JLASC
Journal of Latin American Sciences and Culture

Article

Design and implementation of a bioclimatic housing prototype for the Bolivian highlands

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Abstract: The Mechanical - Electromechanical Engineering research institute, made up of a multidisciplinary team, designs and implements a bioclimatic housing prototype for the Bolivian highlands, located near the Andes Mountains at an altitude of 3,000 to 4,000 meters above sea level. This project was developed and implemented with financing from the Swiss Cooperation for Bolivia, within the Climate Change Adaptation projects.

The design process includes: the sociocultural study of the inhabitants of the region, where direct information is collected from the peasants on the conception of housing in their culture and ancestral construction characteristics of their houses. Subsequently, the climate of the region (temperatures, solar radiation, winds and relative humidity) is characterized with the help of a meteorological station, which provided historical records of 5 years. Those data were sufficient to be able to carry out a reliable characterization, with which the Typical Meteorological Year is determined. Likewise, local construction materials that may be useful in the design are studied, analyzing their thermal and mechanical properties in the laboratory.

Finally, with all the information described, an architectural design is carried out taking into account bioclimatic aspects, ways of harnessing solar energy, distribution of the room and a viable construction cost for the economic reality of the region. The developed architectural model is optimized in an energy simulation program (SITER Vs. 1.2), achieving energy savings of 65%. The software used is owned property of the research institute

The house has been monitored with temperature sensors for about a year and six months, to date it shows good results, where the correct functioning of the elements and constructive forms is evidenced, reflecting a temperature inside the house of around 10 °C above room temperature 24 hours a day.

Keywords: Prototype, bioclimatic housing, alternative energies, energy efficiency, design

Citation: Lamas, E. V., & Calani, S. R. (2023). Design and implementation of a bioclimatic housing prototype for the Bolivian highlands. *Journal of Latin American Sciences and Culture*, 4(6), 39-56. https://doi.org/10.52428/27888991.v5i7.309

Received: February 22, 2023
Accepted: May 11, 2023
Published: July 30, 2023

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1. Introduction

In the last decade, global warming has been named in different scenarios, attributed to the large emissions of carbon dioxide, whose consequences have been shown in different forms, such as droughts, floods, extreme maximum and minimum temperatures, hurricanes, earthquakes, tsunamis, among others. These are recurring and are the product of changing environmental conditions. Several international organizations are creating awareness and implementing aid through projects to adapt to climate change, reduce carbon dioxide emissions, and clean energy, among others.

Currently, the use of primary energy derived from oil is the energy base of many countries in the world, and so it is for Bolivia. Bolivia has an energy matrix based on oil derivatives, with a small percentage of hydroelectric plants in the electricity generation sector and a tiny insertion of renewable energies.

Several organizations worldwide show as a viable means the beginning of awareness of the population about the correct and optimal use of energy, it is the first step towards a possible solution to current environmental problems, as well as adopting and developing new forms of use of the alternative energies available in our environment. It is the premise to start curbing global warming.

In response to these objectives, the present project is developed, in order to reduce the consumption of conventional energy in the daily use of air conditioning in homes, basing the study on the foundation of social, cultural, environmental, architectural and energy saving criteria.

2. Methods

The present work is the result of several years of research carried out by a multidisciplinary work team. This led to the construction of a bioclimatic housing prototype taking aspects not only focused on the construction of the house itself, but also on cultural aspects rooted in our society and ancestral cultures, as well as ensuring the conservative cost in terms of current buildings. So, the steps taken for the construction of the prototype are presented continuation.

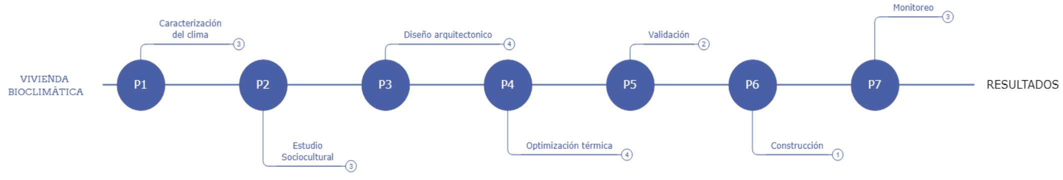


Figure 1. Sequence of steps to follow in the developed methodology

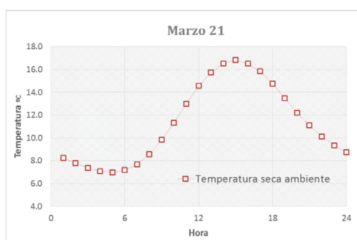
2.1. Climate Characterization

a) ***Geography:*** The bioclimatic house was built in the city of Oruro - Bolivia, located at latitude 17°59’35.5”S and longitude 67°08’10.3”W, near the Andes Mountain range, at an altitude of 3706 meters above sea level, within the highlands region of Bolivia.

