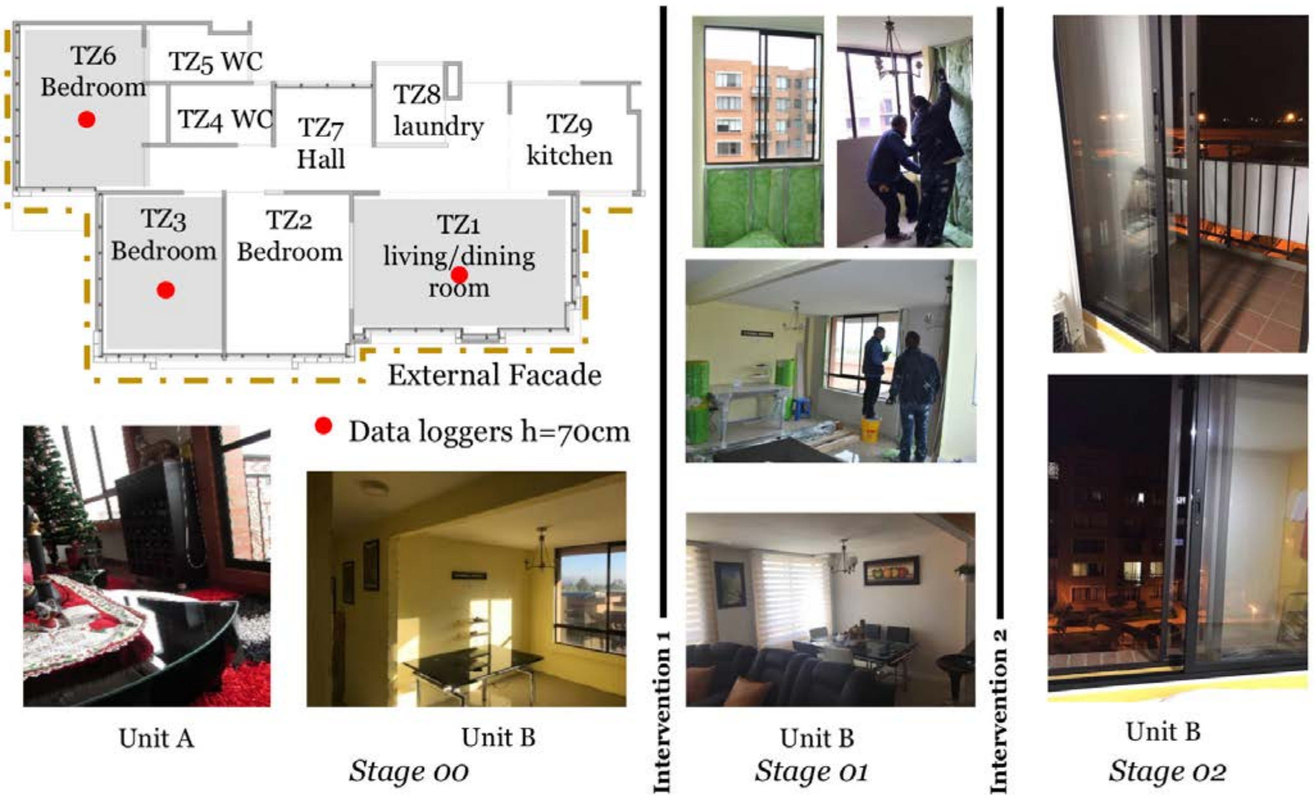

Figure 6. Thermal zones studied indicating the position of the data loggers. Photographs of units A and B during the three stages.

Monitoring the impact of the intervention over a long period was out of this project´s scope and capabilities. The sample was divided into three stages, named as stage 00 (October 19-25), stage 01 (November 22-28) and stage 02 (December 6-12).

