ECONOMIC FEASIBILITY OF PASSIVE STRATEGIES FOR ENERGY EFFICIENT ENVELOPES OF MASS-BUILT HOUSING IN HOT-DRY CLIMATE

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ABSTRACT

The building and construction industry represents 36% of the world's final energy use and 39% of carbon emissions, while the residential sector is responsible for 22% of total energy consumption and 17% of carbon emissions. Therefore, energy consumption reduction measures are required by this sector, without affecting the living conditions of its occupants. In Baja California, Mexico, the more commonly used construction systems in mass-built housing are concrete block walls and cast in place insulated reinforced concrete roof deck. These systems negatively affect comfort conditions, especially in hot summer periods, and therefore increase energy consumption, particularly in areas with an hot-dry climate, such as Mexicali, Baja California. The objective of this article is to determine the cost-benefit of two passive design strategies applied in the housing envelope, which are thermal insulation and ventilated facade. A commercial model of mass-built housing was taken as a benchmark case. Building energy simulations were carried out with the Design Builder® program, whereby the performance of the house was evaluated without passive design strategies (benchmark case) and with applied strategies, that is, variations in thickness and position of the materials that make up the layers of the walls and roof. Additionally, the net present value (NPV) criterion was used to obtain the costs and benefits of the design strategies. The results show the differences in cooling demand, indoor operative temperature, and the total costs, in Mexican pesos, of the application of the strategies; the results show that there are significant energy savings, which contribute to reducing carbon emissions to the environment and provide economic savings for the user.

Keywords: economic feasibility, energy efficient envelope, hot-dry climate, mass-built housing, passive strategies.

1 INTRODUCTION

Elevated energy consumption in the hot arid climate of northern Mexico, including the states of Baja California, Chihuahua, Coahuila, Nuevo León, Sonora, Sinaloa, and Durango, is consistently attributed to the use of air conditioning (AC) units to ensure indoor thermal comfort [1], as well as the use of energy inefficient appliances [2,3]. AC dependency is exacerbated by the construction of thermally inadequate building envelopes, particularly in the housing sector, which consumes 18.8% of the national energy budget [4]. In this climate region, 48.1% of all residential buildings have at least one AC unit, which is used on average for 5–9 hours a day [5]; this represents 75% of all houses with AC in the country. Social housing is an important source of nation-wide energy consumption; it is the most prevalent housing sector in Mexico, with approximately 23 million houses, out of the 30 million overall [6].

Mass-built housing is generally designed without any climatic consideration [7, 8, 9, 10], and therefore, present long-lasting problems for the end user, which span from high indoor temperatures, well outside the thermal comfort range, to negative effects on indoor air quality, and even economic vulnerability, due to the user's need to retrofit their home to comply with adequate living standards.

Building energy use is affected by several factors, in addition to the environmental factors, such as the climatic conditions; the predominant elements of external heat gains are building

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geometry and the thermophysical properties of the building envelope [11]. Passive design strategies have been extensively implemented to reduce energy consumption and carbon emissions [12, 13, 14]. The reduction of external heat gain transfer by minimizing conductive heat flow in the building envelope is recommended in hot arid climates, where there is a significant difference in temperatures between the indoor and outdoor environments, as La Roche [15] points out. The most widely used strategies within this passive design measure include the use of insulation and implementation of a ventilated façade [16–19].

Ventilated facades bring about improvement in the buildings' thermal performance, especially in hot-dry climates, such as Mexicali, in northwestern Mexico [20–22]. This improvement is due to the air flow in the air cavity between the inner and outer layer of the ventilated facade, which reduces direct solar radiation heat gains and removes heat through natural and forced convection, therefore reducing energy demand for cooling [23–26]. While previous studies analyzed varying widths for the air cavity, whose width can vary depending on both the design and the desired energy performance, they did not compare the thermal performance of different materials or construction systems for the outer layer of the façade.

Additionally, insulation has proven its effectiveness at reducing heat gains, since adequate thermal insulation in the housing envelope in extreme climates can present considerable savings in energy consumption, with up to 20% of energy savings and 55% reduction in cooling demand in desert climates [27], as well as improved thermal performance [28]. Even though Mexico's hot arid climatic region has the highest percentage of thermal insulation application in the country, it represents only 14.9% of residential buildings with some type of insulation [5], and only 22.5% of the houses have wall insulation, while almost 90% have roof insulation.

