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Environmental Challenges in the Residential Sector: Life Cycle Assessment of Mexican Social Housing

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Abstract: Social Housing (SH) in Mexico has a potentially important role in reducing both the emission of greenhouse gases and the use of non-renewable resources, two of the main challenges facing not only Mexico but the planet as a whole. This work assesses the environmental impact generated by the embodied stages of a typical SH throughout its life cycle (cradle to grave), by means of a Life Cycle Assessment (LCA). Two types of envelope and interior walls and three types of windows are compared. It was found that SH emits 309 kg CO_2 eq/m^2 and consumes 3911 MJ eq/m^2 in the product stages (A1 to A3) and construction process (A4 to A5); the most important stages are those referring to the products, namely, A1 to A3, B4 (replacement) and B2 (maintenance). Additionally, benefits were found in the use of lightweight and thermal materials, such as concrete blocks lightened with pumice or windows made of PVC or wood. Although the use of LCA is incipient in the housing and construction sector in Mexico, this work shows how its application is not only feasible but recommended as it may become a basic tool in the search for sustainability.

Keywords: life cycle assessment; social housing; embodied stages; embodied energy; embodied greenhouse gases; residential sector; Latin America and the Caribbean

1. Introduction

The population of Latin America and the Caribbean (LAC) represents 8.55% of the world population [1], of which 75% is concentrated in countries with emerging economies (32% Brazil, 20% Mexico, and 22% for Colombia, Argentina, Peru and, Chile together) [1,2]. The high metabolic rates of this region have obliged governments to design and introduce new approaches to separate their economic growth from the use of resources and, consequently, their environmental impact [3].

Although the LAC countries have twice the population of the United States (U.S.), they produce a lower global warming effect. This is similar to the case of the Asian giants, where India emits just 24% of the Greenhouse Gases (GHG) produced by China, despite each being home to 18% of the world's population. Regarding energy consumption, the USA, the European Union (EU), and China consume 4.15, 1.89, and 1.26 times more than the world per capita average respectively, while India and LAC consume 3.88 and 1.47 times less (Table 1). This indicates that the environmental impact indices generated by each country (and region) are discordant with the number of people living in them.

Table 1. Global basic indicators. Data from: [1,4–9].

Country/ Region	Total Population (People) [1]	Urban Population (%) [4]	CO_2 Emissions (%) [5]	CO_2 eq Emissions (%) [6]	Energy Consumption (kwh/Capita) [7]	Population Growth (Annual %) [8]	Household Size (People) [9]
China	1,386,395,000	58	28.27	23.27	3927	0.6	3.4
India	1,339,180,127	34	5.69	5.61	805	1.1	4.6
U.S	325,719,178	82	14.43	11.85	12,984	0.7	2.5
EU	512,461,290	75	9.85	8.78	5908	0.2	-
LAC	644,137,666	80	5.21	10.74	2129	1.0	-
World	7,530,360,149	55	100	100.00	3127	1.2	-

The emerging economies of LAC must face up to important environmental challenges in order to avoid replicating the throwaway society model of the industrialized nations [10]. Among the most important problems is the rise in annual temperature caused by the increase of GHGs and the wasteful consumption of energy (from renewable and non-renewable sources); there are also the residues generated by this consumption, such as Construction and Demolition Waste (CDW) and Municipal Solid Waste (MSW), which play an important part due to the quantities involved.

To overcome their own environmental challenges, LAC countries need to set up schemes to achieve economic and social growth that will avoid unsustainable environmental damage, that is, plans in line with the objectives of the new sustainable development agenda, which are governed by three cardinal axes: Eradicating poverty, protecting the planet, and ensuring prosperity for all [11].

Mexico has the second largest population of the countries in LAC, with more than 129 million inhabitants (80% concentrated in urban areas) [1]. Over the last ten years it has had economic growth of 2.2% [12] and, up to 2017, annual population increase of 1.3% [8] (Table 2); therefore, an increase in energy needs and consumption of natural resources can be expected in coming years, as well as GHG emissions and the CDW and MSW that generate them.

Table 2. Basic indicators in LAC. Data from: [1,4–9].

Country/ Region	Total Population (People) [1]	Urban Population (%) [4]	CO_2 Emissions (%) [5]	CO_2 eq Emissions (%) [6]	Energy Consumption (kwh/Capita) [7]	Population Growth [6] (Annual %) [8]	Household Size (People) [9]
Argentina	44,271,041	92	10.7	6.6	3052	1.0	3.3
Brazil	209,288,278	86	27.7	52.0	2601	0.8	3.3
Chile	18,054,726	87	4.3	2.1	3912	0.8	3.6
Colombia	49,065,615	80	4.4	3.0	1290	0.8	3.5
Mexico	129,163,276	80	25.1	11.5	2090	1.3	3.7
Peru	32,165,485	78	3.2	1.3	1308	1.2	3.8
LAC	644,137,666	80	100	100	2129	1.0	-

2. Environmental Challenges in Mexico

In Mexico, the national inventory of greenhouse gases and compounds is closely linked to scientific and technical criteria established by the Intergovernmental Panel on Climate Change (IPCC). It reported that in 2015 a total of 683 million tons (Gg) of CO_2 eq were emitted, of which 71% were Carbon Dioxide (CO_2) and 21% Methane (CH_4). The inventory also counted 148 Gg absorbed by vegetation (mainly forest and jungle), bringing the net emissions balance to 535 Gg of CO_2 eq (Table 3). Additionally, 1.4% of the total CO_2 and 1.24% of the total CO_2 eq in the world was generated in 2012 (in the LAC group, only surpassed by Brazil) (Table 2).

Table 3. National inventory of greenhouse emissions and compounds. Data from: [13].

Category	Net Emissions Gg CO_2 eq	Total Emissions Gg CO_2 eq
1 Energy	480,878.831	480,878.831
2 Industrial processes and use of products	54,111.761	54,111.761
3 Agriculture, forestry and other land uses	−46,286.569	102,059.499
4 Residues	45,909.010	45,909.010
Total	534,613.033	682,959.101

Of all the emissions (Figure 1), the housing sector emits 3.1% of CO_2 eq, derived from compounds of CO_2, CH_4 and Nitrous Oxide (N_2O) generated by the consumption of natural gas, liquid petroleum gas, kerosene and diesel; there is also CH_4 and N_2O due to the burning of firewood in homes, the emissions generated by their operational energy. Other emissions related to the residential sector are those caused by the energy needed for transport (25.1%) and the construction and manufacturing industry (9.3%); the mineral and metal industries (5.5%) and the elimination of solid waste (3.2%). However, the corresponding proportional part of each must be obtained. It is essential to analyze exhaustively the GHGs that generate the activities that are carried out throughout the life cycle of the residential sector, especially social housing. Which, due to its high representation (88%) in the homes of the country, is a dominant relevance.

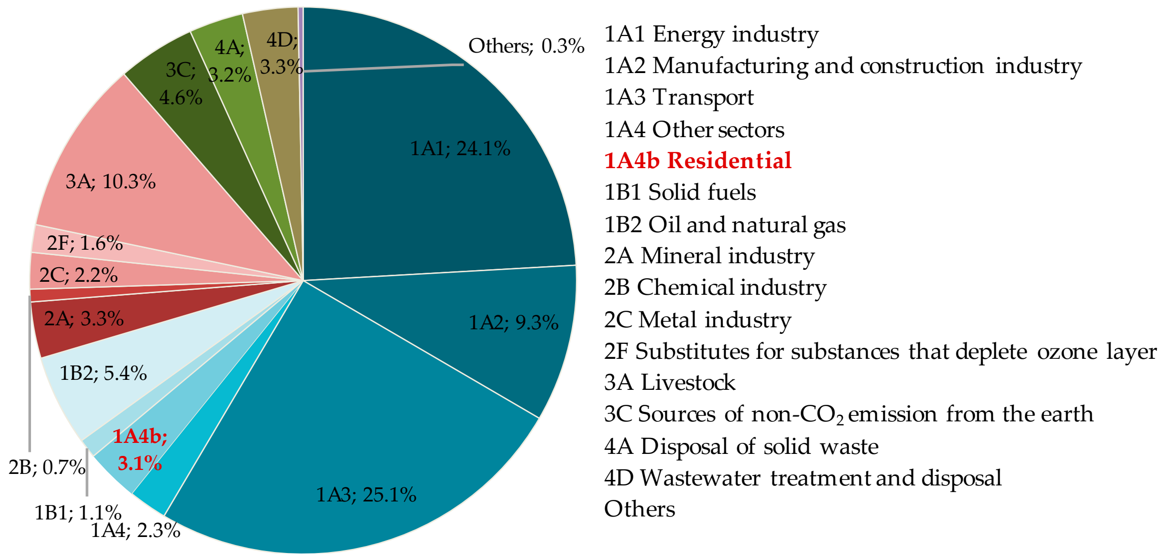


Figure 1. National inventory of greenhouse gas emissions and compounds. Data from: [13].

