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# Embodied energy of conventional load-bearing walls versus natural stabilized earth blocks

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ABSTRACT

According to recent studies, the manufacturing and construction of the structural elements of buildings (for example, columns, beams and load-bearing walls) represent the largest proportion of embodied impacts. Some of these reports highlight the need to analyse the materials and techniques used today in order to make the building sector more sustainable. This paper presents the results of embodied energy and global warming potential, using life cycle assessment (LCA) methodology, for load-bearing walls, being these one of the most common types of structures for buildings. This study analyses through an eco-design tool new options for materials used in the construction of structural load-bearing walls. The research aims to examine the environmental performance of each material alternative assessed: fired clay brick masonry (FC), concrete block masonry (CB), reinforced concrete-based wall (RC), and stabilized soil block masonry (SS); stabilized with natural fibers and alginates. These conventional and new materials – especially those with a low level of embodied energy, such as earth blocks – are evaluated from the point of view of their environmental consequences.



## 1. Introduction

Sustainable construction is a response to the growing awareness of the negative impact of buildings on the environment. Designers (architects and engineers) have an important stake as the selection of materials and construction systems are now of great importance. Due to this significant impact of the construction sector on the environment [1], different measures are now being taken to assess construction activity from a strictly environmental perspective. According to some studies, around 20% of the total impacts are related to manufacturing, construction, demolition processes and final disposal of building materials, elements and systems [2]. Long operation periods, versatility, high structural complexity and material comprehensiveness mean that buildings are treated as intricate and unique objects in ecological studies [3]. Although recent years have seen vigorous scientific evaluation of the environmental impact associated with buildings, there is still a lack of standardized environmental analysis procedures that focus on construction technologies. In this sense, the application of the life cycle assessment (LCA) [4,5] helps to clarify the consequences for the environment of using certain building materials and elements such as composites, and LCA is now recognized as an important tool for the environmental assessment of solutions in the construction industry.

The proper selection of building materials is important for sustainable development, and there is a clear need to design and construct buildings in a way that supports the concept of sustainable development. What is more, the environmental impact of construction material not only depends on the material itself and the other elements used in building, but also on the way they are put into place, the maintenance requirements, the system of longevity and the distance from the purchasing point to the construction site, etc. This means that the selection of materials or building systems requires the exactness of the LCA.

Energy in buildings can be categorized in two types: the amount of energy required for the maintenance/servicing of a building during its useful life operating energy (OE) and the energy capital represented by the building materials used in the production of a building embodied energy (EE). A study of both these types of energy consumption is required for a complete understanding of building energy needs. A building's embodied energy can vary greatly depending on the choice of building materials and techniques. Reinforced concrete walls, fired clay brick masonry, concrete block masonry and beam and block slabs form part of the common conventional construction systems used in the main structure of buildings in Spain. Similar building systems can be found in many other developed and developing countries.

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Alternative building technologies such as stabilized soil blocks can minimize a building's embodied energy [6–12]. Generally, the materials used to construct the structure of a building represent more than 50% of its embodied energy [13]. In this sense, the use of alternative materials, such as mortar/concrete blocks, stabilized soil blocks or fly-ashes instead of materials with high embodied energy content, like reinforced concrete, could cut cumulative energy by 20% over a building's 50-year life cycle [14]. Recycling building materials [15,16] is also essential to reducing the embodied energy level in the building, for instance, the use of recycled steel and aluminium confers can mean savings of more than 50% in embodied energy [17].

Early studies from the 1960s and 1970s focused on the life cycle stages of certain products, and emphasised the analysis of the efficiency of energy consumption and its sources, the use of raw materials and, to a lesser extent, waste disposal. For decades, such studies applied LCA analysis to construction materials due to their high potential environmental impact, and this research is reflected in current literature on the subject. Energy requirements for the production and processing of different building materials, $CO_2$ emissions and the implications for the environment have been studied by Buchanan and Honey [18], Suzuki et al. [19], Oka et al. [20], Debnath et al. [21], Pargana et al. [22] and Praseeda et al. [23]. Some researchers have analysed the proportion of embodied energy in materials used, and carried out LCAs of existing conventional buildings [24,25]. Other approaches and simplifications have also been applied in LCAs for building materials [26], and there are numerous studies in which LCA is used to evaluate the impact of different construction materials and solutions [27–30].

## 2. Research aim and methods

Most part of the papers available in literature use LCA tool in case studies due to the need to fully define all the variables within the limits of the analysis [31–37]. In other cases, research is done by means of a LCA theoretical study through a literature review [22,38–41]. Moreover, other researchers limit the LCA applicable results to a specific climate area [42] or a specific regulatory environment [40]. And there are also models of analysis seeking to apply LCA tool to obtain improvements in the design of the processes of manufacturing and construction [43,44]. This study is not intended to reach the definition level of a given case study but to support designers' environmental concerns establishing a first approximation using the parallelism between structural parameters and LCA of different materials commonly used in load-bearing walls.

Industries that produce building material are considered to be among the largest fuel consumers in the economy, so savings in fuel consumption in this sector could have a substantial impact on an economy's total fuel demand [45]. Moreover, environmental assessments that include the energy used in the production of building materials are vital for extending the life cycle of the product. Environmental assessments of building material production can provide criteria for design decisions when choosing between materials that offer a similar performance for a given application [46]. In this regard, the energy consumption resulting from the manufacturing process of building materials is important in terms of LCA. Materials that require high production temperatures, such as concrete or ceramic, have a big negative impact compared to those whose production temperature is low or zero.