Therefore, this research focused on the evaluation of architectural solutions to reduce cooling demand and its related energy use. The thermal performance of a mass-built house model was analyzed to determine passive design strategies which minimize conductive heat flow through the building envelope, as well as the economic feasibility of the application of these strategies [29] through a cost-benefit analysis, which consists of a study of the return on investments made, with an environmental focus [30].

Taking these considerations into account, the present research evaluated the proposed passive design measures using the building energy simulation (BES) software Design Builder®. The simulation setup includes the climatic data of the studied city and the conditions and characteristics of the selected benchmark case. The simulation scenarios were analyzed with the application of the proposed measures, and favorable results were obtained in relation to energy consumption reduction and increased thermal comfort. In addition, a cost-benefit analysis of each of the studied cases was carried out using the net present value (NPV), which also yielded favorable results for the user.

2 METHODS

The research was carried out with a quantitative approach, which consisted of thermal performance evaluations whereby the behavior of the envelope was analyzed in the benchmark case (BC) and in the case studies with the proposed applications of passive design measures; in addition, the cost-benefit of all the evaluated cases was obtained.

2.1 Climatic conditions

Mexicali is located in Mexico's northwest, in the Sonoran Desert, where it shares an international border with Calexico in the American state of California. The city's climate is classified as BW(h')hw(x')(e')w", hot-dry extreme climate, according to the Köppen-Geiger classification modified by García (2004) for Mexican climates [31]. Mexicali has registered maximum temperatures of 45–54 °C in the summer period [20] and has an annual rainfall of 73.3 mm [32]. Mexicali and Calexico are contiguous cities closely built to the international border, so the weather file used in the building energy simulations is the CZ15RV2.epw from Calexico's Imperial Valley [33].

2.2 Benchmark case

In the selection of the benchmark case, a specific mass-built housing model was selected, with its main facade oriented south; the construction area occupies 41.24 m^2 on a 120.05 m^2 plot. The house has two bedrooms, a bathroom, a living room/dining room, and kitchen as shown in Fig. 1. The construction system is the most commonly used in the city; the walls are made of 0.12 × 0.20 × 0.40 m concrete masonry unit (CMU) blocks, with hollow cells cast with concrete, f'_c = 140 kg/cm^2, at every 0.61 m. The roof is a cast in place insulated reinforced concrete roof deck of 0.17 m in thickness, with concrete f'_c = 200 kg/cm^2 and reinforcing steel #3 (0.0071 m), covered with fiberglass reinforcing mesh and two layers of smooth texture plaster, finished with elastomeric paint.

2.3 Case studies with applied passive design strategies

The investigation considers a benchmark case (BC) and 12 case studies, for which the BC envelope was retrofitted with the application of passive design strategies. The case studies were divided into three groups. Group A, where thermal insulation was used with 0.0254 m (1″) of expanded polystyrene (EPS) applied in each of the orientations of the vertical envelope. Group B was evaluated with an opaque ventilated façade, where the air cavity varied in width, from 0.10 m to 0.35 m, only applied in the southern orientation, due to its greater

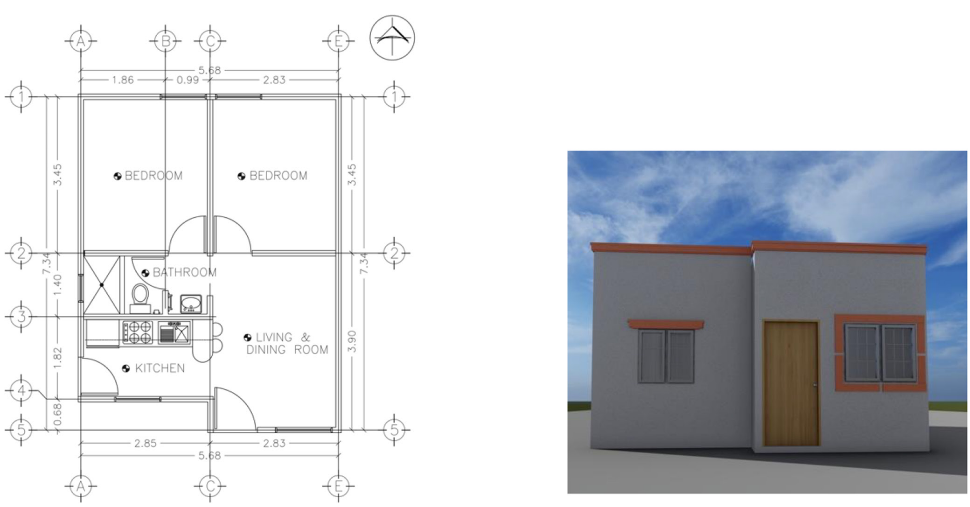

Figure 1: Benchmark case (BC) (source: RUBA construction plans, 2011).