Moreover, in 2017, Mexico ranked 16th in the list of countries with the highest energy consumption in the world, reporting the third consecutive year with an energy independence index equivalent to 0.76; that is, 24% less energy was produced than necessary for the various consumption activities within the national territory [14]. This is despite the country's wealth of natural resources such as gas, coal and renewable energy sources (water, wind, solar and marine energy); however, its economy and energy supply are dependent on fossil fuels, which together with the lack of energy planning is a major cause for concern [15].

The national energy balance in 2017 (Figure 2), shows that the national energy consumption for this year was 9249.75 Petajoules (PJ), of which the 58% corresponding to total energy consumption and 32% to activities inherent to the energy sector (transformation, own consumption, and losses) stand out (Figure 2a). The total energy consumption (Figure 2b) in this year was 5362.8 PJ, which is attributed to the internal market or the productive activities of the national economy, of which the housing sector is responsible for 14%, due to the operating requirements of housing [14]. Additionally, other data needed for this sector is that referring to the proportional part of transport (44%) and industry (35%).

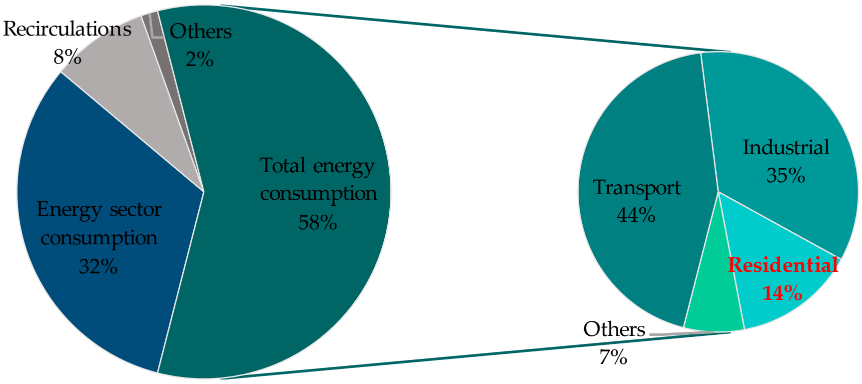


Figure 2. (**a**) National energy consumption: 9249.75 PJ; (**b**) Total energy consumption: 5362.8 PJ. Data from: [14].

Regarding the waste products (Table 4), Mexico generates 0.4% of the world total of CDW and 3.4% of the MSW (second in the LAC region), and although the sum of its waste is lower than that of countries such as China (1,130,000,000 t CDW; 328,922,213 t MSW), U.S (548,000,000 t CDW; 240,380,753 t MSW) and India (530,000,000 t CDW), the impact on a national scale should not be ignored as it has limited management protocols and lacks the infrastructure for waste processing [16].

Of the CDW generated in public and private works, 20% is disposed of in authorized dumps and only 3% is recycled; the rest is used in site levelling, landfills and, inappropriately, in road or street repairs [16]. In this respect, the NOM-161-SEMARNAT-2011 norm came into effect in 2013, stating that construction waste shall be classified as special handling waste, requiring action to be taken for its reuse and recycling or, where appropriate, for its proper disposal [17]. In the case of the 44 million MSW generated annually [18], despite having the General Law for the Prevention and Management of Waste, only 84% are collected, 78.5% are dumped in final disposal sites, and only 9.6% are recycled [19].

Table 4. CDW and MSW. Data from: [18,20–24].

Country	**CDW [20]**	**MSW**	**MSW**
Region	**(t/Year)**	**(t/Year)**	**(kg/Capita.Year)**
Brazil	70,000,000	79,900,000 [21]	382 [21]
China	1,130,000,000	328,922,214 [24]	237 [24]
India	530,000,000	90,000,000 [23]	67 [23]
México	12,000,000	44,432,167 [18]	344 [18]
U.S.	519,000,000	240,380,753 [18]	738 [18]
EU	830,000,000	247,518,803 [18]	483 [18]
LAC	-	131,000,000 [22]	203 [22]
World	3,000,000,000	1,300,000,000 [24]	173 [24]

2.1. Life Cycle Assessment in Mexico

Various methods have been used in recent decades to measure the environmental performance of human and natural activities. One of these is the Life Cycle Assessment (LCA). “LCA, has become a key methodology to evaluate the environmental performance of products, services and processes and it is considered a powerful tool for decision makers” [25]. In Mexico, the LCA was used for the first time in the late 1990s and early 2000s, in a study on waste management carried out by the National Institute of Ecology and Climate [26]. The methodology has been used in several economic sectors in the country, such as the energy [27] or mining industries [28]. According to the study conducted by Valdivia, until 2014 Mexico was the second ranking LAC country in terms of publications referring to LCA (101 articles) [3].

Until 2010 research using LCA had a preferential focus on waste management issues; from that year onwards, studies focused on topics such as the energy sector, the analysis of carbon and water footprints and the construction sector [26]. Within the latter, studies have been carried out on the co-processing of municipal waste used as fuel for a cement kiln [29], as well as the publication of a book on LCA in construction, where topics such as social housing (SH) are analyzed [30].

The housing sector began to attract attention in 2006, when the government introduced life cycle thinking into the National Housing Law [31]. In this respect, Cerón-Palma et al. (2013) measured the Global Warming Potential (GWP) of the operating energy of a SH [32]; as well as proposing strategies to reduce energy demand [33], other studies have focused on optimizing rainwater [34,35]. In addition to the LCA, other tools such as the Building Sustainability Rating Systems [36] and product environmental statements [31,37] have been used.

Although in Mexico the use of LCA in the construction and residential sector is basically nil, its application is feasible and can become a valuable tool in the search for environmental solutions as it has been in various regions of the world [38].

2.2. Housing in Mexico

Housing types in Mexico are classified according to their constructed surface: Economic (30 m^2), popular (42.5 m^2), and traditional (62.5 m^2), known together as SH. There are also medium (97.5 m^2), residential (145 m^2), and residential plus (225 m^2) [39]. In the last five years, more than 2.58 million housing units have been built, of which 88% are SH (11% economic, 47% popular, 30% traditional), while the remaining 12% corresponds to the medium, residential and residential plus models [40]. It is estimated that 600,000 new housing units will be needed annually during the next decade [41].

Due to the high representation of the SH, the National Development Plan 2013–2018 has promoted the issue of sustainable construction in this sector [31]. As a result, in the last decade, Mexico has stood out among the middle-high income level countries due to its Finance Program for Housing Solutions, which aims to provide more sustainable SH. These actions have been considered exemplary with respect to global good practices [36].

According to data compiled up to 2010 by the National Housing Commission (CONAVI), 86% of the housing stock is in use (80.12% permanent use and 5.65% temporary use), while 14% is unoccupied [42]. Until 2015, the inventory of occupied housing showed 31,949,709 private units with an average of 3.7 habitants each [43]; of these, 73% are single-family, 19% are two-family, and 7% are multifamily housing. Multifamily housing is mainly concentrated in the states with the highest population density of the Republic (41% in Mexico City, 15% Mexico State, 7% in Jalisco and 5% in Puebla), while it is practically nil in the rest of the country (an average of 1% per state) due to the persistence of the single-family dwelling [44].

Housing in Mexico has great challenges to face; on the one hand, there are impacts generated throughout its use, and on the other hand, there are environmental impacts arising from the incorporated stages of materials and processes necessary for construction. National inventories of energy and greenhouse gases and compounds have clearly established the impacts generated by the residential sector in its operation (B6, Operational energy [45]); however, it is necessary to define the environmental burdens that are generated from the incorporated activities of its life cycle to consider a “from the cradle to the grave” approach.

2.3. Objectives of the Study

The objectives of this research are (1) to identify the state of the most relevant environmental impacts occurring in Mexico, emphasizing the residential sector, and (2) to achieve an approximation of the environmental impacts generated by this sector. To reach the latter objective, an LCA methodology applied to a representative SH of the Mexican ambit will be used; the elements that make up its envelope will be varied, resulting in a total of six options to be analyzed throughout its life cycle.

3. Materials and Methods

3.1. Goal and Scope of the LCA

The objective of the LCA was to establish the environmental impacts generated by a typical SH in Mexico throughout its life cycle. For the analysis the constructive elements that make up the structure, the envelope (opaque and transparent parts) and the internal partitions were considered, as well as their basic finishes. Previous studies have analyzed the structure, the envelope [46–50] and the interior walls [51,52] of a building because of their contribution to the total environmental loads generated by their incorporated stages and also because of the impact these elements (especially the envelope) have on the energy performance of the building's operational stage.