2.4. Data collection

During the first week (stage 00) indoor conditions in units A and B were monitored with the occupant living in the unit and without any intervention. To analyse the differences between the two units and set a starting point of reference for the before and after of the retrofit. At the end of this period, intervention 1 was fitted on the interior of the facade walls of unit B using commonly available materials. The intervention was comprised of a10mm plasterboard with stucco and paint finish, a vapour barrier, steel studs at 500mm centres, 2.5” (63mm) fibreglass insulation and a waterproof membrane (Figure 7). These materials were chosen as they are off-the-shelf, affordable and easy to find in the local market. They were also the closest materials to the specifications used for the dynamic simulations. The 2.5” insulation thickness was considered appropriate in terms of price and constructional requirements. Although a thicker layer of insulation could arguably improve the thermal performance of the retrofit, it could also increase the thickness of the walls and reduce the internal space in the apartment.

During the second week (stage 01) indoor conditions in both units were monitored in the same way as before. At the end of this week intervention 2 was built in unit B. It was decided not to change the existing windows because installing new windows with more efficient frames increased expenses that were outside the established budget. In addition, changing the window´s design could alter the design of the overall building´s facade, which was not allowed by the local resi-

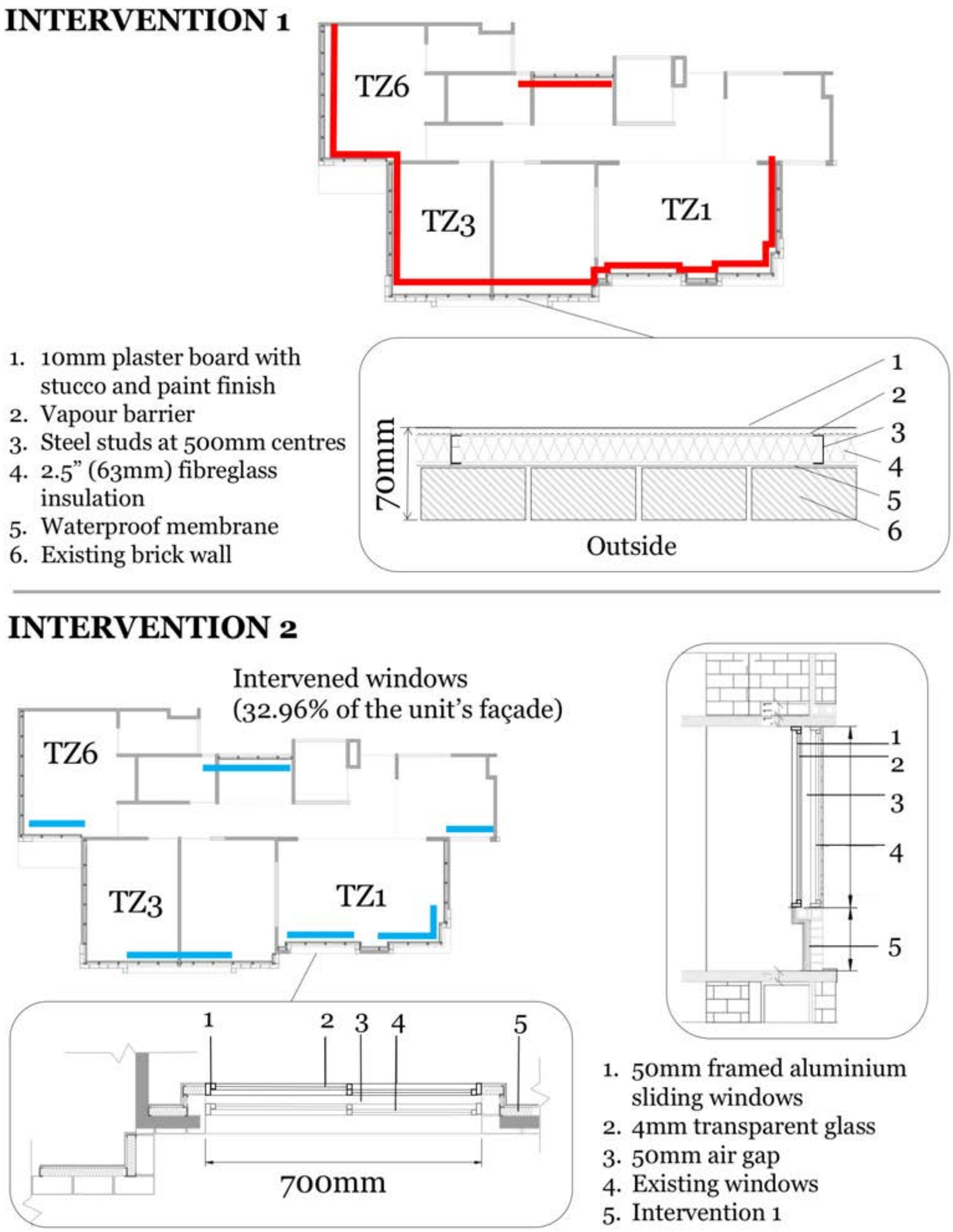

Figure 7. Plans and details of interventions 1 and 2 in unit B.

dent's association. Therefore, the intervention consisted of fitting additional sliding windows (identical to the existing and easy to find on the market) on the inner side of the facade and onto the walls built for intervention 1. Intervention 2 was comprised of 50mm framed aluminium windows (not thermally broken) with 4mm transparent glass, which formed a 50mm air gap with the existing window. During the third week (stage 02) indoor conditions were monitored again to evaluate the impact of intervention 2 compared to intervention 1 and the starting point of reference (stage 00).

3. RESULTS OF THE INTERVENTIONS

3.1. Temperatures and relative humidity percentages

