

Article

Leveraging Life Cycle Cost Analysis (LCCA) for Optimized Decision Making in Adobe Construction Materials

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Abstract: Adobe construction is a longstanding practice in South America and is characterized by its affordability, accessibility, and ecological sustainability. However, the decision-making process regarding the choice of construction materials often relies on subjective factors, disregarding economic implications throughout the life cycle of a building. This study aimed to introduce life-cycle cost analysis (LCCA) as a valuable tool for optimizing decision making in the context of adobe construction materials in South America. This study emphasizes the significance of considering the life-cycle costs associated with adobe construction materials and their impact on decision-making processes. A comprehensive case study was conducted in South America to examine the various adobe construction scenarios. The life-cycle costs of different adobe materials and their associated maintenance strategies were assessed over a period of several decades, considering factors such as material acquisition, construction, maintenance, and repair. The values used in this study are specific to Ecuador, the country where the investigation was conducted.

Keywords: adobe; life cycling cost analysis; LCCA; construction materials



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1. Introduction

Different types of materials respond to many factors, such as the availability of raw materials, traditions, economy, production activities, technologies, and climate. Throughout history, humans have harnessed the Earth's resources to create shelters that provide protection and comfort.

Among the multitudinous construction materials used across cultures and times, adobe is a testament to the ingenuity and resilience of ancient building practices. Particularly in underdeveloped nations, where labor and material prices are subsidized and other building materials and technologies may not be readily available, earth construction has both economic and environmental advantages [1].

Adobe, derived from the Arabic word 'al-tub', meaning brick, is a versatile material composed of clay, sand, water, and an organic binder [2]. Renowned for its sustainability, durability, and thermal qualities, adobe has been utilized for centuries, spanning continents, and shaping architectural landscapes [3].

Ancient civilizations, such as Egyptians, Indians, and indigenous groups worldwide, have long utilized adobe as a building material [4]. Adobe construction techniques depend on the site. For example, adobe buildings in Latin America and the Caribbean have been characterized by relevant seismic activity, which differs between nations because local building cultures, soil types, and climates have led to the development of unique techniques and approaches in each community [5,6].

By utilizing locally sourced materials, adobe reduces the carbon footprint associated with the transportation and manufacturing processes [7]. Furthermore, it is non-toxic,

renewable, and has excellent thermal insulation properties, making it energy-efficient and cost-effective in both hot and cold climates.

In sustainable building practices, construction materials play a crucial role in achieving both environmental responsibility and economic efficiency. Adobe, a traditional building material with known ecological and thermal benefits, has garnered significant attention in recent years. However, several aspects remain, primarily regarding the use of transportation [7]. With the pressing need for sustainable solutions in the construction industry, the incorporation of adobe as a viable alternative has gained prominence worldwide [8,9].

This kind of building minimizes expenses because it is generally basic and easy to accomplish, and it may be built with local materials. The embodied energy and carbon footprints of earth buildings are typically smaller than those of buildings made with more complex materials, such as masonry, concrete, or steel [1].

Adobe is used as a sustainable construction material mainly owing to its five properties: (i) affordable production costs and broad availability; (ii) significant energy savings, primarily using renewable energy; (iii) exceptional workability and ideal mechanical qualities for buildings; (iv) effortless assimilation into the regional ecology, utilizing indigenous resources and methods; and (v) simplicity in recycling construction leftovers [6].

This study focuses on exploring the concept of Life Cycle Cost Analysis (LCCA) within the context of adobe construction materials. LCCA is a method that assesses the total cost of a material, including not just the initial investment but also the costs incurred throughout its entire life cycle [8]. Through a thorough analysis, LCCA provides valuable insights into the economic viability of materials, uncovering their long-term benefits and disadvantages based on the literature.

The article is organized as follows: First, a brief literature review of the use of adobe in South America is presented, along with the results of experimental research and structural analysis of existing buildings. This is followed by the methodology used to conduct the proposed analysis, which includes a description of the factors analyzed and the assumptions made to arrive at the result.

Subsequently, the study of data for the analysis is presented, first describing the initial costs, which refer to the extraction and manufacturing costs. This is followed by operational and maintenance costs and, finally, the costs of disposal and recovery/reuse.

2. Literature Review

2.1. Life Cycle Cost Analysis (LCCA) and Its Importance in Construction Projects

Life Cycle Analysis (LCA) is commonly used to evaluate the environmental impacts of materials and their industrial processes, impact of a project, and consequences generated. It assesses the environmental impact of each stage of the production process from raw material extraction to end-of-life disposal [10,11].

On the other hand, LCCA focuses on evaluating the sustainable economic and socio-environmental development of material manufacturing. This method is utilized in the decision-making process during the planning and design stages to evaluate all economic aspects and activities of a project [11].

This method is capable of achieving multiple advantages for a project, such as decreasing the expenses associated with material procurement, enhancing the ability to estimate realistic quantities of materials, and preventing unnecessary material waste. In addition, LCCA allows the evaluation of various alternatives by considering the costs associated with each option throughout its life cycle. By examining the total cost of each choice, decision makers can identify the most cost-effective option and make informed decisions that provide the best long-term value for money [11,12].

This analysis allows for the evaluation of uncertainties and potential risks associated with the life-cycle costs of a project. By conducting a thorough assessment of risks, such as cost fluctuations, regulatory changes, and technological advancements, decision makers can make informed decisions and mitigate potential consequences.

Giresine et al. [13] conducted a comprehensive study examining both economic and environmental costs in conjunction with the improvement of structural characteristics of masonry walls with respect to seismic and energetic improvement of buildings. To evaluate these aspects, this study focused on seismic indicators, such as variations in base shear strength and ductility, and thermal indicators, such as variations in thermal transmittance. The procedure correlates the cost with the improvement in structural aspects, resulting in curves that allow for the optimal level of structural performance improvement to be achieved in line with the available economic capabilities and/or objectives of the administrator or owner.

Moreover, this analysis can provide information on where construction is feasible and the sources of material extraction, which not only reduces project costs but also minimizes the environmental impact generated by activities, particularly in terms of energy consumption [14]. It is crucial to recognize that improving structural behavior alone is not sufficient; integration with other disciplines must also be considered.

In summary, LCCA plays a crucial role in optimizing decision making through a comprehensive evaluation of costs, facilitating comparative analysis, managing risks, incorporating sustainability factors, and fostering long-term planning. By integrating LCCA into decision-making processes, organizations can make more informed, cost-effective, and sustainable choices that will benefit them in the long run.

2.2. A Look at Traditional Adobe Buildings: The Case Study of Quito, Ecuador

Adobe is still used in certain rural areas in countries such as Ecuador, Perú, Colombia, Bolivia Uruguay, and Chile for its sustainability and thermal properties.

According to the 2022 census conducted in Ecuador, more than 86% of the exterior walls of homes are constructed with concrete, brick, or blocks, whereas only 8.5% of homes have adobe or mud walls [15]. Figure 1 shows the percentages obtained over the past two decades.