exposition to direct solar heat gains (east and west orientations are larger in area but shaded by adjacent houses). The outer layer of the ventilated facade is a lightweight steel framed construction system with 1.22 m (4′) by 2.43 m (8′) gypsum board drywall 0.0127 m (½″) on the interior face of the wall, a rectangular hollow section structure (RHS) of 0.0762 m (3″) at every 0.60 m (24″) in both directions, fiberglass thermal insulation, and exterior finish of 0.0127 m fiber cement board (½″) (Durock USG®). Ventilation grills were added for natural convection inside the air cavity of the ventilated facade. Finally, group C was simulated with the combination of strategies A and B, one case (C1) with the configuration which presented the best performance in group B and the least promising of group A, and the second case (C2), which presented the largest savings in both groups. All case studies are listed in Table 1.

2.4 Building energy simulation

Design Builder® version 5.4.0.021 was used; for the thermal performance evaluation. The location of the city of Mexicali was selected, situated at a latitude 32º 39′ 54″ N, longitude 115º 27′ 21″ W, and an above sea level height of 4 meters [32]. To represent climate conditions, the Energy Plus Weather file (EPW) of the California climate zone 15 was used. Internal heat loads were specified through energy use schedules, for the people, equipment, and lighting indicated in Table 2. A temperature set point of 24–25 ºC was considered [34].

Simulations were performed for the summer period of the studied city (May–October), materials and construction systems as listed in Table 2. It is important to note that when indoor thermal comfort was evaluated, all the case studies were simulated with natural ventilation and only the BC was evaluated with air conditioning and with natural ventilation; this allows the comparison of the BC and the studied cases in natural conditions, and thus can demonstrate the impact of each applied strategy to the indoor thermal conditions of the building.

Therefore, thermal performance and comfort conditions results were obtained, depending on the cooling load (zone sensible cooling), gains per wall (kW/m^2), and comfort based on the predicted mean vote (PMV) model. For the analysis of these data, especially those of thermal comfort, the data obtained by building energy modeling had to be processed in a spreadsheet [35], in order to present data on the scale established by the PMV model in the ISO 7730 standard [36] (Table 3).

Table 1: Case studies with passive design strategies.

Benchmark case (BC)					
Design strategy A: Benchmark case with 0.0254 m (1″) expanded polystyrene insulation					
A1 South		**A2** West		**A3** North	**A4** East
Design strategy B: Benchmark case with ventilated facade (air cavity width)					
B1 0.1 m	**B2** 0.15 m	**B3** 0.2 m	**B4** 0.25 m	**B5** 0.3 m	**B6** 0.35 m
Design strategy C: Benchmark case with combination of group A and group B strategies					
C1 (A1 and B6)			**C2** (A4 and B6)		

Table 2: Simulation setup.

Parameter	Description	Value	Units
Climate data	City	Mexicali, Mexico	
	Location	32.8 °N, −115.67 °W	
	Weather file	CZ15RV2. epw	
	Time zone	GMT -08:00 Tijuana	
Building	Construction area	41.24	m^2
	Main façade	South	
Construction system – U value	BC: concrete masonry unit blocks, cast cores, 0.12 m	2.932	W/m^2 °C
	BC: insulated reinforced concrete roof deck, 0.17 m	0.860	W/m^2 °C
	Design strategy A: Concrete masonry unit blocks, cast cores, 0.12 m with a layer of expanded polystyrene, 0.0254 m	0.988	W/m^2 °C
	Design strategy B: Fiber cement board wall 0.12 m with fiberglass insulation and ventilated façade (with varying air cavity thickness)	0.424	W/m^2 °C
Internal loads	People: (4) users	4,027	W
	Equipment: (2) Stove burner (1) Microwave (1) Coffee maker (1) Blender (3) Television (1) Wireless telephone (5) Cellular phone charger (1) Modem (1) Laptop (1) Bathroom exhaust fan (1) Hair dryer (1) Electric shaver	19,742	W
	Lighting (5) 100 W incandescent light bulb (2) 60 W incandescent light bulb	2,550	W
Cooling system	(3) Mini split 3.28 COP	18,736.7	W
	Turned on, 24 hours, 7 days a week	24–25°C set point	

Table 3: Thermal comfort scale (source: ISO 7730, 2020).