Stage 00 was the period in which the maximum outdoor temperatures were recorded, 14.07ºC on average during the day and 12.29ºC during the night, with a maximum of 19ºC at 11:00 am and a minimum of 9.14ºC at 6:00 am. Additionally, compared to stage 01 and stage 02, temperatures remained higher for longer periods, during the late morning and early afternoon (Figure 8). Average indoor temperatures ranged between 18.89ºC and 19.45ºC for unit A and 19.45ºC and 19.76ºC for unit B. The difference between indoor temperatures for unit A and unit B was on average 0.49°C during the day and 0.40°C during the night. This difference was expected because unit B is located on the fifth floor, with slightly more sun exposure compared to unit A, which is on the third floor. In terms of relative humidity percentage (RH%), the minimum outdoor value recorded during the week was 51.29%, while the maximum value was 89.71%. Indoor RH% values for unit A ranged between 65.96% and 68.81%, whereas for unit B it ranged between 71.18% and 75.97%. The difference between indoor RH% values for unit A and unit B was on average 3.8%. This is linked to the differences in temperature values found between the units.

During stage 01 outdoor temperatures were on average 0.14°C lower during the day and 0.25°C lower during the night, compared to stage 00. The minimum indoor temperature for unit A was 15.72°C and for unit B 16.85°C. The maximum indoor temperature for unit A was 20.02°C and for unit B was 22.28°C. The differences between indoor temperature for unit A and unit B were on average 1.58°C during the day and 1.19°C during the night. These differences show an average increase in temperature in unit B of 1.09°C during the day and 0.79°C during the night, compared to stage 00. A larger gap in temperatures between the units can be observed between 7:00 and16:00 hours. This suggests that solar heat gains were retained for longer periods during the day with intervention 1. Relative humidity percentages increased in both units during stage 01; however, the average gap between values was lower throughout the week compared to stage 00 (Figure 8).

During stage 02 the average outside temperature was 13.86ºC during the day and 12.07ºC during the night. The lowest temperatures of the overall sample were recorded at this stage, with a minimum temperature average of 9.00ºC at 6:00 am. Throughout stage 02, it was observed that temperatures in unit B increased considerably regarding unit A, with an average difference of 2.63ºC during the day and 2.37ºC during the night. Furthermore, temperatures in unit B were more stable, and fluctuations were less pronounced during the 24-hour periods compared to unit A. Maximum fluctuations in unit B did not exceed 1.7ºC, while in unit A there were

