Article

Thermal Energy Performance Simulation of a Residential Building Retrofitted with Passive Design Strategies: A Case Study in Mexico

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Abstract: High energy consumption as a result of an inefficient design has both economic and environmental repercussions throughout the life cycle of a building. In Mexico, the residential sector is the third-largest final energy consumer, therefore improving the performance of existing buildings is considered an effective method in achieving energy savings. Moreover, in Mexico warm climate regions predominate, which impacts energy consumption. This article examines a linked, single-family house located in the hot-humid climate city of Villahermosa, Tabasco (México). DesignBuilder software was used to conduct the thermal energy performance simulation of the existing building (base case) and to evaluate the energy-saving potentials by implementing different passive design strategies. As a result, the annual electricity consumption of the base case decreased a maximum of 2.0% with the passive design strategy in exterior windows, 4.9% in walls and, 13.7% reduction in roofs, the latter being the enclosure with the greatest reduction achieved. Nevertheless, a final adaptation proposal with the passive design strategies, whose results represented the highest energy savings, accomplished a total reduction of 23.5% with a payback period of 5.8 years.

Keywords: passive design strategies; hot-humid climate; thermal energy performance simulation; energy efficiency

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1. Introduction

In the last decade, society has increased energy consumption to carry out its daily activities, and the proper operation of its production processes, both of which are essential to enhance the social and economic well-being of a country [1]. The International Energy Agency (IEA) reports that the global primary energy demand increased by 2.3% in 2018, the largest annual increase since 2010, and well above those in 2015 and 2016. Moreover, similarly to primary energy demand, final energy demand also increased in 2018, by 2.2% [2]. The countries that registered the highest energy consumption were: China (20.71%), the United States (16.04%), India (6.10%), Russia (5.18%), and Japan (2.85%) [1].

The residential sector contributes a substantial portion of global energy consumption and greenhouse gas (GHG) emissions in every country. This sector is responsible for more than 40% of global energy used and for as much as 33% of global GHG emissions [3,4]. According to the Energy Information Administration (EIA), it is projected that the energy consumed in this sector will increase by 65% between 2018 and 2050 [5].

In Mexico, the residential sector is the third-largest final energy consumer [1,6,7], representing 14% of total final energy consumption, while in terms of electrical energy consumption, it accounts for 23% of the national total, and represents 17% of total National GHG emissions [1,8]. Therefore, the implementation of energy efficiency actions and GHG mitigation is of great importance and should be studied in detail for this country. Although there have been significant improvements in the energy efficiency for the residential sector; these efforts have achieved a greater impact in temperate climate regions than in

warm climate regions. This is because the most effective public policies in warm regions have mainly focused on the energy efficiency of electrical appliances, leaving aside the building design, which accounts for the highest energy consumption for these types of regions [9,10]. Moreover, since in Mexico the warm climate regions predominate, due to its geographical position, the thermal performance of a building has a great impact on the energy demand in this sector [9]. The Federal Electricity Commission (CFE, by its acronyms in Spanish), calculates that in Mexico, a user in a warm climate region consumes twice as much electricity as one in a temperate climate [10].

According to the US Green Building Council (USGBC), it is estimated that today, on average, green buildings can reduce energy consumption by 30%. There are several features which can make a building green, one of them is an efficient use of energy [11], where the achievement of an adequate level of comfort is accomplished mainly through the implementation of passive design systems, which take full advantage of the building environment climatic conditions [12–18]. An excellent passive building design can significantly decrease the energy consumption in a building by reducing heating/cooling loads through the building envelope (walls and fenestration) [19–21], which have been proven to be an extremely important influence on thermal performance [22–25].