Model	Standard	Comfort scale – thermal sensation	
PMV	ISO-7730	< −3	Very cold
		−3 to −2	Cold
		−2 to −1	Cool
		−1 to −0.5	Slightly cool
		−0.5 to 0.5	Neutral (comfortable)
		0.5 to 1	Slightly warm
		1 to 2	Warm
		2 to 3	Hot
		> 3	Very hot

2.5 Cost-benefit analysis

The cost-benefit analysis of each case study was carried out. For this, it was necessary to know the total cost of the initial investment that the user would have to make in each of the proposed strategies, the cost of minor and major maintenance (established at two and a half and five years, respectively), the annual rate of inflation [37], the costs from the consumption of electricity [38], and the useful life span of the house established at 30 years (Table 4). To do this, the following net present value (NPV) formula was used:

$$\mathrm{NPV} = -P + \frac{FNE}{(1+i)^n} + \frac{FNE}{(1+i)^n} + \ldots \tag{1}$$

Table 4: Economic evaluation data.

Cost (Mexican currency)						
Wall		Constructive system				Annual rate of inflation
		Initial investment		Maintenance		
Orientation	Area (m²)	Expanded polystyrene[1]	Fiber cement board[2]	Major[3]	Minor[4]	
North	15.47	3,545.56	9,220.12	1,856.40	1,284.01	4%
South	14.02	3,213.24	8,355.92	1,682.40	1,163.66	
East	22.04	5,051.34	13,135.84	2,644.80	1,829.32	
West	20.25	4,641.09	12,069.00	2,430.00	1,680.75	

[1]The cost of expanded polystyrene over existing wall is \$229.19/m^2.
[2]The cost of gypsum board drywall with fiberglass insulation is \$596.00/m^2.
[3]The cost of plaster, molding replacement, and crack repairs is \$120.00/m^2.
[4]The cost of wall painting with detailing is \$83.00/m^2.

where P corresponds to the initial investment, FNE corresponds to the net cash flow of year n (net profit after taxes for the year), and i is the annual inflation rate [39].

The cost-benefit study of passive strategies was carried out, with the purpose of this research being to determine if one or more of the proposed strategies is convenient to the user considering three aspects: thermal, i.e. comfort; energetic, i.e. energy savings; and economic, namely, cost of investment of the application of the passive design strategies in the house.

3 RESULTS

The results are presented in three sections: energy performance, thermal comfort, and cost-benefit. Energy performance results include heat gains (kWh) and zone sensible cooling or cooling loads (kWh); thermal comfort results comprise percentages based on the comfort hours obtained in the summer period, and cost-benefit includes expenses (in Mexican currency).

3.1 Energy performance

Table 5 shows the results in kWh of the simulations of strategy A [40]; this shows that the southern-oriented wall receives higher heat gains than the rest of the vertical envelope, with an excess of 600 kWh per square meter, and thus merits the application of strategy B to the southern wall. Likewise, it is observed that the BC had a total gain for walls close to 10,000 kWh and also that in the case studies, the critical one is the A1 with 1,272 kWh less than in the BC.

Table 6 shows the results of heat gains per wall for the rest of the studied cases; it is observed that the option that resulted in the lowest gains is C2, since its gains, at more than 5,000 kWh, are by 46.16% less compared to BC.

In Fig. 2, a comparison of all case studies is presented [40].

The results of Table 7 show that the best case is also C2, with more than 3,000 kWh saved in energy removal compared to the BC. The case study that presented the least amount of savings was C1 with 795.37 kWh less compared to the BC.

3.2 Thermal comfort

Thermal comfort evaluation in the BC was initially modeled with the HVAC system turned on, and therefore, the results indicated 100% comfort conditions, so it was decided to model the BC with natural ventilation, to establish a comparable baseline for the effect of the applied passive strategies. In the BC, with natural ventilation conditions, less than 800 hours of comfort were obtained, and in the case studies with the application of the design strategies, results showed more than 950 hours of thermal comfort. However, the worst case is the A3 with 985

Table 5: Design strategy A heat gains: Thermal insulation (source: Reyes-Barajas et al. 2020).

Case	**Heat gains per wall (kWh)**	**m^2**	**Heat gain/m^2 (wall surface area)**
CB	9,988.56	72.15	–
A1	8,716.27	14.02	621.52
A2	7,889.90	20.25	389.57
A3	8,908.25	15.47	575.84
A4	7,444.92	22.04	332.30

Table 6: Design strategy B heat gains: air cavity; design strategy C heat gains: combination A and B.

