Thermal comfort analysis of Ayni house at the “Solar Decathlon Latin America and Caribbean 2015”

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Abstract. The Ayni house is a prototype designed and constructed by the National University of Engineering of Peru for the “Solar Decathlon Latin America and Caribbean”, realized in 2015 in Cali, Colombia. In this paper the thermal performance of the Ayni house under the parameters of comfort of the competition is presented.

1. Introduction

The Solar Decathlon is an international university competition created by the Department of Energy of the United States in 2002 to encourage sustainable development, efficient use of energy, implementation of renewable energy, among other aspects, in the sector of construction, at an academic and business level [1]. Since then, it has been held every two years, opening new places on all continents. The realization of these events as educational competitions have proven to be successful according to the professional and technical performance of the students involved, achieving that their knowledge increases in areas related to technical and multidisciplinary aspects [2]. The competition involves the design and construction of a sustainable and efficient house. Undergraduates and recent graduates of the university they represent make up the team that develops the project. Also, they have consulting professors and a representative of the University for the Competition.

The Solar Decathlon comprises ten evaluation areas:

- Evaluations with a jury (six areas): architecture, engineering and construction, communication, marketing and social awareness, urban design, innovation, and sustainability.
- Evaluations through measurements and tests (four areas): energy efficiency, electric energy balance, comfort, and operation of the house.

The National University of Engineering of Peru (UNI) participated in the first Latin American edition, the Solar Decathlon Latin America and the Caribbean 2015 in Cali, Colombia, with the Ayni house project (Ayni, in Quechua language, means reciprocity), a prototype of social housing of passive design, dismountable and mountable on any suitable surface, according to the parameters required by the competition. The design of the Ayni house started with integrating bioclimatic architectural concepts, social awareness, energy efficiency, and sustainability. The main passive design strategies used were natural ventilation and solar protection of openings. Passive design strategies contribute to improve thermal comfort [3].
The thermal behavior of the Ayni house was evaluated with the *EnergyPlus* simulation software. Excellent results can be obtained in the energy performance of both solar systems and room conditioning using this program [4] or with proprietary software that uses the *EnergyPlus* calculation engine [5].

The Ayni house was built in the city of Lima, Peru, on the campus of the National University of Engineering. Once completed, it was disarmed and transported to Cali. There it was assembled again in the Villa Solar at the campus of the University of the Valley of Cali. The Villa Solar housed the 14 competing houses for 38 days, covering the construction stage (10 days), the evaluation and public visit stage (13 days), and the dismantling stage (15 days). The evaluation stage included indoor measurements of air temperature, relative humidity, natural lighting, and acoustic performance. This study uses these measured temperatures.

2. Methodology
The first step in this study was the characterization of the climate of the city of Cali using data from a meteorological station located at the University of the Valley of Cali. Then, two main methods of bioclimatic analysis were used, Givoni psychrometric chart and Mahoney tables, to obtain general architectural design recommendations.

The interior temperature values calculated by simulating the final design of the Ayni house are presented. The *EnergyPlus* program was used for temperature simulations. The program uses the architecture of the house, the climatic information in an interval of one year in Cali, the physical properties of the materials that make up the house (thermal conductivity, density, and specific heat), the occupation of the house and the natural ventilation intervals controlled by opening and closing windows and doors. The simulation was performed for a full year interval and for the competition days, that is, the second week of December. The results obtained through software are useful for the different design stages and to predict the internal behavior of the final design [6].

Then, the thermal comfort, achieved by the Ayni house during the competition week, is analyzed using the measurements made by the organization. The comfort range chosen by the competition is taken as a reference. Finally, a comparison is made between the measured and simulated results.

2.1. Comfort Range
The physical variables measured by the competition to determine the appropriate degree of comfort are: temperature, relative humidity, natural lighting and acoustic. For the present study, we are interested in thermal comfort. This comfort zone is determined by the competition by the equations [7]:

\[
T_{\text{min}} = 0.255T_{ed}+17.9 \degree C
\]

\[
T_{\text{max}} = 0.255T_{ed}+19.9 \degree C
\]

Where \(T_{\text{min}}\) is the minimum temperature of the comfort zone (°C), \(T_{\text{max}}\) is the maximum temperature of the comfort zone (°C) and \(T_{ed}\) is the average outside temperature for a week (°C) calculated from:

\[
T_{ed} = \frac{(T_{ed-1}+0.8T_{ed-2}+0.6T_{ed-3}+0.5T_{ed-4}+0.4T_{ed-5}+0.3T_{ed-6}+0.2T_{ed-7})}{3.8}
\]

Where, \(T_{ed-1}\) is the average daily outside temperature \(i\) days before (°C), taking \(i\) values from 1 to 7. The comfort zone is calculated each day of competition according to the \(T_{ed}\) temperatures (°C) recorded by the meteorological station installed in the Villa Solar.