Mexico has the mandatory standard NOM-020-ENER-2011 (abbreviated as NOM-020) [26] which limits heat gains through the envelope for residential buildings; and the voluntary standard NMX-C-460-ONNCCE-2009 (abbreviated as NMX-C-460) [27] which recommends thermal resistance values (R-value) for envelopes by thermal region [28], but the implementation of efficiency policies in the building sector is complicated due to the devolution of policy responsibility to local jurisdictions. In addition, local municipalities do not have the knowledge or proper technical skills to fully understand the energy deficiencies of buildings and proper funding is needed for the implementation of the existing normativity. An additional problem is that most municipal building standards fail to require the application of NOM-020, even though this federal regulation is currently active and mandatory, and since the local municipalities are the entities that grant building permits, NOM-020 is generally ignored [29]. Furthermore, according to the SmartMarket Report, in Mexico slightly more than one quarter (27%) of people do most of their projects green [30]. Therefore, using building energy modeling (BEM) to compare energy-efficiency options can be a crucial tool to direct design decisions prior to construction or even to optimize energy operation, or explore retrofit opportunities in existing building projects that can generate both economic, social, and environmental benefits. It can be used to perform a detailed analysis of a building's energy use and energy-using systems, to compare project efficiency options, comply with codes or green building certification requirements, optimize on-going energy costs, and inform actual performance [31]. The economic advantages due to the application of energy-saving measures for buildings can be classified into direct or indirect ones. The first depend on the reduction of energy consumption, and are directly evident in the management costs (lowering the costs on the energy bill). By contrast, the latter are more difficult to detect, they consist of an increase in the asset market value due to the improvement of its energy rating [32,33].

However, improving the performance of existing buildings is as critical in achieving the goals of green buildings as the construction of new green buildings, if not more so [30]. According to the National Institute of Statistics and Geography (INEGI, by its acronyms in Spanish), in the country, this sector comprises approximately a total of 35 million inhabited housing units with an average of 3.7 occupants per dwelling [34]. However, it is expected that, by the year 2030, 28% of households in Mexico will require complete or partial improvements, which represent a great opportunity to improve the energy efficiency in this sector [35]. Therefore, the present study takes an existing residential building located in a hot-humid climate of Mexico, specifically the city of Villahermosa, Tabasco, to generate a proposal with passive design strategies, supported by building energy modelling, to improve the usage of energy and consequently the reduction of electricity consumption.

This may establish a replicability criterion for the residential sector with similar climatic regions within the country.

2. Methods

A thermal energy performance simulation of a case study building in Villahermosa, Tabasco (Mexico) was conducted using DesignBuilder software [36]. This analysis aimed to stand for the effect that the passive design strategy has on the energy consumption of the building studied in this case.

2.1. The Case Study

The residential building studied (base case) is a linked, single-family house located in the city of Villahermosa, Tabasco (México). The total building surface area is 198 m² and consists of a total of 3 floors with 4 bedrooms, a study room, a living-dining room, a kitchen, an office, and 4 bathrooms. As shown in Figure 1, the main façade of the building is orientated to the west.

Figure 1. This is a (a) Building location in Villahermosa, Tabasco (Mexico); (b) The main façade of the residential building.

2.1.1. Weather Data

The weather data of Villahermosa, Tabasco was extracted from Meteonom software [37] and added to Designbuilder software. These site-specific weather data were required to perform an accurate energy-consumption assessment of the residential building.

The annual weather data is a critical input for building energy modeling. Therefore, in order to corroborate that the EPW (EnergyPlus Weather Data) file introduced in the software was accurate, the National Meteorological Service (SMN, by its acronyms in Spanish) weather files [38] and the NASA Langley Research Center (LaRC) POWER Project funded through the NASA Earth Science/Applied Science Program files [39] were consulted. Table 1 shows the main climatic parameters of Villahermosa, Tabasco, including the temperature, relative humidity, precipitation, and wind speed.

2.1.2. Building Data

A field study was carried out to investigate the building's data (construction materials, occupancy, lighting loads, HVAC controls, plug loads, and operation schedules). The surface mass, the U-value, and solar factors (of the fenestration only) of the residential building (base case) are shown in Tables 2 and 3. It is worth mentioning that the structural elements of the thermal envelope and interior partitions were typical for this type of buildings in Mexico [40].

Table 1. Climatic parameters of Villahermosa, Tabasco, 2008 to 2018.

Weather Data		
Temperature	Annual average (°C)	26.7 [38]
	Maximum annual average (°C)	31.6 [38]
	Minimum annual average (°C)	21.7 [38]
Relative humidity	Annual average (%)	79.9 [39]
Precipitation	Mean annual (mm)	2258.0 [38]
	Annual average (m/s)	4.1 [39]
Wind speed	Maximum annual average (m/s)	5.9 [39]
	Minimum annual average (m/s)	2.4 [39]

Table 2. Building envelope (opaque elements) and U-values.