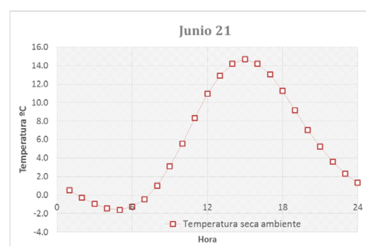
Oruro is located within the tropical belt where the climate is characterized by a dry season, which includes a dry winter (April, May, June, July, and part of August), and an intermittent rainy season (October to February). The other months are transitional, where the difference between a dry year and an increase in humidity on rainy days is noticeable, highly relevant aspects for agricultural and overall productive dynamics.

b) ***Temperature:*** A disclosure of data on the behavior of the temperature of the meteorological station of the Electromechanical Mechanical Engineering Career of the National Faculty of Engineering is carried out, a sample period of 5 years is taken, with which a typical meteorological year is determined, in that way this variable is characterized. The following figures show the behavior of temperature at solstices and equinoxes.

Figure 2. Temperature Characterization of the city of Oruro:



a)



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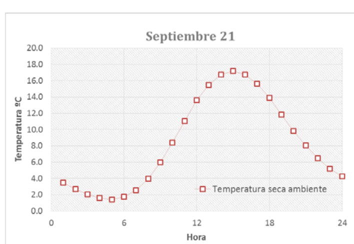
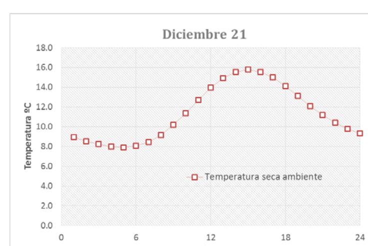


c)



d)

a, b) Temperatures during the autumn and winter seasons **c, d)** Temperatures during the spring and summer seasons *c)* ***Wind:*** The wind dynamics are an important characteristic of highland ecosystems, particularly when they are located in the tropical zone. In this region, the temperature difference within a day is variable, meaning there are very cold nights and extremely hot midday temperatures. The clash between hot and cold winds generates strong wind gusts that start in the afternoon and last until the night. The behavior of the wind in the region has been obtained from the database of a private meteorological station (*meteoblue*), the wind rose figure shown below indicates the direction of the wind, speed and time in hours per year in that the wind blows in the different directions as shown.

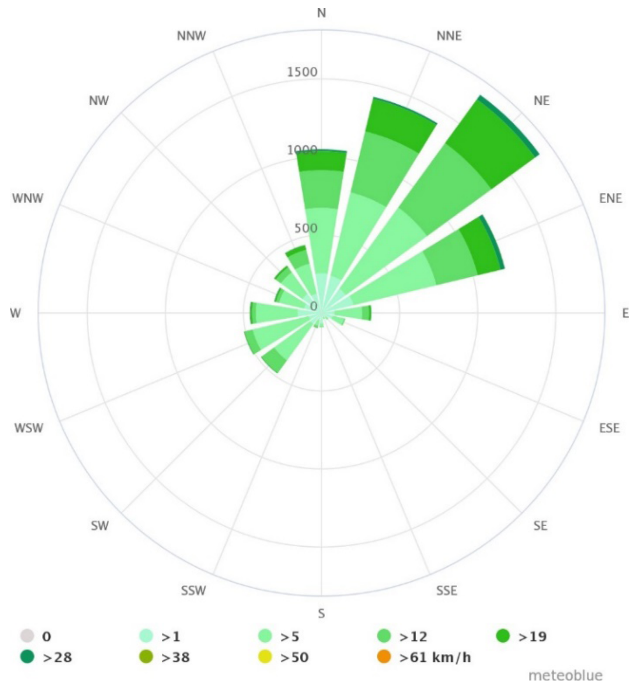


Figure 3. Oruro-Bolivia wind rose (meteoblue: www.meteoblue.com).

d) ***Solar radiation:*** The solar radiation data are obtained from the meteorological station of the Electromechanical Mechanical Engineering Career of the National Faculty of Engineering. The data recorded are of global radiation, which have subsequently been disaggregated into their components, direct and diffuse radiation.

The following graph shows the incidence of direct radiation on a flat horizontal surface.

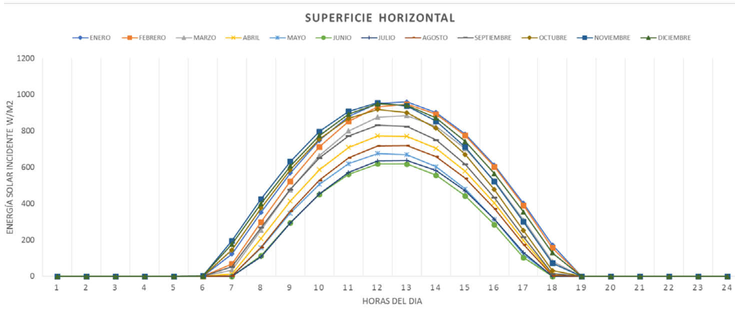


Figure 4. Direct solar radiation on a horizontal surface. Oruro City

Subsequently, based on these data, the direct solar radiation incident on each surface of the building is calculated, in order to quantify the energy available due to solar radiation.