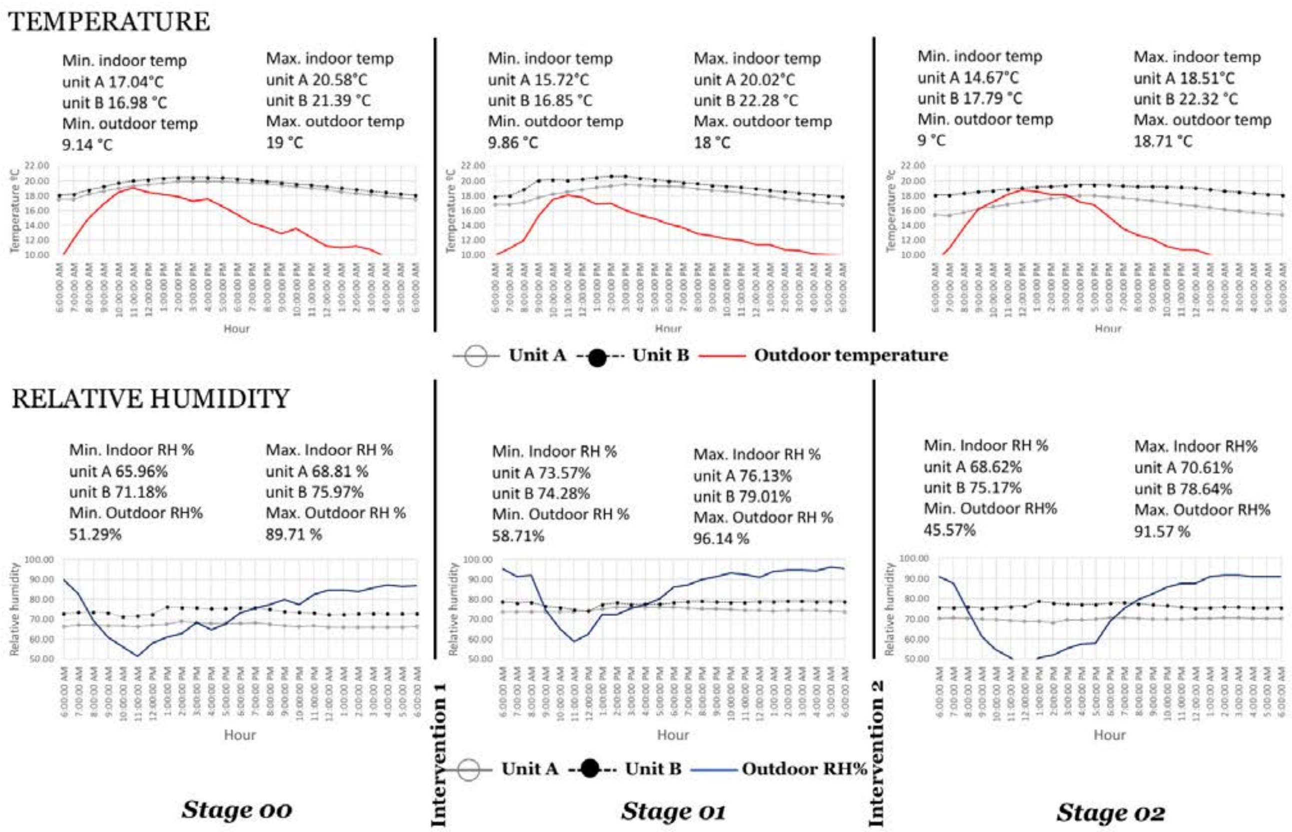

Figure 8. Temperature and relative humidity values.