Elements	Material	Thickness (mm)	U-Value (W/(m ² ·K))	Construction Image [41]
External wall and internal partitions	Plaster, dense	10.0	2.99
	Concrete block, hollow, lightweight	62.1		
	Plaster, dense	10.0		
Roof, internal floor, and external floor.	Porcelain floor	20.0	3.27
	Concrete, reinforced (with 2% steel)	319.0		
	Plaster, dense	13.0		
Ground floor	Porcelain floor	20.0	1.95
	Concrete slab	152.4		
	Compacted soil	304.8		

Table 3. Building envelope (fenestration), solar factors and U-value.

Element	Material	U-Value (W/(m ² ·K))	SHGC	VT
Exterior Windows	Single glazing 6 mm/wood frame	5.05	0.64	0.88
	Single glazing 6 mm/aluminum frame	7.24	0.75	0.88
	Single glazing 6 mm/no frame	5.78	0.82	0.88

Existing publications suggesting thermal properties for concrete materials provide little or no information on the concrete or mortar mixture proportions, limiting the utility for designers desiring to identify inputs for building energy simulation models. However, considering the year of the building construction and specifications of the construction's

Mexican standards, the concrete mixture proportion of the base case was established as 1:4:8.

2.2. Software Election

The energy simulation models were generated and evaluated using DesignBuilder, which is one the most established and advanced building energy simulation tools using the EnergyPlus engine [42]. Designbuilder provides an easy-to-use interface for modelling simulation and quantifying building performance. EnergyPlus is a very powerful simulation engine for studies of building energy including construction, HVAC systems and controls, lighting, thermal mass, and economic analysis. The software is widely used and validated in building energy modelling either for conventional construction materials, or for more complicated building materials such as building integrated phase change materials [43–47].

Since the main purpose of this study was to evaluate the thermal performance simulation of an existing residential building, and due to the possibility of interoperability issues between building information modeling (BIM)–building energy modeling (BEM) appearing during the importation of the BIM information to a building energy analysis software [48–51], which can lead to a rework consisting of re-entering the BIM stored information into the energy model [51], BIM was generated through Designbuilder software.

2.3. Building Modelling

For the creation of the model geometry, a total of 3 building blocks were used, which helped to define the different levels of the building. The building's accessories (such as pillars, shading devices, and balconies) and the two adjacent houses, located in the north and south façade of the building (see Figure 1), were established using component blocks. The two adjacent houses were included in the modeling since both houses' height represent important solar obstructions in the project.

The different views of the 3D building model located in Villahermosa are shown in Figure 2 where building blocks are represented in dark gray color, the component blocks in purple, and the location and visual dimensions for the openings (fenestrations and doors) in light gray.

Each building block was internally divided into different thermal zones through the creation of internal partitions. The thermal zones generated at each level are listed below:

- First level: 4 thermal zones were created, consisting of a kitchen, living-dining room, half bathroom, and a study room (see Table 4).
- Second Level: 7 thermal zones were established, which correspond to the master bedroom, master bathroom, bedroom 1, bathroom 1, bedroom 2, bathroom 2, and a corridor (see Table 4).
- Third Level: 2 thermal zones were defined and consist of an office room and utility room (see Table 4).

Figure 2. Cont.

Figure 2. Visualization of the 3-D building model located in Villahermosa, Tabasco (Mexico): (a) front view; (b) back view; (c) axonometric front view; (d) axonometric back view.

Table 4. Internal partitions defined for the residential building and the surface areas.

	Internal Partitions.	Surface Area (m ²)
First level		① Kitchen 11.0
		② Living- dining room 59.0
		③ Half bathroom 2.2
		④ Study room 9.7
Second level		① Master bedroom 18.3
		② Master bathroom 8.9
		③ Bedroom 1 17.3
		④ Bathroom 1 5.5
		⑤ Bedroom 2 24.7
		⑥ Bathroom 2 5.4
		⑦ Corridor 10.7
Third level		① Office room 15.8
		② Utility room 9.5

Based on the collected information, the internal gains of the building were defined in DesignBuilder software: occupancy, lighting loads, HVAC controls, plug loads (such as miscellaneous, office equipment, and computer), and operation schedules. The cooling set point temperature was set at 25 °C and the assigned values for humidification and dehu-

modification in site were 50% each, in accordance with the thermal comfort established in ANSI/ASHRAE standard 55-2017 thermal environmental conditions for human occupancy. The heating set point was set at 0 °C, because on-site heating is not considered necessary, due to the climatic conditions of the location in this study.

The data of occupancy and operational schedules used to simulate in the software are shown in Tables S1–S3 (Supplementary Material).