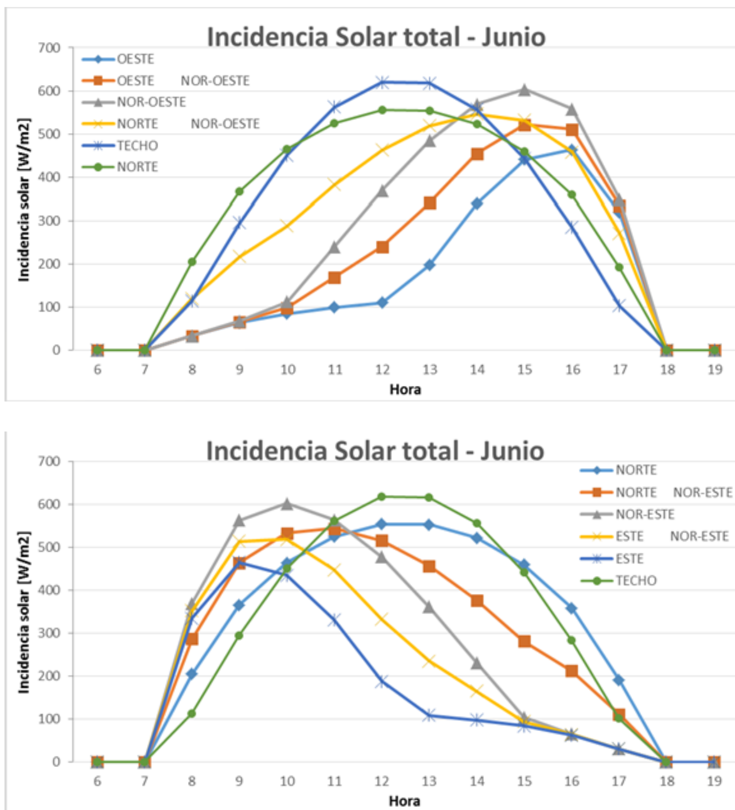


Figure 5. Average solar incidence in the different orientations (16) of the enclosure, June.

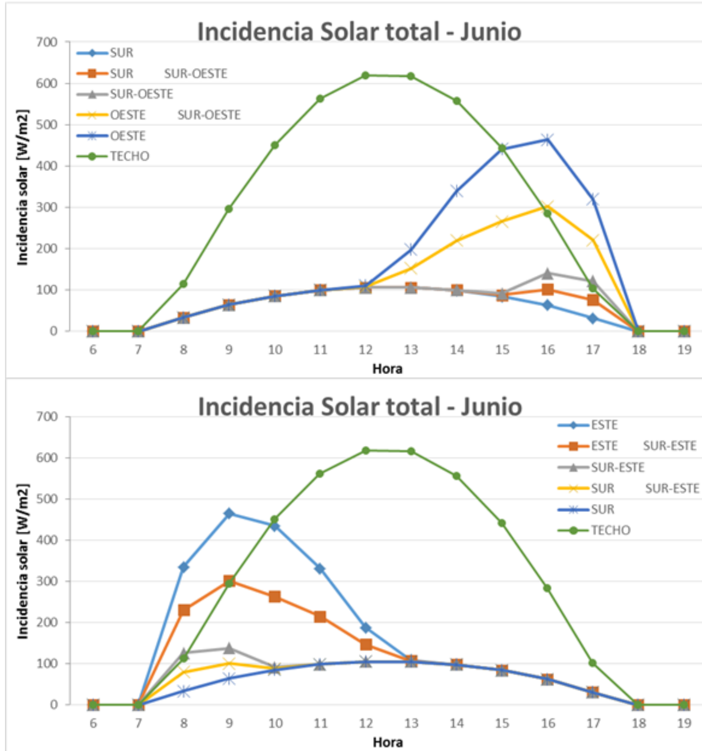
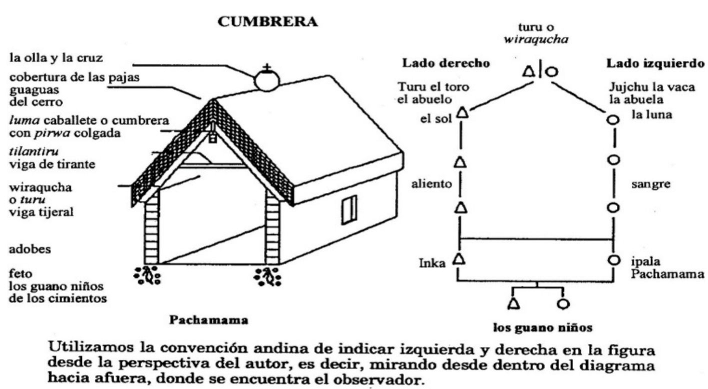


Figure 5B. Average solar incidence in the different orientations (16) of the enclosure month of June (Continuation).