Our study takes an environmental perspective when comparing various conventional technologies for building walls to others that use new low-impact materials. By identifying and quantifying the materials used in the manufacturing processes and applying LCA methodology, we identify the environmental impact of each building alternative studied. Summing up, our study identifies the processes involved in each technology, quantifies their associated impact and compares their environmental performance.

The aim of this research is to compare the environmental aspects and potential impact associated with the construction, maintenance and disposal of walls in three-storey buildings, determining the option with the lowest negative impact in relation to mechanical and structural characteristics. A life cycle assessment was made of three models of housing blocks erected with load-bearing walls that varied according to their material structure. The options compared involved conventional and unconventional building materials, therefore, the study analysed:

- fired clay brick masonry (FC),
- concrete block masonry (CB),
- reinforced concrete-based wall (RC),
- stabilized soil block masonry (SS).

## 3. The conventional and unconventional materials used

All construction material is manufactured from a combination of raw materials that involve energy expenditure and associated waste. Therefore, the energy cost of manufacturing building materials is an essential element in computing environmental impact, and manufacture is probably the element most widely cited when considering the environmental impact of construction materials. This analysis raises typical questions such as: Are the raw materials renewable? Are they scarce? Are they important to the global environment? How much energy is required and how much waste is produced in the manufacture? What impact does this waste have on the environment?. The construction process also involves energy expenditure and produces waste, and also poses more important questions: How much manufactured material is used? Can materials that cause less environmental impact be deployed? How much energy is used? How much waste is produced? What is the environmental impact of the waste? Such questions can only be answered according to the specific structure to which they are applied. Increasing attention is now being given to the construction phase as part of efforts to make construction more sustainable.

To establish a comparative standard, we have chosen common, and not so common, building materials widely used for a specific building typology: Fired clay brick masonry (FC); concrete block masonry (CB), reinforced concrete-based wall (RC), and, the least common element, stabilized soil block masonry (SS). The features of the different construction systems are explained in the following sections.

### 3.1. Fired clay bricks

Bricks are made by shaping a plastic mass of clay and water which is later solidifies by drying and firing. Bricks are among the oldest and most enduring of mankind's building materials. They require a considerable amount of thermal energy during the firing process because they burn at temperatures of between 1000 and 1200 °C, depending on the clay type. Light-coloured clays usually require higher firing temperatures than dark-coloured ones. This thermal energy amounts to 3.75–4.75 MJ per brick [47]. We applied an average value of 4.25 MJ per brick (standard size in Spain: 240 mm × 115 mm × 70 mm) for the comparison and computation of the energy content of buildings and masonry.

### 3.2. Concrete blocks

Light-weight/low-density concrete blocks are commonly used in the construction of envelope walls in multi-storey buildings. They are also used to a lesser extent to build load-bearing masonry walls. The basic composition of the blocks is cement, sand and coarse aggregates (less than 4 mm size). The energy content of the block will mainly depend on the cement percentage. Energy spent in crushing the coarse aggregate also contributes to the block energy calculation. The percentage of cement generally varies between 7 and 10% by weight. The quality of the block, particularly the compressive strength, is the deciding factor in the percentage of cement used. The energy content of a concrete block measuring 400 mm × 200 mm × 200 mm will be in the range of 12.3–15.0 MJ [47].

### 3.3. Reinforced concrete wall

Concrete is manufactured from aggregates (rock and sand), hydraulic cement and water. It usually contains a small amount of chemical admixture, and often has a mineral admixture that replaces a portion of the cement. A typical concrete formulation contains a large quantity of coarse and fine aggregates, a moderate amount of cement and water, and a small percentage of admixture. Most of these constituents are themselves manufactured products, by-products, or materials extracted by mining. In order to assess the environmental impact of concrete manufacture, it is necessary to consider the impact of each separate constituent. The constituent with the highest environmental impact is cement. Portland cement is usually manufactured by heating a mixture of limestone and shale in a kiln to a high temperature (approximately 1500 °C), then intergrading the resulting clinker with gypsum to form a fine powder. Thus, it is not surprising that the embodied energy in Portland cement is high. The average value of the energy required to make cement stands at about 5.85 MJ/kg. The energy required for concrete manufacture, considering all constituents, yields an average energy expenditure of 1.4 MJ/kg [47]. Reinforced concrete is made with steel rods, and the energy consumed in the steel production is 42 MJ/kg [47].

### 3.4. Stabilized soil blocks

The stabilized soil blocks considered in this research are made from a combination of clay soil, water, a natural polymer as stabilizer and animal fiber reinforcement. The polymer used is calcium alginate, which is added to the mixture in the proportion of 1.2% by weight. Calcium alginate is a chemical synthesis of wet chopped seaweed and calcium chloride and sodium carbonate. The animal fibre is raw cut wool, unwashed and unprocessed, and the proportion used is 0.25% by weight. The blocks are cured at room temperature. The energy consumption is based mainly on transport and extraction because they are not fired or steam-cured.

### 3.5. Mortar

Mortar is a mixture of cementitious material and sand. It is used for the construction of masonry as well as plastering and rendering works. According the European standard [48], the mortar used for masonry must have a compressive strength of 7.5 N/mm$^2$, equivalent to a cement–sand ratio of 1–5. This ratio represents energy consumption in the production of 1300 MJ/m$^3$ [47].

