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TUHOUSE: SUSTAINABLE, HIGH-DENSITY SOCIAL HOUSING PROTOTYPE FOR THE TROPICS

TUHOUSE: PROTOTIPO DE VIVIENDA SOCIAL SOSTENIBLE DE ALTA DENSIDAD PARA EL TRÓPICO

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RESUMEN

La presente contribución expone los resultados de la investigación desarrollada en el marco del concurso internacional Solar Decathlon LAC 2019, la cual tuvo por objetivo el diseño y construcción de un prototipo de vivienda económica TUHOUSE (Technically Unique House Using Solar Energy), a escala 1:1, capaz de incorporar estrategias sostenibles y bioclimáticas acordes con la región tropical. Para esto se llevó a cabo una metodología de taller de diseño, basada en el trabajo interdisciplinario entre distintas áreas de la Arquitectura y la Ingeniería, pertenecientes a diversos programas de las Universidades de San Buenaventura y Autónoma de Occidente (Cali, Colombia). El principal aporte metodológico fue lograr aquel trabajo interdisciplinario desde las etapas iniciales, lo cual se suma a que estudiantes y profesores participaran en la construcción del prototipo para finalmente verificar su comportamiento con las pruebas del concurso. Entre resultados de la experiencia, se destaca la propuesta urbana con alta habitabilidad y densidad, y la comprobación de estrategias pasivas de diseño enfocadas en la envolvente del prototipo, que pueden ser replicadas en condiciones similares, pero también la importancia del interrogante sobre la validez del modelo de confort térmico propuesto para regiones tropicales.

Palabras clave
vivienda social, prototipo, sostenibilidad, bioclimática, trópico

ABSTRACT

This work presents the results of research made within the framework of the Solar Decathlon LAC 2019 international competition, which aimed at designing and building a prototype of a TUHOUSE (Technically Unique House Using Solar Energy) affordable dwelling, at a 1:1 scale, a house that is capable of incorporating sustainable and bioclimatic strategies for the tropical region. The methodology consisted of a design workshop with interdisciplinary work from the different architecture and engineering areas in programs at the Universities of San Buenaventura and Autonoma de Occidente (Cali, Colombia). The main contribution of the methodology was to achieve interdisciplinary work from the initial stages, alongside students and teachers participating in the construction of the prototype, before finally checking its performance using the contest's tests. Among the results that stand out from of this experience, are an urban proposal with high habitability and density, the testing of passive design strategies focused on a prototype envelope that can be replicated in similar conditions, but also the importance of the question about the validity of the thermal comfort model proposed for tropical regions.

Keywords
social housing, prototype, sustainability, bioclimatic, tropics

INTRODUCTION

The TUHOUSE prototype is the result of an academic reflection on the role social housing has in the makeup of the residential habitat, and their commitment with improving the environment and the different life quality aspects. TUHOUSE proposes a replicable, flexible social housing model, that is adaptable to different contexts, and to different neighborhoods. The concept of sustainability and bioclimatic strategies are directly related to urban-architectural decisions, in the means that the proposal incorporates sustainability criteria, implementing urban agriculture and composting systems in common spaces, thus favoring the formation of community, and contributing towards generating food security and additional income for the families.

The buildings are proposed in a structural and construction system using large pre-fabricated Recycled Concrete Aggregate (RCA) pieces, which look to substitute the use of non-renewable raw materials, and to reduce the impact of Construction and Demolition Waste on the landscape (Bedoya & Dzul, 2015). In Colombia, a variety of materials are used to build terraced social housing, 99% of which are based on high density masonry, like concrete (Giraldo, Czajkowski & Gómez, 2020).

Understanding social housing as the most prized possession of the inhabitants, it has to solve socio-cultural needs: providing shelter (considering the different ways of life and customs), being able to be transformed to house different kinds of families, and their growth, and being durable (housing is for life, it is the legacy of the family). But it must also consider needs of an economic nature: valuation of the dwelling, profitability and generation of extra income, among others.

Apart from the commitments inherent to the area, nowadays Architecture also has commitments with care for the environment, conservation of the planet, energy efficiency, and comfort. However, some social housing in Cali has poor landscaping and lacks bioclimatic strategies, reaching temperatures of up to 49°C inside (Gamboa, Rosillo, Herrera, López & Iglesias, 2011), and thus, a high discomfort for their inhabitants. As Montoya (2014) says, in general the projects have limited typology exploration and deficient conditions regarding their solar orientation, their protection elements in common spaces, and their facades and roofs. Unfortunately, in most of the current projects, a limited implementation of bioclimatic and sustainable strategies is seen, such as the right orientation, shading on the façade, natural ventilation, which are reserved for a few dwellings among the more favored economic sectors of the population.