1.1. **Sociocultural Study**

In the ancestral Andean culture, there is a conception of housing as a being, which has its own energy, is built with specific elements and forms, and has a specific meaning in Andean cultures, Quechuas and Aymaras. Quispe, in 2005, makes an extensive study about it, the following graph shows a summary about it.



We use the Andean convention of indicating left and right in the figure, from the author's perspective, that is, looking from inside the diagram to the outside, where the observer is.

Figure 6. The Andean conception of housing (Arnold, 1992).

a) Historical transformation of the houses: The houses built by the native Quechuas-Aymaras of the region have particular characteristics in their construction, which are recognizable at first glance, such as,

- The construction materials are typical of the area (adobes[1], Ch'ampa[2], straw[2], etc.) that do not have any treatment and are biodegradable, they have a robust constitution in their walls and roofs.

- The orientation of their homes, if they are in a community, are built and organized in a circular way in order to avoid winds and minimize inclement weather.

- The houses have particular construction characteristics such as the orientation of the door that always faces east, its internal distribution that is strategic with respect to the solar path, among others.

As foreigners settled in the region, they adopted more elaborate and aesthetically pleasing constructive forms that are recovered and brought from other regions of the world. In our case, due to the exploitation of precious minerals in the region, the largest Cultural influence in the area was brought from Europe mainly from Spain.

However, these forms and materials were used in places with different climate characteristics, which are not a good option in our environment due to the particular characteristics of the area. The available buildings are thermally inefficient, and the adaptability of the materials is carried out without any economic technical criteria.

3. Results

1.1 Design

a) ***Environment:*** The bioclimatic house has been built on the premises of the National Faculty of Engineering, it is an environment with little flora, there is little fauna, just a few typical birds of the region (goldfinches), without a shading area for construction

The climatological characteristic of the area is defined by having high levels of global solar radiation during the day, as well as low temperatures at night and in the morning most of the year.

1 Adobe is an unfired brick, a building block made of a mass of mud (clay and sand), sometimes mixed with straw, molded into a brick shape, and dried in the sun.

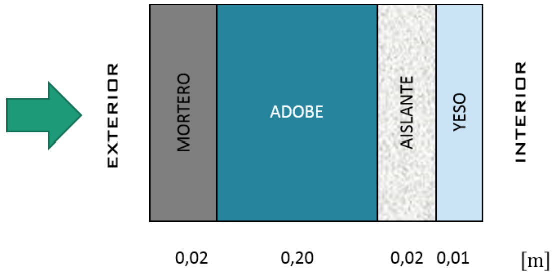
2 The champa is a word in Quechua that is understood as the remains of straw (highland grass) and other remains of local vegetables

Figure 7. Bioclimatic house.

b) ***Materials:*** For the selection of materials, an extensive study of the properties is carried out in existing materials in the region, and, from this, using the most appropriate ones. A differentiated study of different compositions and constructive solutions has been carried out, based on the response factors (Pinazo, 1996), identifying and characterizing the materials with greater thermal inertia and also that show late responses of energy transmission from the outside to the inside and/or vice versa to the thermal zone.

For the walls or lateral walls, two types are proposed: to the south, which is the orientation where there is no solar incidence in the geographical place of study almost the entire year, in addition, where the winds have greater incidence. AA wall with high thermal and insulating inertia is selected, the characteristics see figure [8].

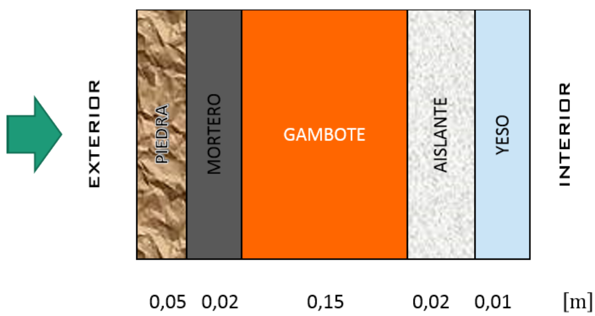
The second configuration of walls is applied to the east, north and west orientation, which has characteristics of less inertia, but maintaining the insulating property. This wall has the characteristics shown in figure [9].



Propiedades	Mortero	Adobe	Aislante	Yeso
k $\left[\frac{W}{m \cdot °C}\right]$:	1,4	0,95	0,046	0,3
ρ $\left[\frac{kg}{m^3}\right]$:	2000	1600	30	800
cp $\left[\frac{J}{kg \cdot K}\right]$:	1000	1840	1000	1000

$$U = 0,771 \left[\frac{W}{m \cdot °C}\right]$$

Figure 8. Configuration and properties of walls facing south.



