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SUSTAINABILITY STRATEGIES FOCUSED ON THERMAL COMFORT AND EMBODIED ENERGY OF EMERGING HOUSING IN THE ANDEAN REGION OF ECUADOR

ESTRATEGIAS DE SOSTENIBILIDAD ENFOCADAS AL CONFORT TÉRMICO Y LA ENERGIA INCORPORADA DE UNA VIVIENDA EMERGENTE EN LA REGIÓN ANDINA DEL ECUADOR

ESTRATÉGIAS DE SUSTENTABILIDADE FOCADAS NO CONFORTO TÉRMICO E NA ENERGIA INCORPORADA DE UMA HABITAÇÃO EMERGENTE NA REGIÃO ANDINA DO EQUADOR

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RESUMEN

Ante los constantes desastres naturales de regiones andinas de Ecuador, se han planteado varias soluciones habitacionales, sin embargo, estas no consideran el confort térmico del usuario ni el impacto ambiental que generan. Esta investigación aborda esta problemática desde una perspectiva bioclimática a través de un modelo de vivienda emergente en un clima andino orientado a asegurar el confort térmico y reducir el impacto ambiental de la construcción. El análisis se enfoca en la temperatura interior y la Energía Incorporada Total (EI_T) del modelo de vivienda. La metodología se divide en la definición del modelo y las estrategias, por un lado y, por el otro, el análisis de estos parámetros a través de simulaciones y cálculos. Además, se realiza un análisis comparativo con otros estudios. Las estrategias definidas fueron la captación solar, masa térmica, compacidad, materiales locales-reciclados y la modulación. Los resultados muestran que el modelo planteado alcanza, de manera pasiva, las temperaturas de confort y la EI_T (2135.38 MJ/m^2) es menor que la de otras viviendas de carácter social.

Palabras clave
masa térmica, habitabilidad, eco-arquitectura

ABSTRACT

Faced with the constant natural disasters in the Andean regions of Ecuador, several housing solutions have been proposed. However, these do not consider the user's thermal comfort or the environmental impact they generate. This research addresses this issue from a bioclimatic perspective through an emerging housing model in an Andean climate, oriented to ensuring thermal comfort and reducing the environmental impact of the construction. The analysis focuses on indoor temperature and the Total Embodied Energy (EE_T) of the housing model. The methodology is divided into the definition of the model and strategies, on one hand, and, on the other, the analysis of these parameters through simulations and calculations. In addition, a comparative analysis with other studies is carried out. The strategies defined were solar gain, thermal mass, compactness, local-recycled materials, and modulation. The results show that the proposed model passively reaches comfort temperatures, and that the EE_T (2135.38 MJ/m^2) is lower than that of other social housing.

Keywords
thermal mass, habitability, eco-architecture

RESUMO

Diante dos constantes desastres naturais nas regiões andinas do Equador, várias soluções habitacionais foram propostas, mas elas não consideram o conforto térmico do usuário nem o impacto ambiental que geram. Esta pesquisa aborda esse problema a partir de uma perspectiva bioclimática por meio de um modelo de habitação emergente em um clima andino que visa garantir o conforto térmico e reduzir o impacto ambiental da construção. A análise se concentra na temperatura interna e na energia total incorporada (EI_T) do modelo de habitação. A metodologia é dividida, por um lado, na definição do modelo e das estratégias e, por outro, na análise desses parâmetros por meio de simulações e cálculos. Além disso, é realizada uma análise comparativa com outros estudos. As estratégias definidas foram ganho solar, massa térmica, compacidade, materiais reciclados localmente e modulação. Os resultados mostram que o modelo proposto atinge passivamente temperaturas de conforto e o EI_T (2135,38 MJ/m2) é menor do que o de outras habitações sociais.

Palavras-chave
massa térmica, habitabilidade, ecoarquitetura.

INTRODUCTION

Natural disasters are an uncontrollable problem around the world and have had a great impact on the social, economic, and, of course, the built environment. Emergency Housing (EH) emerges within this context, defined as a fast temporary housing solution to solve the shelter needs of people affected by disasters (Secretariat for Risk Management, 2018). One of the areas with the highest rate of natural disasters is the Inter-Andean region of South America, mainly due to its geological aspects and extreme rainfall (Marocco & Winter, 1997).

There have been numerous natural disasters in the Andean region of Ecuador in recent decades. In 1993, the landslide of the Josefina-Azuay mountain left 100 dead, affected 5,631 people, and destroyed 1,800 hectares of agricultural and grazing land (Zevallos, 1994). In 1999, the eruption of the Pichincha volcano displaced 2,000 people and polluted the air in the surrounding 200 km (Álvarez & Avilés, 2012). The most recent catastrophe was the landslide in Alausí-Chimborazo in March 2023, which left 32 people dead, damaged 163 houses, affected 1,034 people, destroyed 2.32 km of roads, and hit 26 ha of agricultural area (Adverse Events Monitoring Directorate, 2023).

Given these needs, different proposals have been put forward to solve spatial requirements. However, a post-disaster situation demands much more than a spatial approach, with one of the most important shortcomings being that of Emergency Housing (hereinafter, EH), because this is the protection that people have against inclement weather (Espinosa & Cortés, 2015).