2.4. Validation of the Building Model (Base Case)

To validate the base case model, ASHRAE Guideline 14 was used, which is an established method for measuring a model's accuracy [52–54]. ASHRAE Guideline 14 considered accurate if the mean bias error (MBE) of monthly data is $-5\% \leq \text{MBE}_{\text{monthly}} \leq 5\%$ and $\text{CV(RMSE)}_{\text{monthly}} \leq 15\%$ [47]. The MBE and CV(RMSE) were calculated using Equations (1) and (2).

$$\text{CV (RMSE)} = \frac{\sqrt{\sum_{i=1}^{N_i} [(M_i - S_i)^2 / N_i]}}{\frac{1}{N_i} \sum_{i=1}^{N_i} M_i} \quad (1)$$

$$\text{MBE} = \frac{\sum_{i=1}^{N_i} (M_i - S_i)}{\sum_{i=1}^{N_i} M_i} \quad (2)$$

where CV (RMSE) is the coefficient of variation (CV) of the root mean square error (RMSE); mean bias error (MBE) is an indication of overall bias in a regression model; M_i is the actual monthly energy consumption at instance i ; S_i is simulated monthly energy consumption at instance i ; and N_i is the number of values involved in the error calculation.

2.5. Performance Analysis

The building's performance was evaluated based on the energy performance and economic analysis. Equations (3) and (4) were used to measure the energy savings in the base case building after retrofit.

$$\text{Energy saving (kWh)} = \text{Energy used (base - case)} - \text{Energy used (retrofit)} \quad (3)$$

$$\text{Energy saving (\%)} = \frac{\text{Energy saving (kWh)}}{\text{Energy used (base - case)}} \times 100\% \quad (4)$$

Equation (5) is the discounted payback period (DPP) used as a financial parameter for evaluate the economic feasibility of the final proposal. The DPP is the number of years it takes to break even from undertaking the investment cost (i_0) by discounting the cumulative net present values to base year, which is developed and applied with a specific discounting cash flow approach to evaluate an investment in renovation to improve building quality, thus increasing energy efficiency [55,56].

$$\text{DPP} = i_{NPV(i)=0} \quad (5)$$

where DPP is the discounted payback period; i_0 is the initial investment cost; NPV is the net present value.

The Equation (6) measures the net present value (NPV), which is the sum of the incoming and outgoing cash flows (CF), over a defined time horizon (T), discounted at the discount rate (r), less the initial investment (i_0) [56].

$$\text{NPV} = \sum_{i=0}^T \frac{\text{CF}}{(1+r)^i} - i_0 \geq 0 \quad (6)$$

3. Results and Discussion

3.1. Base Case Simulation

The thermal energy performance simulation was made to analyze the internal and external heat gains/losses of the building. The actual and simulated monthly electricity consumption of the residential building studied (base case) is shown in Table 5. The results showed that the MBE electricity consumption is -4.1% and the CV (RMSE) is 14.1% . Thus, the values are within the acceptable limits to be considered as accurate according to the ASHRAE Guideline 14.

Table 5. The actual and simulated electricity consumption.

Month	Actual (kWh)	Simulated (kWh)
January	442	472.54
February	1670	1661
March		
April	3142	3231
May		
June	3274	3427
July		
August	3058	3143
September		
October	1784	1845
November		
December	483	480

The monthly heat gains result by the base case throughout the year can be seen in Figure 3, caused by walls, ceilings, floors, ground floors, partitions, roof, lighting, miscellaneous, catering, computers and equipment, occupancy, solar gains, and zone-sensible cooling. In this figure, we can see that the greater heat gain is due to the increase in solar gains by exterior windows, followed by the roof, occupancy, and lastly, by the walls. On the other hand, it can be observed that the primary heat loss of the building is due to the interior floors and through the ground floor, which is responsible for reducing the sensible cooling zone of the building.

Figure 3. Monthly heat gains/losses of the base case.

3.2. Passive Design Strategies Proposed

Once the results of the thermal energy performance simulation of the base case were analyzed, different passive design strategies were proposed, which were based on those enclosures and/or openings that had greater contributions of heat gains in the base case: exterior windows, roofs, and walls. Regarding the occupancy, which represents the third position of the heat gains in the base case, it is not feasible to be modified, since it would signify changes in the occupancy hours, the number of occupants, or the current metabolic conditions.