### 3.6. Embodied energy in the models proposed

Considering that three out of four wall types are masonry-based and the other is a combination of concrete and steel, the energy consumption is the sum of the proportions of the different components for each model. Masonry is an assemblage of masonry units (such as bricks/blocks) and mortar. The individual volumes of these two components will depend mainly on the size of the masonry unit. The energy content of the masonry should include that of the masonry units as well as the mortar. Reinforced concrete used in walls will have a steel/concrete proportion related to the resistance required according to the use to which it is put in the construction.

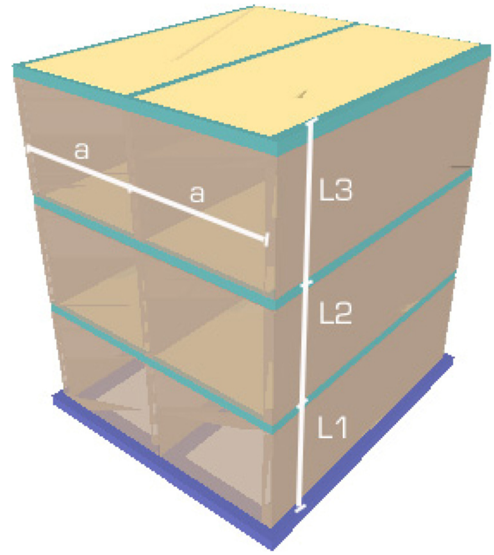


**Fig. 1.** Scheme of the building analysed: "*a*" represents the span (from 3.00 to 4.50 m). L1, L2, L3 represent the height of the different levels.

## 4. Structural parameters

As a study hypothesis, a three-storey building (ground floor + two, see Fig. 1) was chosen as it is a common housing type. The structure of the building is supported by load-bearing walls. An initial variable in terms of the constituent material of the wall is established: fired clay brick masonry (FC); concrete block masonry (CB), reinforced concrete wall (RC) and stabilised soil block masonry (SS). A second variable is the distance between the walls (span): 3.00 m, 3.50 m, 4.00 m and 4.50 m, these being the most common dimensions for this building typology (Table 1). The size of the construction system is calculated in mechanical terms by determining the section of the ground floor's load-bearing walls.

The software used to establish the structure of the models proposed is CYPECAD®, which is used for the analysis and design of building structures in homes, buildings and civil engineering projects that have horizontal and vertical loads. This program is adapted to international regulations and automatically generates hypotheses for any user-defined combination according to the stated premises. Users can also define their own project situations to personalize the combinations to be taken into account in the calculations for the structural elements of the project. Entering data such as the physical parameters of the different materials and the building characteristics in the software gives us the wall dimensions, as shown in Table 2.

## 5. Scope of the LCA

Both types of energy consumption operating energy (OE) and embodied energy (EE), are required for a complete understanding of building energy needs. Building EE specifically can also vary greatly depending on the choice of building materials and techniques at a very early design stage. Moreover, a building wall as an envelope is not just the a bearing wall but commonly composed of a multi-layered system in order to fulfil the standards requirements in terms of conditions of comfort which would introduce other variables in the study such as type and thickness of insulation to be used, quite far from the scope of this study. This study intends to limit the LCA tool taking into account that the present

**Table 1**
Floor area of the building analysed.

| | Span | | | | Span average (m) |
|---|---|---|---|---|---|
| | a3.00 (3 m) | a3.5 (3.5 m) | a4 (4.0 m) | a4.5 (4.5 m) | 3.75 |
| Level L1 | 48 | 56 | 64 | 72 | 60 |
| Level L2 | 96 | 112 | 128 | 144 | 120 |
| Level L3 | 144 | 168 | 192 | 216 | 180 |
| Floor area ($m^2$) | | | | | |

**Table 2**
Summary of the mean values of the walls' thickness and total mass obtained for each load-bearing wall construction after structural calculations.

| | Compressive strength (MPa) | Density ($g/cm^2$) | Medium value of the walls' thickness (cm) Span between walls | | | | | Total wall mass (kg) Span between walls | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 3.0 m | 3.5 m | 4.0 m | 4.5 m | 3.0 m | 3.5 m | 4.0 m | 4.5 m |
| FC | 5.00 | 1.40 | 0.29 | 0.29 | 0.33 | 0.38 | 122.107 | 122.107 | 140.431 | 145.453 |
| CB | 4.00 | 1.50 | 0.20 | 0.23 | 0.25 | 0.35 | 47.098 | 53.865 | 57.248 | 57.248 |
| RC | 25.00 | 2.50 | 0.25 | 0.25 | 0.25 | 0.25 | 130.996 | 130.996 | 130.996 | 130.996 |
| SS | 4.45 | 1.79 | 0.28 | 0.30 | 0.32 | 0.33 | 115.062 | 121.830 | 128.599 | 142.136 |

*Note*: FC: fired clay brick masonry; CB: concrete block masonry; RC: reinforced concrete-based wall; SS: stabilized soil block masonry.

research is not focused on a case study analysis. Hence it is not possible to calculate OE (considering insulation, depending on the transmittance of the wall elements, etc). By contrast this study is a first approximation that links embodied energy and global warming potential with resistance parameters in different construction materials used for building structures.

The aim of the LCA applied in this study is to obtain the values for the embodied energy and global warming potential (GWP) impact categories associated with the construction of four types of load-bearing wall: fired clay brick masonry (FC), concrete block masonry (CB), reinforced concrete-based wall (RC) and stabilised soil block masonry (SS). We evaluated a three-storey building whose total height is 9.90 m. The construction consists of three parallel walls each 8.00 m long. The distances between the walls are 3.00 m, 3.50 m, 4.00 m and 4.50 m.