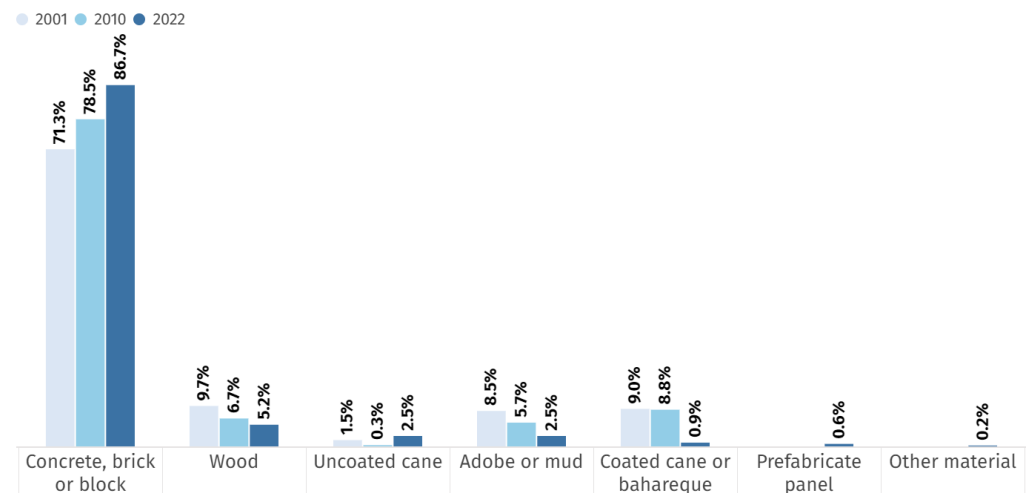


Figure 1. Percentage of houses according to the predominant exterior wall material [15].

The census data were also categorized by rural and urban areas, as depicted in Figure 2, which illustrates that the use of adobe is predominant in rural areas.

Records dating between 1450 and 1534 [16] show the use of adobe as a construction material on walls during the Inca conquest. This mixture consisted of vegetable fibers with clay and sand, which enhanced the cohesion and resistance of the construction.

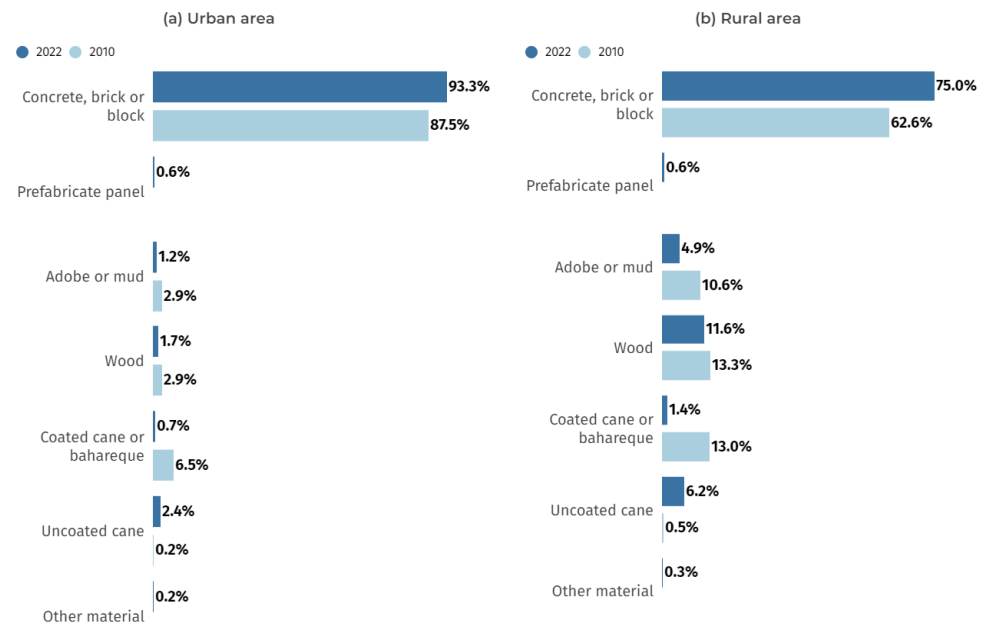
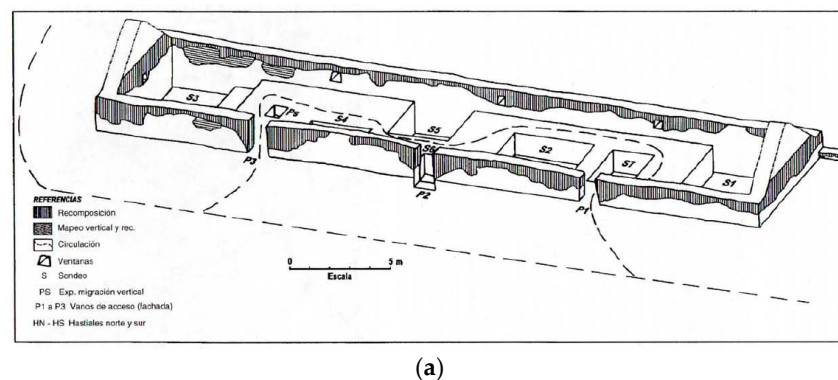


Figure 2. Percentage of houses according to the predominant exterior wall material [15], (a) urban area; (b) rural area.

At the end of the 19th century, buildings and structures whose masonry was composed of adobe blocks had already existed in Ecuador, particularly in the Andean region of the country. These structures were mostly religious buildings, such as churches, monasteries, and convents [17], which resulted from Spanish conquest. Some researchers have suggested that the use of adobe predates the Inca conquest [18].

However, during the Spanish conquest of America, adobe was no longer the predominant material. Spanish missionaries taught indigenous people how to make molds and import ovens to produce adobe bricks, thus allowing for the creation of blocks with greater resistance and a standardized size. This enabled the design and adaptation of more comfortable spaces.

Furthermore, the Inca structures underwent not only adaptation and redesign but also transformation. An example of this is described by Peñaherrera [16], who asserted that the Catholic temple of La Merced in Quito was the result of modifying a pre-Columbian temple. The hypothesis posits that the main facade and the base that supports the tower were once the walls of the Inca temple were situated on this site, as shown in Figure 3.



(a)

Figure 3. Cont.



(b)



(c)

Figure 3. Convent of La Merced Quito over the years. (a) The proposed Inca structure, hypothesized to be the foundation upon which a Catholic convent was subsequently erected [19]; (b) Convent of La Merced—Quito, 1910–1920 (Photography by Instituto Nacional de Patrimonio Cultural); and (c) Convent of La Merced—Quito [20].

Over the years, historians have proposed that some Inca buildings, whose thick walls were made of adobe, served as the foundation for new structures proposed during the conquest era, thus providing adobe with a patrimonial feature as construction material.