The reference dwelling is a built and practical prototype in the Mexican ambit; five additional alternatives are proposed by varying interchangeable and feasible materials and construction solutions in the local practices. Of the six options to be analyzed, all have in common the structure (consisting of foundation slabs, columns and beams of reinforced concrete, and roof slab of reinforced concrete lightened with Expanded Polystyrene Pieces, EPS), the exterior and interior wooden doors, and the basic finishes (1.5 cm thick mortar for exterior and interior walls, 1.5 cm thick plaster for roof slab, and vinyl paint for all cases). The elements that differed were the exterior and interior walls (two types of concrete pieces: (1) Hollow Block of 12 × 20 × 40 Filled with Expanded Perlite (PE) and (2) Solid Partition of Lightened Concrete with Pumice Aggregates of 10 × 14 × 28 (PU)) and windows (three types: Aluminum (AL), PVC (PV) or Wood (WO)). The nomenclature used is shown in Figure 3.

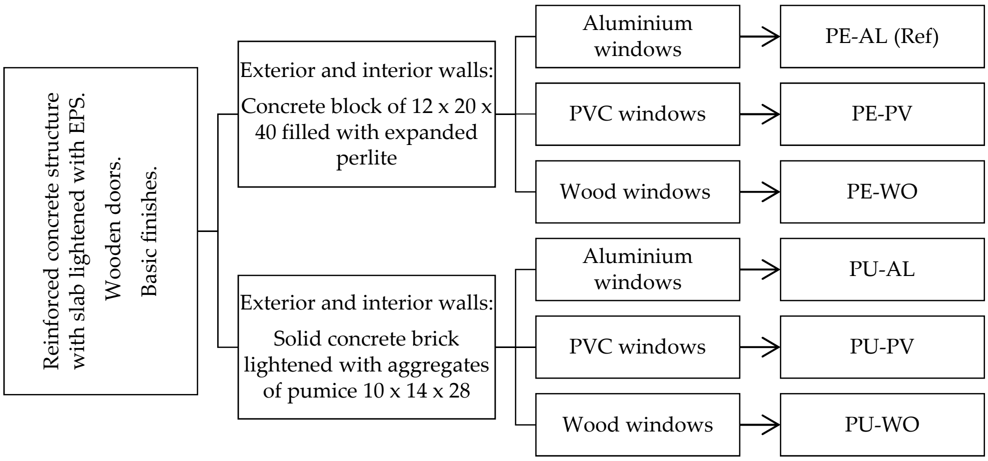
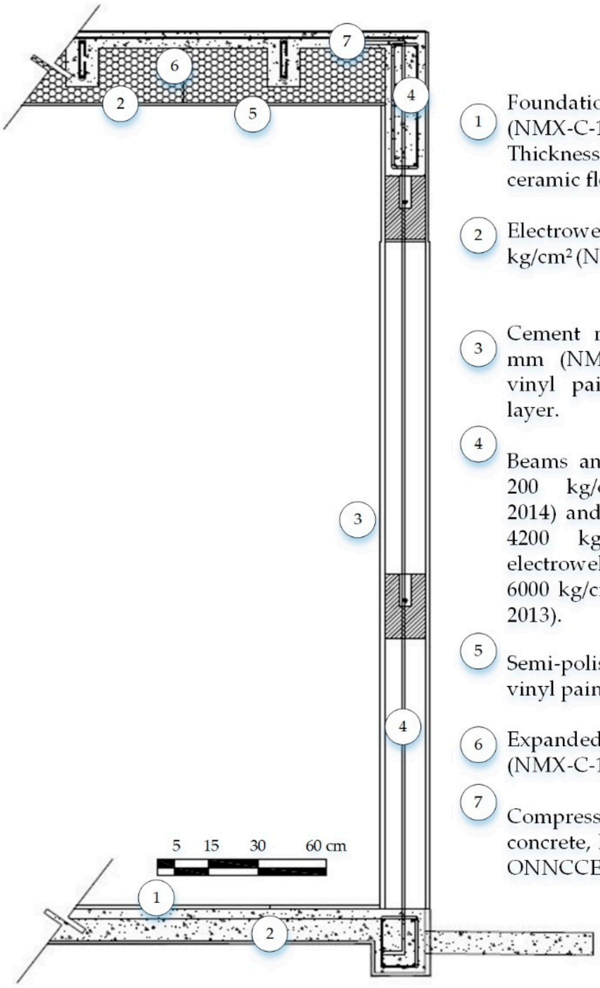


Figure 3. Nomenclature and elements of the options analyzed.

The basic characteristics of the structure are illustrated in Figure 4, and Figure 5 shows the configuration of the exterior and interior walls, as well as the location and dimensions of the doors and windows of the SH.

The established functional unit was the 42 m^2 dwelling (Figure 5), with a useful life of 50 years according to previous research [53–56]. Its dimensions correspond to those of popular housing, which is nationally the most representative (47% which, together with the traditional and economic housing, makes up 88% of the SH [40]). The analyzed elements allow an approximate estimate of the environmental impact generated by a Mexican SH in all stages of its life cycle; in addition, any changes of the proposed elements are required to be equivalent with respect to their thermal, structural, and functional capacities, thus allowing for their possible comparison and the best environmental choice.



① Foundations slab, F´c = 200 kg/cm² (NMX-C-155-ONNCCE-2014). Thickness 10 cm, planned finish and ceramic floor.

② Electrowelded mesh 6x6-6/6. Fy = 5000 kg/cm² (NMX-B-290-CANACERO-2013).

③ Cement mortar finished, thickness 15 mm (NMX-C-021-ONNCCE-2015) and vinyl paint, in exterior and interior layer.

④ Beams and columns of concrete. F´c = 200 kg/cm² (NMX-C-155-ONNCCE-2014) and steel reinforcenment of Fy = 4200 kg/cm² and/or prefabricated electrowelded reinforcement of Fy = 6000 kg/cm² (MNX-B-290-CANACERO-2013).

⑤ Semi-polished finishing of plaster and vinyl paint.

⑥ Expanded polystyrene 1.2x0.60x0.17 (NMX-C-137-ONNCCE-2010).

⑦ Compression layer, thickness 5 cm of concrete, F´c = 200 kg/cm² (NMX-C-155-ONNCCE-2014).

Figure 4. Cross section of basic characteristics of the structure.

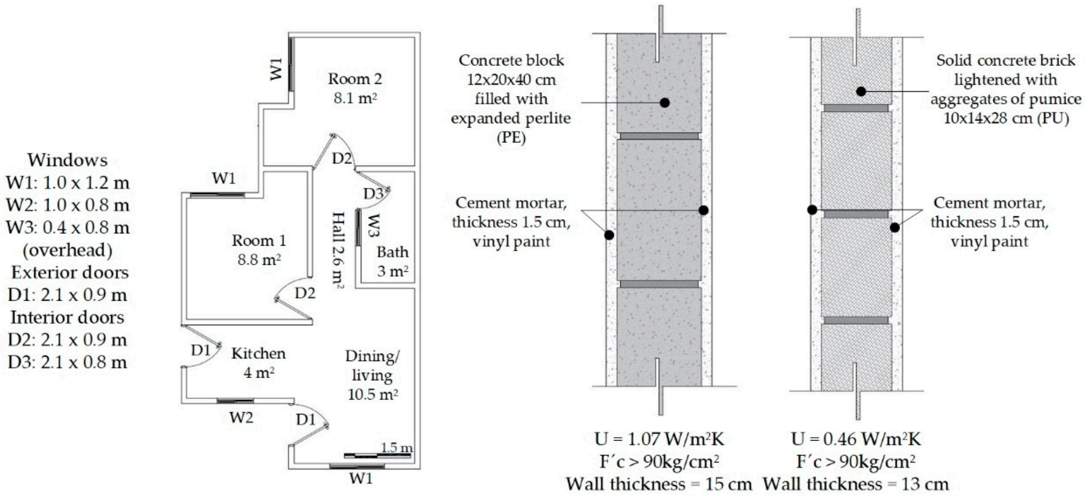


Figure 5. Social housing area, dimensions of doors and windows, and configuration of the exterior and interior walls.

Despite the initiatives of CONAVI aimed at the construction of sustainable housing and related programs, it has not yet been possible to comply with the regulations on energy efficiency in SH; however, these efforts have led to the search for solutions and practices that show a continual improvement, as reported in previous studies [36]. The walls of the reference prototype are one example of this. They have eco-technology used in SH (expanded perlite insulation to fill the concrete blocks, with a thermal conductivity coefficient (λ) of 0.042 W/mK); however, its Thermal Transmittance (U), equal to 1.07 W/m^2K, does not comply with NOM-020-2011 (U = 0.476 W/m^2K for cities with extremely hot climates to U = 0.909 W/m^2K for cities with temperate-cold climates [57]). Therefore, the construction of concrete walls lightened with pumice aggregates (λ = 0.052 W/mK) was proposed, with similar characteristics of functionality and compressive strength (13 cm thick, F´c > 90 kg/cm^2), but with improved thermal performance due to the intrinsic properties of the material. This results in walls with a U equal to 0.46 W/m^2K (complying with NOM-020-2011 for the least favorable case; Figure 5).

