ISSN 2712-0562
Original Research
Sustainable Engineering and Innovation
Vol. 5, No. 2, December 2023, pp.177-188
https://doi.org/10.37868/sei.v5i2.id227

Evaluation of the thermal performance of housing envelopes as passive cooling systems

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Received Nov. 3, 2023
Revised Dec. 12, 2023
Accepted Dec. 18, 2023

Abstract

Over the years, climate change has generated an increase in the average temperature of the planet, which has led to greater consumption of electrical energy for the use of air conditioning systems. Insulating envelope materials are considered a viable passive solution as they offer internal air conditioning, cooling, and/or heating of buildings that lead to thermal comfort with reduced energy consumption. This article compares the application of different insulating materials in an existing single-family home located in a hot-dry climate. To this end, the procedural methodology has been applied by carrying out a bibliographic review of different involutes currently used in the construction of the buildings and 14 models are proposed that will be simulated under the same input variables of the base model and meteorological data of the city of Bucaramanga validated from a meteorological station located on site. The results of the simulations show that all 14 models show a decrease in temperature with reference to the "base model"; This difference can be explained by the presence of the selected materials that slightly change the thermal properties of the wall. Finally, this research allowed us to determine that the occupants of the simulated spaces in the base model are inside the thermal comfort range by 61.96%, which represents 5,438 hours of the modeled year, having 38.03% of hours of discomfort in the measured time. This study can be useful for the selection of envelopes and different buildings with passive cooling requirements.

Keywords: Passive cooling, Thermal envelopes, Energy simulation, Energy saving; Insulating materials

1. Introduction

Energy is a factor in driving global economic growth [1], [2]. The growth of housing construction and the tendency to improve the level of human thermal comfort has brought increases in the demand for energy that is still satisfied with the use of fossil fuels, contributing negative consequences to the environment [3]. When looking at energy-demanding sectors, the construction sector is one of the energy-consuming sectors with a high source of carbon emissions [4]. Construction accounts for approximately 40% of total global energy use. This percentage may increase by 12% and 37%, respectively, due to an increase in energy consumption for space heating and building cooling by 2050[4]. The optimal way for reasonable use and decrease of energy demand is the general change in living standards and comfort needs for heating and cooling in different climate zones. As a consequence, it is necessary to take measures to reduce energy consumption through the implementation of various renewable technologies and systems [5]. Thus, both new and old buildings are the main objective of energy policy worldwide.

Currently, Colombia has a high energy demand, which has become a problem due to the use of natural resources that are declining, generating high energy costs since buildings do not have energy-saving designs [6], In accordance with this, it seeks to encourage the generation of new energies for the country [7]. The need to create simulations that allow comfort in homes implies thinking about reconditioning and proposals that contemplate generating non-conventional sources of energy in accordance with Law 1715 of 2014, which are environmentally and economically sustainable [8], and the evaluation of the thermal-energetic behavior through a simulation of electrical energy consumption, emphasizes that modifications in the envelope design notoriously affect the final energy consumption [9]. Likewise, the analysis of different envelopes for thermal adaptations using passive elements allows obtaining data in relation to the use of energies, which is necessary for the generation of new designs [10], as the process of optimizing them in passive heating is important [11]. In addition, sustainable energy development in Colombia requires various energy efficiency plans [12], seeking to improve their energy recovery capabilities under certain conditions [13]. To do this, it requires generating strategies with simulations using enveloping materials [14]. The problem with the depletion of conventional energy resources and the high energy demand urgently requires the search for other alternatives that allow the use of natural resources with the use of enveloping materials, using passive heating, and cooling techniques for the construction of houses. Colombian homes seek to have a better quality of life, improving thermal comfort, living in cool buildings, and even more so in hot humid, and hot dry climates [15]. Thermal insulation seeks to reduce excess heat, control temperature, reduce costs, and take advantage of sunlight and natural energy sources [16].

The use of envelope materials in construction is gaining renown in the industrial and domestic sectors as a passive cooling technique, improving the energy efficiency of buildings [17]. Among all technologies, incorporating phase-change materials (PCMs) into buildings is a novel approach to reducing cooling and heating loads on buildings [18]. But concrete, cement, sand, bricks, and wood are universally used building materials that store heat energy as a form of sensible energy [19]. But for countries that have not reached these technologies and their research will take time, there are other materials of daily use in construction such as wood, polymers, and wool, among others [20]. These materials, which are used in building envelopes, insulate heat, which delays and even reduces the peak of the heat wave within the building structure. Therefore, the ambient temperature remains comfortable for most of the day and the cooling system uses less energy. When the temperature drops at night, the envelope keeps the heat stored inside the house, resulting in a comfortable room temperature at night [21]. This shows that the variation of building envelopes is favorable, particularly in extremely hot and cold climates when the internal conditions of the building are kept at a comfortable level consuming a considerable amount of energy [22], [23].

This research is based on the design of a semi-detached single-family house in a hot dry climate in this region, with common construction characteristics that are found in a high percentage of the furniture stock, over 70%. This reference design is used to analyze the impact of the application of different house involutes by means of thermal-energy simulations. This analysis makes it possible to prioritize rehabilitation actions and estimate their internal temperature obtained because of external temperatures and variation of enveloping materials, as well as to calculate the hours of occupational thermal discomfort in each case.