3. Ayni house
A multidisciplinary team made up of students and graduates from the careers of architecture, civil engineering, mechanical engineering, electrical engineering, physical engineering, sanitary engineering, economic engineering, and electronic engineering designed the Ayni house. The design, from its conception, involves all careers.
Cali is located at 3° 26’ north latitude, 76° 31’ west longitude, and at an average altitude of 1018 meters above sea level. The climate of this region is Tropical Sabana, category Aw in the Köppen classification. Climate information of Cali was provided by the Solar Decathlon organization, from a meteorological station located within the University of the Valley. The annual average temperature is 24.2 °C, the average maximum temperature is 29.8 °C, the average minimum is 19.0 °C, and the average annual temperature range is 10.8 °C. Temperatures can reach up to 36.4 °C and drop to 11.5 °C. The annual average relative humidity is 73.3%, the annual average maximum is 100% and the annual average minimum is 54.1%.

The average daily solar energy of Cali is 4.65 kWh/m². The monthly values are shown in figure 3. The average annual rainfall of Cali is 1600 mm. The monthly values are shown in figure 4. The prevailing wind direction is NOO, with speeds from 2.1 m/s to 8.8 m/s (figure 5).
3.1. Bioclimatic analysis

Observations show that the physical and mental activities of human beings develop optimally in a certain range of climatic conditions. Outside this range, their work efficiency decreases, while the stress and risks of suffering a related disease increase [8].

The climatic data of Cali was analyzed under two methodologies. First, in a psychrometric graph, we applied the Givoni method [9]. Then, we applied the Mahoney tables [10]. Finally, a bibliographic review of bioclimatic recommendations was made following the results of the applied methods.

3.1.1. Givoni psychrometric chart. Givoni’s comfort graph [9] suggests limits and zones of climatic conditions within which there are design strategies and recommended natural air conditioning systems to provide comfort within the building.
A comfort zone is located on a psychrometric chart, based on expected interior temperatures in buildings without mechanical air conditioning systems and appropriately designed for the site. The temperature and humidity measurements are located in the chart as blue squares (figure 6), and by the location of these, three main strategies can be identified: natural ventilation, mass cooling, and internal gains.

3.1.2. Mahoney Tables. The Mahoney method [10] is used to evaluate the requirements of thermal comfort in traditional houses and new houses, especially in tropical climates [12]. The method consists of several stages of analysis. The first stage is the registration of the monthly climatic data. This information has already been presented and synthesized previously. Then, the comfort limits and the warm (C), well-being (B) or cold (F) conditions are obtained for day and night (table 1).

| Table 1. Mahoney method, comfort limits and monthly comfort diagnosis. |
|-----------------------------------------------------------|
| Temperatures | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| Tmax (°C)     | 29.9 | 29.9 | 30.2 | 29.7 | 29.3 | 29.5 | 30.3 | 30.9 | 30.3 | 29.2 | 28.8 | 29.1 |
| Superior day comfort (°C) | 27.0 | 27.0 | 27.0 | 27.0 | 27.0 | 27.0 | 27.0 | 29.0 | 27.0 | 27.0 | 27.0 | 27.0 |
| Inferior day comfort (°C) | 22.0 | 22.0 | 22.0 | 22.0 | 22.0 | 22.0 | 22.0 | 23.0 | 22.0 | 22.0 | 22.0 | 22.0 |
| Tmin (°C)     | 19.2 | 19.2 | 19.3 | 19.4 | 19.4 | 19.0 | 18.3 | 18.5 | 18.8 | 18.9 | 19.0 | 19.0 |
| Superior night comfort (°C) | 21.0 | 21.0 | 21.0 | 21.0 | 21.0 | 21.0 | 21.0 | 23.0 | 21.0 | 21.0 | 21.0 | 21.0 |
| Inferior night comfort (°C) | 17.0 | 17.0 | 17.0 | 17.0 | 17.0 | 17.0 | 17.0 | 17.0 | 17.0 | 17.0 | 17.0 | 17.0 |
| Thermal sensation Day | C | C | C | C | C | C | C | C | C | C | C | C |
| Thermal sensation Night | B | B | B | B | B | B | B | B | B | B | B | B |
| Indicator | H1 | H1 | H1 | H1 | H1 | H1 | H1 | H1 | H1 | H1 | H1 | H1 |

Each month is evaluated according to the conditions of Mahoney method [10], obtaining 12 months with the H1 indicator (air movement required) and 2 months with the H3 indicator (rain protection).