Larger buildings have begun to use rocks from the slopes of Pichincha as foundations and bases for walls, which were constructed using earth construction techniques. However, mixtures of sand with lime and gypsum began to be used as coatings for these masonry works, which subsequently allowed for the replacement of earth techniques, over all the adobe, with cement techniques. Nonetheless, public and residential buildings have endured to the present day.

As Ecuador is situated on the Pacific Ring of Fire, seismic forces have weakened its structure, resulting in the modification of several churches, monasteries, convents, and

residential buildings to enhance safety [21]. However, adobe masonry remains a part of the structure of these buildings, which are primarily located in the historic center of Quito.

Despite the passage of time, laws such as the Organic Cultural Law have ensured preservation and maintenance of adobe structures. The Instituto Nacional de Patrimonio Cultural maintains an inventory of more than 23,000 heritage structures, each incorporating various construction techniques [22]. Quito, declared a World Heritage Site by UNESCO on 8 September 1978, is the city with the highest historical value in the country. Figure 4 shows the number of heritage buildings classified as residential, commercial, or educational buildings.

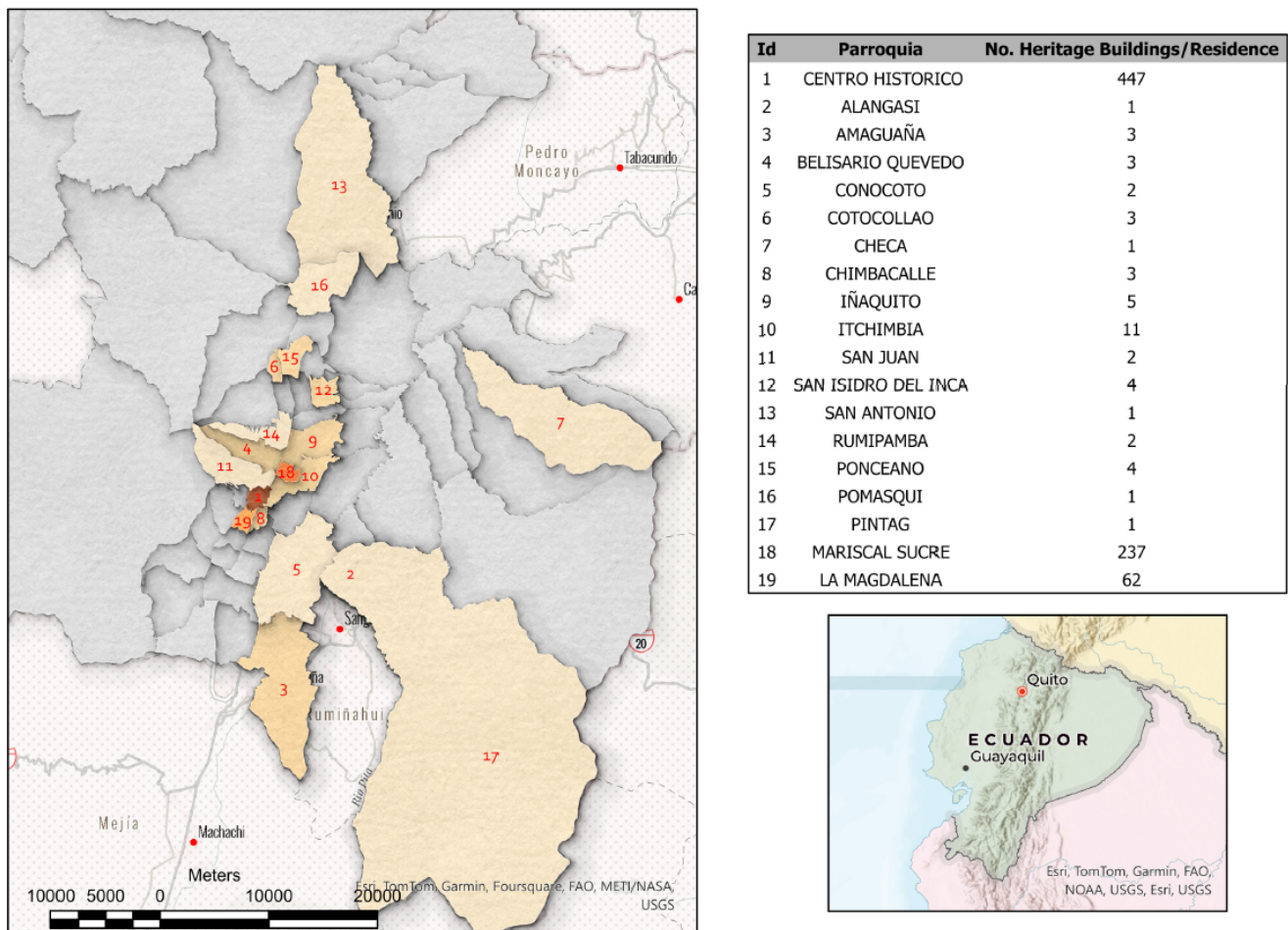


Figure 4. Number of heritage buildings and residences in Quito, Ecuador (Database of Instituto Nacional de Patrimonio Cultural; Graphs by Authors).

The diagram indicates that the majority of the city's historic structures are situated in Quito's old town, with many of these buildings featuring adobe masonry that have conserved techniques and materials since the 18th century. One of these structures is Hotel San Francisco, situated on the streets of Guayaquil and Sucre in the city's central district. Currently, these types of buildings are subject to ongoing maintenance owing to their commercial operation. Hotel San Francisco dates back to the early 18th century, approximately 1704 [22].

The property features traditional construction techniques, with stone foundation walls, adobe and brick load-bearing walls, a stone floor in its courtyard, surrounded by stone columns with a base and simple capital, and wooden columns and floors in the upper story. Modified areas have been constructed using modern building techniques involving the use of metal structures for structural reinforcement [22].

Adobe has been the preferred material for constructing load-bearing walls and masonry walls since the Incan era, and its manufacturing technique gained greater importance and refinement from the 18th century onwards. The fact that structures made of adobe have endured until the present day and are used for residential, commercial, or educational purposes indicates the material's excellent durability over time.

However, new construction techniques that use cement as the main raw material and its ease of industrialization have allowed it to become the primary material for buildings in Ecuador since the mid-19th century, displacing adobe and thus erasing the history of a nation.

2.3. *Adobe as Construction Material*

2.3.1. Raw Materials

Adobe is a traditional building material consisting of a mixture of clay, sand, water, and organic materials, such as straw or grass [23]. These materials are locally available, abundant, and typically do not require extensive extraction. Consequently, the impact of raw material extraction on the environment is minimal.

In Latin America, adobe bricks are commonly fabricated using 15% clay, 32% silt, 30% sand, and 23% gravel, and organic materials, such as straw/sawdust, are added to enhance the mechanical properties [24].