3.2. Boundaries and Functional Unit

The analysis considered the Stages of Product (A1 to A3) and Construction Process (A4 to A5); Maintenance (B2) and Replacement (B4), Demolition (C1), Transport (C2) and Disposal (C4). The Use (B1), Repair (B3), and Refurbishment (B5) stages were excluded, being considered dependent on the user; Waste Processing (C3) was also omitted as immediate dumping is the single most used scenario in the Mexican context [16]. The analysis may be considered cradle to grave, according to the proposal of annex 57 of the IEA EBC for evaluating the incorporated energy and the CO_2 eq emissions. Annex 57 complements the international ISO 21931-1 and European EN 15978 standards for the evaluation of building structures to improve transparency for the multiple stakeholders in the LCA process [58]. The limits of the LCA system are shown in Figure 6.

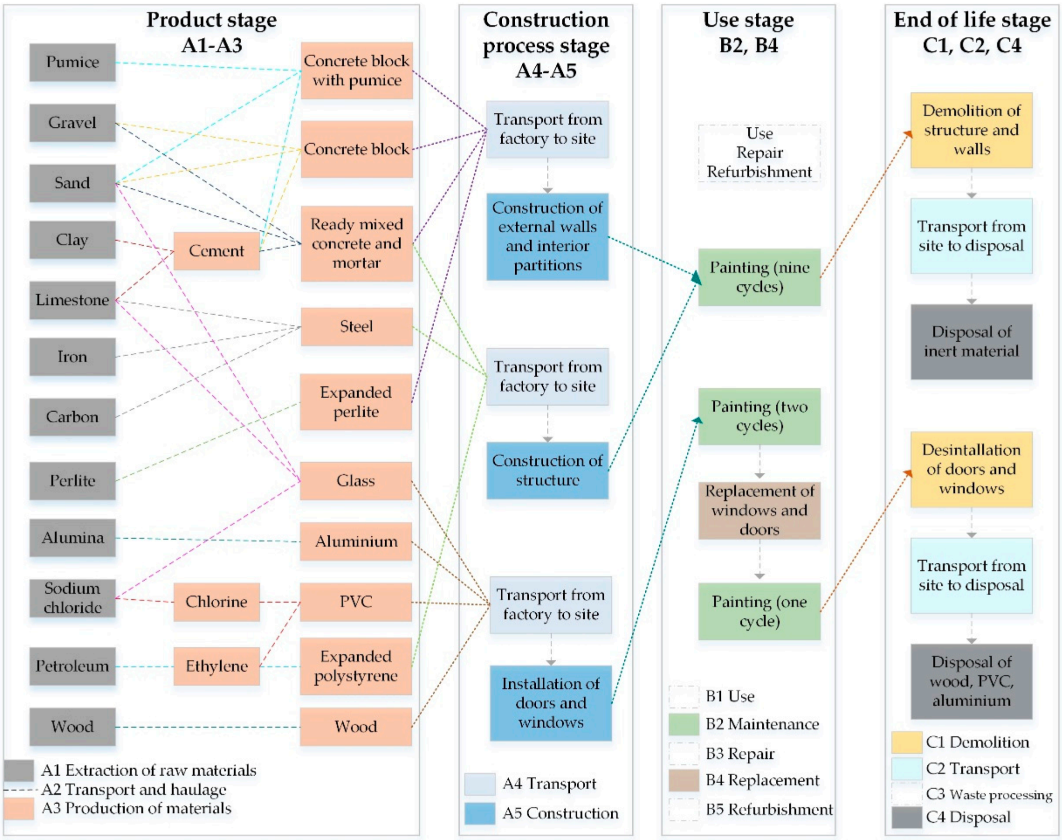


Figure 6. The life cycle of SH in Mexico.

3.3. Life Cycle Inventory

Two databases were used, one specializing in the quantification of materials and construction processes at the Mexican level, CYPE [59], and another specializing in life cycle inventories, ecoinvent 3.1 (2014) [60]. However, since ecoinvent initially included products and activities exclusively at the

European—in particular the Swiss—level, recent versions incorporate global, and sometimes specific, processes from countries outside Europe, as in the case of Mexico or North America. Previous studies conducted in Mexico using ecoinvent have obtained favorable results [29,32,61–64]; and although their use might presuppose a limitation, this is in turn an available tool that generates reliable approaches to environmental impacts.

3.3.1. Product Stage (A1 to A3)

The product stage included the manufacture of the structure, the envelope, the internal partitions, and the basic finishes. The weights obtained from the inventory were also considered with a 5% waste rate. The required quantities of each material used and the corresponding dataset are shown in Table 5. The processes and materials used (taken from ecoinvent) were adapted to the conditions of the SH; however, in the specific case of the windows (AL, PV, and WO), the dataset analyzed represents a more efficient window than those used for the SH; although the weights and dimensions were adapted to the conditions of the project, in the case of these elements, it is prudent to consider the results as values of close environmental impact.

Table 5. Inventory of materials of the product stage.

Element	Material	Quantity	Ecoinvent Dataset [1]
Structure	Concrete (m^3)	13.8	Concrete production 20 MPa, RNA only, RoW
	Steel (kg)	975.4	Reinforcing steel production, RoW
	EPS (kg)	193.1	Polystyrene foam slab production, RoW
	Block (kg)	1869.0	Concrete block production, RoW
	Mortar (kg)	211.8	Cement mortar production, RoW
	Water (m^3)	0.05	Tap water production, conventional treatment, RoW
	Ceramic tile (kg)	776.3	Ceramic tile production, RoW
	Cement (kg)	316.9	Cement production, Portland, RoW
	Plaster (kg)	633.8	Stucco production, RoW
Doors	Exterior doors (m^2)	3.8	Door production, outer, wood-glass, RoW
	Interior doors (m^2)	5.5	Door production, inner, wood, RoW
PE wall	Block 12 × 20 × 40 (kg)	12,199.5	Concrete block production, RoW
	Mortar (kg)	6638.5	Cement mortar production, RoW
	Water (m^3)	0.3	Tap water production, conventional treatment, RoW
	Expanded perlite (kg)	196.8	Expanded perlite production, RoW
	Vinyl paint (kg)	24.3	Alkyd paint production, white, water-based, product in 60% solution state, RoW
PU wall	Pumice block (kg)	8155.9	Lightweight concrete block production, pumice, RoW
	Water (m^3)	0.3	Tap water production, conventional treatment, RoW
	Mortar (kg)	6941.9	Cement mortar production, RoW
	Vinyl paint (kg)	19.7	Alkyd paint production, white, water-based, product in 60% solution state, RoW
Windows	Aluminum-window (m^2)	0.8	Market for window frame, aluminum, $U = 1.6$ W/m^2K, GLO [2]
	PVC-window (m^2)	0.8	Market for window frame, poly vinyl chloride, $U = 1.6$ W/m^2K, GLO [2]
	Wood-window (m^2)	0.8	Market for window frame, wood, $U = 1.5$ W/m^2K, GLO [2]
	Glazing 3 mm (kg)	2.4	Market for glazing, double, $U < 1.1$ W/m^2K, GLO

[1] RNA: Northern America; RoW: Rest of the World; GLO: Global. [2] Its characteristics correspond to a window with measurements of 1.6 × 1.3 m, with frame visible area ≈ 0.5 m^2, and U value of 1.6 W/m^2K, weight per m^2 of frame visible area of 50.7 kg for aluminum, 94.5 kg for PVC and, 80.2 kg for wood.

3.3.2. Construction Process Stage (A4 to A5)

In Mexico the greatest impact on the demand for electricity in homes occurs in the northern and coastal areas of the country—warm climates—where the use of cooling equipment is more common than heating equipment [57]; therefore, for better representativeness, the analyzed SH is assumed to be located in the Northwest of Mexico, using in this work the proposed alternative that satisfies the most unfavorable U-value corresponding to the cities of Hermosillo, Guaymas, and Mexicali (0.476 W/m^{2}K).

The environmental impact generated by a truck operating with a load capacity of 7.5–16 t, measured in Tons-kilometers (tkm), was determined for a complete travel cycle (round trip) of the material. The maximum dimensions of the truck correspond to those established by the communications and transport secretariat for long distance roads ET-A (maximum load of 17.5 t) and for short distance roads D (maximum load of 11 t) and Euro 4 engine [65].

The values considered for the distances travelled were an average of the journeys between the hypothetical center of each capital of the north-western states of the country (Baja California, Baja California Sur, Chihuahua, Durango, Sinaloa, and Sonora) and the nearest factories of each type of material previously established in the inventory (determined using Google maps). The resulting values were: 15 km for concrete, steel, EPS, doors, and windows; 20 km for vinyl paint; 400 km for ceramic floors; 470 km for steel; and 510 km for expanded perlite (methodology used in previous studies [66,67]). The quantities required for each construction alternative are shown in Table 6.

Table 6. Inventory of processes of transport from factory to site (A4).