Finally, recommendations and design guidelines are obtained based on the number of months with the different indicators, which in this study have been synthesized [12] in the following list:

- North-south orientation (east-west longitudinal axis), protection of direct sunlight of openings and a light and reflective roof (with air chamber) to reduce solar gains.
- Rooms in a single row and open spaces for penetration of breezes.
- Large openings, 40-80% of the wall area, in north and south walls, at the height of the body and windward for natural ventilation in the direction of prevalent winds.
- Protection from rain. Light walls with high thermal transmission to cool indoor environment.

3.1.3. Bioclimatic recommendations. Following the results obtained from Givoni and Mahoney, the following general design recommendations were proposed as the main strategies:

- Natural ventilation: open spaces are needed in front and behind the house, as well as large openings at the height of the body, oriented in the predominant direction of the wind (northwest) and in the opposite direction (southeast) to favor permanent cross ventilation.
- Solar protection: use of eaves and parasols on windows to prevent direct sunlight from entering the home and protect them from rains.
- Envelope: light, low thermal mass, with clear and reflective surfaces (walls and ceilings respectively). Use of air chamber or insulation in the ceiling.
• Internal thermal mass and gains: low thermal mass and internal gains typical of electrical
appliances and inhabitants to maintain an energy balance at night.

Some of the recommended strategies to improve natural ventilation [13] include:

• It is preferable to have an inlet opening larger than the outlet.
• An open floor plan allows higher wind speeds indoors. The openings must be placed in the
desired direction of the airflow.
• The different directions of the winds that reach the house must be considered so that when
entering the house they do not create a wind shadow.

3.2. Implemented bioclimatic techniques
The implemented bioclimatic techniques in the Ayni house can be grouped into cooling, heating, and
insulation techniques. The cooling techniques are: open flat and oriented towards the NW for permanent
ventilation, a shaded space from where the air enters the house, openings and walls protected from solar
radiation and light, insulated and reflective roof (figure 8).

Figur 7. Cooling strategies.  Figure 8. Heating strategies.

The heating techniques are: internal loads (electrical equipment and occupants) and thermal mass in
the internal walls (drywall). The insulation techniques are: air spaces in the walls that are used as shelves
and an enclosure with internal insulation (figure 8).

3.3. Final design of the Ayni
The Ayni house was designed with prefabricated elements. This allows it to be disassembled and
assembled. The materials and thermal conductivity of the envelope are describe in table 2.

| Table 2. Materials and thermal conductivity of the envelope. |
|-----------------------|----------------|
| **Materials**         | **Thermal conductivity** |
| Walls                 | 0.74 W/m²K          |
| Fiber cement plate    |                   |
| Polyester wool        |                   |
| Plasterboard          |                   |
| Floor                 | 2.37 W/m²K          |
| OSB                   |                   |
| Material               | R-value (W/m²K) |
|------------------------|-----------------|
| Wood laminate / ceramic|                 |
| Zinc-aluminum          | 0.34            |
| Expanded polystyrene   |                 |
| Vinyl                  |                 |

4. Simulations with the final design

The simulations carried out with the Ayni house serve to verify the behavior of the house under the bioclimatic strategies implemented and to validate some decisions of choosing the technique that obtained the best results. The results shown below were worked with the final design of the Ayni house using the EnergyPlus software and considering the presence of 5 people with typical hours of use of a single-family house, as well as the typical electrical equipment.

4.1. Thermal analysis

Using the EnergyPlus software, the thermal behavior of the Ayni home was obtained for one year (monthly average) and for the competition month (hourly average). Table 3 summarizes the average values obtained in the simulation and the climatic data.

Figure 9. Final design of the Ayni house.
It is observed that the average outdoor and indoor temperature remains very similar in both cases, 23.7 °C and 23.4 °C respectively, in the maximum and minimum values, and therefore in the thermal amplitude, exists a great variation. There is a 5.5 °C reduction in the average maximum temperature (measured outside and simulated inside) and a 2.7 °C increase in the average minimum temperature (measured outside and simulated inside). The thermal amplitude is reduced to 8.2 °C.