According to Cocco et al. [5], the hot climate and clayey soil in Argentina have contributed to the development of adobe blocks containing a substantial amount of sand and straw. The production of adobe blocks in the country is characterized by a composition of 60% sand, 27% silt, and 11% clay, along with a noteworthy quantity of straw.

In contrast, blocks in Bolivia are characterized by a composition comprising 20% sand and silt, 60% clay, and a small proportion of straw. The frigid climate and sandier soil present in the country obviate the need for such measures [5].

Research conducted in Peru has revealed that certain structures constructed with adobe bricks in several urban areas exhibit a composition of adobe comprising roughly 30–40% coarse soil and 60–70% fine soil. The soil in question was classified as clay with low plasticity (CL) in accordance with ASTM D-2487 [25]. However, two of the seven samples had clay contents below 10–20%, which is the lower boundary recommended for adobe blocks in the literature [25].

A separate investigation carried out within a structure situated in the Historic Center of Quito, Ecuador, revealed that the composition of the soil consisted of 3.4% gravel, 28.6% sandy, and 67.6% fine silt clay particles. Subsequently, according to ASTM D-2487 standards, the soil was categorized as CL-ML [26]. Several scholars concur with the findings of Álvarez et al. [13], who indicated that the ideal soil composition for adobe production ranges from 55% to 75% sand, 10% to 28% silt, and 15% to 18% clay.

The Peruvian Ministry of Housing, Construction, and Sanitation has laid out precise guidelines for clay soil composition. According to their specifications, when dealing with clay soil, the inclusion of straw or sawdust is imperative as the primary material. Moreover, it is crucial to note that the proportion of water employed in the molding of adobe units should not exceed 20% of the dry material weight [27]. Investigations detailed that adobe could possess different densities, as these values were obtained from structures located in different parts of the world, as shown in Table 1.

Table 1. Dry density (γ_d) of adobe at different locations.

Autor [Source]	Research (Year of Publication)	Dry Density (γ_d , g/cm ³)	Location	SUCS Classify
Escalante et al. [26]	The Physical and Mechanical Characterization of Accelerated Aging Adobe in the Historic Center of Quito (2022)	1.559	Quito, Ecuador	ML
Sadeghi et al. [28]	Experimental characterization of adobe vaults strengthened with a TRM-based compatible composite (2021)	1.460	Yazd, Iran	---
Saroza et al. [29]	Undertaking a study on the simple compression resistance of Adobe constructed with soils sourced from Crescencio Valdés, Villa Clara, Cuba. (2008)	1.775	Villa Clara, Cuba	CL
Torrealva et al. [25]	Seismic retrofitting project: testing of materials and building components of historic adobe buildings in Peru (2018)	2.650	Lima, Perú	CL
Giaireton et al. [30]	Material characterisation of heavy-weight and lightweight adobe brick walls and in-plane strengthening techniques (2021)	1.400–1.600	Nelson, New Zealand	---

2.3.2. Manufacturing and Installation Process

Upon presentation of the materials utilized in the production of adobe, it is essential to delineate the manufacturing process, identify the workforce responsible for its creation, assess productivity, and calculate the associated costs.

This procedure represents the most rudimentary method that involves the utilization of solar energy to dry objects; however, it is necessary to clarify that the extraction of materials is considered heavy equipment to improve performance, and these costs will be considered in the energy expenses. A mixture of clay, sand, water, and organic materials such as straw or animal dung. This traditional building material has been used for centuries to construct homes and structures in the area [31]. The use of adobe offers insulation properties, helping to keep the interior cool in hot climates and warm during colder seasons. Additionally, adobe structures have proven durable and resistant to natural disasters, making them suitable for the geographical conditions of this region.

The methodology involves the formation of clay, followed by a drying process that is executed in sunlight. The soil was thoroughly mixed within a hole in the ground using an appropriate quantity of water to facilitate stirring with a shovel [32].

The molds were arranged in a thin layer of sand on the ground. Before employing them, they were moistened to prevent clay from adhering to their walls, making them difficult to remove [33]. Following the filling of the mold with the moist mixture, a pressure of approximately 40 tons was exerted through hydraulic presses, resulting in a considerable enhancement of the resistance of the product. The enduring nature of an adobe or its lifespan is estimated to be approximately 200 years [34].

There is no requirement to smoothen the surface of the bricks or corners. Any deficiencies can be rectified by incorporating a small amount of additional earth materials [24]. Following the completion of the process, it is imperative to expose the pieces to sunlight for a minimum of three days to dry them adequately.

After this period has been observed, the pieces were removed from the molds and allowed to dry for an additional 72 h for two weeks [24]. The duration of time available for the bricks to settle typically spans between four and six weeks, and this period is contingent upon the climate conditions of the location in question, as well as the caliber of the adobe required for the construction that will utilize the bricks [33].

The construction procedures that will be considered are outlined in the construction standards Norma E.08 Design and Construction with Reinforced Earth [27] and Ecuadorian

Construction Standard—two-story residential buildings and 5 m high stories [35]. To install the adobe masonry, the site must first be prepared, which involves cleaning the area, leveling the soil, and ensuring that it is free of debris and unwanted vegetation. The necessary materials include adobe bricks and adobe mixtures, which typically consist of clay, sand, and water and should have a consistency similar to that of adobe [33,36].

Once the adobe bricks and mortar are ready, the process of laying the bricks begins, with a thin layer of mortar applied between each brick to ensure their union. It is important to ensure that the joints between the bricks are adequately sealed. The bricks should be leveled and plumbed, meaning that they are perfectly vertical and horizontal.

Finally, the adobe masonry must be allowed to dry and cure properly. This may take several weeks or even months, depending on weather conditions. All the processes are summarized in Figure 5.