Process	PE-AL	PE-PV	PE-WO	PU-AL	PU-PV	PU-WO	Ecoinvent Dataset
Lorry operation (tkm)	3454	3455	3455	3141	3142	3142	Transport, freight, lorry 7.5–16 metric ton, EURO4

For the assessment of the Construction Stage (A5), the processes and materials necessary for the formwork of the structure (with wood and steel) were considered, as well as those for the transport, discharge, and vibration of the concrete used in the structure and for mixing the mortar used in the walls. The quantities used are shown in Table 7.

Table 7. Inventory of materials/processes of the construction process (A5).

Element	Material/Process	Use Time	Ecoinvent Dataset [1]
Formwork of the structure	Steel (kg)	37.51	Reinforcing steel production, RoW
	Wood (m^3)	0.23	Sawnwood production, softwood, kiln dried, planed, RoW
PE alternatives	Potency less than 18 kW (h)	8.73	Machine operation, diesel, <18.64 kW, steady-state, GLO
	Potency greater than 75 kW (h)	1.76	Machine operation, diesel, ≥74.57 kW, steady-state, GLO
PU alternatives	Potency less than 18 kW (h)	9.01	Machine operation, diesel, <18.64 kW, steady-state, GLO
	Potency greater than 75 kW (h)	1.76	Machine operation, diesel, ≥74.57 kW, steady-state, GLO

[1] RoW: Rest of the World; GLO: Global.

3.3.3. Use Stage (B2, B4)

Of the stage of use, those stages corresponding to the useful life of each material during the building's 50 years of useful life were considered, that is, the Maintenance (B2) and the Replacement (B4) of the elements. The maintenance intervals and replacement cycles obtained from the literature are shown in Table 8.

The elements that needed Maintenance (B2) were the doors, the windows (painting every ten years = 3 cycles) and the walls (painting every five years = 9 cycles). In the Replacement stage (B4), the doors and windows are the elements with a useful life less than the SH, and so their replacement is considered at 30 years (one replacement cycle in the total timeline of the SH). The quantities required are listed in Table 9.

Table 8. Maintenance intervals and replacement cycles for SH elements. Data from: [54,55,68–72].

Element	Useful Life (Years)	Activity Maintenance	Maintenance Cycle	Replacement Cycle
Reinforced concrete structure	50 [68]	-	-	-
External and internal walls	>50 [69,70]	-	-	-
Ceramic tiles	50 [68]	-	-	-
Interior and exterior doors	30 [55,71]	Paint every 10 years [54]	3	1
Windows	30 [54]	Paint every 10 years [54]	3	1
Vinyl paint	5 [72]	Paint every 5 years	9	-

Table 9. Inventory of materials/processes of maintenance and replacement.

Stage	Element	Quantity	Ecoinvent Dataset
B2	Paint doors (kg)	5.94	Alkyd paint production, white, water-based, product in 60% solution state, RoW[1]
	Paint windows WO (kg)	0.52	Alkyd paint production, white, water-based, product in 60% solution state, RoW[1]
	Paint walls (kg)	218.25	Alkyd paint production, white, water-based, product in 60% solution state, RoW[1]
	Transport for WO (PE/PU, tkm)	8.99	Transport, freight, lorry 7.5–16 metric ton, EURO4
	Transport for AL-PV (PE/PU, tkm)	8.97	Transport, freight, lorry 7.5–16 metric ton, EURO4
B4	Exterior doors (m^2)	3.8	Door production, outer, wood-glass, RoW[1]
	Interior doors (m^2)	5.5	Door production, inner, wood, RoW[1]
	Aluminum windows (m^2)	0.8	Market for window frame, aluminum, U = 1.6 W/m^2K, GLO[1]
	PVC windows (m^2)	0.8	Market for window frame, poly vinyl chloride, U = 1.6 W/m^2K, GLO[1]
	Wood windows (m^2)	0.8	Market for window frame, wood, U = 1.5 W/m^2K, GLO[1]
	Glazing 3 mm (kg)	2.4	Market for glazing, double, U < 1.1 W/m^2K, GLO[1]

[1] RoW: Rest of the World; GLO: Global.

3.3.4. End of Life Stage (C1, C2, C4)

The CDW management scenarios in Mexico are limited by the scarcity or even lack of infrastructure. There is only one CDW recycling plant in the whole country, in Mexico City (Recycled concretes); nevertheless, this is a pioneering initiative not only in Mexico but also in the LAC region [73]. The NOM-161-2011 [74] sets out the requirements for special waste management (where the CDW are included) and is obligatory for large-scale generators of waste (>80 m^3).

In this sense, at the end of life stage, the energy required for the operation of the demolition equipment of the structure and walls (C1) of the SH (pneumatic hammer, cutting equipment, and portable compressor) was considered. Subsequently, the effect of the operation of the transport truck (C2) was obtained by the same process previously established in A4. The average distance between the hypothetical center of each reference city to the dump was 30 km. Finally, the total amount of CDW generated by SH was calculated to obtain the impact of its landfill disposal (C4) (processing in a recycling plant being currently impossible). The materials used were considered inert, as being of petrous, metallic, and petroleum origin, so their processing did not pose a potential risk. The quantities are shown in Table 10.

Table 10. Inventory of materials/processes of the end of life. Data from: [60].

Stage	Process	Quantity	Ecoinvent Dataset
C1	Use time PE alternatives (h)	187.54	Machine operation, diesel, <18.64 kW, steady-state, GLO[1]
	Use time PU alternatives (h)	185.33	Machine operation, diesel, <18.64 kW, steady-state, GLO[1]
C2	Lorry operation PE-AL (tkm)	3477.44	Transport, freight, lorry 7.5–16 metric ton, EURO4
	Lorry operation PE-PV (tkm)	3479.56	Transport, freight, lorry 7.5–16 metric ton, EURO4
	Lorry operation PE-WO (tkm)	3478.87	Transport, freight, lorry 7.5–16 metric ton, EURO4
	Lorry operation PU-AL (tkm)	3241.22	Transport, freight, lorry 7.5–16 metric ton, EURO4
	Lorry operation PU-PV (tkm)	3243.34	Transport, freight, lorry 7.5–16 metric ton, EURO4
	Lorry operation PU-WO (tkm)	3242.64	Transport, freight, lorry 7.5–16 metric ton, EURO4
C4	Inert waste PE-AL (kg)	57,319.06	Treatment of inert waste, inert material landfill, RoW[1,2]
	Inert waste PE-PV (kg)	57,957.34	Treatment of inert waste, inert material landfill, RoW[1,2]
	Inert waste PE-WO (kg)	57,992.62	Treatment of inert waste, inert material landfill, RoW[1,2]
	Inert waste PU-AL (kg)	54,020.30	Treatment of inert waste, inert material landfill, RoW[1,2]
	Inert waste PU-PV (kg)	54,055.59	Treatment of inert waste, inert material landfill, RoW[1,2]
	Inert waste PU-WO (kg)	54,044.07	Treatment of inert waste, inert material landfill, RoW[1,2]

[1] RoW: Rest of the World; GLO: Global. [2] Module Treatment of inert waste, inert material landfill, RoW, contains exchanges to process-specific burdens (energy, land use) and infrastructure.

3.4. Environmental Impact Assessment

More than 40% of world energy consumption and 30% of the GHGs can be attributed to the construction industry [58]. Therefore, both effects measured in their respective impact categories have been considered inherent to this sector and have been addressed in previous investigations [75–79]. In this sense, the categories of impact selected for analysis in this study are those referring to energy and embodied emissions of SH, which are climate change and embodied energy. Additionally, to complete the information, two more categories have been chosen, which like the previously mentioned have been considered to have a global effect: Human toxicity and Abiotic Depletion Potential (ADP). The environmental impact methods used were, therefore, IPCC 2013 for the GWP (climate change), Cumulative Energy Demand (CED, for embodied energy), and CML 2001 for Human Toxicity Potential (HTP) and ADP.

4. Results

The analyzed SH generates an environmental burden (including all the stages of A to C) of 17 t CO_2 eq, 252.5 Gigajoules (GJ) eq, 104.3 kg antimony eq, and 9.4 t Paradichlorobenzene (1,4-DCB) eq (average of the six options). Of these, just the construction of the SH (finished product A1 to A5) generates a load of 13 t CO_2 eq, 165 GJ eq, 71 kg antimony eq, and 7 t 1,4-DCB eq (Table 11), i.e., more than 70% of the average impacts of all the categories analyzed when the embodied stages of the life cycle are considered.

Table 11. Impacts generated by the SH in stages A, B, and C.