In the climate of this region, whose minimum temperatures drop below 9 °C (National Institute of Meteorology and Hydrology of the Republic of Ecuador [INAMHI], 2017), solving this thermal housing problem is a great challenge, since physical-mental well-being (Hughes et al., 2019), energy demand (Andersen et al., 2017), and occupant health difficulties (Fonseca-Rodríguez et al., 2021) must also be considered. This means that EH solutions must consider strategies to solve thermal discomfort.

Several institutions have led EH projects through prototypes that prioritize ease of construction (TECHO, 2020) because they are transitional solutions. For this reason, they opt for lightweight materials such as chipboard and zinc roofs for their construction, which do not solve deficient indoor comfort in this climate. In addition, these prototypes focus on providing a temporary housing solution, although affected parties have often turned them into a permanent homes.

Recovery for those affected by a natural disaster is a complex process that begins with the integration into a new social nucleus, finding land where they can build or a building they can rent and, of course, reestablishing their economic situation. This means that they are often forced to convert their temporary homes into permanent ones (Lines et al., 2022).

EH prototypes that consider the thermal aspect in their design and construction have been implemented in several countries. However, these are not completely sustainable, since many models focus on the use of heating and insulation to reduce losses in cold climates and, consequently, reduce operational demand (Thonipara et al., 2019).

In this regard, Hong (2016) proposes an EH prototype in Korea made of metal containers with insulation on the walls and ceilings, as well as heating. In turn, Sinohara et al. (2014) analyze the thermal comfort of three types of EHs in Japan with a low U-factor which, in winter, reach an average temperature between 11-14°C. This is because they do not use constant heating due to the high cost involved.

The reduction of the envelope’s U-factor is a globalized strategy and regulation to achieve sustainable housing (Gullbrekken et al., 2019). However, other studies show that the effectiveness of insulation depends on the climatic context (Curado & Freitas, 2019) and can be replaced by solar gains and thermal mass (Santana Oliveira et al., 2022).

Although the use of insulating materials in these prototypes can ensure comfort in the spaces, it also implies a high environmental impact due to high Embodied Energy consumption (Torres-Quezada et al., 2022). As for materials, expanded polystyrene entails 127 MJ/kg (Azari & Abbasabadi, 2018), while brick involves 2.52 MJ/kg (González Stumpf et al., 2014). In terms of housing, buildings with high insulation standards, such as the case of Sweden, have a total Embodied Energy (EE_T) of 5,530 MJ/m^2 (Thormark, 2002), and in the Netherlands, 6,400 MJ/m^2 (Koezjakov et al., 2018). In Ecuador, on the other hand, common single-family homes have an EE_T of 3,600 MJ/m^2 (Torres-Quezada et al., 2022).

The concern to ensure the habitability of EHs in terms of thermal comfort has been addressed in several studies around the world, although research is scarce in Andean climates. It is also necessary to reflect that the time affected families stay in an EH varies from 0.5-5 years (Hong, 2016), and in many cases, it becomes permanent housing (Lines et al., 2022).

Thus, this study addresses the housing deficit due to natural disasters from a sustainable perspective, considering the thermal conditions through passive strategies and the environmental repercussions of their construction. The objective is to evaluate the impact of passive strategies applied to a transitory-permanent EH model on indoor temperature and Embodied Energy in a city in the Ecuadorian Andean zone.

METHODOLOGY

The methodology addresses two phases. The first defines the passive strategies and the model to be studied. In the second, the analysis of the thermal performance and the environmental impact of the proposal is made using digital simulations and an EE calculation, respectively. The city of Ambato, located 2,580 meters above sea level in the Andean region of Ecuador, has been taken as a case study (Figure 1).

The choice of this city is supported, on one hand, because its climate is characteristic of the Andean region of Ecuador, with low temperatures, high thermal oscillations, and moderate precipitation (Figure 2). On the other hand, its geographical location is in an area quite exposed to natural disasters (Secretariat of Risk Management, 2018).

STRATEGIES AND MODEL

In this phase, passive strategies have been defined based on Givoni's psychrometric abacus (1969) (Figure 3), which has been used in previous studies to determine bioclimatic strategies in other regions (Da Casa Martín et al., 2019). For this analysis, the Climate Consultant 6.0.15 software has been used (Climate Consultant, 2020). The climate file (EPW) used in this software, and for the subsequent thermal simulations, was obtained from climate.onebuilding.org (2020).

According to this information, Ambato remains in thermal discomfort in most hours of the year (8,048), and only 8.1% of the annual hours in comfort. The most important guidelines defined are internal gains, heating and humidification, direct solar gains, and high thermal mass.

Based on the strategies, the literature on their passive application shows that the use of insulation to reduce heat losses is promoted most (Iwata et al., 2023). The strategy that follows it in importance is the use of the air chamber to reduce the thermal transmittance of

Figure 1. Location of the city of Ambato, Andean area of Ecuador. Source: Preparation by the authors.