The passive design strategies proposed for the residential building are described hereafter:

- **Exterior windows:** To reduce the solar gains, which represent the greatest heat gain, it was proposed to add another glass with a thickness of 13 mm in all the windows placing air in between them (see Figure 4). In the same way, since the frames influence the thermal behavior of the window, it was proposed to change the aluminum frames to wooden frames and place wooden frames on exterior windows with “no frames”, to improve their thermal properties. Table 6 describes the thermal properties of the exterior windows, both base case and with the proposed passive design strategy.
- **Roof:** To reduce the heat gains in this enclosure and maintain the interior thermal comfort, a passive design strategy was proposed on roofs through the installation of expanded polystyrene (EPS) insulation panels. A total of 4 different thicknesses of the insulation material was proposed, to achieve compliance with the U-values established in two different Mexican standards: the official Mexican standard NOM-020-ENER-2011 [26], whose adoption is mandatory, and the Mexican standard NMX-C-460-ONNCCE-2009 [27], which is voluntary. Both standards focus on limiting the heat gains through the building envelope. Regarding the NMX-C-460, the Mexican standard suggests specifications for R-values in three categories: “minimum”, “habitability”, and “energy-saving” [27]. The construction layers and the thermal properties of the roofs in the base case building and the building with the proposed passive design strategy are shown in Table 8, in which scenario 1 corresponds to the base case building (without thermal insulation), scenario 2 represents the three categories of the NMX-C-460, and scenario 3 corresponds to the compliance with the NOM-020.
- **Walls:** As in roofs, the installation of expanded polystyrene (EPS) insulation panels inside the building was proposed as a passive design strategy to reduce the thermal load (heat-cold) on the walls. A total of 4 different thicknesses of the insulation were proposed to achieve compliance with the U-values of two different Mexican standards: The official Mexican standard NOM-020 [26], and the voluntary Mexican standard NMX-C-460 [27]. Table 7 describes the construction layers and thermal properties on walls of the different simulated scenarios: the scenario 1 corresponds to the base case building, which has no thermal insulation on walls, scenario 2 describes the three categories of the NMX-C-460, and scenario 3 corresponds to the compliance with the NOM-020.

Figure 4. Passive design strategy proposed for the external window.

Table 6. Thermal properties of the exterior windows in the base case building and the building with the proposed passive design strategy.

Fenestration Type	Base Case Building: Single Glazing 6 mm			Passive Design Strategy on Exterior Windows: Double Glazing 6 mm/13 mm Filled with Air/Wood Frame		
	U-Value (W/(m ² ·K))	SHGC	VT	U-Value (W/(m ² ·K))	SHGC	VT
Wood frame.	5.05	0.64	0.88	2.87	0.57	0.781
Aluminum frame.	7.24	0.75	0.88			
No frame.	5.78	0.82	0.88			

Table 7. Construction layers and thermal properties of the walls in the base case building and the building with the proposed passive design strategy.

Passive Design Strategy on Roofs: Thermal Insulation		Material	Thickness (mm)	U-Value (W/(m ² ·K))	Construction Image [41]
Scenario 1		Plaster, dense	10.0	2.99
		Concrete block, hollow, lightweight	62.1		
		Plaster, dense	10.0		
Scenario 2	Minimum	Plaster, dense	10.0	1.00
		Concrete, reinforced (with 2% steel)	62.1		
		Plaster, dense	10.0		
		Expanded polystyrene (EPS)	23.3		
	Habitability	Plaster, dense	10.0	0.91
		Concrete, reinforced (with 2% steel)	62.1		
		Plaster, dense	10.0		
		Expanded polystyrene (EPS)	26.8		
	Energy saving	Plaster, dense	10.0	0.71
		Concrete, reinforced (with 2% steel)	62.1		
		Plaster, dense	10.0		
		Expanded polystyrene (EPS)	37.3		

Table 7. Cont.

Passive Design Strategy on Roofs: Thermal Insulation	Material	Thickness (mm)	U-Value (W/(m ² ·K))	Construction Image [41]
Scenario 3	Plaster, dense	10.0	0.53
	Concrete, reinforced (with 2% steel)	62.1		
	Plaster, dense	10.0		
	Expanded polystyrene (EPS)	54.8		

Table 8. Construction layers and thermal properties of the roofs in the base case building and the building with the proposed passive design strategy.