The residential sector also consumes around 20% of the country's total energy (Energy Mining Planning Unit [UPME, in Spanish], 2019), and from this consumption, depending on the economic conditions, between 40% and 60% is destined for climate control through air conditioning, cooling, and the use of fans (UPME, 2018).

The TUHOUSE prototype was built by students and professors, at a 1:1 scale, within the 2019 Solar Decathlon contest for Latin America and the Caribbean (LAC), and considers the lessons learned by the team in the previous version in 2015 with the MIHOUSE prototype. In said prototype, the architectural and bioclimatic exploration of concrete as an envelope material began (Cobo, Villalobos & Montoya, 2019), along with the first tests on use and reuse of water, waste management through homemade compost heaps, and the incorporation of solar energy using solar panels on the roof (López & Holguín, 2020). This allows presenting to the general non-scientific public, possible alternatives to be included, extending the role of academia outside the boundaries of the University. In this sense, it is worth adding that the project generates alliances not just between universities, but with the public and business sectors.

Therefore, it is pertinent in this revision, to refer to the so-called adaptive thermal comfort model proposed by the international ASHRAE standard in its latest version (ASHRAE/ANSI) for naturally ventilated buildings. This model, led by authors like Auliciems (1975) and Nicol, Humphreys & Roaf (2012), which is based on the average room temperature of a place, emerges as a critique to the ranges established under controlled conditions, part of the analytical model promoted by ASHRAE (ASHRAE, 2005), and revisited for Colombia in NTC 5316 (Colombian Institute of Technical Standards and Certification -ICONTEC, 2004). The analytical model emerges from laboratory run research in contexts with the four seasons (Fanger, 1972; Fanger & Toftum, 2002), which is why its revision in other contexts is needed, like tropical ones (Herrera and Rosillo, 2019), just as seen in recent studies in schools in the tropics (Zapata *et al.*, 2018)

The sustainable and bioclimatic aspects of the proposal are presented below, along with an analysis of the parameters required by the context (temperature between 22°C and 25°C, and relative humidity between 40% and 60%) to reach thermal comfort, which have little relation to the inhabitability of naturally ventilated spaces during the entire year.

METHODOLOGY

The urban-architectural proposal in question, emerges from a fourth year projects workshop in the Architecture Program, which uses the Solar

Parameter	Values set
Indoor room temperature (Ta)	22°C a 25°C
Relative humidity (%)	40% a 60%

Table 1. Thermal parameters proposed by the Solar Decathlon LAC 2019 Contest. Source: Solar Decathlon (2019).

Decathlon LAC 2019 international contest as the reference framework, which places emphasis on using renewable energy, comfort, and protecting the environment. The project made for the contest is called TUHOUSE, and for its two and a half year development, a multidisciplinary team of students (50) and professors (10) was formed, from two universities in the region (San Buenaventura-Cali and Autonoma de Occidente), with complementary knowledge in the areas of bioclimatic architecture, habitat, urban agriculture, environment, sustainability, and renewable energies. This allowed not just addressing all the issues requested by the contest, but addressing them in an innovative way, through an interdisciplinary approach (Baumber, Kligyte, Bijl-Brouwer, Van Der & Pratt, 2020; Herrera, Rey, Hernández & Roa, 2020).

The main stages of the work were: a) urban and architectural grounds, considering the place and the population; b) thermal-energy simulation; c) costs; d) prefabrication and construction of a housing prototype at a 1:1 scale; and, e) monitoring and verification of the operation of the strategies.

Methodologically speaking, for the design phase, the proposal was developed in an applied research laboratory-workshop, which involves project, sustainable and bioclimatic aspects, alternating the design processes with checks, using software simulations (like Formit and DesignBuilder) and observations in the bioclimatic laboratory (heliodon and smoke table). Once the prototype was built in a later phase, a series of measurements were made onsite. This methodology, inherent to the bioclimatic process (San Juan et al., 2013), which incorporates bioclimatic analysis, initial and final sizing, and measurements to compare hypotheses, is very rewarding in the students' learning process, as it passes from the conventional design to the energy optimized one (Montoya, 2020), and transcends learning in the classroom, to originate the possibility of facing the knowledge received from real actions as well as from confirming the results.