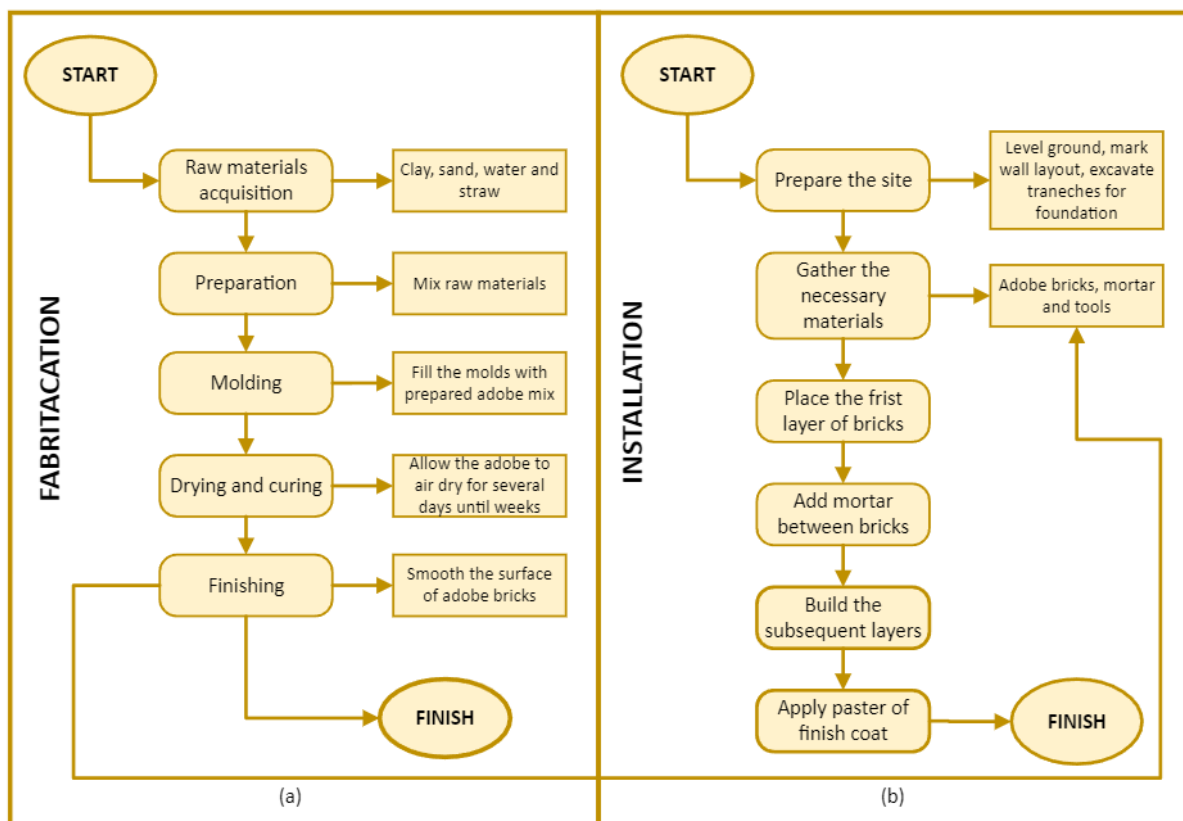


Figure 5. Process flow of adobe (a) manufacturing and (b) installation (graphs by authors).

Infrastructure constructed with adobe possesses superior resistance to temperature fluctuations compared to traditional prefabricated concrete structures. However, their limited resistance to flooding precludes their use in coastal areas [37]. It is only necessary to analyze the structures found in the historic centers of Quito, Cuenca, Cartagena de Indias, and Lima. These structures date back to the Spanish conquest of the American empire to verify the durability of this material over time [26].

It is crucial to recognize that the infrastructure designed for residential purposes earlier was constructed by artisans who did not possess formal academic qualifications but relied on their own knowledge and experience, as well as advice from fellow practitioners in the field [38].

Vargas et al. [39] proposed that, while maintaining adobe masonry presents the issue of humidity that can be generated in the lower floors, particularly during heavy rainfall, one potential solution is to cover or plaster adobe walls. However, to maintain the low cost

of installation, the authors suggest that plastering should be performed using the same mortar used to join the adobe blocks.

The lack of maintenance of structures coupled with the use of new construction techniques involving concrete has resulted in the loss of traditional construction techniques using adobe. Consequently, there is a lack of infrastructure maintenance using materials compatible with the original materials [40].

Vallejo et al. [40] conducted a study in a rural parish located in Pintag, Quito, Ecuador and found that the deterioration of the residence was due to lack of maintenance. Among the issues found, it was discovered that 55% of the deterioration of housing was due to a lack of maintenance and 25% was due to the natural aging of materials. Therefore, 80% of the causes of deterioration could have been prevented with constant maintenance.

As previously mentioned, there are over 23,000 heritage structures in Ecuador, many of which are constructed with adobe walls and/or masonry. However, after more than 300 years, they have required structural modifications and reinforcements following the seismic events of the last century. One example is presented by Chacon et al. [41], who conducted work on the former Simón Bolívar College located in the historic center of Quito owing to structural problems. The space was vacated in 2013 and student activities were relocated to another site.

The analysis employed a moulded element that considers the ratio between the dimensions of the finite elements and the main lengths of the wall element. It is assumed that external forces act in the direction of the most resistant plane of the wall and that the adobe walls have little capacity to resist lateral loads outside the plane. According to the study, 90% of the walls were subjected to a load that exceeded the cutting capacity of the adobe, which was concluded as a failure and partial collapse of the elements.

The reinforcement proposals are as follows: (i) a wall header beam located at the top of the walls, (ii) injections of mud paste with liquid clay or silica, and (iii) intervention with complete low-density concrete coatings with an electrically welded mesh. However, this study does not show an analysis of the cost and environmental impact of these.

One of the primary causes of deterioration in structures could be lack of maintenance; however, changes in both live and dead loads have also contributed to this deterioration in the same way. Nevertheless, adobe structures have endured for over 300 years, demonstrating their resilience and sustainability; however, like other materials, they require continuous maintenance to maintain their integrity.

3. Methodology

Korentz et al. [42] affirmed that the building construction process could be divided into three distinct stages: investment, service, and demolition. By conducting Life Cycle Cost Analysis (LCCA), it is possible to evaluate the costs associated with each period. The literature and local adobe makers provided the input and output data for this investigation.

3.1. Analysis Factors

Several factors must be considered when conducting an LCCA for adobe construction, which will be analyzed in the following steps shown in Figure 6.



Figure 6. LCCA steps for analyzing (graphs by authors).

3.2. Considerations for Analysis

Conducting an LCCA specifically for adobe as a construction material may present some challenges because adobe buildings vary in design, location, and maintenance practices. Therefore, this study considered the techniques, materials, and modifications applied in South America [6] in countries such as Ecuador, Perú, Colombia, Bolivia Uruguay, and Chile to analyze LCCA.

For analytical purposes, we gathered comprehensive information on material characteristics and properties. These data were sourced from the esteemed Laboratory of Materials Resistance, Soil Mechanics, Pavements and Geotechnics, Pontificia Universidad Católica del Ecuador. Additionally, to provide accurate cost details, we relied on information curated by Cámara de la Industria de la Construcción from Ecuador and Empresa Pública Metropolitana de Movilidad y Obras Públicas from Quito, Ecuador.

3.3. Functional Unit (FU)

For this analysis, we assessed the functional unit as an adobe brick measuring $10 \times 20 \times 40$ cm or 8000 cm^3 . The selection of this functional unit was based on the results of a literature review, which suggested that it was frequently used for the comparison of various building materials to guarantee that all inputs and outputs from adobe manufacturing were related.

Furthermore, it is worth noting that in South America, conventional masonry constructions predominantly employ adobe and concrete bricks measuring $10 \times 20 \times 40$ cm [5]. This allowed for a detailed cost comparison between the utilization of adobe and concrete bricks.