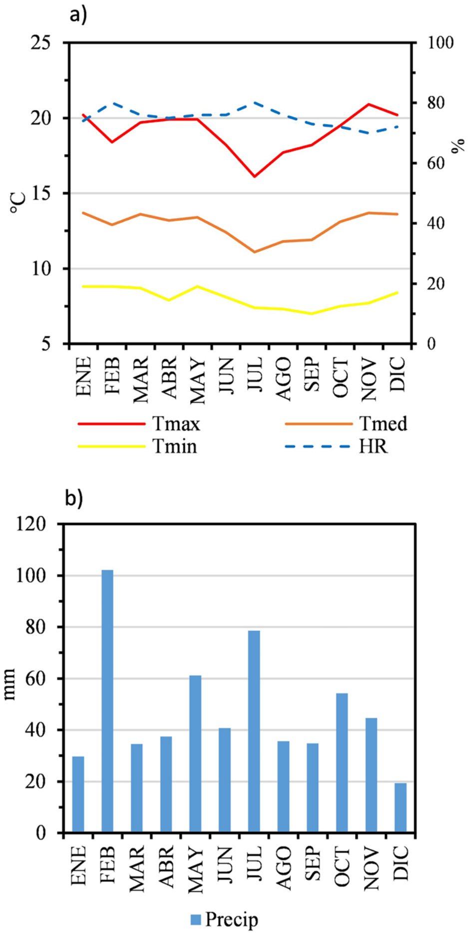


Figure 2. (a) Relative humidity (RH); Maximum (*Tmax*), mean (*Tm*), and minimum (*Tmin*), monthly average temperature, and b) monthly precipitation of Ambato. Source: Preparation by the authors based on data obtained from INAMHI (2017).

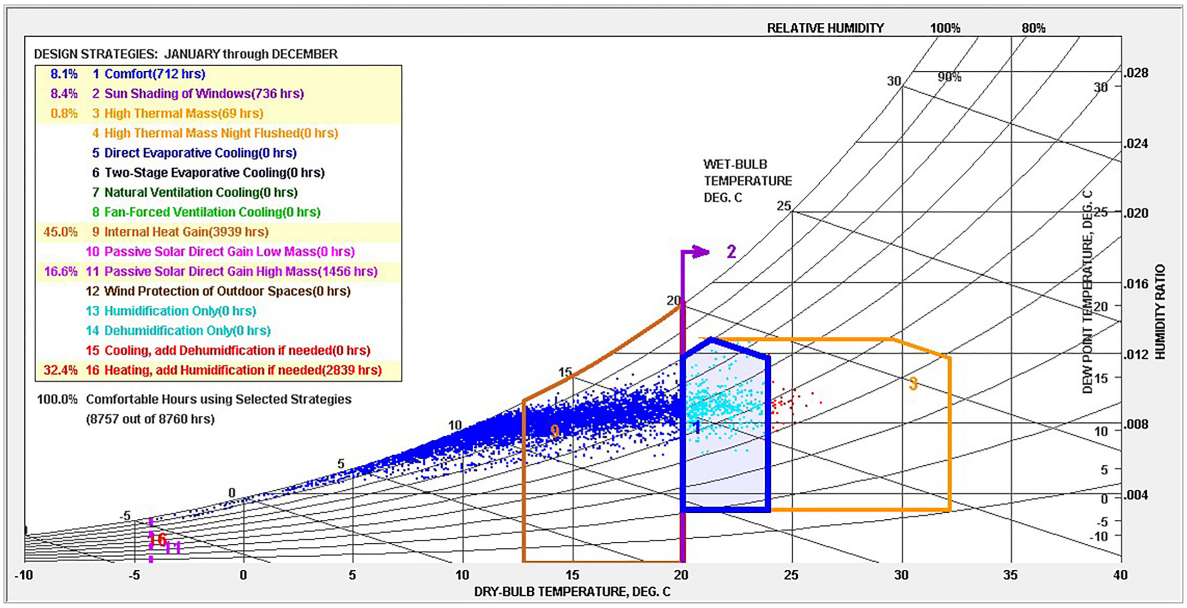


Figure 3. Givoni's psychrometric abacus (1969) of Ambato's climate. Source: Preparation by the authors in the Climate Consultant software (2020).

Table 1. EH model strategies Source: Preparation by the authors.

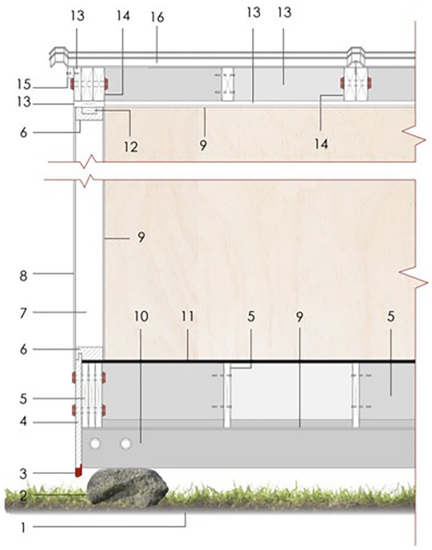
Strategy	Description
Internal gains	The internal distribution prioritizes adjoined spaces to take advantage of the heat from cooking, users, and lighting.
Solar gains	The openings are oriented to the east and west with an opening percentage of 30%, which allows capturing solar radiation during the day and controls heat losses at night.
Thermal mass	East and west walls with high thermal mass
Insulation	Air chamber on north and south walls, on roof and floor.
Orientation	Longer facades to the east and west.
Compactness	The houses are grouped in pairs to reduce the contact surface with the outside.

the envelope (O'Hegarly et al., 2021). It should be noted that this study focuses on minimizing the use of insulation materials to reduce the environmental impact.