After the prototype was made at the site determined by the contest, called Villa Solar, continuous indoor measurements were made of the room temperature (°C), relative humidity (%), air quality (CO_2), illuminance (lux) and energy generation with the specialized equipment provided by the contest. In addition, specific measurements were made on the elements of the envelope, both inside and outside, with a Nubee infrared thermometer. The energy consumption (kWh) was measured through specific tasks on the prototype, that implied using household appliances and devices. The acoustic parameters, like the sound pressure level (dB) and the reverberation time, were measured on a specific day by the organizers using specialized equipment. In terms of thermal comfort, the values indicated in Table 1 would need to be reached.

To analyze the thermal comfort, the range proposed by the contest was compared with the range proposed by the adaptive model (ASHRAE/ANSI, 2017), indicated in Equation 1:

$$\text{Tacep} = 0.31 * T(\text{pma (out)}) \pm 17.8 \pm \text{T\_lim} \quad (1)$$

Where:
Tacep =Acceptable temperature
T(pma(out) = Average outdoor temperature
T_lim = Temperature Limits, which can be ±3.5 for an acceptance of 90%. (Nicol *et al.*, 2012).

RESULTS AND DISCUSSION

THE URBAN PROPOSAL

The urban proposal is based on a sustainable design of a high-rise social housing complex, of 5 and 8 floors, and a density of 120 dwellings/hectare. The complex is formed using an urban grouping system of buildings that form public and private urban spaces, capable of adapting to the different social and climate contexts of each place. In some cases, the common space par excellence is the site, and in others, the street. Both foster meeting, identity and co-existence. In the words of Samper: "What is key is not the design of the dwellings themselves, but rather the search for new urban patterns. Working to seek new urban patterns implicitly leads to new dwelling typologies[1]" (2003, p. 20)

1 Free translation

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Surface	Exposed to the sun	In the shade
Concrete	49.2°C	28.3°C
Outdoor paving stones	39.4°C	29.1°C
Earth with vegetation	35.4°C	27.0°C

Table 2. Reduction in temperatures, TUHOUSE project. Source: Prepared by the Authors.

The careful layout of the buildings (orientation, distancing and height) manages to form shaded spaces which, accompanied by native trees and vegetation, allow a significant reduction of solar irradiance, generating a suitable micro-climate. Wind plays a key role when it comes to dissipating the heat produced by the materials and elements of the project. The succession of broad (premises) and narrow spaces (streets and entrances), produce the so-called "Venturi effect" which, along with the presence of green facades in narrow places, achieves a passive cooling of the winds that enter the complexes. These are all strategies for the warm climate of Cali recommended by emblematic authors (Olgyay, 1963) (Figure 1). According to the measurements taken in situ, these strategies manage to reduce temperatures by up to 10 degrees (Table 2).

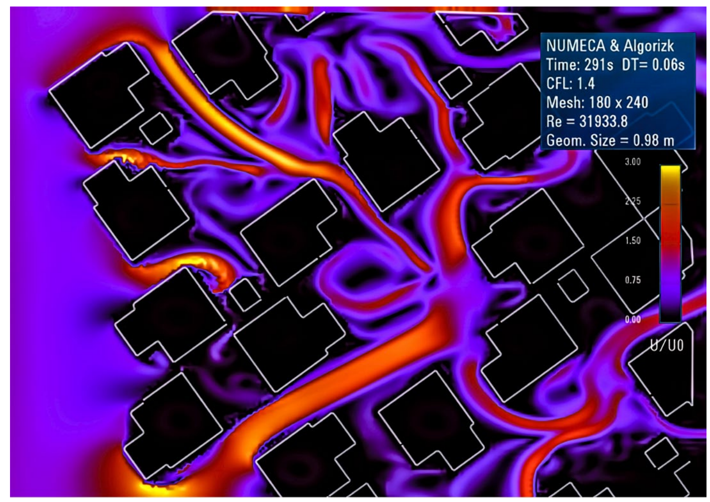

Figure 1. Wind behavior. Wind Tunnel. Source: Prepared by the Authors.

The housing complex also has cultural, educational and productive facilities; a bicycle mobility system connected to the city's cycle-path network; and a productive urban orchard and fruit tree system, that generates additional income for the complex's inhabitants while fostering environmental quality. In the understanding that the quality of life is not exclusively limited to inhabitability inside the dwelling, the idea is to minimize possible negative impacts and promote the sustainable use of common spaces (Cobo *et al.*, 2019) (Figure 2).