Case	Heat gains (kWh)
B1	8,025.68
B2	8,001.74
B3	7,977.8
B4	7,956.3
B5	7,934.36
B6	7,911.76
C1	7,927.10
C2	5,371.79

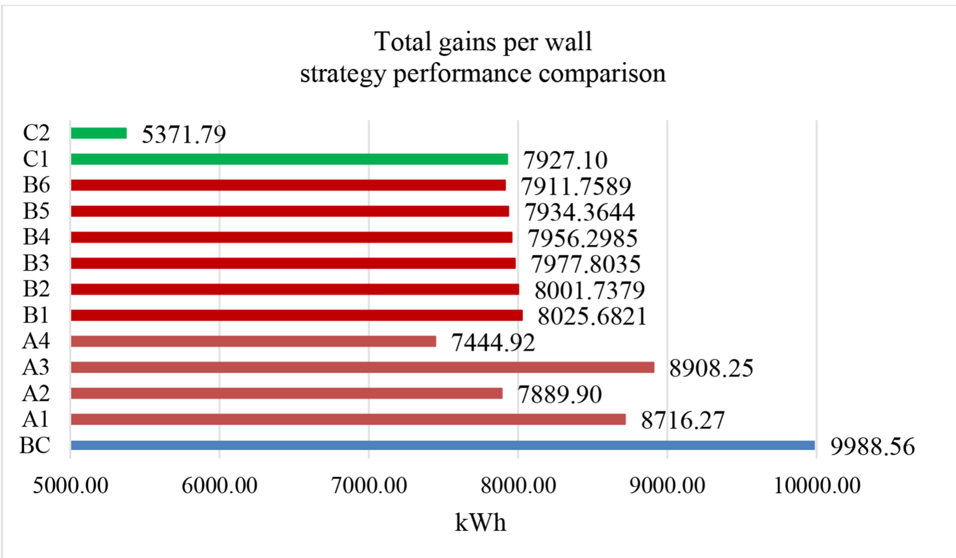

Figure 2: Case studies heat gains per wall.

comfort hours more than the BC, while the case with the most comfort hours is C2 with more than 1,300 hours compared to the BC (Table 8).

3.3 Economic evaluation: cost-benefit

It is shown that with all the proposed design strategies, there are savings in energy consumption compared to the BC, so that any strategy applied to the house is considered favorable. Additionally, the economic evaluation, with the use of the NPV formula for each case study, confirmed that all cases presented both energetic and economic savings. The amount saved depends on the case study applied, for example, if case C1 is used, the saving with respect to the BC is more than $14,000 Mexican pesos ($696.62 USD); on the other hand, if the case A4 is applied, savings are four times higher than with C1 (Table 9).

Table 7: Case studies cooling load.

Case	Cooling load (kWh)
BC	−17,337.63
A1	−16,113.77
A2	−15,339.30
A3	−16,285.66
A4	−14,870.49
B1	−16,007.1
B2	−16,411.7
B3	−16,480.3
B4	−16,483.8
B5	−16,496.1
B6	−16,502.7
C1	−16,542.26
C2	−14,005.41

Table 8: Case studies thermal comfort.

Case	Comfort hours in summer	Total hours in summer period	Percentage
BC	786		17.8
A1	995		22.5
A2	1,035		23.4
A3	985		22.3
A4	1,032		23.4
B1	1,027		23.3
B2	999	4,416 h	22.6
B3	1,309		29.6
B4	1,319		29.9
B5	1,323		30.0
B6	1,333		30.2
C1	1,346		30.5
C2	1,387		31.4

Thus, in Fig. 3, the total costs of the BC and the case studies are shown; it is observed that BC, appropriate maintenance for the useful life span of the house, the cost would be \$245,898.02 Mexican pesos (\$12,235.56 USD). It is also observed that in the cost-benefit analysis, the option that represents the greatest economic savings is the A4 case, while the one with the lowest savings is C1.

Table 9: Economic savings in case studies.