Passive Design Strategy on Roofs: Thermal Insulation		Material	Thickness (mm)	U-Value (W/(m ² ·K))	Construction Image [41]
Scenario 1		Ceramic/porcelain	20.0	3.27
		Concrete, reinforced (with 2% steel)	319.0		
		Plaster, dense	13.0		
Scenario 2	Minimum	Ceramic/ porcelain	20.0	0.71
		Concrete, reinforced (with 2% steel)	319.0		
		Plaster, dense	13.0		
		Expanded polystyrene (EPS)	38.3		
	Habitability	Ceramic/ porcelain	20.0	0.48
		Concrete, reinforced (with 2% steel)	319.0		
		Plaster, dense	13.0		
Energy saving		Expanded polystyrene (EPS)	62.8	0.38
		Ceramic/ porcelain	20.0		
		Concrete, reinforced (with 2% steel)	319.0		
		Plaster, dense	13.0		
	Expanded polystyrene (EPS)	82.1			

Table 8. Cont.

Passive Design Strategy on Roofs: Thermal Insulation	Material	Thickness (mm)	U-Value (W/(m ² ·K))	Construction Image [41]
Scenario 3	Ceramic/ porcelain	20.0	0.53
	Concrete, reinforced (with 2% steel)	319.0		
	Plaster, dense	13.0		
	Expanded polystyrene (EPS)	55.8		

3.3. Simulation of the Different Passive Design Strategies

For the present model, the thermal energy performance simulation of the building with the different passive design strategies described in the previous section was carried out. The aim was to evaluate the thermal energy performance and observe the impact that each passive design strategy represents in the reduction of the heat gains. The results obtained for each of the passive design strategies are described below:

- Exterior windows: The output energy performance of the building by replacing the fenestration type was analyzed and compared with the base case. A reduction in energy consumption of 2% was observed, going from energy consumption of 14,416.76 kWh to 14,129.09 kWh, described in Table 9.

Table 9. Energy performance of the base case vs the building with the proposed passive design strategy on exterior windows.

	Base Case	Passive Design Strategy on Exterior Windows:
		Double Glazing 6 mm/13 mm Filled with Air/Wood Frame
Annual electricity consumption (kWh)	14,416.76	14,129.09
Energy saving (kWh)	0.00	287.67
Energy saving (%)	0.0%	2.0%

The results of the heat balance with the implementation of the proposed passive design strategy in exterior windows are shown in Figure 5. The solar gains from exterior windows decreased in comparison with the base case (Figure 3) and, therefore, the sensible cooling of the zone. In general, the average reduction percentage obtained from solar gains in exterior windows was 22.81%, with March, May, and June being the months with the highest external heat gains with 487 kWh and, on the contrary, the month with the lowest heat gains was February with 420 kWh. Regarding the sensible cooling zone, it was reduced by 1.96% compared to the base case.

- Roofs: Table 10 shows the energy performance results and Figure 6 shows the heat gains/ losses as a result of the thermal energy performance simulation of each passive design strategy on roofs. As expected, the lower energy consumption compared to the base case (see Figure 6), corresponded to the building that complies with the NOM-C-460-ONNCCE-2009 [27] in the range of “energy saving” (Figure 6c) since it is the one with the best thermal properties. On the other hand, the lowest savings in energy consumption presented was the one that complies with the same standard, but for the “minimum” range (Figure 6a).
- Walls: Regarding the energy performance of the building with passive design strategy on walls, as shown in Table 11 and Figure 7d, the proposal that had the greatest energy savings compared to the base case corresponded to the building that complies with the NOM-020 [26] standard, since it is the one with the best thermal properties. On

the other hand, the one with the minimum energy savings was the one that complies with the NMX-C-460 [27] standard for the “minimum” range (Figure 7a).

Table 10. Energy performance of the base case vs the building with the proposed passive design strategy on roofs.

	Base Case	Passive Design Strategy on Roofs: Thermal Insulation with EPS			
		NMX-C-460-ONNCCE-2009			NOM-020-ENER-2011
		Minimum	Habitability	Energy Saving	
Annual electricity consumption (kWh)	14,416.76	12,678.89	12,500.15	12,441.99	12,529.88
Energy saving (kWh)	0.00	1737.87	1916.61	1974.77	1886.88
Energy saving (%)	0.0%	12.1%	13.3%	13.7%	13.1%

Table 11. Energy performance of the base case vs the building with the proposed passive design strategy on walls.