In terms of the proposed framework, this study should yield results that answer the question: what is the environmental impact of the processes related to the construction of each combination proposed?

According to the study aim, the functional unit is the total surface of the walls in each case.

The system assessed is composed of each process in the production, construction, maintenance, deconstruction and final disposal of all components of the building structure. It does not include those processes related to the operational phase of the dwelling. The system includes the following processes:

- Manufacture of building products. For each building material involved in the construction, all goods and services provided from beginning to end are considered. Machine manufacture and territorial infrastructure processes have also been taken into account.
- Assembly and construction. This covers the processes that integrate all products and services on site in each of the dwellings studied. The transportation of building materials from factory to site, and the placement of building products are also evaluated.
- Maintenance and repair. This includes all repair operations and maintenance of building components, also taking into account the replacement of those materials that are less durable.
- Dismantling and demolition. The study evaluates all processes at the end of the life of the building that involve the dismantling and demolition of the dwelling: demolition, removal of building elements and transportation of demolition materials for recycling or disposal.
- Disposal and recycling. This covers all processes involving material following dismantling and demolition, that is, the deconstruction of building materials.

The environmental data on wool and algae are found in recent studies by Biswas et al. [49] and Resurreccion et al. [50]. The environmental data concerning the rest of the building materials come from the Ecoinvent V.2 database [47].

The calculation procedure to obtain the life cycle inventory is described by Zabalza [51] and García [52] as follows:

1. Identification and quantification of the initial building products and auxiliary materials – including replacement materials – involved in the life cycle. The quantities of building materials has been calculated as follows:
   a. The materials required to build each type of wall have been determined. The building materials are defined in Section 3. As overview, the following materials take part:
      Fired clay brick masonry (FC): cement, water, sand, hydraulic lime, bricks.
      Concrete block masonry (CB): cement, water, sand, concrete blocks
      Reinforced concrete-based wall (RC): concrete, reinforced steel in bars; steel, saw timber and solvents in formwork.
      Stabilized soil block masonry (SS): clay plaster, algae, wool.
   b. The thickness of each load bearing wall is calculated considering the structural parameters defined in Section 4.
   c. The quantities of building materials (i.e. mortar, concrete blocks, formwork or reinforced steel) are obtained for each type of wall.
2. Identification and quantification of the basic processes associated with construction and deconstruction. Depending on the volume of material used in construction, and by applying the ratios set by Kellenberger et al. [53], the energy (electricity power and diesel used in building machines) used in the operations of construction, maintenance and demolition of each model is obtained. The processes related to transport are obtained by determining the mass of material transported associated with each material used, and considering the distance from factory to site and from the site to landfill. Were considered medium distances for each material, assuming an urban construction site according to the method described by Garcia [52]. Finally, the processes associated with the end of life of the materials used

**Table 3**
Inventory list of the materials used and corresponding name in the Ecoinvent V.2. database. Unitary values for global warming potential and embodied energy.

| Component | ID | Name (Ecoinvent) | Ud | Global Warming Potential 100a *CML* 2001 kg $CO_2$-Eq | Embodied Energy *Cumulative Energy Demand* MJ |
|---|---|---|---|---|---|
| Solvent | 443 | Solvents, organic, unspecified, at plant | kg | 2.12 | 65.77 |
| Sand | 464 | Gravel, round, at mine | kg | 0.00 | 0.06 |
| Cement | 484 | Cement, unspecified, at plant | kg | 0.77 | 3.56 |
| Hydraulic lime | 488 | Lime, hydraulic, at plant | kg | 0.83 | 4.82 |
| Brick | 495 | Brick, at plant | kg | 0.22 | 2.84 |
| Concrete | 504 | Concrete, normal, at plant | $m^3$ | 265.22 | 1447.23 |
| Concrete block | 537 | Cement mortar, at plant | kg | 0.20 | 1.52 |
| Clay | 538 | Clay plaster, at plant | kg | 0.02 | 0.52 |
| Diesel (Const.-Dem.) | 559 | Diesel, burned in building machine | MJ | 0.09 | 1.38 |
| Electricity (Const.-Dem.) | 698 | Electricity mix, Spain | kW h | 0.50 | 10.90 |
| Reinforced steel | 1.141 | Reinforcing steel, at plant | kg | 1.34 | 20.94 |
| Steel formwork | 1.141 | Reinforcing steel, at plant | kg | 1.34 | 20.94 |
| Metal packing | 1.154 | Steel, low-alloyed, at plant | kg | 1.63 | 26.16 |
| Steel wire | 1.154 | Steel, low-alloyed, at plant | kg | 1.63 | 26.16 |
| Supplementary mat. | 1.154 | Steel, low-alloyed, at plant | kg | 1.63 | 26.16 |
| Transport | 1.943 | Transport, lorry 32 t | tkm | 0.17 | 2.81 |
| Plasticizer | 1.998 | Alkylbenzene sulfonate, linear, petrochemical, at plant | kg | 1.53 | 59.97 |
| Final disposal | 2.221 | Disposal, inert material, 0% water, to sanitary landfill | kg | 0.01 | 0.33 |
| Water | 2.288 | Tap water, at user | kg | 0.00 | 0.01 |
| Saw timber | 2.507 | Sawn timber, softwood, planed, kiln dried, at plant | $m^3$ | −713.13 | 12,792.19 |
| Algae | A001 | Algae, at regional storehouse[a] | kg | 0.0200 | 20.0000 |
| Sheep wool | P001 | Wool mat, at plant[b] | kg | 15.2600 | 24.9150 |

[a] Data provided by Resurreccion et al. [50].
[b] Data provided by Biswas et al. [49].

are determined. For this final stage, disposal in a landfill scenario is established.