As for internal gains and heating, the literature highlights the contributions made by individuals and equipment (Zhou et al., 2019). Finally, Curado and Freitas (2019) propose solar gains as a fundamental strategy for direct and indirect contributions. In addition to the strategies given by Givoni's abacus (1969), the application of an air-to-ground heat exchanger called the trombe wall or the green wall, stands out (Dabaieh & Serageldin, 2020).

The only strategy used for this study was compactness (García Mitjans, 2022) since the others involve a very high investment and upkeep. All these strategies are summarized in Table 1.

Next, research was made on materials with low environmental impact and the most representative vernacular construction systems in this region. Torres-Quezada & Torres-Avilés (2023a) determined that concrete and metal are the materials of the Andean region with the greatest impact on the total embodied energy of housing in the last 4 decades. In addition, this study shows that finishing materials such as cement plaster, porcelain, laminated wood, or stainless steel also have a high environmental impact. Another important point is that the excessive use of glass can drastically



1. Natural soil
2. Stone base of the site.
3. Drip groove, Greentec (TPG2) 40x10mm
4. Greentec (TPG2) 200x10mm
5. Pine boards 195-19mm
6. Pine slats 1, 80x40mm
7. Air chamber e=80mm
8. Greentec board (TPG1) 2440x1220x5mm
9. Plywood board 2440x1220x5.2mm
10. Pine beam 145x38mm
11. Greentec board (TPG2) 2440x1220x10mm
12. Pine slat 2 40x20mm
13. Pine board 195x19mm
14. Pine beam 145x38mm
15. Pine slat 40x20 mm
16. Greentec board (TCP) roof cover type 2400x1160x5mm.

Figure 4. Constructive overview of the model. Source: Preparation by the authors.

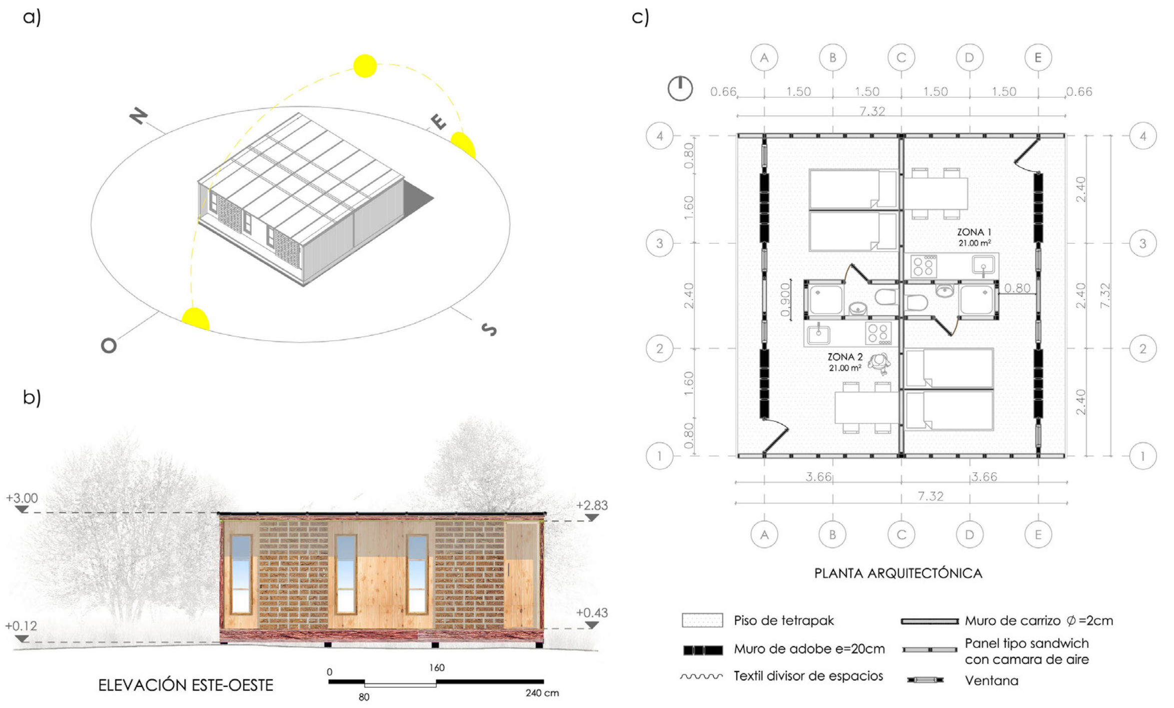


Figure 5. a) volume, b) east-west elevation, and c) architectural floorplan of the model. Source: Preparation by the authors.

increase the dwelling's EE, which in turn, reduces its thermal mass causing lower temperatures and greater thermal oscillations (Torres-Quezada & Torres-Avilés, 2023b).

On the other hand, other studies highlight the importance of using recycled materials to build EHs (Arslan, 2007; Arslan & Cosgun, 2008). Their most important considerations are the use of natural or recycled materials such as earth, wood, or recycled poly-aluminum. Natural materials which reduce the environmental impact of housing (Rodríguez et al., 2021) are a fundamental part of Ecuador's vernacular architecture (Yepez, 2012).

Based on these studies, the specific characteristics of the proposed prototype's constructive system were defined (Figure 4).

The Andean EH model is based on the following: the north and south walls are made by a sandwich-type panel; the outer layer is a Greentec-type board made of poly-aluminum (TPG1); and the inner one is a plywood board, separated by an air chamber.

Table 2. Simulation parameters. Source: Preparation by the authors using DesignBuilder (2016).