	Base Case	Passive Design Strategy on Walls: Thermal Insulation with EPS			
		NMX-C-460-ONNCCE-2009			NOM-020-ENER-2011
		Minimum	Habitability	Energy Saving	
Annual electricity consumption (kWh)	14,416.76	13,874.93	13,845.72	13,782.57	13,714.65
Energy saving (kWh)	0.00	541.83	571.04	634.19	702.11
Energy saving (%)	0.0%	3.8%	4.0%	4.4%	4.9%

3.4. Final Proposal for Adaptation of Passive Design Strategies

Once the energy performance of the building was analyzed with the simulation of the different adaptation proposals with passive design strategies in exterior windows, roofs, and walls, a final adaptation proposal was established, selecting those passive design strategies whose results represented the highest energy savings in the building, in order to evaluate its final energy performance and to ascertain the total energy savings that the implementation of these strategies presents in comparison with the base case. Table 12 shows the passive design strategies chosen and the results in total energy savings.

As shown in Figure 8, the heat gains and losses of the building with the final adaptation proposal described in Table 12 decreased significantly in comparison to the base case (Figure 3). Regarding heat gains, specifically, we can see that the walls were the enclosure with the highest average reduction percentage, with 79.38%, going from 157.30 kWh to 32.43 kWh; followed by the roofs with 40.85% (from 520.11 kWh to 307.66 kWh); and, thirdly, exterior windows with a 23.55% reduction (from 601.58 kWh to 459.91 kWh), since the proposed strategies are mainly focused on reducing the heat gains of these enclosures and openings. Regarding the heat losses of the building, we see that a reduction was also obtained and the sensible cooling of the area presented a decrease of 33.28% (from −561.72 kWh to −374.77 kWh).

On the other hand, we can corroborate that the behavior of sensible cooling zone is related to the average temperatures of the state of Tabasco, since the higher the outside temperature, the greater the sensible cooling required by the building. The months of May and July are the months with the highest sensible cooling in the area, with −583.78 kWh. Moreover, the percentage of energy savings in consumption from the base case shows that the more sensible cooling zone is required in the building, the higher the percentage of energy saving is achieved. However, January and December showed an increase in energy consumption needed to achieve thermal comfort (see Figure 9).

Figure 5. Heat gains/losses in the building with the proposed passive design strategy in exterior windows.

(a)

(b)

Figure 6. Cont.

(c)

(d)

Figure 6. Heat gains/losses in the building with the proposed passive design strategy on roofs in compliance with: (a) NMX-C-460-ONNCCE-2009 “Minimum” range; (b) NMX-C-460-ONNCCE-2009 “Habitability” range; (c) NMX-C-460-ONNCCE-2009 “Energy saving” range; (d) NOM-020-ENER-2011.

(a)

Figure 7. Cont.

Figure 7. Heat gains/losses in the building with the proposed passive design strategy on walls in compliance with: (a) NMX-C-460-ONNCCE-2009 “Minimum” range; (b) NMX-C-460-ONNCCE-2009 “Habitability” range; (c) NMX-C-460-ONNCCE-2009 “Energy saving” range; (d) NOM-020-ENER-2011.

Figure 8. Heat gains/losses in the building with the final adaptation proposal of passive design strategy.

Table 12. Energy performance of the base case vs the building with the final proposal with passive design strategies.

	Base Case	Final Proposal with Passive Design Strategies:
	Exterior windows: Single glazing 6 mm/wood, aluminum, and no frame. Roofs: Without thermal insulation. Walls: Without thermal insulation.	Exterior windows: Double glazing 6 mm/13 mm filled with air/wood frame. Roofs: With thermal insulation complying with the NOM-C-460-ONNCCE-2009 (Energy saving). Walls: With thermal insulation complying with the NOM-020-ENER-2011.
Annual electricity consumption (kWh)	14,416.76	11,030.44
Energy saving (kWh)	0.00	3,386.32
Energy saving (%)	0.0%	23.5%

	January	February	March	April	May	June	July	August	September	October	November	December
Mean Temperature (°C)	22.8	24.6	26.1	28.2	29.3	28.4	28.4	28.4	27.9	25.1	25.1	24.0
Sensible cooling zone (kWh)	-140.5	-162.2	-345.9	-497.3	-583.8	-518.9	-583.8	-535.1	-427.0	-356.8	-200.0	-145.9
Energy saving (%)	-3.87	6.84	21.74	28.25	29.71	28.71	29.18	29.41	27.42	23.38	8.75	-6.88

Figure 9. Mean temperature (°C) of Tabasco vs sensible cooling zone (kWh) and monthly energy savings of the building with the final proposed of passive design strategy.