Figure 2. Image of the complex's public space. Source: Prepared by the Authors

ARCHITECTURAL AND SUSTAINABLE PROPOSAL

This proposal considers that social housing must comply with 4 basic conditions to be inhabitable and sustainable: the housing must be progressive and productive (Samper, 2002), as well as replicable and flexible, the main principles that allow different families to freely live. The housing spaces must allow adapting to the changing needs of the family, just as the AURA team (University of Seville, Spain and Santiago de Cali University, Colombia) proposes, implementing progressive modular systems and flexible spaces determined by the real estate (Herrera, Pineda, Roa, Cordero & López, 2017). Something that does not occur with the current offer, where families have to adapt to the dwelling. In order to attain this quality, the dwellings must be laid out from the start, to be open to extensions and remodeling as the family deems fit, and so that, they can even become a source of income, namely productive dwellings. These are principles that were tried out in the last version of the Solar Decathlon contest, in 2015, and that demonstrated their urban and architectural feasibility as a system (Cobo *et al.*, 2019).

The project process must also be sustainable: optimizing design processes to then optimize construction processes and the use of resources. It is for this reason that the proposed housing unit is

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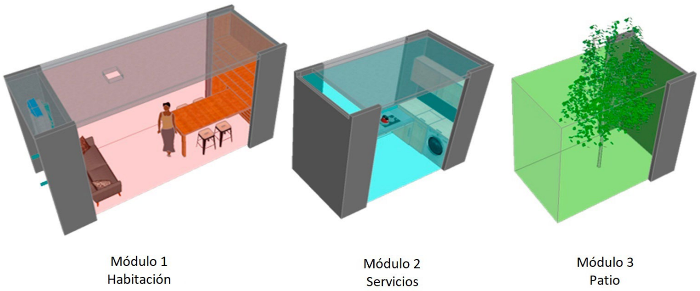

Figure 3. Prototype modules. Source: Prepared by the Authors.

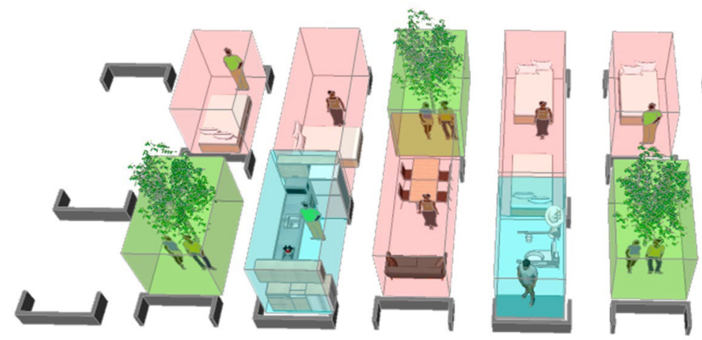

Figure 4. Flexibility and progressiveness. Source: Prepared by the Authors.

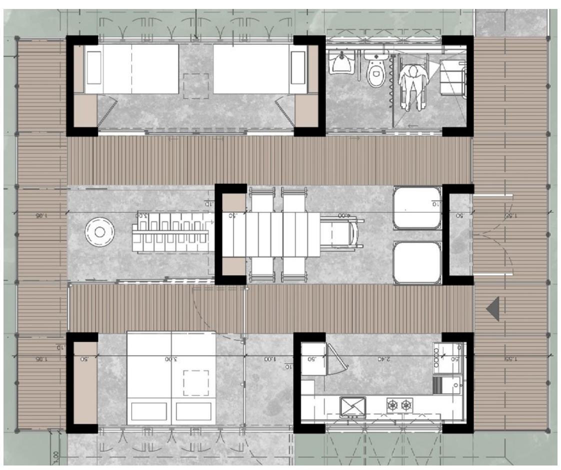

Figure 5. Floor Plan. Source: Prepared by the Authors.

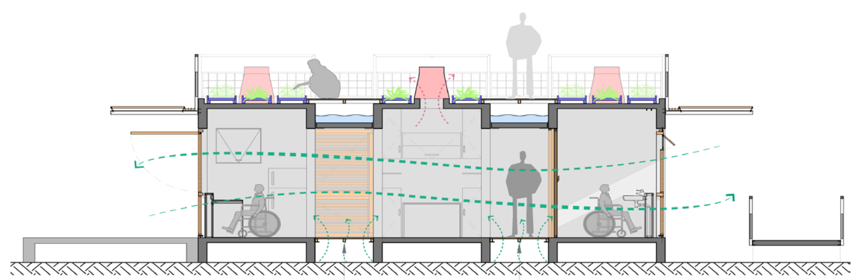

Figure 6. Cross-section. Source: Prepared by the Authors.

conceived as a "Lego", formed by two base modules, where the space-shape-structure is defined in a single element (Figure 3).