2. Method

This section establishes the procedural methodology for the development of the research structured in five stages, as shown in Figure 1. The methodology begins with A) Model preparation, where the climatic parameters of the area and information for the modeling of the cases are established; B) Construction of models, based on the technical and structural characteristics, varying the enveloping material according to the classification made; Once the model has been built, the third stage of C) Simulation of the dynamic behavior of the house is carried out, to finally obtain the data of the temperature and internal humidity of each of the areas of the house; (D) Analysis of the behavior of the temperature as a function of the outside temperature and variation of the envelope, and calculation of the hours of thermal discomfort by means of the methodology used by the Institute of Hydrology, Meteorology and Environmental Studies of Colombia [16]; in the final stage E) the comparison of the results of the models in relation to the hours of thermal discomfort is established.

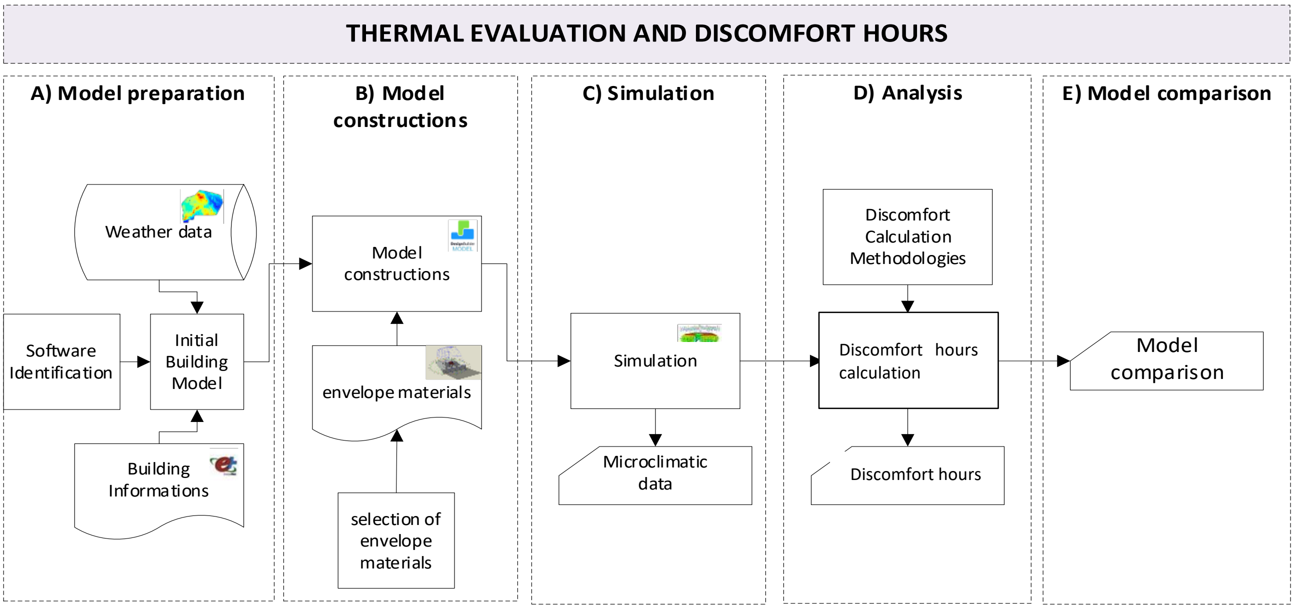


Figure 1. Methodology for the determination of hours of discomfort because of sunlight

2.1. Description of the base case housing

The house studied is in the city of Bucaramanga, Santander, Colombia (Figure 2). The climate in Bucaramanga according to the climate classification of the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) [24]. It is warm, and dry, with an average temperature of 24°C. The house has adjoining buildings on the north and south sides, separated from the houses on the opposite side by a small park with grass and trees. The house was built with traditional materials such as brick, cement, and stucco, it has a built area of 126 m2 distributed over two floors.

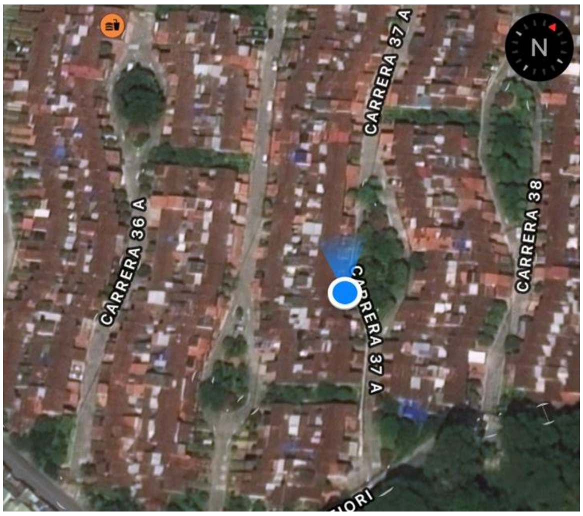


Figure 2. Location and orientation of the house

Table 1. General description of the property

Basic Parameters	Specification
Location	7°08′N 73°08′O
Total Area	126 m^2
Height of the house	2,5 meters on each floor
Structure	Brick/Cement/Stucco

2.1. Software tool

The house is a two-story house with no heating, ventilation, and air conditioning (HVAC) system of less than 200 m^2, so thanks to the precision of the Design Builder software, it is selected as a tool for energy and environmental design and analysis. The base design of the selected typology is shown in Figure 3.