Element	Material	Thickness (mm)	λ (W/mK)	U (W/m^2(k)
Floor	Greentec_TPG2	10	0.50	2.15
	Air chamber	200		
	Plywood	5.2	0.15	
North/south wall	Greentec_TPG1	5	0.50	2.20
	Air	80		
	Plywood	5.2	0.15	
East/west wall	Adobe	200	0.17	0.76
Interior wall	Plywood	5.2	0.15	2.08
	Air	80		
	Plywood	5.2	0.15	
Windows	Single glazing	4	0.90	6.121
Roof	Greentec flat type	5	0.50	2.20
	Air chamber	100		
	Plywood	5.2	0.15	
	General simulation features			
	Latitude/Longitude		-1.24908/-78.61675	
	Altitude		2597 masl	
	Surface Area		53.58m^2	
	Occupation		0.15 persons/m^2	
	Infiltrations		1.5 ren/h (constant)	
	Lighting		2W/m^2 (18-22h)	
	Kitchen		3W/m^2 (7-8h/12-13h/18-19h)	

The floor contains a TPG2 board and a plywood board inside, with an air chamber between them. The most concerning envelope surface in the thermal aspect was the roof, since it is where the greatest heat losses occur (Torres-Quezada et al., 2018). Therefore, the roof has a flat poly-aluminum (TCP) board on the outside and plywood on the inside that acts as the ceiling, separated by an air chamber. For the east and west walls, adobe has been used to increase the model's thermal mass. Finally, the windows are 4mm single glazing with wooden frames.

As for the morphological characteristics, the proposal combines 2 living spaces for Zone 1 (Z1) and Zone 2 (Z2), each intended for one family. The morphology is based on 2.40x1.20m modules, which are the panel's commercial modular units. Modulation as the basis of the design will avoid material wastage and, therefore, reduce the environmental impact.

Regarding the indoor layout, all the spaces have been linked around the kitchen to take advantage of the internal gains. The bathroom, which is accessed from the living, is placed next to this space (Figure 5).

In this way, the prototype is conceived as a short- and long-term habitable space that has an adobe wall which is not a quick constructive system, but whose inclusion solves thermal aspects that must be considered in EHs. According to this, and given its modular design, the model allows its

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[1] (ECU_TU_Ambato.Intl.AP.841470_TMYx.2004-2018)

Table 3. Specifications and quantities of the materials used. Source: Preparation by the authors based on data obtained from: [1] Vázquez, (2001); [2] Shukla et al., (2009); [3] ECUAPLASTIC (2021); [4] Hammond & Jones (2008) [5] EDIMCA (2021); [6] González Stumpf et al., (2014); [7] TECNICGLASS (2021).

* the *EE* of poly-aluminum has been obtained based on the weighted values of polyethylene (89.96 MJ/kg) and aluminum (108.6 MJ/kg) recycled to 50%, which have a proportion of 80% and 20% respectively.

Product	P/u (kg)	Quantity (u)	EE (MJ/kg)
Adobe	9.6 [1]	266	0.97 [2]
TCP*	14.30 [3]	28	93.69 [4]
TPG1*	15 [3]	12	93.69 [4]
TPG2*	27.4 [3]	18	93.69 [4]
Beam	10.91 [5]	57	1.5 [6]
Board 1 [3]	7.34 [5]	118	1.5 [6]
Board 2 [3]	3.57 [5]	14	1.5 [6]
Slat 1 [3]	3.68 [5]	120	1.5 [6]
Slat 2 [3]	0.92 [5]	39	1.5 [6]
Plywood board [3]	7.66 [5]	63	15[4]
Glass plate [4]	10.8 [7]	6	16.81[4]

transformation into housing units with a larger area and with the capacity to house more users for extended periods.

CONFIGURATION AND CALCULATION OF THE MODEL

THERMAL SIMULATIONS

The DesignBuilder software is used with its Energy Plus calculation engine to analyze the model's internal thermal behavior and evaluate the effectiveness of the proposed strategies (DesignBuilder, 2016). The indoor air temperature (*Tai*) has been taken for this evaluation as a reference parameter.

As a first step, the climatic inputs and the characteristics of the model have been configured. The city's climate file was obtained from climate.onebuilding.org (2020).

After that, the thermal characteristics of all the material elements of the envelope have been defined. In addition, possible external infiltrations, occupation, and sources of internal loads are established. Infiltrations have been defined using Torres-Quezada et al. (2019), where the approximate values are stipulated considering the constructive characteristics of the houses in Ecuador. All these parameters are detailed in Table 2.

Below, two days of analysis have been chosen to accurately represent the average weather conditions (Average Day) and the average cold conditions (Extreme Day) in the city under study. These days have been determined from the outdoor temperature values obtained from INAMHI (2017).

For the Average Day, a mean temperature of 12.5°C has been considered, accompanied by maximum and minimum values of 17.9°C and 8.45°C, respectively. In the case of the Extreme Day, the lowest average temperature recorded monthly during the course of the year (11°C) has been chosen, along with a maximum temperature of 16.23°C and a minimum temperature of 6.82°C.

Once these data were obtained, two days were chosen from the simulation climate file that fit these values. As a result, 08/03 (Average Day) and 09/08 (Extreme Day) were chosen as the corresponding simulation days.