The rooms -bedroom, dining room, living room, study- are laid out in the larger module, and the services -kitchen, bathroom, yard-, in the smaller module. The way in which these units are organized, considering a circulation system and around a yard, allows forming a variety of flexible and progressive housing units, both in use and in construction, to house different types of families (Figure 4). This layout also allows taking advantage of the environmental conditions that the yards of traditional houses in the region provide, like shading, ventilation, moisture and cooling by evaporation (Figure 5), in a similar way to other prototypes of Solar, like Patio 2.12, which revisits the traditional Andalusian house, and incorporates passive strategies that respond, among other factors, to the hot summer, in a similar way to the case presented here (Terrados, Baco & Moreno, 2015).

Alongside providing shelter, the outlined dwelling generates food (on its roof and facades), comfort and energy. The proposal reuses graywater and collects rainwater; uses technology and materials that are environmentally sustainable; is coherent and effective in different settings and facing the problems of urban density (Figure 6).

In addition, this is a self-sustainable and efficient project, where each element it has, has several roles. The east-west façade and the roof (the ones affected most by solar radiation), are covered by a green envelope that has three main roles: insulating the concrete structure from solar radiation -which constitutes one of the main recommendations for a tropical climate (Evans & Schiller, 1994; Konya, 1980)-, producing food and purifying the air, contributing to reduce environmental contamination. The design includes a bioclimatic transition space between the indoors and outdoors (Figures 7 and 8, and Table 3), similar to the hallway of traditional houses in the region (Herrera *et al.*, 2017).

The south-north facades are open to take advantage of the cross circulation of the wind -another strategy suggested for a tropical climate (Olgyay, 1963)-,

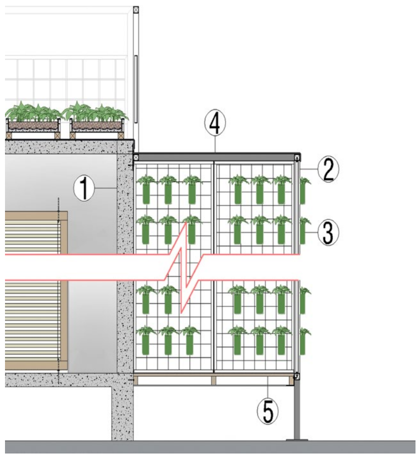

Figure 7. Facade cross-section. Source: Prepared by the authors

Figure 8. Entrance space, green envelope. Source: Prepared by the authors.

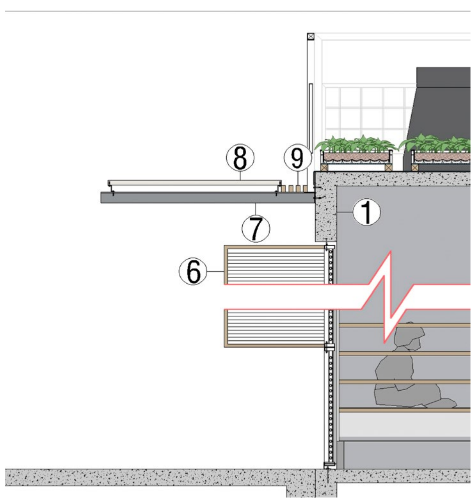

Figure 9. Cross section along the facade. Source: Prepared by the authors.

Figure 10. South facade. Source: Prepared by the Authors.

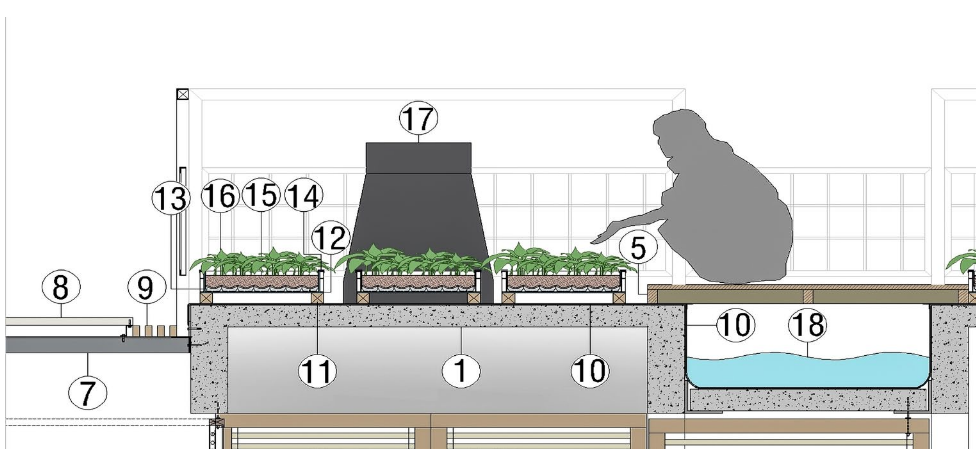

Figure 11. Detail of the proposing dwelling roof. Source: Prepared by the Authors.