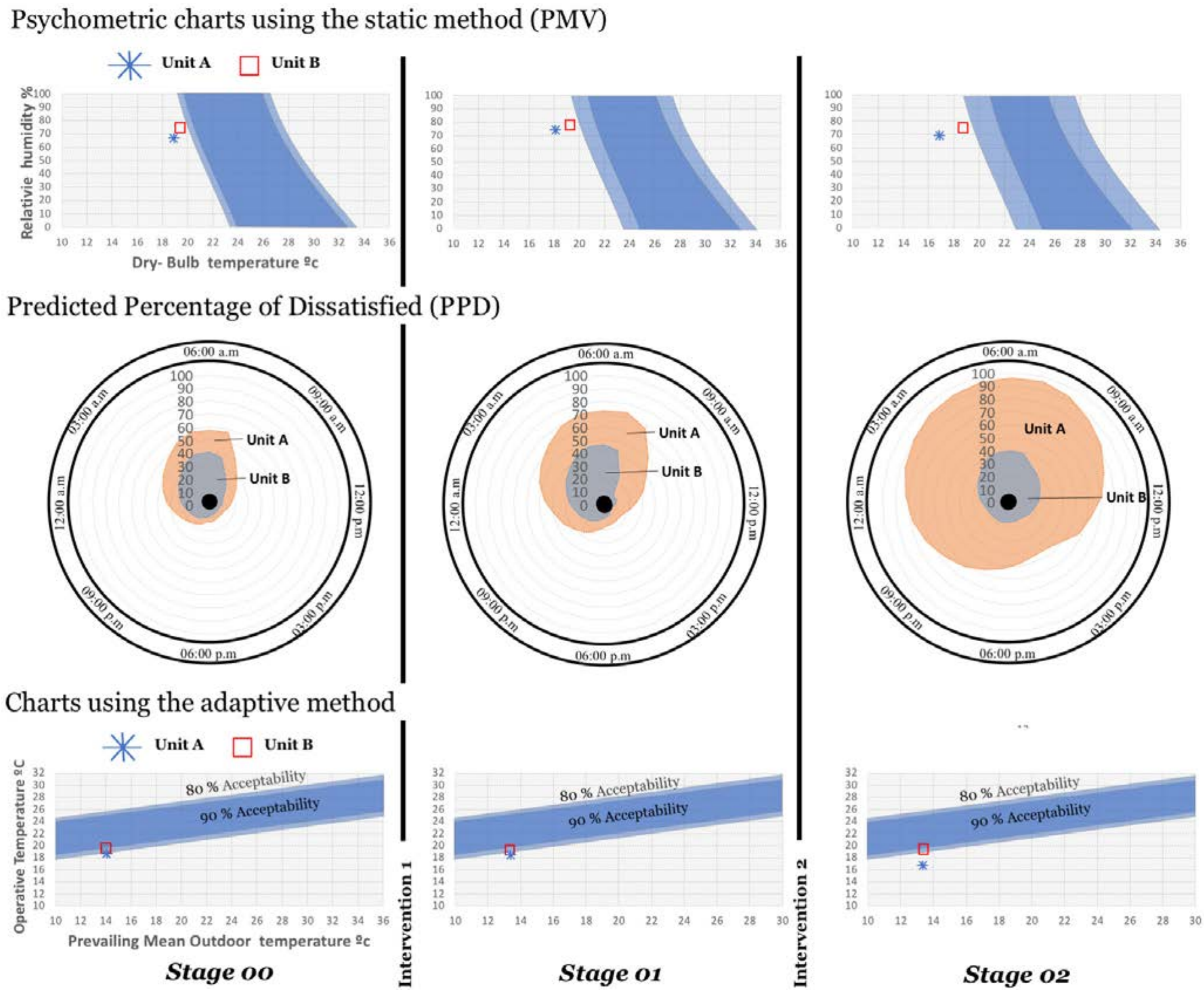

Figure 9. Charts using the static method (PMV and PPD) and charts using the adaptive method.

fluctuations above 3.8ºC. In general, during stage 02, relative humidity percentages in unit B were slightly higher than the values recorded in stage 00, but lower than the values in stage 01. The gap between values in unit B and unit A was smaller compared to stage 00, but larger compared to stage 01. It can be observed in figure 9 that RH% values were more constant in unit B compared to unit A, throughout the three stages, despite changes in the outdoor conditions.

Table 4 indicates that TZ3 (second bedroom) was slightly warmer throughout the sample than the other two zones studied. This is due to its smaller size, its corner location, and because its window-to-wall ratio is less than in TZ1 and TZ6.

3.2. Thermal comfort and satisfaction assessment

The static and adaptive models were again used during this phase for thermal comfort assessment. The temperature and RH% values were collected with data loggers, while other values such as MRT, air velocity, clothing insulation, metabolic rates and activity levels were calculated using the surveys, in a similar way as with the case study. Figure 9 shows psychometric charts with the CBE tool that illustrate levels of compliance from the perspective of the PMV method. It can be observed in the charts that comfort zone ranges are different at each stage, according to temperatures and humidity variations. Unit B remains close to these ranges, although it is outside the comfort zones that are considered acceptable with this assessment method. Unit A is not only outside these zones but also moves further away from the comfort limits during stages 01 and 02. This suggests that intervention 1 and 2 allowed unit B to stay closer to these limits.