Impact Category[1]	**PE-AL**			**PE-PV**			**PE-WO**			**PU-AL**			**PU-PV**			**PU-WO**			**AVERAGE**		
	A	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
GWP	13.3	2.5	1.7	13.0	2.2	1.7	12.9	2.1	1.7	13.3	2.5	1.6	13.0	2.2	1.6	12.9	2.1	1.6	13.1	2.3	1.7
EE	170	54	35	167	51	35	168	53	35	164	54	34	161	51	34	162	53	34	165	53	34.4
ADP	73.7	19.6	15.6	71.9	17.8	15.6	70.9	16.9	15.6	71.3	19.6	14.9	69.4	17.8	14.9	68.5	16.9	14.9	71.0	18.1	15.3
HTP	7.9	2.7	0.5	6.8	1.6	0.5	6.8	1.6	0.5	7.6	2.7	0.5	6.6	1.6	0.5	6.5	1.6	0.5	7.0	2.0	0.5

[1] GWP: t CO_2 eq; EE: GJ eq; ADP: kg antimony eq; HTP: t 1,4-DCB-Eq.

The product stage is established as that of greatest contribution (A1 to A3: 57% CED, 61% ADP, 71% HTP-GWP), followed by that of replacement (B4: 6% GWP, 8% ADP, 12% CED, 15% HTP) and maintenance (B2: 6% HTP, 7% GWP, 9% ADP-CED); it is therefore established that the stages with greater environmental effects are those involving finished products (A1 to A3, B2 and B4: 78% CED-ADP; 85% GWP; 91% HTP), in this case, those used in constructing the building, the paint for its maintenance, and the replaceable objects (windows and doors). Meanwhile, the stages referring to the processes produce significantly less effect; from greater to lesser, they are those relating to transport (A4 + C2: 3.3% HTP, 7.7% GWP, 9.3% CED, 10.1% ADP), to construction/demolition (A5-C1: 3.7% HTP, 6.1% GWP, 7.6% ADP, 9% CED), and lastly, to their final disposition (C4: 1.5% GWP, 1.6% HTP, 3.7% CED and 3.9% ADP) (Figure 7).

Previous research has dealt with the embodied impacts of a building (or its elements), studying different stages such as A1 to A4 [80], A1 to A5 [66,79,81], A and C [51] and A to C [48,49,82,83]; similar to this study, these works found that the greatest environmental detriment occurs in stage A1 to A3, with values ranging from 85% to 99% for those who evaluated up to A1 to A5 [51,66,79–81] and from 60% to 80% for those who evaluated the complete cycle (A to C) [48,49,82,83]. For the rest of the stages, the results depended on the different criteria established in each study, so there are still discrepancies in the results obtained. Nevertheless, the data obtained in this work is found within the previously reported intervals; for example, the studies that evaluated B1-B5 reported values ranging from 11% to 25% [48,49], those that studied A4, from 1% to 9% [51,66,79–81], those that evaluated A5 from 1% to 8% [49,51,66,79–81], while those that studied the C stages showed intervals from 1% to 3% [48,51] up to 23% [49], this stage showing the most variation.

Figure 7 shows how the greater variability occurs when a wood or PVC window is changed to aluminum for the HTP, going from 11–12% to 19% of the total damage. This can be attributed to the high amounts of contamination produced in the aluminum production process, which includes substances such as CO_2, Sulfur Dioxide (SO_2), Polycyclic Aromatic Hydrocarbons (HAP), Perfluorocarbons (PFC), Tetrafluoromethane (CF_4) and Hexafluoroethane (C_2F_6) [84]. Similar to the study by Yasantha et al. (2007), where it was found that although wooden windows have a better environmental (and economic) performance, aluminum windows were preferred socially [85].

On the other hand, the damage caused by A1 to A3 is more evident for the GWP (70–72%), which is because the most representative materials used in the SH (concrete, steel, ceramic pieces, mortar) are linked with the emission of GHGs [13,66,67,86], due to the chemical reactions in their manufacturing processes and the high content of carbonates in their basic components, such as limestone or clay [87,88]. The greatest variation found in the impact categories was in stage A1 to A3, with a difference of 14% between the GWP (72%) and the CED (58%). This difference in the representation of the CED is spread over the rest of the stages, above all in B4 and B2 (because the manufacture of paint and window materials is more closely linked to energy consumption [86,89] than to GHG emissions) and in A5 and C1 (for the energy used by the machinery).

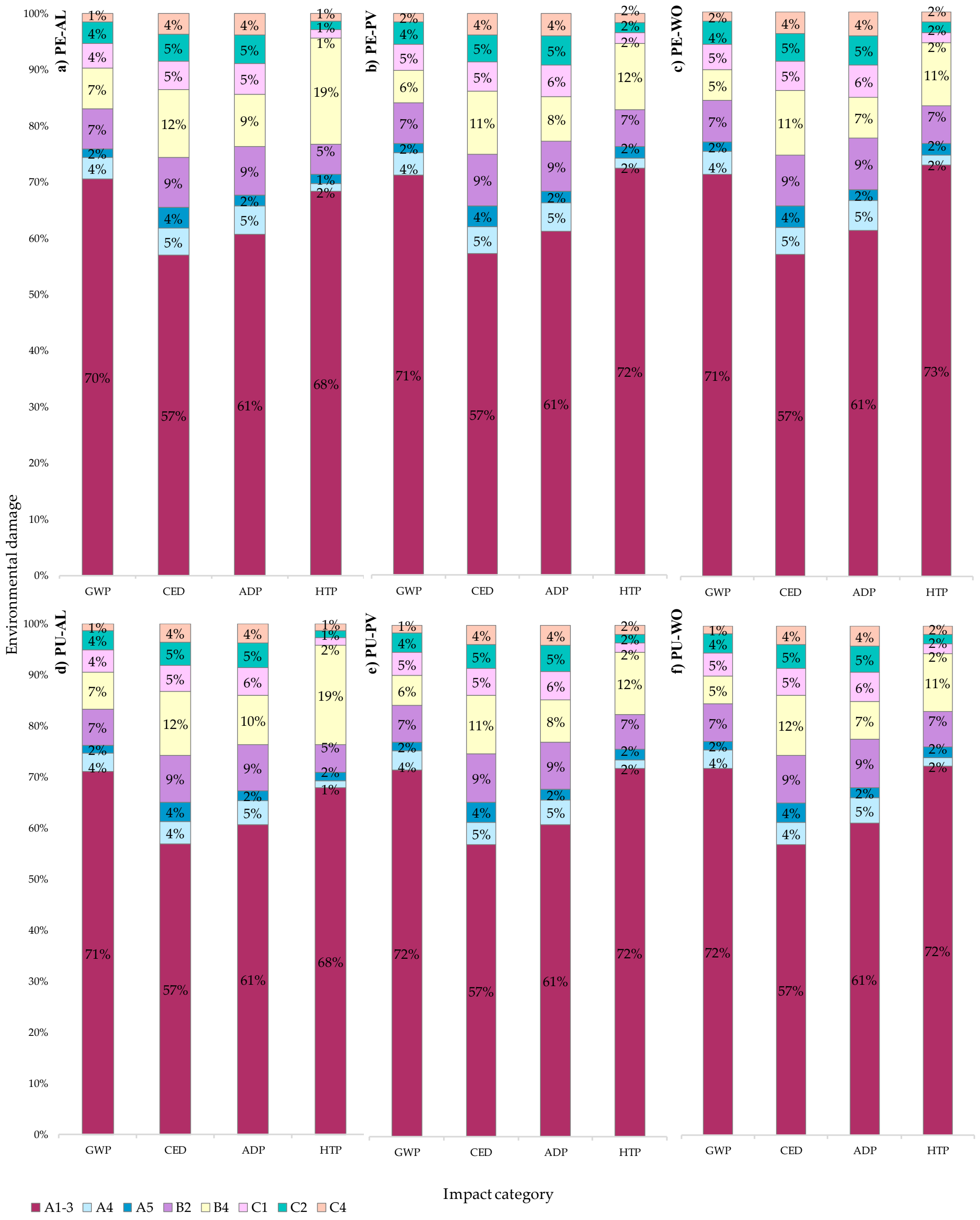


Figure 7. Percentage of environmental damage generated by each stage analyzed in the entire life cycle for: (**a**) PE-AL, (**b**) PE-PV, (**c**) PE-WO, (**d**) PU-AL, (**e**) PU-PV and, (**f**) PU-WO.

Analyzing each impact category separately (Figure 8), it was seen that the least favorable option in all cases was that of the reference (PE-AL), which is more pronounced in the stages A1 to A3 and B4. Previous studies have found that the production of aluminum (stages A1 to A3 or B4) requires high energy consumption [89], up to six times that of steel per unit of weight [86], as well as the inherent contaminants [84]. Therefore, the least favorable of the six combinations analyzed is that which includes heavy material with a moderate load potential and light material with a high load potential.