For December, the thermal amplitude drops from 23 °C to 14.4 °C (8.6 °C difference), the maximum value is reduced by 5.7 °C and the minimum value is increased by 3 °C.

5. Results and discussion

5.1. Villa Solar measurements
One of the tests of the competition is the comfort conditions achieved in the home. To do this, the competition organization installed humidity, temperature, and lighting sensors in three areas of the house: living room, kitchen, and bedroom. These sensors worked for the 10 days. However, the assembly of the Ayni house was delayed by 5 days and the sensors only registered the last 5 days of the competition.
Figure 12. Temperatures measured by the organization of Solar Decathlon inside and outside the Ayni house from December 9th to 14th. Exterior temperature (Te) and interior temperature (Ti).

Figure 12 shows the temperatures measured by the organization during the competition. The outside temperature was measured in a meteorological station installed in Villa Solar. The indoor temperature shown corresponds to the temperature measured in the Ayni living room. The comfort range calculated for those days of competition goes from 24 °C to 26 °C. Table 4 summarizes the obtained average values. It can be seen that the interior maximums are slightly less than the exterior maximums and the interior minimums are greater than the exterior minimums.

Table 4. Average measured temperatures inside and outside the Ayni house.

|                      | Average  |
|----------------------|----------|
|                      | Outside  | Inside   |
| Maximum temperature (°C) | 33.1     | 32.2     |
| Average temperature (°C)    | 25.8     | 26.8     |
| Minimum temperature (°C)     | 20.3     | 22.6     |
| Thermal range (°C)            | 12.8     | 9.6      |

The average maximum indoor temperature is 0.9 °C lower than the average maximum outdoor temperature. The average minimum indoor temperature is 2.3 °C higher than the average outdoor maximum temperature. The interior thermal amplitude is 3.2 °C less than the exterior.

Table 5 shows the number of hours of comfort inside the Ayni home compared to outside. We went from 9.8% to 22.0%. The number of hours in comfort has doubled.

Table 5. Hour distribution of comfort.

|        | Outside | Inside |
|--------|---------|--------|
| Hours  | 12.0    | 27.0   |
| Percentage | 9.8%   | 22.0%  |
5.2. **Comparison between simulated and measured data**

Table 6 summarizes the temperature values expected by the simulation for the month of December and the values measured on the days of competition.

| Difference between outside and inside | Simulations | Readings |
|---------------------------------------|-------------|----------|
| Maximum temperatures (°C)             | - 5.7       | - 0.9    |
| Minimum temperatures (°C)             | + 3.0       | + 2.3    |
| Average temperatures (°C)             | - 0.3       | - 0.2    |
| Thermal ranges (°C)                   | - 8.7       | - 3.2    |

It is observed that the house has behaved in the sense of the simulation, but not with the expected values. The maximum temperatures have not decreased as expected in the simulation. It is the most noticeable difference between the measured and simulated results (4.8°C). This difference directly affects the thermal range performance. The measured thermal range decreased 5.5°C less than the simulated one. This could be because there was more daytime ventilation than planned and simulated. The vents were kept open during the day to avoid discomfort from high humidity due to the use of kitchen appliances. This effect should have been considered in the simulation.

6. **Conclusions**

The number of hours within the comfort zone inside the Ayni home, compared to the outside, rises from 9.8% to 22.0%, considering temperatures. There are still 78% of hours outside of the comfort zone. To reach 100% of the time within the comfort zone, as defined by the competition, active air conditioning is required.

Measurements of temperature inside the home show that the simulation correctly predicts the direction of improvement, however, not the expected value. Maximum indoor temperatures were expected to drop 5.7 °C below the outside temperature, but have only dropped 0.9 °C. Low ventilation had been considered in the hours of maximum temperature for the simulation, however, on the days of competition, it was preferred to ventilate the house to avoid high humidity. The difference between the measured and simulated values of temperature shows that the daytime ventilation strategy adopted during the competition increased the indoor temperature.

As there were only few days of monitoring of the interior conditions of the house, it is not possible to obtain a reliable understanding of the performance of the passive systems implemented [14].

The design recommendations and bioclimatic strategies given are based on three points: a general study for hot climates, a special study for the city of Cali, and computational calculations and simulations. All of them are aimed to improve interior comfort, reducing the maximum values of temperature, and reducing the temperature range. However, this was insufficient to achieve that the interior temperature of the house is within the comfort range designated by the competition.

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