3.5. Economic Analysis

The annual economic savings that could be achieved if the proposed strategies were implemented were calculated through a discounted payback period. To carry out the above, the estimated initial investment cost was calculated through the average market prices of Villahermosa, Tabasco as shown in Table 13. As a result, the initial investment cost of the passive design strategy proposed is \$39,364.30 MXN in total.

As shown in Table 12, the total energy saving of the retrofitted building with the final proposal for adaptation of passive design strategies is 3386.32 kWh, which represents a total energy saving of 23.50%. The electricity price in this region according to the building electricity bills is \$2.28/kWh, therefore, the cost of saved electricity is \$7720.82 per year.

The discounted payback period was calculated using Equation (5), resulting in 5.8 years based on a discount rate of 4.02% [57]. Moreover, in accordance with the guide to estimated useful life and depreciation percentages [58], the useful life of a residential building is approximately 50 years. The residential building studied (base case) has been occupied for 18 years since 2003 and considering that the retrofitting project will last for a month, the owner could start to turn a profit in 2027 and continue to benefit for the remaining 26 years.

Table 13. Estimation of the initial investment cost.

Passive Design Strategy	Unit Cost ¹	Project Volume	Total Cost ¹
Exterior windows: Double glazing 6 mm/13 mm filled with air/wood frame.	\$345.11/m ²	41.61 m ²	\$14,359.86
Roofs: With thermal insulation complying with the NOM-C-460-ONNCCE-2009 (Energy saving).	\$64.09/m ²	101.01 m ²	\$6474.00
Walls: Thermal insulation with expanded polystyrene (EPS) complying the NOM-020-ENER-2011.	\$63.78/m ²	254.65 m ²	\$16,242.00
Brick layer specialist	\$163.46/day	2 persons	\$2288.44/week

¹ The prices are expressed in Mexican pesos (MXN).

4. Conclusions

Through building energy modeling (BEM), it is feasible to evaluate the energy performance of the building studied, which will depend on both external and internal heat gains of the building; the modeling can also be used as a base tool to determine the impact that passive design strategies will entail for improve the energy-efficiency of the building. The simulation results show that the envelope of a building has an enormous impact on the amount of energy necessary to maintain the interior temperature within a comfortable range: a consequence of the hot-humid climate region of the location. Thus, by improving the thermal properties of these enclosures, we can reduce the amount of heat that enters the building, therefore reducing the amount of energy needed for cooling. Moreover, the annual electricity consumption of the residential building (base case) decreased when simulating each of the strategies proposed for the enclosures, reaching a maximum reduction of 2.0% in exterior windows, up to 4.9% in walls and a 13.7% reduction in roofs, the latter being the enclosure with the greatest reduction achieved. On the other hand, the results of the final adaptation proposal showed the greatest energy savings by improving the energy efficiency of the building, reducing electricity consumption by up to 23.5% compared to the base case. Moreover, the economic analysis showed that the payback period for the final proposal with the passive design strategies was 5.8 years, therefore the owner can be benefited in the remaining lifetime of the building.

The results of this study are of particular interest given since the structural elements of the thermal envelope and interior partitions of the simulated base case building are typical for the residential buildings in Mexico. Therefore, this study can be replicable not only in Villahermosa, Tabasco but in those federal entities whose climatic regions are similar to the one studied. On the other hand, it is imperative to highlight the importance of the implementation of current efficiency policies in Mexico for both new and existing residential buildings, since the results shown a great reduction in the annual electricity consumption through the improvement of the thermal envelope.

Although there are several passive design strategies, this study evaluated the reduction of energy consumption through the implementation of passive design strategies in the walls, roofs, and exterior windows, which had greater contributions of heat gains in the base case. Therefore, this study aims to be a guideline for evaluating the impact that different passive strategies entail in different climates and their adaptation to existing residential buildings. However, future work should be conducted with the use of different passive design by means of thermal energy performance simulation, to accomplish a

greater reduction of electricity consumption with the consideration of the thermal balance of the building.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/su13148064/s1>. Table S1. Data of the internal gains (occupancy) used to simulate in the software. Table S2. Base-case building operation schedules per room for weekdays. Table S3. Base-case building operation schedules per room for weekends.

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