Finally, the thermal results will be analyzed against the comfort range (18-26°C) established by the Ministry of Urban Development and Housing (2011).

EMBODIED ENERGY CALCULATIONS

To evaluate the proposal's environmental impact, the Embodied Energy (*EE*) of the materials is taken as a parameter, which is the energy required by each material to produce one unit of weight (Kumar et al., 2022). Specifically, this study analyzes the total *EE* value of each material and the total value (EE_T) of the model. Additionally, to make comparisons with other studies, EE_T is related to the total construction area (MJ/m^2).

To obtain the EE_T (MJ) of the housing, equation 1 is used, which entails adding together the EE_T of each of the materials.

$$EI_T = \sum(EIxP) \quad \text{......................(Equation 1)}$$

Where EE is the specific embodied energy of each material (MJ/kg) with a Cradle-to-gate calculation approach, with the exception of wood which has a Cradle-to-site approach. P is the total weight of each material (kg), obtained by multiplying the weight per unit of each material by the total number of parts used in the model. The specifications and quantities of each of the materials are shown in Table 3.

RESULTS AND DISCUSSION

THERMAL SIMULATIONS

Figure 6 shows the results of the indoor air temperature (*Tai*) of Z1 and Z2, and the outside air temperature (*Te*) on the Average Day. In addition, the comfort range (18-26°C) has been plotted. On one hand, in Z1, the average *Tai* is 22.2°C with a daily oscillation of 6.1°C, with a minimum *Tai* of 19.2°C (6 am) and a maximum *Tai* of 25.3°C (7 pm). On the other hand, in Z2 it is determined that the average *Tai* is 23.3 °C. The daily oscillation is 7.4°C with a minimum *Tai* of 19.9 °C (6 am) and a maximum *Tai* of 27.3°C (8 pm).

According to these results, the *Tai* de Z1 stays within the comfort range throughout the day. Also, in Z2 there are no thermal discomfort temperatures, except between 5 pm – 9 pm. During this period, the *Tai* of Z2 is 1.3°C above the comfort range.

To understand the strategies proposed and the results shown in detail, Figure 7 indicates the heat fluxes in Z1 and Z2 analyzed on the Average Day.

The maximum *Tai* in the two zones evidences an approximate delay of 6 hours compared to *Te*. This delay is mainly influenced by the thermal mass of the adobe walls, together with the lighting and cooking contributions, and in the case of Z2, by direct solar gain through the windows.

The minimum *Tai* in Z1 and Z2 stays at around 20°C, which reflects the effectiveness of the strategies proposed in the vertical and horizontal envelope. The losses through the roof and floors are minimal during the day. The greatest losses are due to the walls, mainly due to the north and south walls. On the contrary, the influence of the east wall on Z1 and the west wall on Z2 means the losses are reduced from 4 pm.

This flow is reduced and remains very close to 0 until 8 am, and in Z2 it even becomes positive. Finally, the heat flow through partitions is very close to 0 kWh throughout the day, because these walls exchange heat with adjacent areas, and not with the outside.

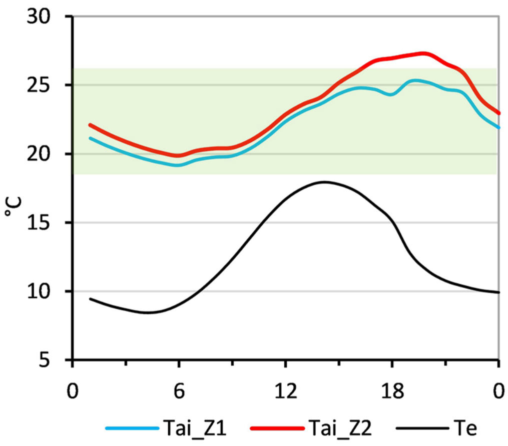

Figure 6. *Tai* of Z1 and Z2, and Te on the Average Day. Source: Preparation by the authors.

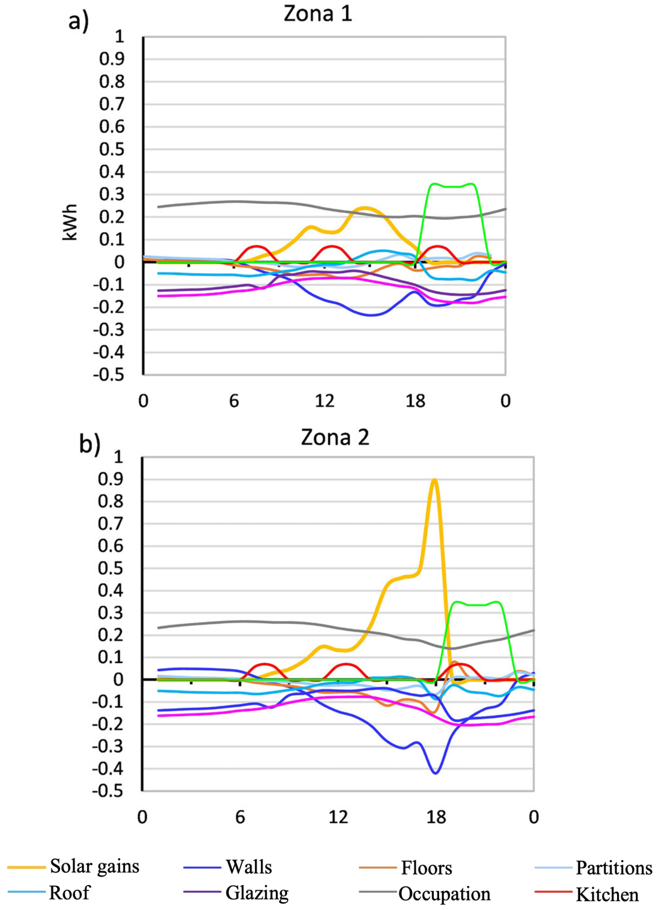

Figure 7. Heat fluxes of Z1(a) and Z2(b) on the Average Day. Source: Preparation by the authors.