Propiedades	Piedra	Mortero	Ladrillo Gambote	Aislante	Yeso
k $\left[\frac{W}{m \cdot °C}\right]$:	3,5	1,4	1,03	0,046	0,3
ρ $\left[\frac{kg}{m^3}\right]$:	2750	2000	2140	30	800
cp $\left[\frac{J}{kg \cdot K}\right]$:	1000	1000	1000	1000	1000

$$U = 0,811 \left[\frac{W}{m \cdot °C}\right]$$

Figure 9. Configuration and properties of walls facing east, north and south.

For the windows, double glass was used, with the configuration of two glass walls separated by an air space that serves as insulation, which has the following configuration and characteristics:

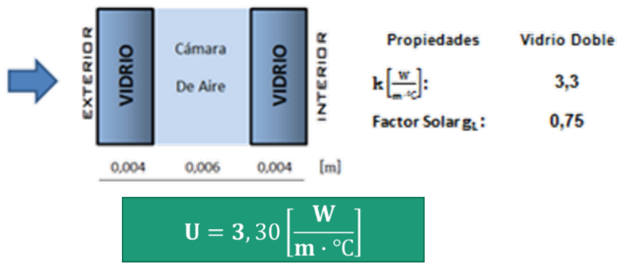


Figure 10. Configuration and properties of glazing in windows.

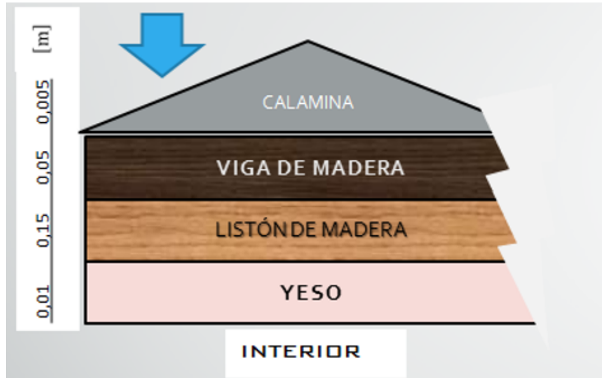
The floor (enclosure with greater heat transmission due to low temperatures throughout the year, average 5°C), materials of high thermal inertia were used, it is recommended to insulate the enclosure from the ground. However, this action makes the costs rise, for which the composition of the soil sought the balance between cost and heat transmission. The characteristic of the composition of the soil is [11].

Propiedades	Tierra	Piedra Andesita	Mortero	Cola Parquet	Parquet Liviano
$k\left[\frac{W}{m\cdot °C}\right]$:	0,52	3,5	1,4	1,4	0,23
$\rho\left[\frac{kg}{m^3}\right]$:	2000	3000	2000	2000	620
$cp\left[\frac{J}{kg\cdot K}\right]$:	1840	820	1000	1000	1600

$$U = 2,264\left[\frac{W}{m \cdot °C}\right]$$

Figure 11. Configuration and properties of the floor.

Finally, for the roof, a ceramic material (tile) was proposed that has insulating properties and thermal inertia. Due to economic limitations, the installation was carried out with a calamine roof with gypsum plaster, which has the following characteristics and properties:



Propiedades	Yeso	listón de madera	Tablón de Madera	Calamina Metálica
k $\left[\frac{W}{m\cdot°C}\right]$:	0,3	0,23	1,4	17
ρ $\left[\frac{kg}{m^3}\right]$:	800	775	2000	7900
c $\left[\frac{J}{kg\cdot K}\right]$:	1000	1600	1000	880

U = 1,8 W/mºC

Figure 12. Configuration and properties of the roof.

c) ***Room distribution:*** The distribution of the rooms is carried out with two important concepts: first, the hours of use of the room, and second, the availability of incident energy from solar radiation, which can be used to air-condition the room.

Therefore, the room was distributed as shown in figure [13].

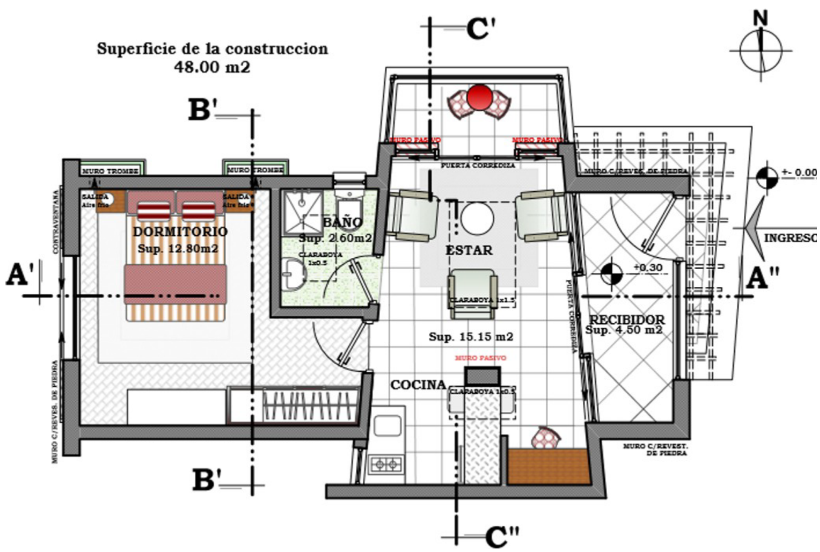


Figure 13. Distribution of the rooms in the house.

d) ***Heat gain elements:*** To take advantage of the abundant solar energy in the region, passive energy gain elements are chosen. In our case, three elements are installed:

The first is two Trombe walls located on the north side, installed in the north enclosure of the bedroom, elements that have appropriate characteristics to take advantage of solar energy and contribute to the air conditioning of this area.