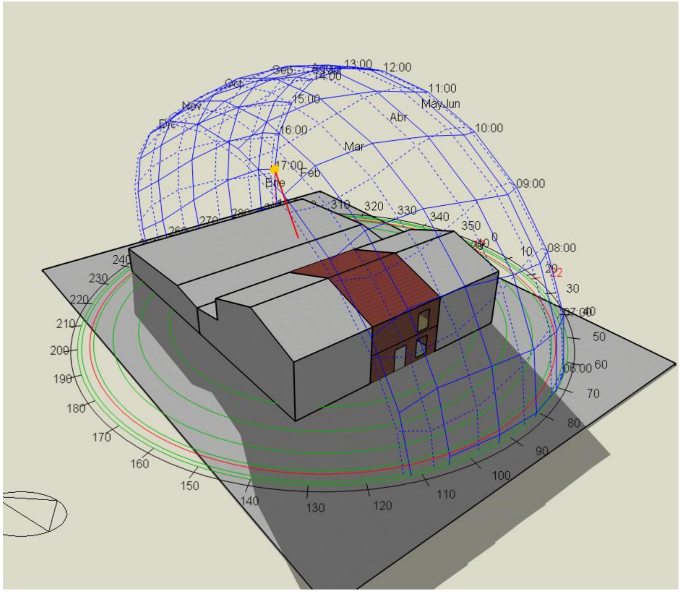


Figure 3. 3D Symmetrical Model (Design Builder)

This tool allows us to obtain data on the average expected vote (MVP is the index that reflects the average value of the votes cast by a large group of people with respect to a thermal sensation scale) and information related to the materials of the proposed envelopes are necessary to evaluate the internal temperature of the house, the hours of comfort and discomfort. Therefore, it begins by choosing the archive of meteorological data of the city of Bucaramanga validated from a meteorological station located on-site, during the testing period to be applied in the different selected envelopes. Figure 4 presents the month-to-month behavior in the study area, presenting both diffuse and direct radiation, wind speed, atmospheric pressure, temperature, and humidity.

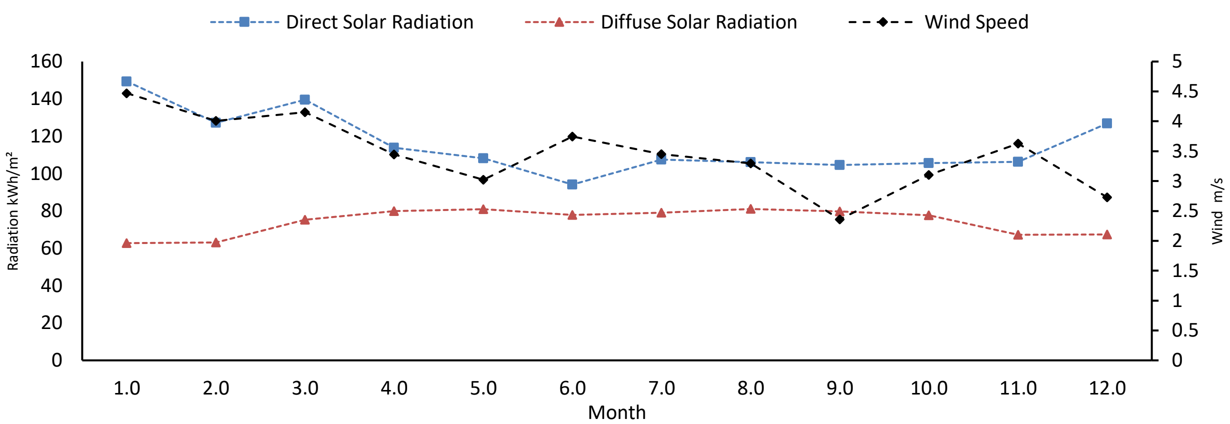


Figure 4. Climate data from the model (Design Builder)

As a passive strategy, characteristic data on geometric properties and boundaries with adjacent buildings were entered into the software using the "component block" option so that the program considers adiabatic shadows and adjacencies.

On the other hand, the "occupation schedule" of the house was established according to Figure 5, with a defined parameter for the occupancy density of 0.031 people/m2 since it is a family dwelling inhabited by four people, reflecting a real operating mechanism as much as possible. Additionally, considering the location of the dry warm climate zone, it is not necessary to calculate thermal gains by ASC or HVAC.