3. Determination of input and output of each unit process. The Ecoinvent V.27. database and published LCA studies [41,49–51] has been used to obtain environmental information on each unit process. Each identified unitary process is assigned the value of global warming potential (GWP) and cumulative energy demand. Table 3 shows the unitary values for GWP and primary embodied energy of the materials used.
4. Inventory and Assessment. Table 4 shows the inventory of the materials used for each type of construction. The impact assessment was carried out using the CML 2001 method in relation to the GWP impact category, and the “cumulative energy demand” calculation was used to obtain primary embodied energy.

## 6. Results and discussion

A graphic comparison of embodied energy values and the global warming potential of the individual wall types is shown in Figs. 2–7 and a extensive list of the values in Table 5.

Regarding cumulative energy demand, for a three-levels building, fired clay brick wall constructions (FC) score highest and concrete block walls (CB) the lowest. The mean values for each type were 395,834.71 MJ and 145,027.43 MJ respectively. The mean values for stabilized soil walls (SS) and reinforced concrete walls (RC) were 266,562.54 MJ and 309,213.86 MJ. The contribution of the manufacturing phase to these results is significant, representing mean percentages in relation to the total stages that range from 38.11% (SS) to 51.59% (FC). The construction phase is also important, representing more than 25% in all cases. Comparative results are similar for the global warming potential impact category for a three-levels building: fired brick wall constructions (FC) again score highest and concrete block walls (CB) the lowest. The mean values for each type were 29,188.97 kg eq-$CO_2$ and 13,716.86 kg eq-$CO_2$. The mean values for stabilized soil walls (SS) and reinforced concrete wall (RC) were 16,201.10 kg eq-$CO_2$ and 27,505.15 kg eq-$CO_2$. The contribution of the manufacturing phase to these results is also significant, with average percentages in relation to the total stages ranging from 44.07% (SS) to 71.83% (FC). The construction phase also contributes significantly to the total impact, with mean values spanning 16.53% (CB) and 31.93% (SS).

Looking at Table 5 it can be seen that the GWP/$m^2$ obtained for the average of the three levels studied is higher for the RC 153.24 and slightly lower for FC 146.21, with the SS 79.68 being half the RC and almost double the CB 47.83. Variations from the CED when considering the four materials slightly modify this rate being FC 1957.62 MJ the highest average consumption followed by RC 1793.65 MJ. The ratio between the results of SS 1303.64 MJ and CB 736.04 MJ is virtually identical with respect to energy consumption and $CO_2$ emissions, being SS double vs. CB.

If the three levels are analysed independently, the main consideration to be taken into account is the practical equivalence of emissions between SS and CB for one store height buildings (1 level) mainly due to the decrease in thickness required for SS blocks. The higher the building height, the higher the difference between the proportions of $CO_2$ emissions between CB and SS. Moreover, this better behaviour of SS for GWP for low structures is less favourable in the case of CED.

To evaluate the results shown in Table 5, the first question to be addressed is the relationship between the compressive strength of the different wall materials, hence the various thicknesses required for the ground floor level walls and the distances between the walls. For the comparison we took as a starting point the fact that the strength of fired clay brick masonry and stabilized soil block