Figure 14. Passive heat gain elements, attached greenhouse and Trombe wall.

In the same orientation (north), an attached greenhouse is installed, separated from the thermal area or rooms by a sliding door, an important element to take advantage of high thermal gains from incident solar energy.

e) ***Architectural design:*** The economic availability has made it possible to locate a single-family home with an area of 48 [m2] with a north orientation, without obstacles in the orientation of greater solar incidence. The geometry is represented in [13].

1.2 Model optimization: The thermal optimization of the model has been carried out using the Siter program version 1.2, developed at the Research Institute. Where the orientation, geometric north, the use of suitable materials in the enclosures, the geometry of the transparent elements, and the thermal gains, among others, have been optimized. There is an energy saving of 65% in the improved house compared with the house built with conventional elements.

1.3 Validation The simulation of the thermal behavior of the house in conditions (a typical day) is carried out with the multidisciplinary software COMSOL, where the thermal behavior can be verified, showing heat gain in the installed elements. In the solarium, temperatures of 30 to 40°C or more are reached, which is controlled by the entry of energy into the thermal zone through the sliding door that separates both zones, to have the comfort temperature.

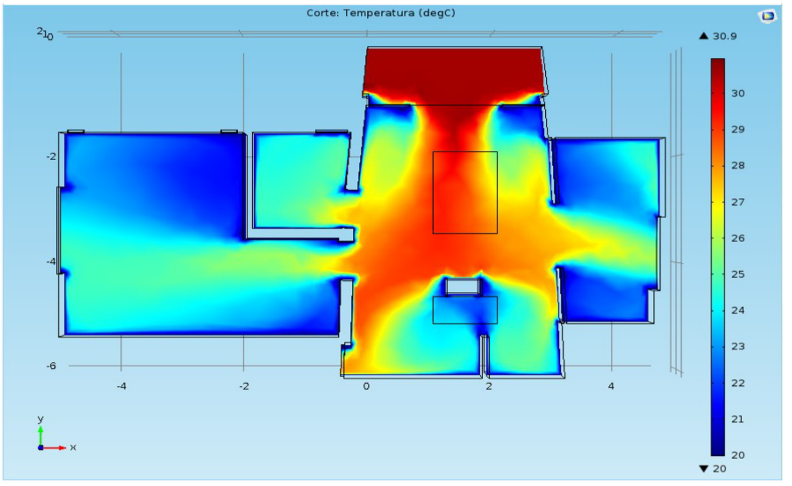


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Figure 15. Simulation of heat gain by the attached greenhouse on a day in June (COMSOL Multiphysics).

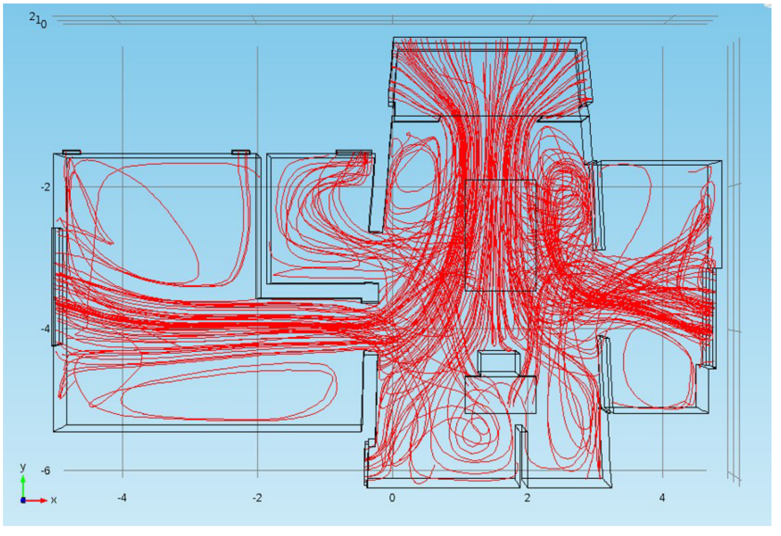

Figure 16. Heat propagation lines in the different rooms (COMSOL Multiphysics).

The isoclines of energy gain in figure [16] show the importance of each construction element, in the enclosures. The composition of the materials, conductivity, and thermal inertia of each one establishes the heat gain during the day, and that, in later hours (twilight and night), is progressively returned to the thermal zone. The thermal conductivity makes it easier for that stored energy not to be lost, dissipating to the outside in the following hours.