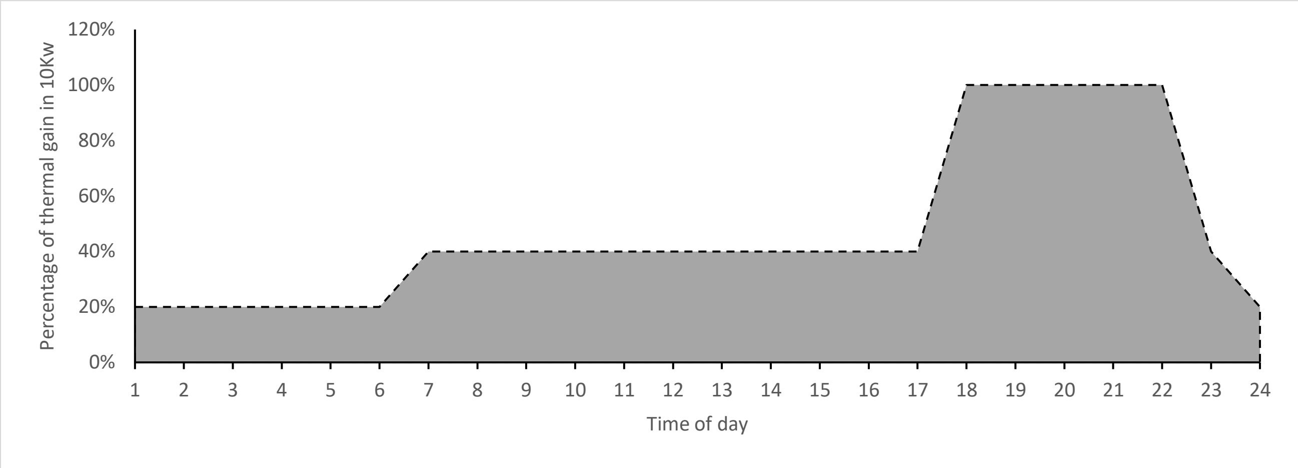


Figure 5. Occupancy percentages by hours of the day

The comfort analysis performed in software based on the MVP is shown in Figure 6, where the curve obtained to comply with the comfort levels according to the case study is presented. It is interesting to note that, although the PMV index is between -0.46 and -0.1 corresponding to a neutral thermal sensation (i.e., neither hot nor cold), there is a PDD<10%, indicating that almost 10% of people feel the thermal environment as uncomfortable. According to the UNE ENE ISO 7730:2006 standard, the reference values for global thermal well-being correspond to -0.5<PMV< +0.5 or PPD<10% [25].

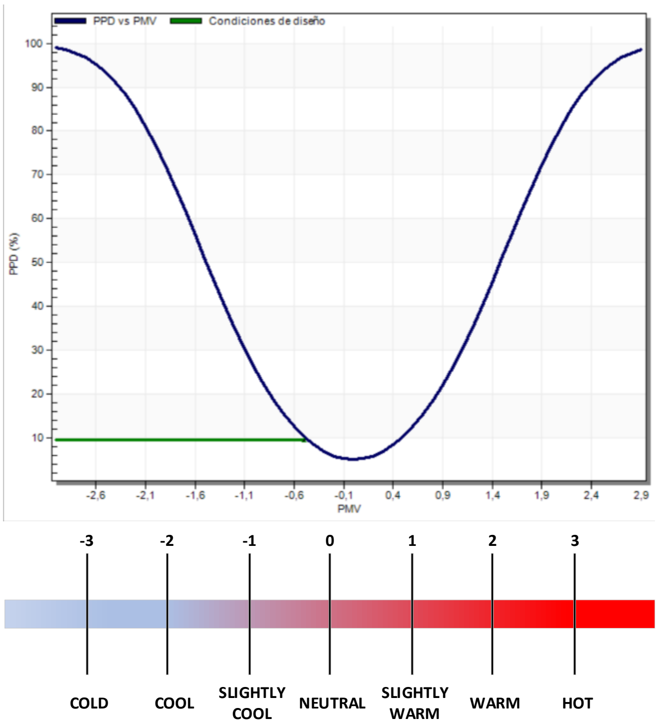
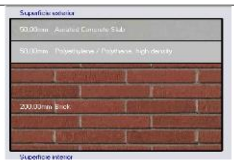


Figure 6. Comfort analysis according to PMV vs PPD. Expected Percentage Dissatisfied (PPD) in relation to the Average Expected Vote (PMV). PMV-Wind Chill Index
(Own creation of information from [26])

2.2. Simulation and models

Insulating materials are materials used in construction to resist heat transfer depending on their properties [27]. The selection of the type of insulation materials is important when passively cooling or heating a home. For this, the work of the different insulation materials must be considered. To start with the simulations, a matrix of the construction of the models to be simulated is constructed, which will be carried out by applying the envelopes found and presented in Table 2 to analyze the internal thermal behavior and its hours of discomfort.

Table 2. Simulation models

Model	Material envelope	Length (m)	Image	Model	Material envelope	Length (m)	Image
1	Nothing	0,05		9	Glass	0,05	
2	Polyurethane	0,05		10	Cellulose	0,05	
3	Polyurethane	0,1		11	Cork	0,05	
4	Polyurethane Concrete	0,05		12	Dust wooden	0,05	
5	High polystyrene	0,05		13	Expanded perlite	0,05	
6	Low polystyrene	0,05		14	Coconut fiber	0,05	
7	Fiber vegetal	0,05		15	Sheets wooden	0,05	
8	Rock	0,05					

Once the detailed test models have been created, a simulation of the "base model" is initially carried out, where it is considered that the house does not have insulation installed in any structural element. The simulation is carried out for a typical year from January 1 to December 31 to compare it with the different results of each envelope model proposed above. This "base model" is called Model 1. In this test, the air and radiant temperature, the operating temperature, and the exterior dry bulb temperature are set in Figure 7 respectively according to the comfort conditions of the dwelling. The results show hours of thermal discomfort greater than 250 hours per month, for all months.