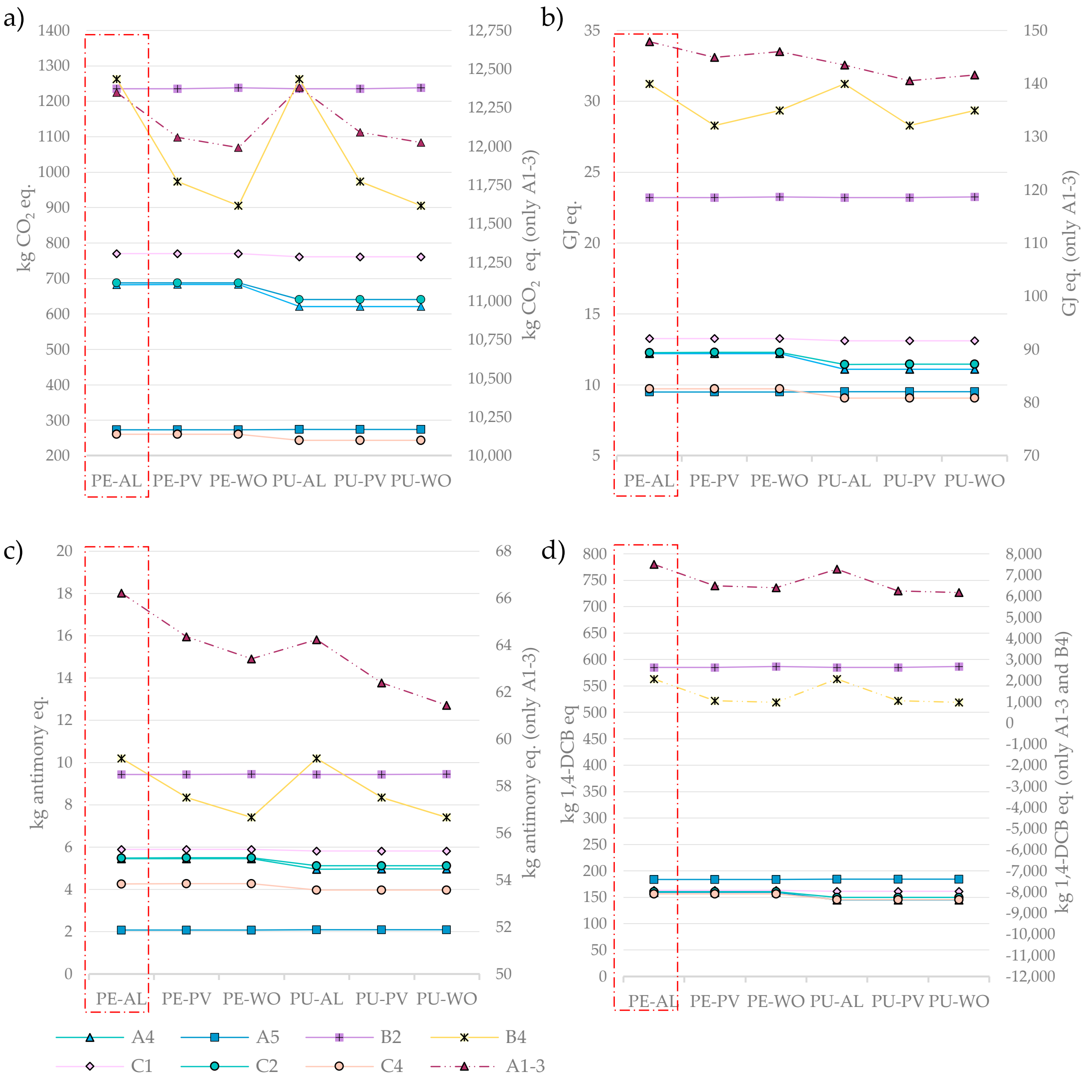


Figure 8. Environmental damage generated by each stage analyzed of the six alternatives of SH in the four impact categories: (**a**) GWP, (**b**) CED, (**c**) ADP and, (**d**) HTP.

Furthermore, when the stages with higher variability are discarded (A1 to A3 and B4, Figure 8), it can be seen that the options using PU are more favorable than those using PE, which can be attributed to the fact that the pumice aggregates are lighter than the conventional ones [90]. This coincides with previous research that recommends the use of volcanic materials—among them pumice—as they may significantly reduce the environmental damage [91]. Therefore, the options with the best environmental performance in all the impact categories were the PU-WO and the PU-PV.

Given the importance of the construction industry in the use of energy [47] and GHG emissions [92], in Figure 9 these categories are dealt with separately, breaking the CED down into its proportional Renewable (Re) and Non-Renewable parts (n-Re). The percentage of CED (n-Re) for all cases is significantly higher than the CED (Re), being 84.8% for stage A, 67.6% for stage B and 98.8% for stage C of the CED total. Of the three stages, B makes greater use of renewable sources due to the use of wood in the doors and windows, followed by A, especially when the options PE-WO and PU-WO are evaluated. Some authors mention the advantages of using wood due to the low energy requirements of its manufacture [76]. Similarly, it can be seen that stage C is practically dependent on CED (n-Re), due to the machinery (C1) and vehicles (C2) used.

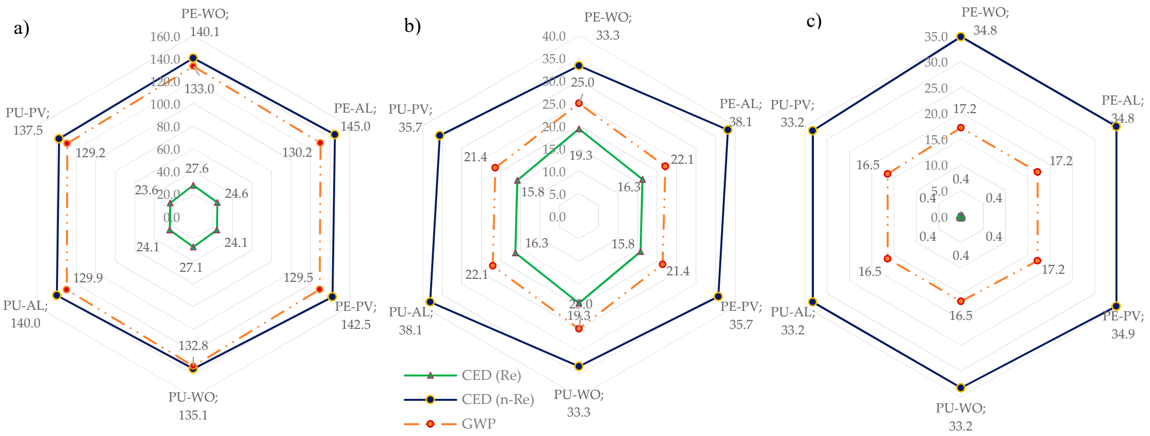


Figure 9. GWP, CED (Re), and CED (n-Re) caused at each stage of the SH: (**a**) A1 to A5, (**b**) B2, B4 and, (**c**) C1, C2, C4.

The results found for the CO_2 eq emissions and the consumption of incorporated energy are figures that are found in the list of effects reported by other researchers (Table 12). The information has been compared with that of residential, office, and commercial buildings, all of which have similar characteristics in terms of the materials used in their construction (reinforced concrete framework and traditional masonry). The majority evaluate the same components of the building (including the structure and envelope) which enables comparison. In SH the interior partitions are also evaluated.

Table 12. kg CO_2 eq and MJ eq generated by 1 m^2 of building in stages A, B and C. Data from: [48,49,78,93–95].

				kg CO_2 eq/m^2			MJ eq/m^2		
Study	**Database**	**Building Type**	**Location**	**A**	**B**	**C**	**A**	**B**	**C**
Current study	ecoinvent 3.4	Detached house	Mexico	309	54	40	3911	1251	815
Iddon et al. [93]	ICE 2.0	Detached house	UK	296	-	-	-	-	-
Islam et al. [48]	AusLCI	Attached house	Australia	257	64	-	3743	1257	-
Othman et al. [49]	Athena	Office building	U.S.	480	77	127	5597	1133	2030
Goggins et al. (floor slab) [95]	Bibliography	Office building	Ireland	211	-	-	1167	-	-
Gustavsson et al. [94]	ENSYST	Residential building	Sweden	-	-	-	3569	-	159
Sandanyake et al. [78]	AGGA/Alcorn	Commercial building	Australia	524	-	-	-	-	-

The SH analyzed emits 309 kg CO_2 eq/m^2 and needs 3911 MJ eq to perform stages A1 to A5; it also emits 54 kg CO_2 eq/m^2 and needs 1251 MJ eq for stages B2 and B4, similar to what was reported by Iddon et al. (2013) [93], Islam et al. (2015) [48] and Gustavsson et al. (2010) [94]. Additionally, when the impacts of the SH are compared with multi-story commercial or office buildings, although the results alternate within the same level of effect, the values tend to be higher in an interval of 30% to 40%. The stage showing most variation was C; as each study focused on specific end of life scenarios, their comparison was not feasible.

For stages A and B, the level of comparison is especially interesting, as each study was carried out in different geographical regions and with different databases. Therefore, it can be argued that the LCA is an objective methodology which allows global results in the residential sector to be obtained and it has been possible to standardize them, above all in the Product Stage (A1 to A3).