**Table 4**
Inventory list of the construction materials used.

| Wall type | Component | Id | Ud | Average values per building | | |
|---|---|---|---|---|---|---|
| | | | | 1 Floor | 2 Floors | 3 Floors |
| FC | Sand | 464 | kg | 15,281.65000 | 35,109.93500 | 59,484.84500 |
| | Cement | 484 | kg | 1987.63000 | 2981.44500 | 2981.44500 |
| | Brick | 495 | kg | 15,289.20000 | 34,372.80000 | 58,506.30000 |
| | Diesel (Const.-Dem.) | 559 | MJ | 16,244.20841 | 36,847.69204 | 62,406.82722 |
| | Electricity (Const.-Dem.) | 698 | kW h | 717.74280 | 1628.09815 | 2757.41667 |
| | Transport | 1943 | tkm | 3459.45500 | 7835.09150 | 13,252.50278 |
| | Plasticizer | 1998 | kg | 9.92000 | 14.88500 | 14.88500 |
| | Final Disposal | 2221 | kg | 34,594.55000 | 78,350.91500 | 132,524.65324 |
| | Water | 2288 | kg | 2026.15000 | 4700.55500 | 8023.21000 |
| CB | Sand | 464 | kg | 1713.83000 | 3427.66000 | 5141.49000 |
| | Cement | 484 | kg | 222.91000 | 445.82000 | 668.74000 |
| | Concrete block (20.20.40) | 537 | kg | 13,534.20000 | 27,068.40000 | 30,451.95000 |
| | Concrete block (30.20.40) | 537 | kg | 0.00000 | 0.00000 | 5075.32500 |
| | Concrete block (35.20.40) | 537 | kg | 0.00000 | 0.00000 | 11,842.42500 |
| | Diesel (Const.-Dem.) | 559 | MJ | 5828.86346 | 11,657.73548 | 19,897.39043 |
| | Electricity (Const.-Dem.) | 698 | kW h | 257.54562 | 515.09163 | 879.15695 |
| | Transport | 1943 | tkm | 1569.92800 | 3139.85700 | 5386.49700 |
| | Plasticizer | 1998 | kg | 1.11000 | 2.23000 | 3.34000 |
| | Final Disposal | 2221 | kg | 15,699.28000 | 31,398.57000 | 53,864.97000 |
| | Water | 2288 | kg | 227.23000 | 454.46000 | 681.70000 |
| SS | Clay | 538 | kg | 133,488.00000 | 70,081.20000 | 125,145.00000 |
| | Diesel (Const.-Dem.) | 559 | MJ | 48,528.97155 | 25,477.71007 | 45,495.91083 |
| | Electricity (Const.-Dem.) | 698 | kW h | 2144.23006 | 1125.72078 | 2010.21568 |
| | Transport | 1943 | t km | 14,382.36000 | 7550.73900 | 13,483.46250 |
| | Final Disposal | 2221 | kg | 135,367.20000 | 71,067.78000 | 126,906.75000 |
| | Algae | A001 | kg | 1555.20000 | 816.48000 | 1458.00000 |
| | Sheep wool | P001 | kg | 324.00000 | 170.10000 | 303.75000 |
| RC | Solvent | 443 | kg | 38.88000 | 116.64000 | 116.64000 |
| | Concrete | 504 | $m^3$ | 18.54000 | 55.62000 | 55.62000 |
| | Diesel (Const.-Dem.) | 559 | MJ | 16,199.48120 | 48,581.53378 | 48,598.44184 |
| | Electricity (Const.-Dem.) | 698 | kW h | 715.76655 | 2146.55250 | 2147.29957 |
| | Reinforced steel | 1141 | kg | 192.46000 | 384.91000 | 577.37000 |
| | Steel formwork | 1141 | kg | 576.00000 | 1728.00000 | 1728.00000 |
| | Metal packing | 1154 | kg | 3.50000 | 1.78000 | 10.50000 |
| | Steel wire | 1154 | kg | 0.89000 | 10.50000 | 2.67000 |
| | Supplementary mat. | 1154 | kg | 9.99000 | 29.51000 | 29.96000 |
| | Transport | 1943 | t km | 5100.92300 | 15,282.77950 | 15,302.76250 |
| | Final Disposal | 2221 | kg | 47,373.32000 | 141,926.14000 | 142,119.94000 |
| | Saw timber | 2507 | $m^3$ | 0.28800 | 0.86400 | 0.86400 |

masonry is quite similar (between 5.00 and 4.00 MPa), while that of reinforced concrete-based walls is five times higher (25 MPa). This difference assumes a slight alteration in thickness in the case of short distances between the walls but which will increase as the distances become greater. This variation means that reinforced concrete-based walls are much thinner (20–40% less) over bigger distances (4.5 m) than the rest of the building materials used for making comparisons in this research.

Another relevant issue is the influence of the block or brick format and the constituent materials of the walls. In this case, this difference results in the concrete block masonry having less than half the mass of the remaining walls. The factor sees an increase in