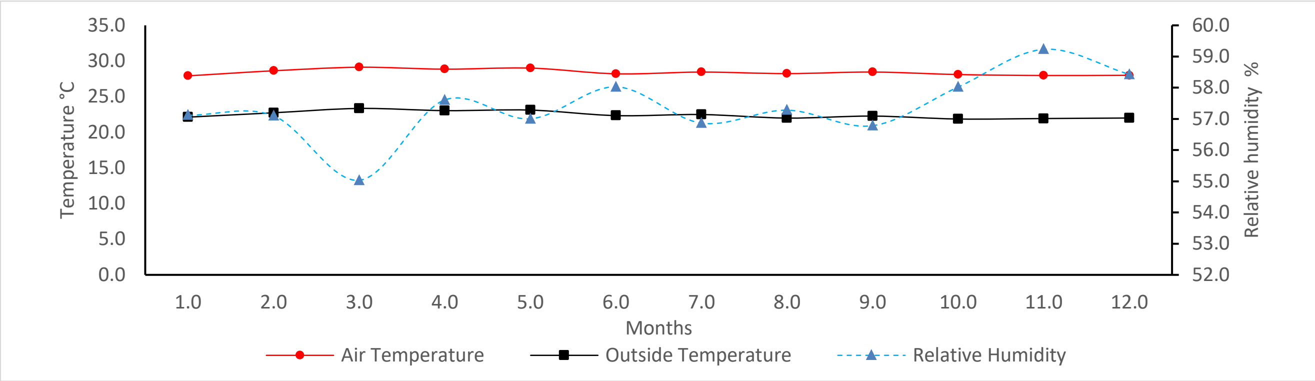


Figure 7. Month-by-month thermal comfort analysis

Additionally, this preliminary simulation shows the hourly behavior of the operative, radiant, air, and dry temperatures in Figure 8, where a higher operating temperature is always presented. Likewise, it can be observed that humidity presents a variable behavior with minimum peaks of 40% and maximum peaks of 80%.

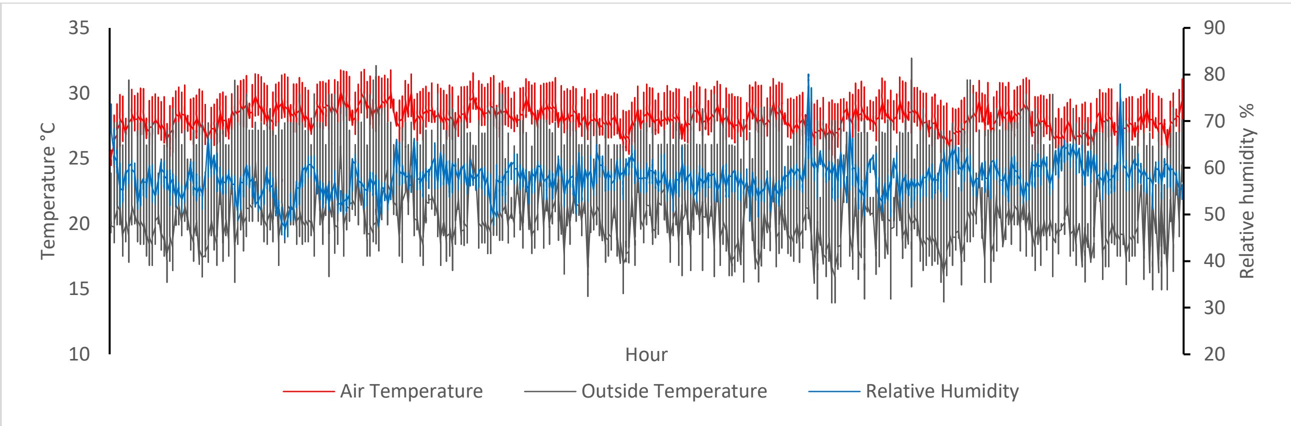


Figure 8. Hourly residential thermal comfort by simulation period

The results of the simulation show that the thermal gains expressed in KW/h are mostly presented by the roof of the house with values between 150 and 220KW/h approximately. Followed by walls and floor with an average of 50KW/h. On the other hand, the external ventilation for hourly air renewal is between 0.5 and 1.2 m/s, as shown in Figure *10*9 and Figure 10.