1.4 Building

The construction was carried out with local labor, supervised by professionals knowledgeable in the matter.

The construction took an approximate time of 9 months, and it was concluded in March 2018. The funds for this project to be executed were obtained through a contest in the project "Applied Research Projects for Adaptation to Climate Change" that are financed thanks to the Swiss Cooperation in Bolivia.

1.5 Monitoring

Finally, once the construction of the bioclimatic housing prototype has been completed, a monitoring unit is installed in the home, where the temperature is recorded at 6 strategic points: outside temperature, attached greenhouse temperature, bathroom temperature, living room temperature, bedroom temperature, and the temperature of the hall, in addition to the temperature outside, relative humidity, wind speed and direction, global radiation. On the inside there are also records of relative humidity.

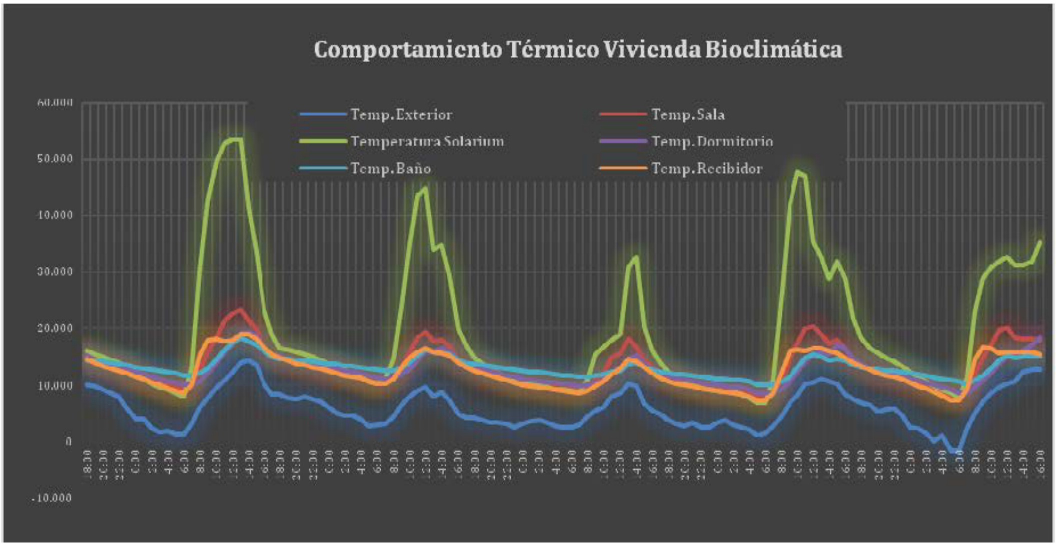

Figure 18. Temperatures recorded in the bioclimatic house from June 6 to 9, 2019.

It should be clarified that the use of housing is for an office, whose hours are from 8:30 a.m. to 12:30 p.m. and from 2:00 p.m. to 6:00 p.m.

The behavior of temperatures is shown in Figure 18, where it is observed that the house has an efficient thermal behavior in all the monitored environments, in the winter months, as well as the temperature difference between the interior and the exterior of around 10 °C.

The temperature in the adjoining greenhouse reaches 50 °C, being the fundamental contribution to air conditioning the house, it is evident that the temperature reached in this element is too high and is outside the recommended limits of comfort, the flow of energy between the rooms and the townhouse from is controlled with the sliding door, the opening of this element is established in relation to the temperature of the townhouse and is done manually by the occupants of the house.

In the same graph shown above, it can be seen that the bath has a stable behavior of temperature, the records oscillate in 7°C of ΔT, the maximum temperature recorded is 19°C and the minimum is 12°C. For an Iclo of 1.25 (Iclo is defined as the coefficient of thermal insulation of clothing or clothing worn by a person, 0 naked and 1.5 very warm), for the manifested Iclo value and with minimal activity of the occupants, the thermal sensation of 18°C is within the comfort standards in our area.

1.6 Contrasting with a Conventional model

The contrasting of the results obtained of the proposed architectural model (bioclimatic housing) was carried out with a similar architectural model (conventional housing), the exception is, the conventional housing uses building materials commonly used in the constructions of the region or the cities of the Bolivian Altiplano.

The results are quantified in the need for both houses to maintain thermal comfort conditions, in all spaces, 24 hours a day and 365 days a year. Because of to the climatological characteristics of the region, there is only the need to maintain the comfort condition in heating and not in cooling.