Case	Present net value ($ – MXN)
A1	35,324.58
A2	49,292.85
A3	29,552.53
A4	61,496.02
B1	32,319.70
B2	21,356.46
B3	19,535.58
B4	19,355.58
B5	18,957.07
B6	18,738.94
C1	14,539.39
C2	53,139.53

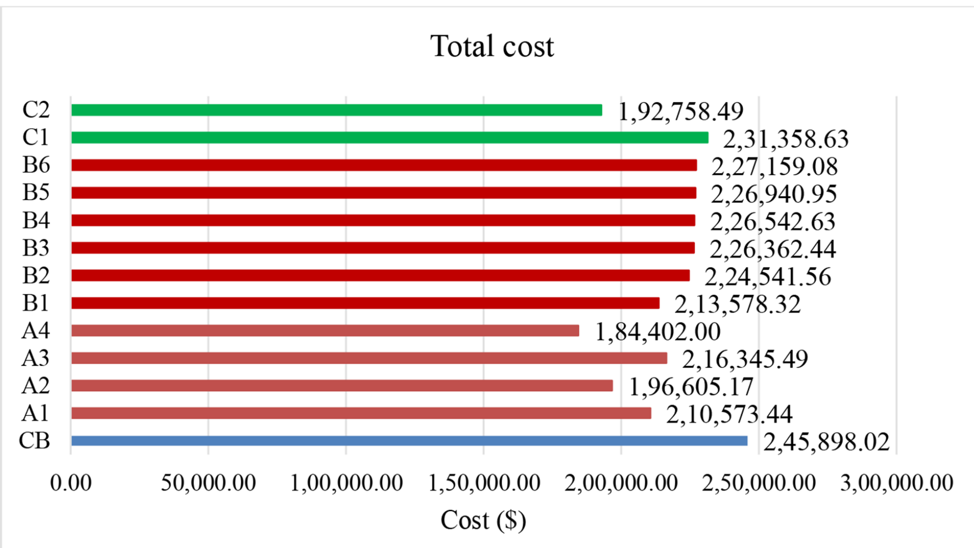

Figure 3: Total cost of design strategy implementation.

4 DISCUSSION

Given the climatic conditions of Mexicali during the summer period, where temperatures reach over 40 °C, and the current construction systems, which do not allow comfortable conditions inside the house unless an air conditioning unit is used, it is feasible to increase the energy efficiency of an existing house with the integration of passive design strategies in the envelope according to the geographical orientation. For this to be effective, it is necessary to balance the decrease in heat gain with the increase in thermal comfort conditions for the user, within a framework of economic viability.

Energy efficiency regulations promote the use of thermal insulation to reduce energy consumption when using a mechanical air conditioning system. The use of a second design strategy, such as the ventilated facade, will improve the thermal performance of the housing envelope further.

5 CONCLUSIONS

For the selection of passive strategies, it is necessary to use the criteria of thermal performance (heat gain), energy performance (energy to be withdrawn), thermal comfort conditions (hours), and economic viability (cost-benefit) in a balanced and joint manner.

According to the heat gain per square meter with thermal insulation (strategy A), the south orientation is the one with the highest heat gain, 60% more than that of the west and 87% more than that of the east. This shows that measures are required to decrease heat gain in the south orientation.

The implementation of an opaque ventilated façade with an air cavity (strategy B) in the south orientation turned out to be adequate due to the location of the house on the lot. Each increase in air cavity width by 0.05 m decreases heat gain by around 22–24 kWh; increasing the width up to 0.35 m was key to achieving a balance between the factors analyzed for the selection of design strategies.

It is observed that there is a greater number of hours of comfort with ventilated facade techniques than with thermal insulation; the number of hours of thermal comfort is directly increased by increasing the width of the air cavity; and that the increments from a width of 0.20 m to 0.35 m are not significant.

Regarding the cost-benefit, the best option was thermal insulation in eastern orientation (strategy A4); however, from the perspective of energy consumption and comfort, it does not provide significant improvement, while the A4 strategy with the addition of the air cavity of 0.35 m costs only $8,300 Mexican pesos more than A4. Hence, there is no significant economic difference, but there is considerable benefit in energy consumption and comfort.

Consequently, it was determined that the option with the greatest benefits is the combination of the ventilated façade with an air cavity width of 0.35 m (south wall) and the thermal insulation in the east wall (strategy C2). With the application of this design strategy, it was possible to reduce heat gains per wall by more than 4,000 kWh and the cooling load by just over 3,000 kWh, compared to BC. Likewise, it is the best case for comfort, since it managed to increase thermal comfort by 13.6% inside the house.

Finally, it is clearly demonstrated that the implementation of passive design measures, such as thermal insulation and opaque ventilated façades, has a favorable impact in hot climates and in turn benefits the user, since these strategies improve the thermal indoor environment, which causes electrical energy savings and therefore economic savings.

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