Location	No.	Materials	Thickness	Conductivity
Wall	1	3000 Psi reinforced concrete	10	0.97
Facade cage	2	Electro-welded metal mesh	5	58
		Bamboo	60	0.28
Green facade	3	Recycled PET plastic bottles	2	0.24**
		Earth	60	0.8*
		Aromatic plants	-	-
Cage roof	4	35% black polyshading (LXA) Anti-UV (Polyethylene)	1	0.35
Pallet floor	5	Wood	25.5	0.15
Facade windows	6	Wooden strips	25.5	0.15
		Bamboo poles	60	0.28
Eave	7	Solar panel metal support structure	38.1	0.28
	8	Solar panel	70	1.05
	9	Monterrey pine wooden beams	50.8	0.28
Roof	10	TPO SINTOFOIL SIL waterproof membrane (EELAB certified) (ethylene-propylene)	1.2	0.24
	11	Monterrey pine wooden steps	50.8	0.28
	12	Recycled plastic baskets	25.4	0.50
	13	Base of personal PET bottles	2	0.24
	14	NT 1600S Geotextile (polypropylene)	1.5	0.24
	15	Wet earth	150	0.8*
	16	Plants	-	-
	17	Aluminum sheet solar chimney	5	204
	18	Concrete water channel	10	0.97

Table 3. Thermal conductivity of the materials used in building the TUHOUSE prototype.Source: IRAM 11601 (2002); Van der Vegt & Govaert (2005).

and are protected by large eaves which, apart from producing shading and protecting from the rain, support the solar panels that provide solar energy to the dwelling (Figures 9 and 10, and Table 3).

Special attention must be paid to the fifth façade, especially in the context of Cali, due to its warm climate conditions, but also because of the social conditions (Sánchez, 2019). A covered orchard was designed here, which is used to collect rainwater in the two large channels placed under the removable wooden pallets, and that work for circulation (Figure 11). This technique also allows airing the roof through a ventilated chamber (Table 3), as a bioclimatic strategy focused on the horizontal surface, which receives at least 50% of the solar radiance in the tropics (Olgyay, 1963).

Using these criteria, the hypothesis held by Becker, Goldberger and Paciuk (2007) is reinforced, who suggested that the design aspects with the highest impact on climate control, are the orientation, the openings on facades, and the thermal resistance of the walls and roof.

ENERGY AND ENVIRONMENTAL PARAMETER MEASUREMENTS

The outdoor environment temperature (Ta) measurements have average values of 24.5°C, with maximums of 32.4°C and minimums of 18.2°C. While the average outdoor relative humidity is 74.5%, with a maximum of 94% and minimum of 45%. These values are consistent with the local weather conditions, which have minimum variations during the year, typical of

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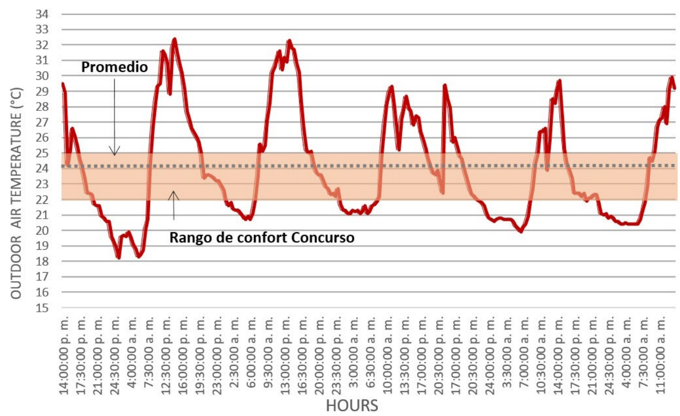

Figure 12. Outdoor temperature. Source: Prepared by the authors.