To conduct an operational, repair, and maintenance analysis, a one-square-meter masonry wall was scrutinized and compared to the projects and works carried out in the study area. Although the advantages of waste and debris reuse will be considered, the

costs associated with disposal will not be considered, as the system for removing materials from floors is the same for brick and concrete blocks.

4. Data Analysis

4.1. Initial Cost

This section includes the price per unit ($10 \times 20 \times 40$ cm or 8000 cm^3) of adobe construction material that requires the extraction of (i) raw materials and (ii) manufacturing.

4.1.1. Raw Materials

Based on the literature and considering that the adobe is fabricated in a cold climate, it can be concluded that the adobe for this region (in the dry mass of adobe) is composed of the following:

- 60% of fine soil, which is a mixture of clay and silt.
- 40% of sand.
- 1:5 organic material (such as straw or sawdust) by volume, which was incorporated into the overall composition [9,27].

In Table 2, the first column contains the materials to be used, followed by the mass percentages of fine soil and sand required for manufacturing. The third column was added because the adobe manufacturing standards Norma E.08 Design and Construction with Reinforced Earth [27] and NORMA CHILENA NCh3332 Structural design—Retrofitting of historic earth buildings—Requirements for structural design planning indicate [43] that the amount of water and vegetal fibers should be in volume.

Table 2. Quantities necessary to fabricate an adobe brick measuring $10 \times 20 \times 40$ cm.

Material	Percentage (%) by Mass	Percentage (%) by Volume	Mass Requires (g)
Fine (clay/silt)	60	----	7483.20
Fine sand	40	----	4988.80
Fibers (straw or sawdust)	----	20	0.2600
Water content	---	20	2994.40 ¹

¹ Considering the temperature of the water at 19°C (the prevailing water temperature in Quito, Ecuador), we obtained a density of 0.998 g/cm^3 .

The last column shows the results of the corresponding mass calculations. To obtain these masses, the dry density of the adobe was assumed to be 15.29 kN/m^3 (1.559 g/cm^3), which is the value obtained from a structure located in the Center Historic of Quito, as indicated in Table 1. To acquire the material costs, it is imperative to obtain the volume of each component. This can be achieved by utilizing the dry density of each material, which enables us to perform accurate calculations.

In our extensive analysis, we have allocated the corresponding values of 1.40 g/cm^3 and 1.70 g/cm^3 to represent the density of fine soil and fine sand, respectively. These values were derived from the data presented in Appendix A.

With these data and the defined dimensions, the masses in the bulk of each material were obtained.

We standardized the materials by mass to assess their cost based on volume, as shown in Table 3. The values for the quantity of materials are presented in the first column, whereas the third and fourth columns represent the percentages of waste and fluffing, respectively. These values were adjusted to reflect the results shown in the fifth column.

Table 3. Quantities and costs of the materials.

Material	Volume (cm ³)	% Waste	% Fluffing	Total Volume (cm ³)	Cost per Unit (\$/m ³) ¹	TOTAL
Fine soil	5345.14	0.50	25.00	6714.83	3.1400	0.0221
Fine sand	2934.59	0.50	25.00	3686.58	18.0100	0.0664
Straw/Sawdust	1600.00	1.00	10.00	1768.80	0.0143	2.53×10^{-5}
Water	2498.17	0.5	0.00	2510.66	0.6200	0.0016
					TOTAL (M)	0.0891

¹ The cost is affected by the mechanical assistance provided by machinery for the extraction of raw materials. The costs were included within the same price with an average distance of 5 km [44].

The cost of each materials was obtained from databases of Cámara de la Industria de la Construcción from Ecuador and Empresa Pública Metropolitana de Movilidad y Obras Públicas.

The price for extracting the material, including the utilization of heavy machinery for artisanal block production and shorter production times, was determined to be USD 0.0891 per adobe block.

4.1.2. Manufacturing

The fabrication of adobe blocks will be undertaken by a team of workers comprising (i) an expert in the manufacturing process and (ii) two assistants to support production. This group of workers will be utilized for both the manufacturing process and the installation of 1 m² of wall using adobe blocks.

The production of adobe bricks by a group of workers can yield between 13 and 16 units per hour. Nevertheless, the drying time hinders the accelerated production and overall efficiency of the group. Consequently, artisanal adobe producers generally prefer to receive orders for these materials based on demand [36].

In Ecuador, wages are paid on an hourly basis, equivalent to eight hours of work, and their rates are determined by the Ecuadorian General Controller's Office for both installation and manufacturing.

To evaluate the manufacturing performance of adobe blocks, data from numerous local production analyses conducted in Ecuador, particularly in Azuay province, have been utilized. It has been determined that the production of adobe blocks reaches 6.23 cubic meters per month, which corresponds to an output of 38.52 h per cubic meter. However, this assumption assumes that the demand for production is low and, therefore, may not be representative.

To produce a block with specified dimensions, a manufacturing performance of 0.0002 h per unit (adobe block) was achieved based on the literature and experience in the region. The costs were obtained from the Cámara de la Industria de la Construcción based on the yields of concrete blocks and bricks, both for installation and manufacturing.

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However, this assumption assumes that the demand for production is low and, therefore, may not be representative. To produce a block with specified dimensions, a manufacturing performance of 0.0002 h per unit (adobe block) was achieved based on the literature and experience in the region.

Table 4 presents the basic composition of the work team required for extraction, with the job classification code provided by the Ecuadorian General Controller's Office in the second column, which allows us to identify workers' wages. The third column indicates the number of workers needed, but it is important to note that the 0.1 and 0.5 provided for the labor inspector and expert in manufacturing correspond to the requirement of dedicating 10% and 50% of their time to the job, respectively.

Table 4. Cost of extraction and fabrication of raw materials in the Ecuadorian territory for manufacturing an adobe block.

Type of Worker	Ecuadorian Classify	Quantity A	Hourly Wage B	Cost per Hour C = A × B	Yield D	TOTAL E = C × D
Extraction						
Inspector of work	C1	0.10	4.55	0.4550	0.0009	0.0004
Heavy Machinery Operator	C1	1.00	4.33	4.3300	0.0009	0.0039
Expert in the extraction	D2	1.00	4.10	4.1000	0.0009	0.0037
Assistants	E2	1.00	4.05	4.0500	0.0009	0.0036
Fabrication						
Expert in the manufacturing process	D2	0.50	4.10	2.165	0.0002	0.0004
Assistants	E2	2.00	4.05	8.100	0.0002	0.0016
TOTAL (O)						0.0136

The fourth column shows the hourly wage established by Ecuadorian law for the year 2023, and the cost per unit is the product of the columns for quantity and hourly wages. The fifth column represents performance, which is an assumed value based on the country's experience and the analysis conducted in this section. Finally, the total cost is the product of the cost per hour, based on the yield.

The labor expenses associated with the procurement of materials amounted to USD 0.0136 per adobe block.