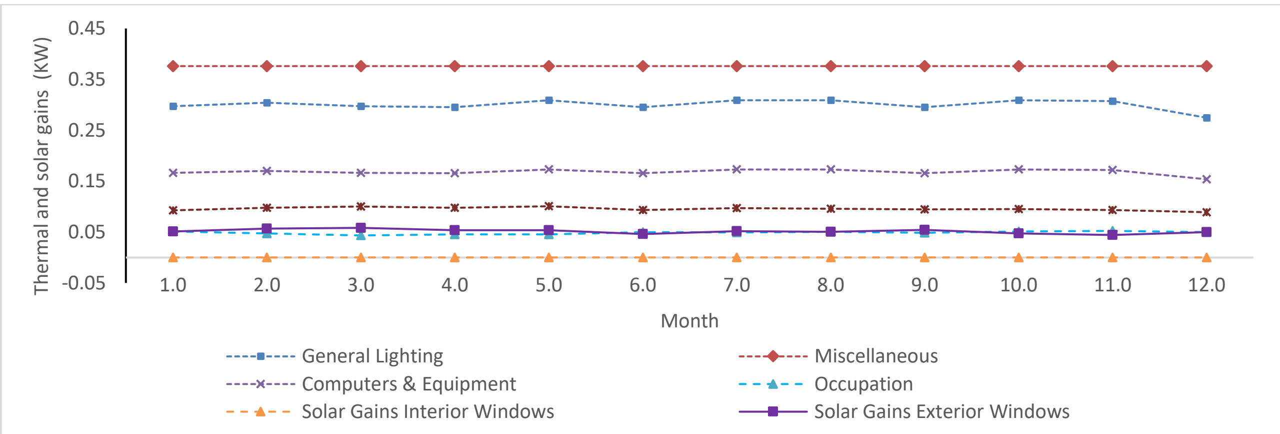


Figure 9. Elements of thermal gains

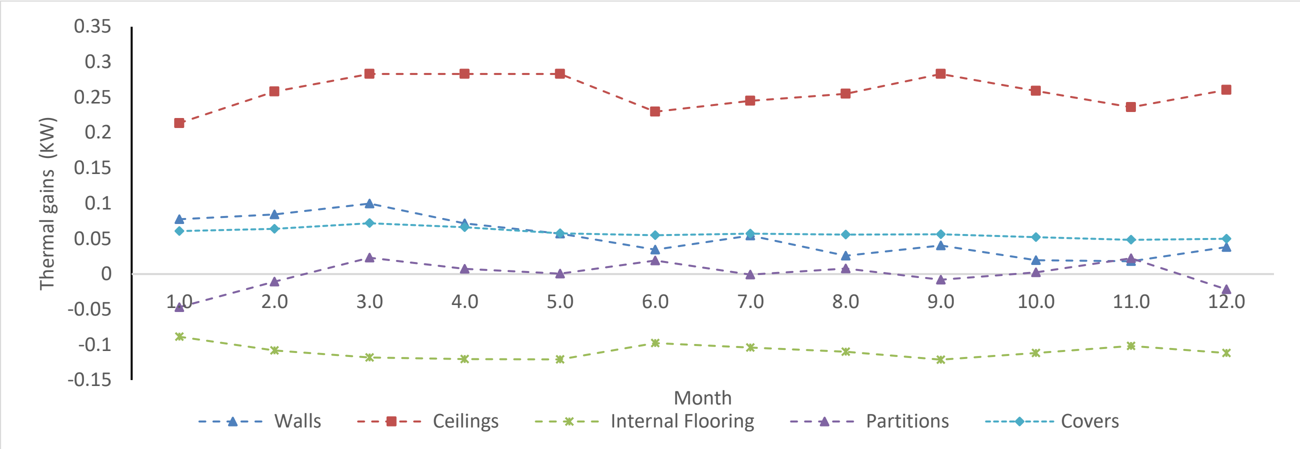


Figure 10. Thermal gain zones

Once the "base model" has been defined and using the meteorological data of Bucaramanga measured on-site, 28 simulations of the proposed models are carried out, characterizing each envelope and applying the selected material as follows: 7 models with the envelopes inside and 7 outside (to establish if their location generates any incidence in the internal thermal behavior). Each model calculates 8,760 internal temperature data and 8,760 thermal discomfort analysis data, for a total of 17,520 data analyzed by simulation. These tests show the effect of envelopes on the home. It is important to note that the air conditioning option is not selected, and therefore the heating and cooling system is turned off.

3. Results

Improving the heat transfer characteristics of the envelope can effectively improve the overall thermal performance and quality of the building's indoor thermal environment. In this work, the heat transfer data of the envelope obtained by simulation were analyzed to identify the parts with the greatest contribution to heat transfer and to determine the best alternative for optimization and transformation of the envelope.

The results of the simulations of the calculated average temperature of the hours of the year are reported in Figure 11. Average temperature by model. All 14 models show a decrease in temperature with reference to the "base model" (M1). This difference can be explained by the presence of the selected materials that slightly change the thermal properties of the wall. On the other hand, the results show that the location of the envelope both on the outside and inside of the structure did not reflect any influence on the behavior of the internal temperature. Likewise, the test data of the 14 models in terms of the average temperature by specific material, revealed a minimum average temperature of 27.96 °C from M8 to M11, and with a difference of 0.02°C it is presented from M12 to M15, reflecting a similar behavior in the interior temperature obtained in the previous results. From Model 2 it can be evidenced that it is close to the temperature value of M1, indicating that polyurethane with a thickness of 0.05m does not show improvement as an enveloping material for this study area.