Considering the representativeness of the housing types in Mexico (11% economic, 47% popular, 30% traditional, 12% medium, residential, and residential plus [40], each of which was assigned 4%), it was possible to obtain an approximation of the effects of their embodied stages. One square meter of construction (A1 to A5) produces 309 kg of CO_2 eq and needs 3,911 MJ; as about 600,000 new housing units are built annually in Mexico [41], the total annual effect of the residential sector in stages A1 to A5 (until the finished house) is 11,275.8 Gg CO_2 eq and 142.5 PJ eq of energy (Table 13).

Table 13. Gg CO_2 eq and PJ eq generated annually by the construction of housing in Mexico.

Housing	**Area**	**Gg CO_2 eq/m^2**	**PJ eq/m^2**	**Annual Housing Construction**	**Gg CO_2 eq/m^2**	**PJ eq/m^2**
Economic	30.00	9284.30	117,318.50	66,000.00	612.76	7.74
Popular	42.50	13,152.75	166,201.21	282,000.00	3709.08	46.87
Traditional	62.50	19,342.28	244,413.55	180,000.00	3481.61	43.99
Medium	97.50	30,173.96	381,285.13	24,000.00	724.18	9.15
Residential	145.00	44,874.09	567,039.43	24,000.00	1076.98	13.61
Residential +	225.00	69,632.22	879,888.77	24,000.00	1671.17	21.12
Total				600,000.00	11,275.78	142.48

Additionally, using the national inventory of CO_2 eq emissions and compounds, these figures represent 2.1% of the net emissions (taking absorption into account), and 1.7% if total emissions are considered. Added to the 4% emissions from the housing sector due to consumption of natural gas, liquid petroleum gas, kerosene, diesel, and firewood in the operating stage [13], this means that 6.1% of the annual emissions may be attributed to the residential sector. Similarly, as regards the national energy inventory [14], the figures represent 2,7% of the annual consumption. This, when added to the 14% operational energy consumption, gives an estimated total of 16.7% of energy attributed to the residential sector (Table 14).

Table 14. GHGs and energy of the residential sector necessary for the construction of housing (A1 to A5) and its operational energy (B6). Data from [13,14].

Impacts of Residential Sector in Mexico (Stage)	**Quantity**	**National Representativeness**	
Emissions Gg CO_2 eq (A1 to A5)	11,275.8	2.1% [1]	1.7% [2]
Emissions Gg CO_2 eq (B6) [13]	21,279.9	4.0% [1]	3.1% [2]
Net emissions Gg CO_2 eq [13]	534,613.0		
Total emissions Gg CO_2 eq [13]	682,959.0		
Energy consumption PJ eq (A1 to A5)	142.5	2.7%	
Energy consumption PJ eq (B6) [14]	751.6	14.0%	
Total energy consumption PJ eq [14]	5362.8		

[1] Considering net emissions. [2] Considering total emissions.

Although it is evident that performance in the housing sector in Mexico is steadily improving, it is essential to deal with the accelerated changes that are being caused by environmental damage, not only at a regional level but also at a global one. The residential sector has an enormous potential to reduce these environmental burdens (including those of greatest concern today, such as climate change and the depletion of resources and non-renewable energy), throughout the various sectors that are required for its praxis. In this regard, it is necessary to opt for locally available materials, with high percentages of reuse, with thermal properties that enable energy optimization and, of course, that these should come where possible from renewable resources or from the discreet use of non-renewable resources.

On the other hand, while the importance of SH in the residential sector is indisputable, there is also a need to apply sustainability criteria to medium and residential housing. Although their representativeness is lower, in this work it was estimated that the resources invested in them (because of their size) could generate loads greater than 30% in GWP and CED, and the application of eco-technologies could be economically feasible (limitation present in the SH).

Moreover, while it is true that the LCA is a methodology that has been used in Mexico for decades [26], extending its application to one of the country's most demanding sectors would provide opportunities for reducing environmental burdens. This, through knowledge of the most commonly used materials and the processes required throughout the life cycle of a dwelling. This knowledge would enable the best environmental performance options to be chosen, and the opportunities for improvement would be identified.

5. Conclusions

The present study has assessed the environmental impacts generated by an SH throughout its embodied life cycle; a comparison of six alternatives was made by varying their elements (walls and windows), and it was possible to apply the LCA methodology to Mexico's residential sector with promising results. In addition, a review of the country's environmental situation focusing on the most relevant problems facing the residential sector was made.

It was found that throughout the cycle the SH analyzed generates an environmental burden of 17 t CO_2 eq, 252.5 GJ eq, 104.3 kg antimony eq, and 9.4 t 1.4-DCB eq; the requirements of stages A1 to A5 stand out, exceeding 70% of the impact in all the categories analyzed. In general, the stages with the greatest environmental effect are those containing a finished product (A1 to A3, B2, and B4: 78% CED-ADP; 85% GWP; 91% HTP), while the stages referring to the processes have a considerably lower impact. For A4 + C2 the figures are 3.3% HTP, 7.7% GWP, 9.3% CED, and 10.1% ADP. For A5 + C1 they are 3.7% HTP, 6.1% GWP, 7.6% ADP, and 9% CED. Finally, C4 has 1.5% GWP, 1.6% HTP, 3.7% CED, and 3.9% ADP.

The greatest variability in the results comes from changing the wood or PVC windows for aluminum windows in the HTP category, passing from 11–12% to 19% of the total damage, which is attributed to the aluminum production process.

The most unfavorable of the six cases analyzed was the reference sample (PE-AL), while the options with the best environmental performance were PU-WO and PU-PV for all impact categories. Environmental advantages can arise from using aggregates that could lighten the concrete for configuring the walls, as long as their environmental burden is equal to or less than that of conventional aggregates, and their basic attributes are not reduced.

The SH evaluated emits 309 kg CO_2 eq/m^2 in A1 to A5, 54 kg CO_2 eq/m^2 in B2 and B4, and 40 kg CO_2 eq/m^2 in C1, C2, and C4. It requires 3,911 MJ eq in A1 to A5, 1,251 MJ eq in B2 and B4, and 815 MJ eq in C1, C2, and C4. This data was collated with recent studies and, although they were carried out in different regions and developed with different databases, the results show consistency. Therefore, it was concluded that the methodology generates objective and global results in the residential sector and that, with the continuous improvement in standardization, it is increasingly possible to apply around the planet, especially in stages A1 to A3.

On the other hand, although ecoinvent regularly incorporates information from different regions of the world, it is urgent to create local databases in Latin America or in the case of Mexico expand the number of data for the existing one—mexicaniuh [96].

Considering the annual amount of the different types of dwellings built and their effect per m^2 as obtained in this study, an estimate of the annual impact of the residential sector on the finished housing (A1 to A5) was obtained. This was 11,275.8 Gg CO_2 eq, or 2.1% of net emissions. When added to the 4% emitted in the operation of the dwelling (B6) and the compound emissions, according to the national GHG inventory, this gives a total of 6.1% emissions attributed to the residential sector. Similarly, according to the national energy inventory, the estimated energy required by the residential sector in its finished housing phases (A1 to A5) is 142.5 PJ, or 2.7% of annual consumption. When added to the 14% operational energy consumption, this gives a total estimate of 16.7% of energy attributed to the residential sector.

Finally, it will be interesting in future research to obtain the CO_2 eq emissions of the residential sector and the energy eq required to carry out phases B and C annually, as well as to know the environmental impacts produced by public and commercial buildings (in addition to civil works), with the aim of obtaining the total burden generated by the construction industry in Mexico.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

1,4-DCB	para-dichlorobenzene
A1 to A3	Product stage
A4 to A5	Construction process stage
ADP	Abiotic depletion potential
AL	Aluminum
B1	Use
B2	Maintenance
B3	Repair
B4	Replacement
B5	Refurbishment
C1	Deconstruction/demolition
C2	Transport
C_2F_6	Hexafluoroethane
C3	Waste processing
C4	Disposal
CDW	Construction and demolition waste
CED	Cumulative energy demand
CF_4	Tetrafluoromethane
CH_4	Methane
CO_2	Carbon dioxide
CONAVI	National Housing Commission
EPS	Expanded polystyrene
EU	European Union
Gg	Millions of tons
GHGs	Greenhouse gases
GJ	Gigajoules
GLO	Global
GWP	Global warming potential
HAP	Polycyclic Aromatic Hydrocarbons
HTP	Human toxicity potential
IPCC	Intergovernmental Panel on Climate Change
LAC	Latin America and the Caribbean
LCA	Life Cycle Assessment
MSW	Municipal solid waste
N_2O	Nitrous oxide
n-Re	Non-Renewable
PE	Hollow block of 12 × 20 × 40 filled with expanded perlite
PFC	Perfluorocarbons

PJ	Petajoules
PU	Solid concrete brick lightened with pumice aggregates of 10 × 14 × 28
PV	PVC
Re	Renewable
RNA	Northern America
RoW	Rest of the World
SH	Social housing
SO_2	Sulfur dioxide
tkm	ton-kilometer
U	Thermal transmittance
U.S.	United States
WO	Wood
λ	Coefficient of thermal conductivity

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