It is expected that 20% of the labor cost will be allocated to the procurement of necessary tools for the manufacturing process [45], such as picks, shovels, brooms, and other implements, at a rate of USD 0.004 per adobe block for the extraction process. The heavy machine can reach values almost double the labor force [45], and the value is assumed to be USD 0.0272. This amount is referred to as TOTAL (E) and takes the value to USD 0.0276.

Alvarado S. [7] undertook a comparative analysis of adobe production in three factories located within the province of Azuay, Ecuador. The energy consumption, comprising electricity and fuel, required for the extraction of materials, transportation of the raw material, and the production of the final product, was determined to be 52.54 kWh and 52.92 kWh for two and one of the factories analyzed, respectively.

With regards to energy expenditure, the average monthly energy consumption for a block adobe production plant is 52 kWh. This suggests that each individual block of the adobe consumed approximately 0.067 kWh. As of the current date in Ecuador, the electricity tariff was fixed at 0.0920 USD per kWh by Resolution No. ARCERNNR—009/2022 [46]. Consequently, the total energy cost for a single adobe block is 0.0061 USD (K).

Regarding administrative expenses associated with the manufacturing process, it is essential to consider factors such as the upkeep of the workspace, remuneration for administrative personnel, and other indirect expenses that contribute to the cost of an adobe block. Although these expenses are projected to account for up to 60% of the direct costs in some projects [32,47] within the construction sector in Ecuador, they can reach up to 20% of the direct costs [44,45], as shown in the fifth row of Table 5.

The expense associated with the creation of an adobe block measuring 10 × 20 × 40 cm amounts to USD 0.1637, which translates to 16 cents in United States currency. This price reflects the costs associated with the artisanal manufacturing and drying of the blocks as well as their extraction. The total costs and corresponding percentage of contribution for each section are listed, with the intention of discussing the results obtained, as shown in Table 5.

Table 5. Cost of fabrication of a brick of adobe ($10 \times 20 \times 40$ cm).

Description		Cost (USD)	Participation (%)
Raw materials	M	0.0891	54.5
Labor force	O	0.0136	8.3
Tools and machines	E	0.0276	16.8
Energy waste ¹	K	0.0061	3.7
DIRECT COST—DC (M + O + E + K)		0.1364	
Indirect cost	ID	0.0273	16.7
TOTAL (DC + ID)		0.1637	100

¹ Includes transportation at approximately 5 km.

4.2. Operational Cost

For operational expenses, the installation of one square meter of adobe will initially be considered, and thereafter, the cost of a $10 \times 20 \times 40$ cm adobe block will be determined.

To conduct this analysis, a customary procedure for constructing masonry walls in the area was considered. Furthermore, it has been assumed that the preceding tasks, such as foundation laying, establishment of columns and beams supporting masonry, and other preparatory work, have already been completed.

The construction process that will be considered is outlined in the construction norms Norma E.08 Design and Construction with Reinforced Earth [27], NORMA CHILENA NCh3332 Structural design—Retrofitting of historic earth buildings—Requirements for structural design planning [43], and Ecuadorian Construction Standard—Two-story residential buildings and 5-m-high stories [35]. The process specifies the appropriate stacking of adobe bricks and mortar filling of blocks with a thickness of $e = 2.00$ cm with a cement-sand ratio of 1:6, which will be considered for cost analysis.

In the cost analysis, expenditures were categorized into three distinct categories: materials to install (detailed in Table 6), labor, and equipment. This classification has been affected by productivity rates derived from the local construction experience and methodology employed in Ecuador. The mortar used in the analysis was the dosage recommended by Norma E.08 Design and Construction with Reinforced Earth [27] with a straw–soil ratio of 1:2.

Table 6. Costs of materials for installing 1 m square of adobe brick ($10 \times 20 \times 40$ cm).

Material	Unit	Quantity	Unit Cost	Total Cost
Fine soil	m ³	0.009	3.1400	0.0283
Fine sand	m ³	0.006	5.3600	0.0322
Straw	Saco	0.001	7.0000	0.0070
Water	m ³	0.008	0.6200	0.0050
Adobe brick	u	13.0000	0.1637	2.1281
			TOTAL (A)	2.2006

The values presented in the following table are those calculated for the preparation of mortar, whereas the cost of adobe brick corresponds to those obtained in the manufacturing cost section, and the total cost corresponds to the product of the quantity and unit cost.

The dynamic in Table 7 corresponds to the one presented in Table 4, but it involves another group of workers and performances that correspond to the installation.

With respect to the expense associated with the installation tools, it is hereby acknowledged that a cost equivalent to 5% of the labor expenses will be considered, as these tools primarily require basic carpentry equipment and therefore do not represent a significant financial burden. This value is equal to 0.3528 USD (C). For administrative expenses, the same allocation method used in the preceding section will be employed, whereby 20% of the direct costs will be assigned to indirect expenses. The total costs are listed in Table 8.

Table 7. Cost of labor for installing 1 m square of adobe brick (10 × 20 × 40 cm).

Type of Worker	Ecuadorian Classify	Quantity A	Hourly Wage B	Cost per Hour C = A × B	Hour per Unit D	TOTAL E = C × D
Inspector of work	C1	0.10	4.55	0.4550	0.8200	0.3731
Construction worker	D2	1.00	4.10	4.1000	0.8200	3.3620
Assistants	E2	1.00	4.05	4.0500	0.8200	3.3210
					TOTAL (B)	7.0561

Table 8. Total cost of installation 1 m square of adobe brick (40 × 20 × 10 cm).

Description	Cost (USD)	Participation (%)
Materials A	2.2006	19.0
Labor force B	7.0561	61.2
Tools and machines C	0.3528	3.1
DIRECT COST—DC (A+B+C)	9.6095	
Indirect cost ID	1.9219	16.7
TOTAL (DC + ID)	11.5314	100

4.3. Replacement/Repair Costs

For the analysis of the cost of adobe masonry, it has been considered that the plastering process will be recurrent at regular intervals and will depend on the climatic conditions of the area. Hence, only the cost of plastering that is required at least once a year has been presented.

The same dosage of plastering material was used for the mortar between the adobe blocks. However, the yields of lime putty are different, so the costs presented take this into account.

Tables 9 and 10 show the costs of materials and labor, respectively. The dynamic in Table 10 corresponds to that presented in Table 4, but it involves another group of workers and performances that correspond to the installation.

Table 9. Costs of plastering material of 1 m square of adobe brick (40 × 20 × 10 cm).

Material	Unit	Quantity	Unit Cost	Total Cost
Fine soil	m ³	0.009	3.1400	0.0283
Fine sand	m ³	0.006	5.3600	0.0322
Straw	Saco	0.001	7.0000	0.0070
Water	m ³	0.008	0.6200	0.0050
			TOTAL (D)	0.0725

Table 10. Cost of labor of plastering material.