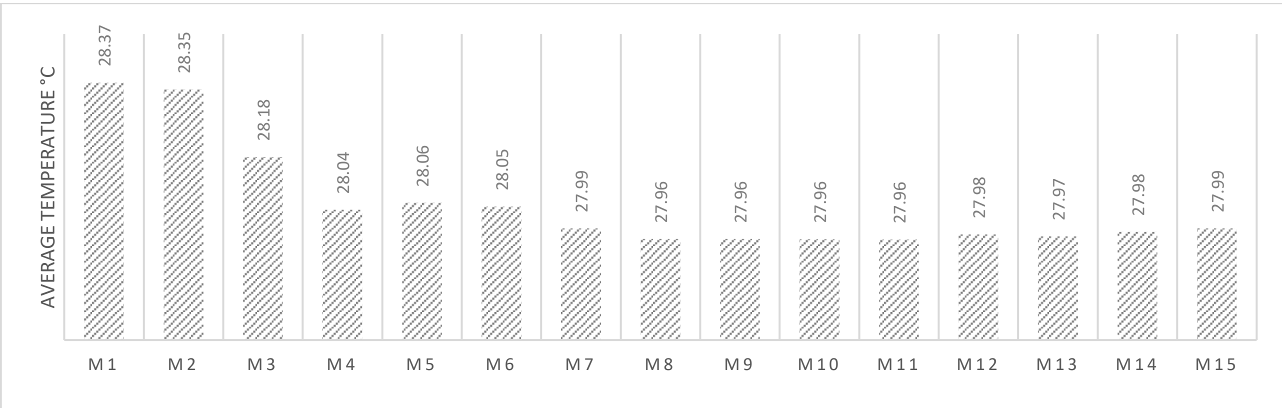


Figure 11. Average temperature by model

As shown in Figure 11, the results of the percentage difference in temperature reduction of the envelopes by material between the base model and the proposed models indicate that from M8 to M11 they have a cooling percentage of 1.44%, being slightly higher, unlike the other models that range between 0.05 and 1.34%. On the other hand, although M2 and M3 did not get a significant increase compared to the other models, they showed an improvement compared to M1.

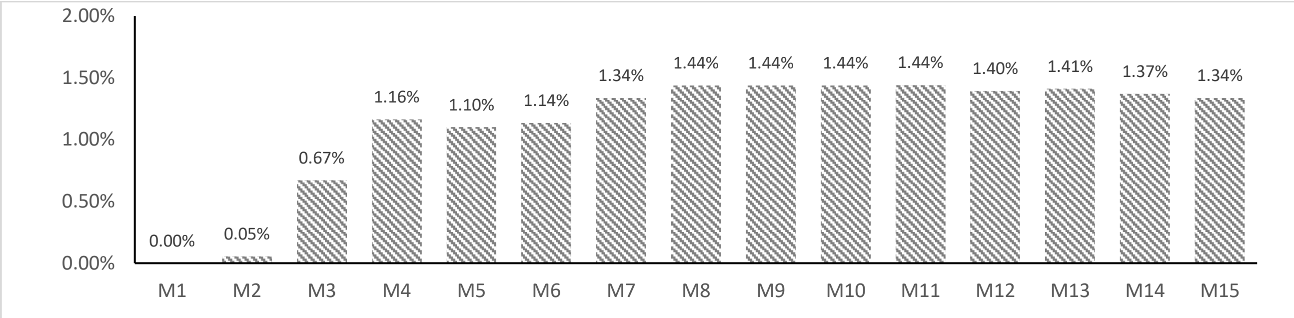


Figure 12. Percentage temperature difference between base model and enveloped models

According to the data obtained in Figure 13, throughout the simulated year, the hours of discomfort in the M3 to M15 models vary from 1,340 to 1,342 hours, being higher than the M1 base model and the proposed M2 with a difference between 6 and 4 hours. This is because the applied materials do not provide a shield to the wall, which caused negative effects on the thermal interior environment, increasing the temperature and generating an uncomfortable thermal sensation; for this hot-dry climatic zone, the simulated models confirmed the poor performance in the thermal insulation of the walls of the house (Figure 13. Comparison of hours of discomfort).