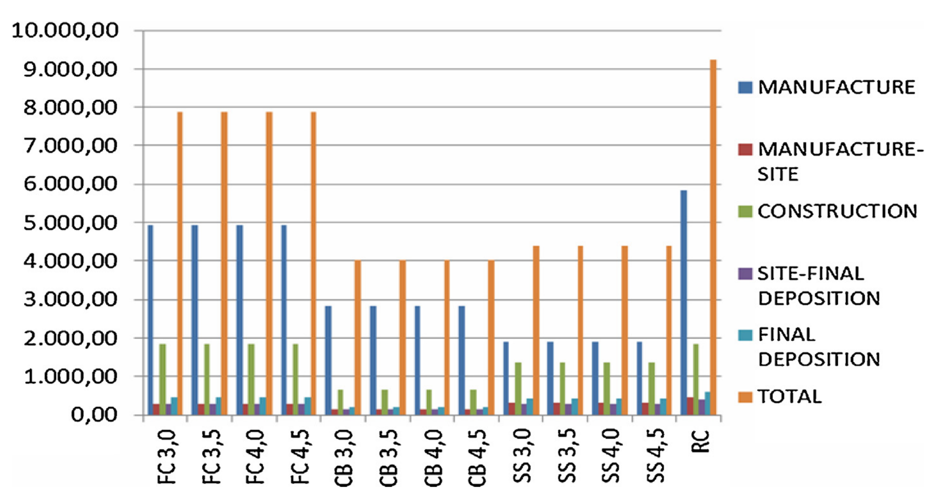


**Fig. 2.** GWP 100a (kg eq-$CO_2$) for each type of load-bearing wall for the one-level model.

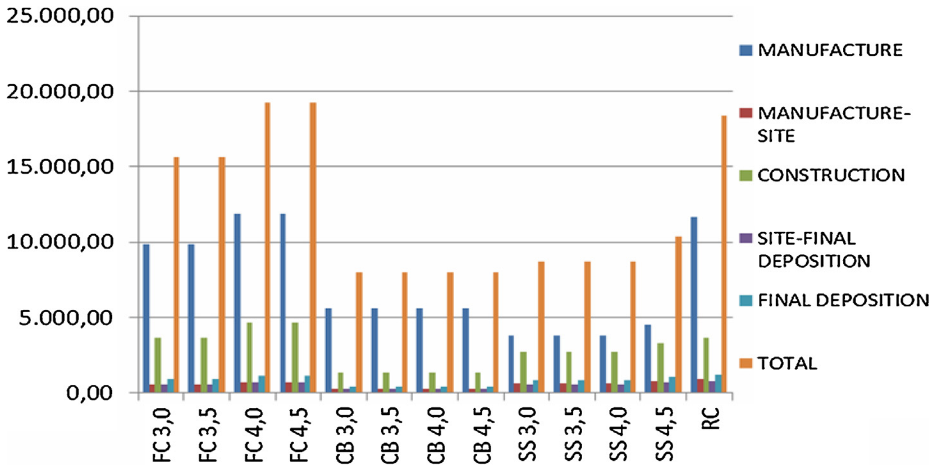


**Fig. 3.** GWP 100a (kg eq-$CO_2$) for each type of load-bearing wall for the two-levels model.

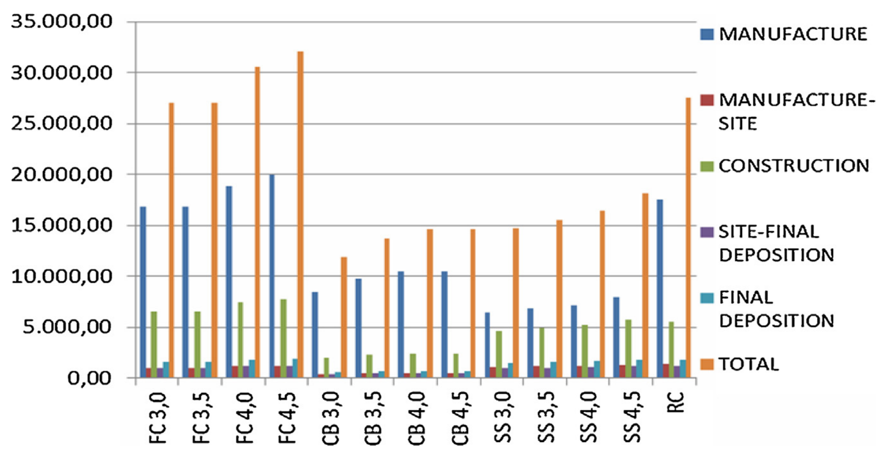


**Fig. 4.** GWP 100a (kg eq-$CO_2$) for each type of load-bearing wall for the three-levels model.

mass of up to three times between reinforced concrete-based walls and concrete block masonry (for a 3.0 m distance), and between fired clay bricks masonry and concrete block masonry (for a distance of 4.5 m). There is no linear increase in the difference between the mass of the materials and the widening between walls.

In this study wall dimensions were decided just by means of structural calculations. However, in addition to satisfying the structural requirement, the outer building walls also have to fulfil other requirements as a building envelope. In this case the thermal parameters (such as heat transfer coefficient) of the walls should be taken into account before running LCA. In any case, the inclusion of the thermal conductivity variables would require selecting the examples proposed through a more defined case study. Thus the differences between inner and outer walls should be considered and so complementary materials for insulation or thermal comfort could be included to fulfil the requirements due to a given climatic zone. These variations would imply a new perspective for the present investigation and for an specific case quite possibly

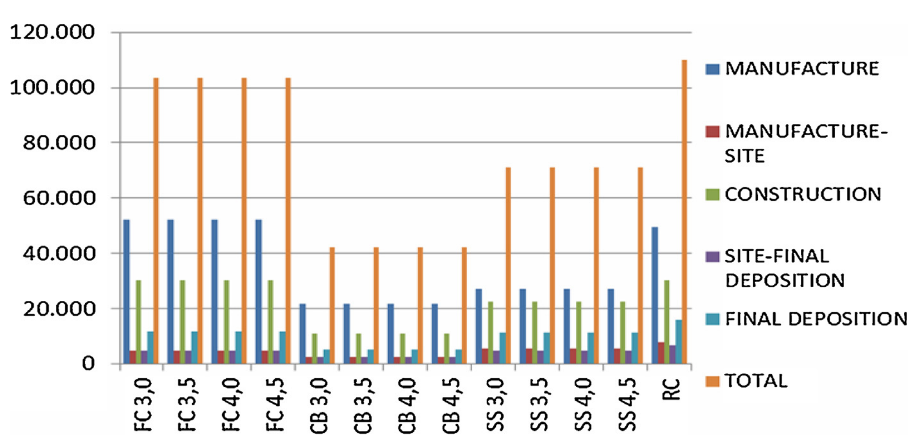


**Fig. 5.** Cumulative energy demand (MJ) GWP 100a (kg eq-$CO_2$) for each type of load-bearing wall for the one-level model.

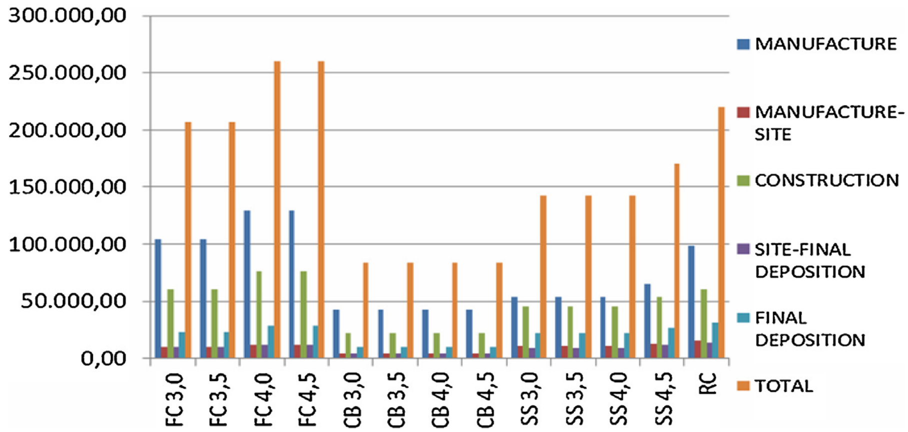


**Fig. 6.** Cumulative energy demand (MJ) GWP 100a (kg eq-$CO_2$) for each type of load-bearing wall for the two-levels model.