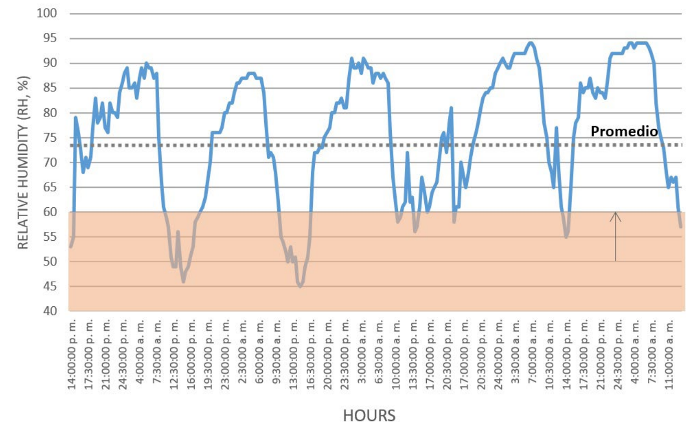

Figure 13. Outdoor relative humidity. Source: Prepared by the authors.

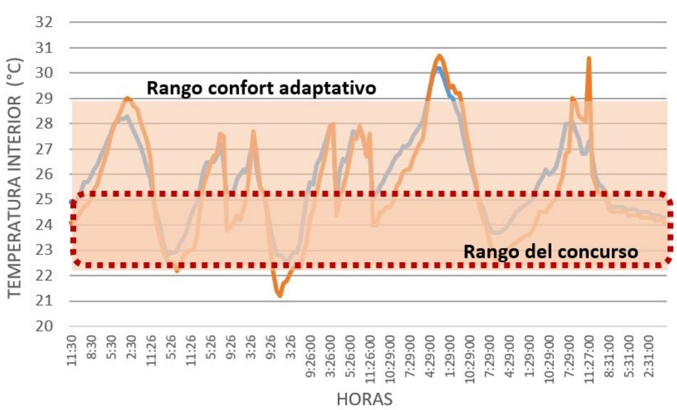

Figure 14. Temperature inside the prototype. Source: Prepared by the authors.

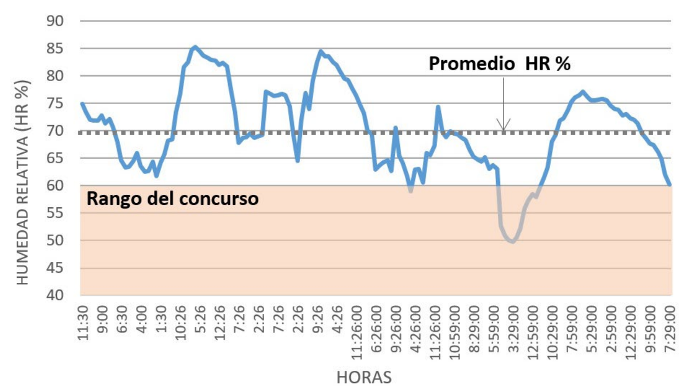

Figure 15. Relative humidity inside the prototype. Source: Prepared by the authors.

tropical and equatorial contexts, like that of this study.

Figures 12 and 13 present the records taken during the 7 days of competition. In these graphs, the hygro-thermal comfort values indicated by the contest can also be seen, along with those of the local conditions, typical of tropical regions.

Regarding the behavior of the spaces inside the prototype, in Figure 14 it can be seen that, despite maintaining an average indoor temperature of 25°C, it is only the during the morning and the early hours that the comfort range proposed by the contest is reached. On the other hand, if the comfort analysis is made using the comfort range proposed by the adaptive model, it is between 21.8°C and 28.8°C (see Equation 1), typical of the tropical contexts and of buildings with natural ventilation, and we see that most days and temperatures are outside the range.

Regarding relative humidity, the values were outside the range of the contest and close to those recorded outdoors, which correspond to naturally ventilated buildings. As can be seen in Figure 15, the average of 70% RH inside the prototype, was close to the outdoor average recorded during the same days (75% RH).

By focusing the analysis of measurements during a typical day of the competition, it is possible to see (Figure 16) that, according to the range proposed by the contest, the prototype is in comfort only at night and early in the morning. While, under the adaptive model, it is only outside the comfort range during the afternoon (1:30 to 4:30pm), with temperatures close to 29°C. This has important energy implications, given that facing a higher comfort requirement, as is the case of analysis considering the range indicated by the contest, using the international standard (designed for other contexts with marked seasons), a thermal design can be assumed that implies a higher energy consumption derived from the need to cool the dwelling's internal conditions.