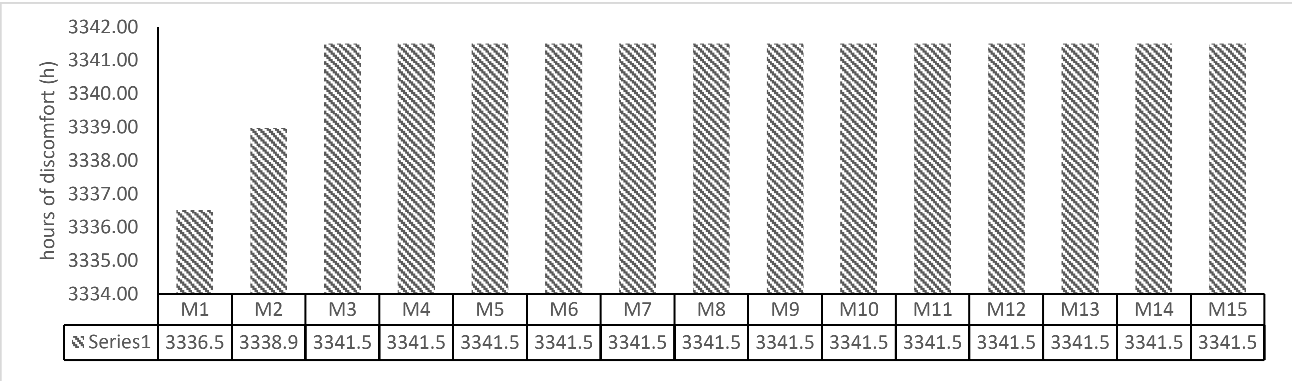


Figure 13. Comparison of hours of discomfort

The hours that set a trend in the thermal discomfort of the models are presented in Figure 14, highlighting the morning and afternoon time slots (between 8 a.m. and 7 p.m.). Nine hours of thermal discomfort were detected inside the house, being closely related to the peak solar hours of the climatic zone of the study; this indicates that, after absorbing the heat from solar radiation throughout the day, the temperature rises internally.

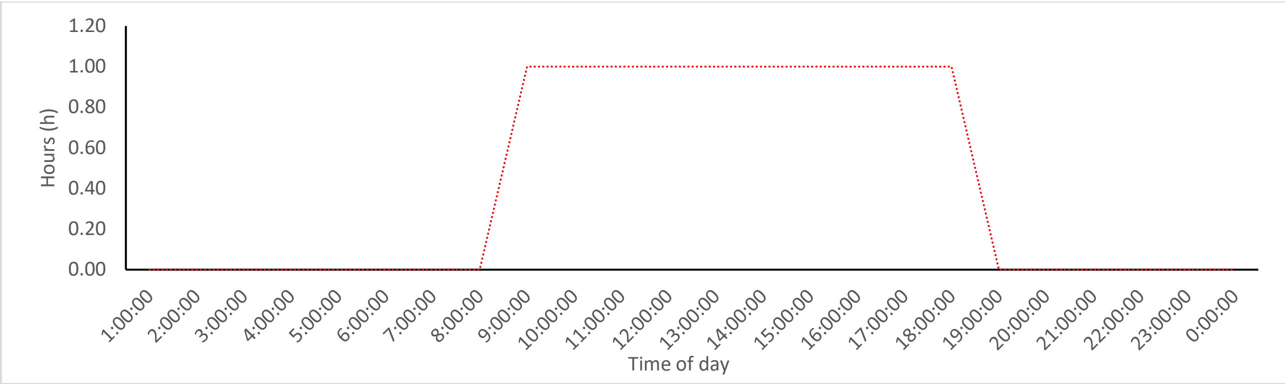


Figure 14. Behavior by hours of discomfort per day

4. Conclusions

The present research modeled an existing two-family house, and 14 wall models were proposed with different types of insulation materials and thermal characteristics simulated in the computational tool Design Builder. This article aims to analyze the different models proposed to optimize the envelope of the study area with a hot-dry climate and reduce the hours of thermal nonconformity. The results of the simulations during the established year were mainly based on the average interior temperature and the number of hours of discomfort generated by the occupants.

This tool made it possible to determine that the envelope of the case study house is not homogeneous, this is due to the heat losses and gains detected during the year analyzed. These materials presented a similar thermal conductivity value, which generated a heat transfer between each surface layer from the outside to the interior of the simulated house, similar to the simulated house, there are temperature differences in the simulations between the conventional construction material without enclosure and with envelopes with a maximum reduction of 1.44%, having an initial average temperature of 28.37°C reducing to 27.96°C (envelopes such as cellulose, cork, wood powder, expanded perlite, coconut fibers, wood sheets).

The methodology applied in this research allowed us to determine that the occupants of the simulated spaces in the base model are inside the thermal comfort range by 61.96%, which represents 5,438 hours of the modeled year, having 38.03% of hours of discomfort in the measured time. Likewise, when performing the simulations with different envelopes and despite the decrease in temperature between the models, the results of hours of thermal comfort were the same in all the models with envelopes, which is contrary to what was expected in the hypothesis of this research, in which it was assumed that by applying different involutes a thermal comfort of 100% of the measured time would be generated. This is because even though the temperature is lowered, it is still high in relation to the comfort parameters.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

Funding information

The financing of this research was carried out by Unidades Tecnológicas de Santander - UTS, led by the Rector Ph D. Omar Lengerke Pérez.

Acknowledgements

Special thanks to the UTS Research and Extension Directorate, led by Javier Mauricio Mendoza Paredes.

Author contribution

The contribution to the paper is as follows: J. G. Ascanio-Villabona, B. E. Tarazona-Romero, M. A. Duran-Sarmiento, O. Lengerke, L. A. Betancur-Arboleda: study conception and design; J. G. Ascanio-Villabona, simulation and data collection, J. G. Ascanio-Villabona, B. E. Tarazona-Romero, M. A. Duran-Sarmiento, L. A. Betancur-Arboleda, analysis and interpretation of results, J. G. Ascanio-Villabona, O. Lengerke, L. A. Betancur-Arboleda, draft preparation J. G. Ascanio-Villabona. All authors approved the final version of the manuscript.

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