On the other hand, on the Extreme Day (Figure 8), the average *Tai* of Z1 is 20.7°C, with a minimum *Tai* of 17.5°C and a maximum *Tai* of 23.7°C. The *Tai* of Z1 and Z2 are within the comfort range, except for a

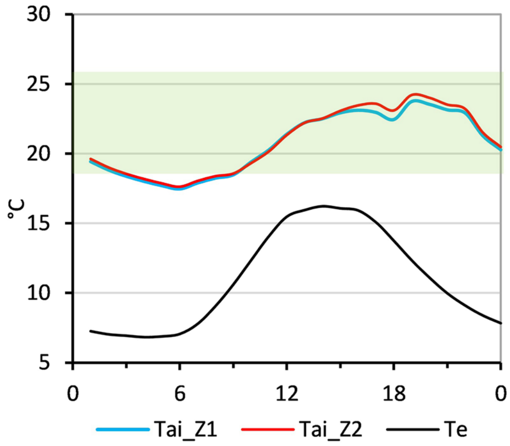

Figure 8. Tai of Z1 and Z2 and Te on the Extreme Day. Source: Preparation by the authors.

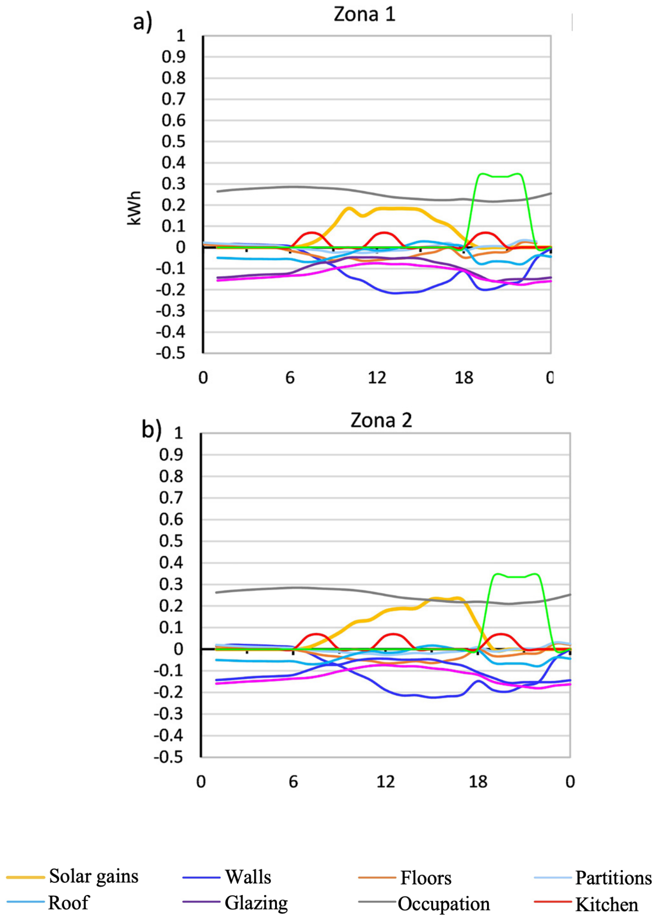

Figure 9. Heat fluxes of Z1(a) and Z2(b) on the Extreme Day. Source: Preparation by the authors.

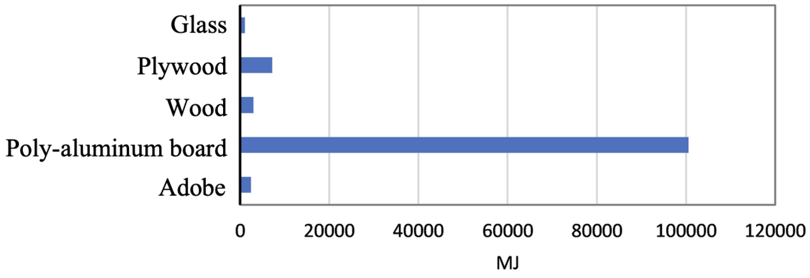

Figura 10. EE_T of the materials used in the Andean model. Source: Preparation by the authors.

few night hours. However, it is only 0.5°C below the comfort range.

In contrast to the Average Day, the maximum *Tai* does not exceed the upper limit and the thermal oscillation is lower. Again, the maximum *Tai* shows a delay of approximately 6 hours, which is mainly influenced by the thermal mass of the east and west walls and by the contributions of lighting, cooking, and solar gains. The latter is much lower than on the Average Day, since on the Extreme Day most of the solar radiation is diffuse (Figure 9).

Finally, the minimum *Tai* reaches up to 17.5°C, which is lower than the Average Day. However, it remains within the comfort range.