Photovoltaic panels are implemented that capture solar energy to convert it into electricity, generating

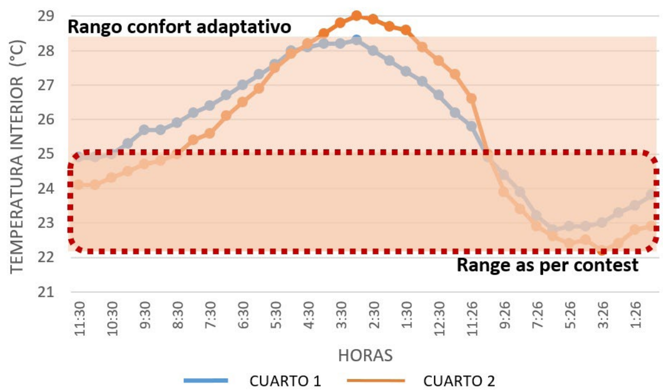

Figure 16. Temperature of a typical day inside the TUHOUSE prototype. Source: Prepared by the authors.

energy self-sufficient homes, to reduce carbon dioxide emissions through the photovoltaic system that produces 3578 kWh a year. By using electricity efficiency, the project's consumption is reduced by almost 40%, which is equal to 1166 kWh saved a year.

The average daily energy consumption of the prototype remained the same during the 8 days of the competition at 58 kWh, responding to the goal of the contest to keep it under 70 kWh. This was achieved thanks to high efficiency household appliances and LED lightbulbs for lighting. Regarding the energy balance, ideal at 0 kWh, was -3.4 kWh here, as a difference between the energy exported to the grid (35.98 kWh) and that imported (39.39 kWh), which allowed it to come third in this test (Macias, 2020).

In sustainability terms, the reuse of graywater (after treatment) is laid out, alongside taking advantage of rainwater for activities that do not require drinking water and that represent an elevated percentage in the home's daily consumption, such as the use of toilets and the green areas and garden watering. The shower and handbasin graywater are collected, in a so-called "eco-guardian" device, to reuse it in cleaning tasks. A rainwater storage tank and interceptor system are also implemented. All this with the purpose of reducing drinking water consumption by 16%, and the amount poured into sewers by 40%. These strategies seek to offset the costs of the drinking water and sewerage service.

The project reduces waste generation for final disposal, correctly separating waste at the source, and disposing organic waste in a composting unit. Using these two measures, around 80% of that generated is used. Alongside this, strategies are proposed to suitably manage the solid waste generated in each one of the phases: construction, operation and demolition.

As a contribution to sustainability, the housing prototype is built with a system of large prefabricated concrete pieces, made from different components that are considered industrial waste, like furnace ash or those from burning bamboo husks from the industry of the region, supplies that also allow improving resistance in the mixes used. This concrete, once its service life is over, does not just become a recycling material for manufacturing non-structural elements, like floor stones, eventually whole pieces can be reused in another type of construction, achieving from this point of view, a high sustainability.

CONCLUSION

The bioclimatic design process implemented in the transversal and interinstitutional course, allowed testing the design decisions made through measurements and simulations, to finally apply the knowledge acquired, in the construction of the prototype in Villa Solar. This was possible thanks to contests like Solar Decathlon, which encourages a dynamic of theoretical-practical learning, essential for Architecture Faculties.

In this framework, the successful behavior of architectural strategies was verified while providing comfort: shading on concrete surfaces exposed to radiation, forming a thermal mass, especially on the roof through the orchard, green envelope, crossed ventilation, permeable façade for ventilation and constant air renewal. Strategies which, with a doubt, were explored for other prototypes of the contest through interesting variations and applications.

The good thermal performance of concrete was shown through the prototype, relevant evidence if it is considered that this is the main material social housing is currently built with, using strategies like shading and double facades, to achieve a comfort situation in terms of the adaptive comfort model.

As has been shown, the ranges demanded by the contest do not match the tropical climate of Cali. This leads to needing to revise said ranges for future versions of the competition in tropical settings. The ranges proposed promote a higher thermal demand and, therefore, the presence of prototypes with mechanical climate control to reach said values, which is uncommon in social housing in Latin American cities.

Finally, it is worth mentioning that, for the competition and execution times, the prototype could not be built in RCA. However, this is a challenge for the future. On the other hand, it is important to highlight that the measures focused on using single-use plastic waste were successful, as a result supplies were generated for elements of the envelope, the seeding and other architectural components, which will be explored further once the prototype is converted in the Housing Laboratory, led by the two universities involved in this project.

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