With the adaptive model, the results show that unit A and unit B are both within the 80% satisfaction zone during stage 00. However, during stage 01 and 02, unit B remains in a similar position while unit A moves away from the acceptable limits of comfort. This behaviour is very similar to the one shown in the PMV psychometric charts. The information in the charts was used to develop the graphics of figure 9, which show theoretical levels of occupant satisfaction. This figure indicates that intervention 1 and 2 helped to decrease the percentages of dissatisfaction in unit B considerably, as these are maintained in a range of 5% to 45%, during stage 01, and stage 02. Whereas in unit A, dissatisfaction rates increased with the outside temperatures´ fluctuations, from an average of 70% during stage 01 to as high as 90% during stage 02. Smaller percentages of dissatisfaction in unit B were observed during both the morning and afternoon periods in the case of stage 01, and mainly during the afternoon period in stage 02.

Table 4. Temperature data during the three stages of the field research.

DAY TEMPERATURES 06:00-18:00											
Thermal zone	**Outdoor temp.**			**Avg. indoor temp.**		**dT= B-A**	**Avg. dT**	**Min. indoor temp.**		**Max. indoor temp.**	
	Avg.	**Min.**	**Max**	**UNIT A**	**UNIT B**			**UNIT A**	**UNIT B**	**UNIT A**	**UNIT B**
STAGE 00											
(TZ1)				19.45	19.76	0.31		17.26	18.41	20.58	20.42
(TZ3)	14.07	9.14	19.00	19.01	19.6	0.59	0.49	17.04	16.98	20.09	21.39
(TZ6)				18.89	19.45	0.56		18.09	18.75	19.46	19.91
STAGE 01											
(TZ1)				18.39	19.75	1.36		16.93	18.62	19.46	20.74
(TZ3)	13.93	9.86	18.00	18.36	20.53	2.17	1.58	15.72	16.85	20.02	22.28
(TZ6)				18.59	19.8	1.21		17.62	17.91	19.34	20.19
STAGE 02											
(TZ1)				17.1	19.75	2.65		15.58	17.84	18.07	21.09
(TZ3)	13.86	9.00	18.71	16.86	19.63	2.77	2.63	14.67	17.79	18.51	22.32
(TZ6)				16.72	19.2	2.48		15.67	18.84	17.65	21.43
NIGHT TEMPERATURES 18:00-06:00											
Thermal zone	**Outdoor temp.**			**Avg. indoor temp.**		**dT = B-A**	**Avg. dT**	**Min. indoor temp.**		**Max. indoor temp.**	
	Avg.	**Min**	**Max**	**UNIT A**	**UNIT B**			**UNIT A**	**UNIT B**	**UNIT A**	**UNIT B**
STAGE 00											
(TZ1)				18.81	19.45	0.65		17.31	18.41	20.11	20.35
(TZ3)	12.29	9.14	15.43	18.62	18.76	0.14	0.40	17.05	17	19.88	20.66
(TZ6)				18.98	19.38	0.4		18.15	18.79	19.43	19.79
STAGE 01											
(TZ1)				18.1	19.65	1.55		17.02	18.7	19.11	20.52
(TZ3)	12.04	9.86	14.21	17.54	18.51	0.97	1.19	15.81	16.85	19.65	19.76
(TZ6)				18.42	19.46	1.04		17.7	18	19.35	20.02
STAGE 02											
(TZ1)				16.49	18.59	2.1		15.64	17.74	17.74	19.35
(TZ3)	12.07	9.00	15.14	16.45	18.48	2.03	2.37	14.76	17.57	18.31	19.54
(TZ6)				16.59	19.57	2.98		15.74	18.85	18.31	19.8