If we compare these results with the other EH studies mentioned, emergency homes in other regions tend to use, as in the case of Korea, insulation and heating to achieve thermal comfort (Hong, 2016), or if one of these is not used, there will be thermal discomfort, as seen in Japan (Sinohara et al., 2014). In the case of the Ecuadorian Andean region, this study shows that there are other strategies to achieve a Tai of 24°C, so following models such as those of Korea and Japan would imply unnecessary economic and environmental expenditure.

EMBODIED ENERGY CALCULATIONS

Figure 10 shows the EE_T of each of the materials used in the model. The highest EE_T is found in poly-aluminum boards with 100,586 MJ, followed by plywood and wood with 7,239 MJ and 3,023 MJ, respectively. Finally, there is glass and adobe. It should be noted that glass, even with the small percentage used, has almost the same value as adobe, which is much more representative in the model. The EE_T of the whole house is 114,414 MJ.

For comparative analysis, Figure 11 shows the EE_T value related to the total area of the dwelling (53.58m²), along with the values of other social housing in Ecuadorian Andean climates. This typology has been chosen due to the lack of local EH data.

Table 4 shows the characteristics of the dwellings used for the comparative analysis.

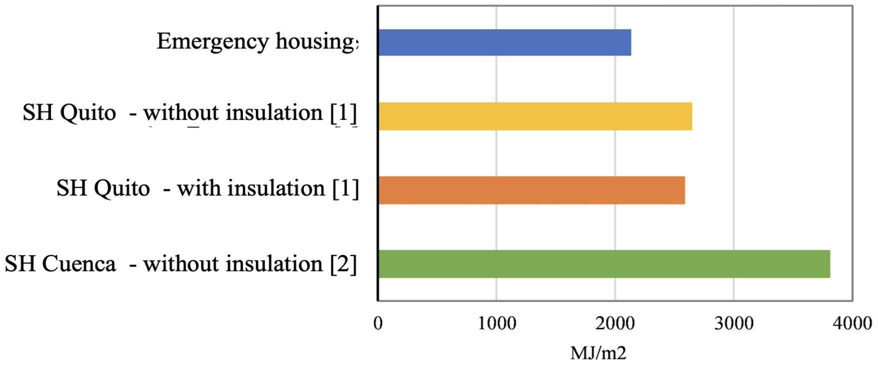

Figure 11. EE_T of the proposed model, and EE_T of social housing in Ecuador. Source: Preparation by the authors based on data obtained from: [1] Macias et al. (2017), [2] Torres-Quezada & Torres-Avilés (2023a).

Table 4. Characteristics of social housing in Ecuador. Source: Preparation by the authors based on data obtained from: [1] Macias et al. (2017), [2] Torres-Quezada & Torres-Avilés (2023b).

Housing	Walls	Roof	Area (m²)
SH_Quito_without insulation [1]	10 cm concrete	Galvalume	55
SH_Quito_with insulation [1]	sandwich-type, fiber cement boards, and 8 cm expanded polystyrene	Galvalume	55
SH_Cuenca_without insulation [1]	Plastered concrete block	Fiber Cement	60

The results show that the proposed model has an EE_T of 2,135.38 MJ/m², which is less than the energy spent by social housing in Quito and Cuenca. In the case of the Quito SH without insulation, this has 2,640 MJ/m², while the SH with insulation is 2,580 MJ/m². The dwelling built in Cuenca has an EE_T of 3,806 MJ/m².

According to what has been presented, it is seen that the most significant difference is manifested in the housing built in Cuenca (1,671 MJ/m²), which features concrete block walls that greatly increase its EE_T. In contrast, the houses of Quito show a difference of 505 MJ/m² with the ones devoid of insulation and 445 MJ/m² with those which have insulation.

These data show that housing without insulation has a higher EE_T than housing with insulation because the former has a system built of concrete walls, which significantly raises its EE_T. It should be mentioned that in these homes the doors, floors, or windows have not been considered for the calculation.

This comparative analysis shows the high impact that the use of insulating and industrialized materials has in increasing the EE_T. In the proposed prototype, poly-aluminum is the material with the greatest impact, even when it is recycled. This implies that its excessive use is counterproductive. However, it is chosen for its easy maintenance and durability under the region's climatic conditions.

CONCLUSION

From this study, it can be concluded that the passive strategies proposed, namely, direct solar gains, thermal mass, compactness, and the use of internal gains, are effective for an EH to reach comfort on both an Average (23.5°C) and Extreme (21.8°C) Day in the Andean climate. Both the results obtained and the minimum temperature (approx. 18°C) highlight that the use of insulation in this climate is not necessary, as it can be replaced by an air chamber.

On the other hand, it is possible to determine that the EE_T of the proposed construction system is lower than that recorded in other social prototypes with energy efficiency standards. This model represents 60% of social housing in Ecuador.

The poly-aluminum boards used in the model, although they are manufactured from recycled material, have high levels of embodied energy since the percentage that is recycled is not high and, in addition, the reused polyethylene and aluminum require a large amount of energy for their production. This opens a line of research on the effectiveness of recycling these and other materials in construction systems.

Finally, this research highlights that the use of passive strategies in the Andean region of Ecuador may be sufficient to achieve thermal habitability, reduce environmental impact and, more importantly, reduce both the use of unnecessary materials and the economic value of the prototype. The results of this study can be put into practice and promote the collaboration of local labor for their construction since it integrates vernacular construction systems and others that are easy to install.

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