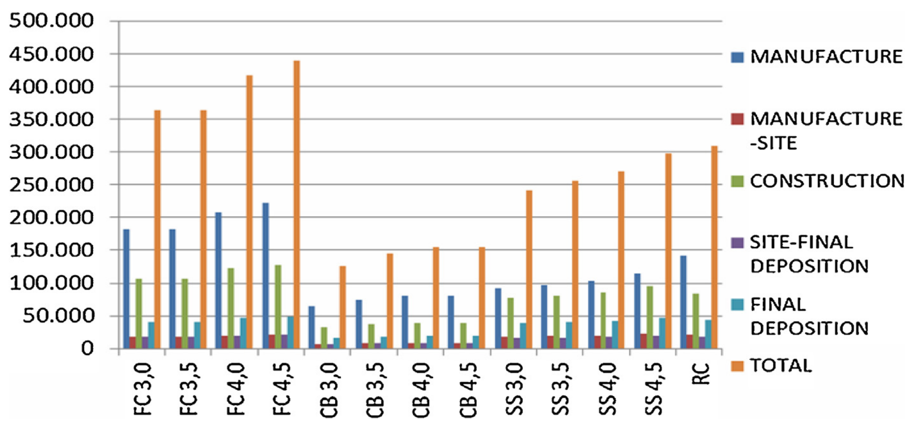


**Fig. 7.** Cumulative energy demand (MJ) GWP 100a (kg eq-$CO_2$) for each type of load-bearing wall for the three-levels model.

**Table 5**
Mean environmental impact values showed by type of material used and building height.

| | | Global warming potential GWP 100 years (kg eq-$CO_2$) CML 2001 | | | Cumulative energy demand (MJ) | | |
|---|---|---|---|---|---|---|---|
| | GWP Total | GWP/m$^2$ | Average GWP/m$^2$ | CED (MJ) | CED/m$^2$ | Average CED/m$^2$ | |
| FC | 1 level | 7868.38 | 131.14 | 146.21 | 103,585.25 | 1726.42 | 1957.62 |
| | 2 levels | 17,440.57 | 145.34 | | 233,683.83 | 1947.37 | |
| | 3 levels | 29,188.97 | 162.16 | | 395,834.71 | 2199.08 | |
| CB | 1 level | 4037.67 | 67.29 | 47.83 | 42,093.77 | 701.56 | 736.04 |
| | 2 levels | 7980.46 | 66.50 | | 84,100.61 | 700.84 | |
| | 3 levels | 13,716.86 | 76.20 | | 145,027.43 | 805.71 | |
| SS | 1 level | 4386.23 | 73.10 | 79.68 | 71,145.05 | 1185.75 | 1303.64 |
| | 2 levels | 9112.18 | 75.93 | | 149,312.04 | 1244.27 | |
| | 3 levels | 16,201.10 | 90.01 | | 266,562.54 | 1480.90 | |
| RC | 1 level | 9230.64 | 153.84 | 153.24 | 109,914.35 | 1831.91 | 1793.65 |
| | 2 levels | 18,367.88 | 153.07 | | 219,742.56 | 1831.19 | |
| | 3 levels | 27,505.15 | 152.81 | | 309,213.86 | 1717.85 | |

would improve the LCA relationship between SS and CB considering that CB has much less mass comparing to SS, but certainly provides much less thermal comfort than SS.

## 7. Conclusions

The significant findings from this study are:

- In all four materials studied, the LCA phases that most clearly determine the final results are manufacturing and construction. For a three-levels building, in the manufacturing process, the embodied energy is between 38 and 51% of the total, and the $CO_2$ emissions range from 44 to 72%. In the construction phase the embodied energy is between 25.5 and 31.8% and the $CO_2$ emissions range from 16.5 to 32%.
- In terms of the distances (span) between walls, stabilized soil block masonry (SS) obtained much better overall LCA results than fired clay brick masonry (FC) or reinforced concrete wall (RC).
- When comparing LCA results between stabilized soil block masonry (SS) and concrete block masonry (CB) for all distances between the walls, SS scored worse than CB. The proportion between these values is increased as the building height is increased. The average embodied energy value calculated for SS, 266,562.54 MJ, doubled that obtained for CB, at 145,027.43 MJ. Comparing SS and CB for $CO_2$ emissions, these are less relevant as the difference is only 12%, ranging from an average value of

16,201.10 kg eq-$CO_2$ (SS) to 13,716.86 kg eq-$CO_2$ (CB). The explanation lies in the difference between total wall mass, which is 2–3 times higher for SS than for CB.

- The difference in final LCA results increases when the span between walls extends. This establishes a relationship to be taken into account when designing the building structure, between the type and characteristics of the building and the choice of structural material from the embodied energy and $CO_2$ emissions perspective.

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