4. CONCLUSIONS

With this study, it was possible to confirm general suggestions from past theoretical research that indoor conditions in the typical social housing projects currently built in Bogotá are below acceptable comfort levels, which results in low levels of satisfaction. This work goes further by analysing the problem in detail and in a real context through the case study. All the monitored units were outside the thermal comfort zones recommended by both the static and the adaptive models. Additionally, the occupant's surveys showed high levels of dissatisfaction. It is argued that the problem lies in the existing mono-layer facade configuration of these buildings, which is not efficient in providing indoor thermal comfort. Potential solutions that could help alleviate comfort problems were analysed to choose the most viable. Two passive and low-tech post-occupancy interventions were selected and refined. These were tested during fieldwork achieving their objective, as they proved to increase indoor temperatures and noticeably improve the occupants' comfort and satisfaction as a result. With intervention 1, there was a 1.09ºC temperature improvement on average during the day, while with intervention 2, the improvement was 2.14ºC. These temperature improvements bring indoor levels of comfort much closer to the acceptable ranges, according to both the static and the adaptive models. With the adaptive model, the interventions are within the 80% acceptability limit. Even though the temperature increase was relatively modest, it is argued to be appropriate for the context of social housing in Bogotá. The main reason is that the interventions were cost-effective and practical to implement by the occupants. Considering there is a lack of policy and government incentives towards these types of improvements, these interventions are viable and realistic. The retrofit comprised two phases (intervention 1 and intervention 2), so occupants could build them progressively according to their means.

The results gathered on-site were simulated on the initial reference model to establish the thermal load necessary to raise the temperature to the achieved levels. The simulation showed that a monthly load of 174.12 kW/h was needed and to raise the air temperature by an average of 1.09°C. Likewise, the needed load to raise it by 2.14°C was 447.52 kW/h. This information was used to estimate the potential costs of heating the units with mechanical means (central heating), taking the costs of energy supply for the units as reference. According to the local energy supplier (Codensa) the value of 1 kWh in Colombia pesos for March 2017 was COP 453.72, which in UD dollars is approximately USD 0.16. Therefore, to achieve a 1.09°C temperature increase could represent a monthly cost of COP 79,002 (approximately USD 27.17) and to achieve a 2.14°C temperature increase could represent a monthly cost of COP 203,049 (approximately USD 69.84). These costs are substantial, considering that the current minimum salary in Colombia is COP 737,717 (approximately USD 253.74).

For this study, the total costs of intervention 1 alone were COP 5´769,306 (approximately USD 2,003) and of intervention 1 and 2 together was COP 9´945,306 (approximately USD 3,454), prices that were within the initial budget. If these costs are compared to the potential costs of heating the units to the achieved levels, it can be inferred that the cost of the overall intervention would be amortised in 28 and 49 months respectively. This time is relatively short in the context of the life expectancy of the materials used and the building as a whole, which could be 65-100 years in broad terms. It is important to emphasise that a post-occupancy retrofit could be substantially more expensive than a solution implemented during the construction phase of the building.

In terms of temperature fluctuations, the interventions succeeded in reducing the discomfort produced by cyclical indoor temperature variations, for both day and night. Hourly fluctuations between temperatures are noticeably less pronounced in unit B from stage 00 to stage 02. This also suggests an improvement since fluctuations are believed to contribute to thermal discomfort within indoor environments (18).

Apart from the benefits discussed above, the analysis of the proposed interventions also revealed some limitations. For example, regarding relative humidity, it was observed that the implementations helped to reduce the gap between RH% in both units. However, the results are not yet satisfactory, as average humidity levels are still high. By increasing the air-tightness of unit B's façade, there was less renewal of air through the gaps in the window frames. This limited passive ventilation, which normally helps to lower RH%. Therefore, further research is needed regarding ways to reduce RH% in the proposed interventions and in the general context of social housing in Bogotá. Furthermore, it is suggested that additional solutions and measures could be tested on-site to complement the findings in this study. For example, a third intervention could incorporate operable wooden shutters fitted on the inner side of the windows, which would reduce heat losses throughout the night. The interventions in this work were aimed for use in existing social housing constructions; however, the insights of this study could be extrapolated to other residential buildings. Finally, the findings could be beneficial to construction stakeholders and policymakers involved in the current development of thermal comfort standards in the country.

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