The results of the comparison are shown below:

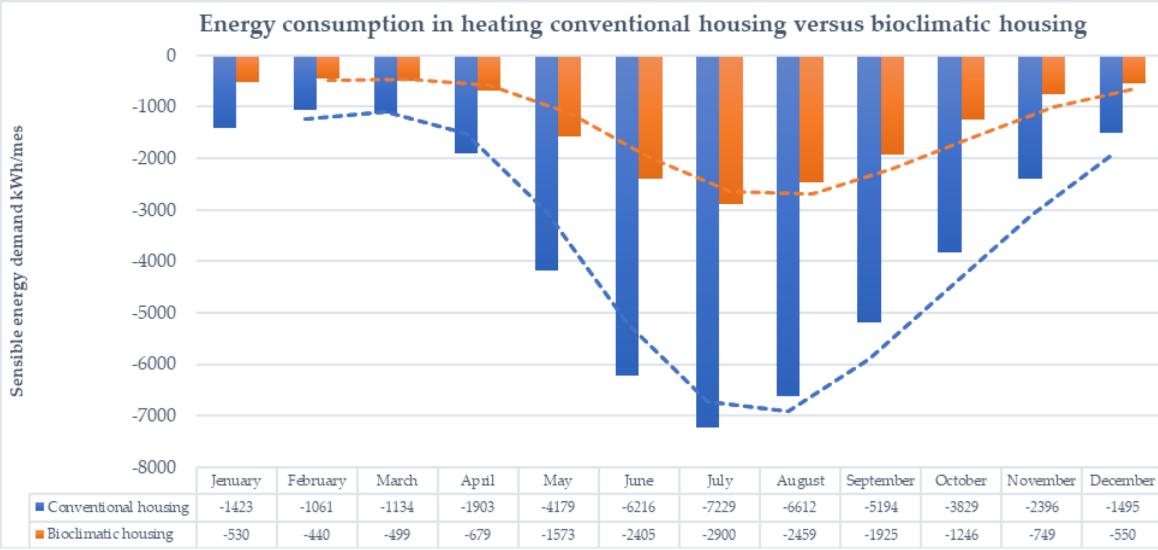

Figure 19. Energy consumption in heating conventional housing versus bioclimatic housing.

The comparison of a house built with conventional materials and the bioclimatic is in Figure 19. It can be seen that a conventional house, per year, consumes energy for heating in 42540 kWh/year, however, the bioclimatic house for the same service the energy consumption for heating is 15740 kW/h/year. The energy savings are considerable. A saving of 63% is recorded, in a similar work carried out by Flores Larsen et.al [3], the results of energy saving were 50% for actions of similar study conditions. Therefore, it can be noted that the presented proposal has greater efficiency and energy savings.

4. Conclusions

It is possible to characterize the behavior of the ambient temperature over a year, based on the historical data of the meteorological station of the Electromechanical Mechanical Engineering Career of the National Faculty of Engineering, the type year has been generated.

With the global solar radiation records obtained from the same meteorological station, the incident direct radiation on the walls and enclosures of the bioclimatic house is disaggregated and calculated.

Sociocultural information is acquired about the conception of housing in the Quechua and Aymara cultures of the region through direct interaction with the peasants of these cultures.

It is possible to characterize materials typical of the region that are applicable in civil constructions of medium magnitude such as adobe, volcanic stones, among others, due to their particular characteristics of their density and mechanical resistance. They are not applicable to buildings of large magnitudes.

The construction cost of the bioclimatic house is reasonable and is around 50 dollars per square meter, more than a regular construction in the region.

The thermal assessment and simulation make it possible to carry out an accurate diagnosis of the thermal behavior of the house. This option makes it easier to improve the design, location, choice of construction materials, among others, allowing significant savings in conventional energy consumption.

The bioclimatic house presents an appropriate thermal sensation behavior. Regarding the outside temperature, in winter, there is a difference of around 10°C, very noticeable when entering the bioclimatic house.

The design and implementation of a bioclimatic house for the Bolivian highlands is an option to be considered for future buildings and/or modifications or redesigns of existing buildings. They can be built with bioclimatic criteria and materials suitable for the climate of the region, while taking advantage of the renewable energies of the environment.

Solar energy is abundant in the region, which is a valuable resource to be considered for any type of use. The cost of adopting bioclimatic criteria and materials proposed in this article represents around 10% of the cost of common buildings in the region (reference cost is 400 US dollars per square meter in common buildings) and the energy savings with the implementation of the studied alternative represent an initial energy saving of 65%.

Author Contribution

The built prototype is a replicable housing model in the Bolivian highlands. As evidence of this, in partnership with AEVIVIENDA (State Housing Agency of Bolivia), 17 bioclimatic houses have been constructed for people with disabilities in the Vichuloma neighborhood - Oruro, with funds from the Bolivian state.

Funding

The housing was built with funds from Swiss cooperation in Bolivia through the Climate Change Adaptation projects, managed by COSUDE and AGRUCO.

Acknowledgements

Thanks to COSUDE for providing the opportunity to implement the research project, to the Technical University of Oruro - Faculty of Engineering - Mechanical Engineering Department for collaborating in the implementation of the prototype and providing all the support in the project's development. Lastly, thanks to the beneficiaries of the research, who have played an important role in its consolidation.

Conflict of interest

The authors declare no conflicts of interest.

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