Type of Worker	Ecuadorian Classify	Quantity A	Hourly Wage B	Cost per Hour C = A × B	Hour per Unit D	TOTAL E = C × D
Inspector of work	C1	0.10	4.55	0.4550	0.5200	0.2366
Construction worker	D2	1.00	4.10	4.1000	0.5200	2.1320
Assistants	E2	1.00	4.05	4.0500	0.5200	2.1060
					TOTAL (E)	4.4746

With respect to the expense associated with the installation tools, it is hereby acknowledged that a cost equivalent to 5% of the labor expenses will be considered, as these tools primarily require basic carpentry equipment and therefore do not represent a significant financial burden. This value is equal to 0.2237 USD (F). For administrative expenses, the

same allocation method used in the preceding section will be employed, whereby 20% of the direct costs will be assigned to indirect expenses. The total costs are listed in Table 11.

Table 11. Total cost of plastering 1 m square of adobe brick (40 × 20 × 10 cm).

Description		Cost (USD)	Participation (%)
Materials	D	0.0725	1.3
Labor force	E	4.4746	78.1
Tools and machines	F	0.2237	3.9
DIRECT COST—DC (D+E+F)		4.7708	
Indirect cost	ID	0.9542	16.7
TOTAL (DC + ID)		5.7250	100

4.4. Disposal Costs or Resale/Recovery Value

Appropriate disposal or recycling methods must be considered when an adobe structure reaches the end of its useful life. Although adobe is a natural material, its proper disposal may entail additional expenses. It is essential to consider any potential resale or recovery value when conducting a Life Cycle Cost Analysis (LCCA) if the adobe structure is sold or repurposed during its lifespan.

As a product of the soil, this material can be returned to the environment in a sustainable manner, either through authorized waste management facilities or by reusing the soil for nonstructural fill. However, the restoration and reconstruction of patrimonial interior spaces have demonstrated that these interventions can take various forms depending on the needs of the space and its intended purpose [48]. Nonetheless, there is always a possibility of restoration.

Nonetheless, the durability of adobe infrastructure does not necessarily result in significant waste. Rather, ongoing maintenance is required to prevent waste, as observed in long-standing construction throughout Latin America [49,50].

5. Results and Discussion

Analysis of the cost of adobe production, including its extraction, indicates the ease of manufacturing the material and its low cost. However, it is important to note that there is a significant disadvantage compared with concrete prefabricates. Currently, concrete prefabricates can be mass-produced, whereas adobe elements must be ordered, as they are not immediately available in the market. This implies that the non-industrialized process of adobe increases the final cost of the product, putting it at a disadvantage compared with concrete prefabricates. Therefore, in most situations, concrete prefabricates are preferred for masonry construction.

The labor force is a determinant factor in the increase in installation costs for an adobe. As has been observed, labor represents at least 60% of the total installation cost for adobe and 78% of the cost for adobe masonry repair. In contrast, in prefabricated concrete masonry, labor accounts for 59% of repair costs, which amounts to a difference of almost 20 percentage points.

This phenomenon is because adobe is considered a “traditional” material that was used during colonization in America. Over the years, there has been industrialization and advancement in construction techniques, which has led to concrete being the preferred material for builders. This preference has forced labor to specialize and acquire experience in techniques that involve the use of concrete, leaving aside traditional techniques.

The lack of use of adobe in construction has resulted in a lack of experience among the labor force in this type of construction. This means that to use adobe blocks, it is necessary to seek a specialist, which translates to higher costs and lower efficiency compared to techniques that involve the use of concrete.

The preservation of historical structures in several Latin American countries, including Ecuador, Peru, Colombia, Chile, and Bolivia, presents a significant financial challenge. This

can be ascribed to the high prices of raw materials, the scarcity of these materials, and the cost of specialized labor. Consequently, numerous structures remain in a state of disrepair or are demolished owing to safety concerns.

It is crucial to highlight that this situation has led to disregard for traditional construction methods and materials, which were the foundation and inspiration for modern materials. Despite research demonstrating the sustainability and environmental benefits of adobe, its use has been limited owing to industrialization and a preference for materials such as wood, metal, and concrete. The workforce's proficiency in handling these materials, particularly concrete, has contributed to their popularity.

The results obtained from the cost analysis are divided in the same manner as in the preceding section.

5.1. Initial Cost

The cost obtained was 0.16 USD, which was obtained from the analysis of the extraction of materials and the manufacturing of a $10 \times 20 \times 40$ cm adobe block. Each stage considered the necessary materials, which had an impact on the total cost of 54.4%. The necessary labor was also considered, which represents 8.3% of the total cost. Equipment and/or heavy machinery were also considered, accounting for 16.8% of the total cost. Similarly, indirect costs were considered, representing administrative and unexpected expenses, which constituted 16.7% of the total costs, as shown in Figure 7.

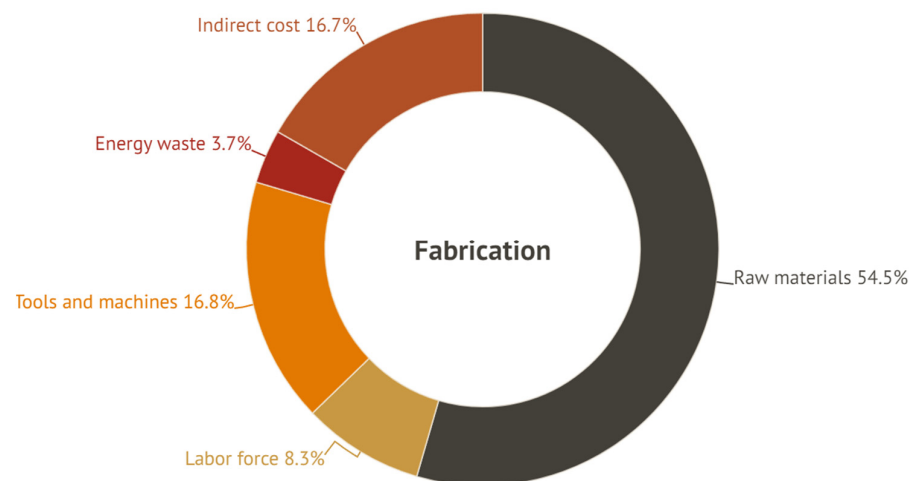


Figure 7. Percentages of incidence in fabrication of adobe bricks (graph by authors).

According to the Cámara de la Industria de la Construcción, the cost of a $40 \times 20 \times 10$ cm concrete block in Ecuador is expected to be 0.41 USD in December 2023, while the cost of a lightweight concrete block is 0.25 USD [45].

Meanwhile, the price of bricks in the market as of December 2023 is 0.45 USD [45]. It is necessary to mention that costs may vary between sectors because of the mass production of the product. Comparing the current prices in Ecuador, it can be observed that a block of adobe is significantly more affordable than a block of concrete and bricks and even more cost-effective than lightweight blocks that have less volume than a solid block, as shown in Figure 8.

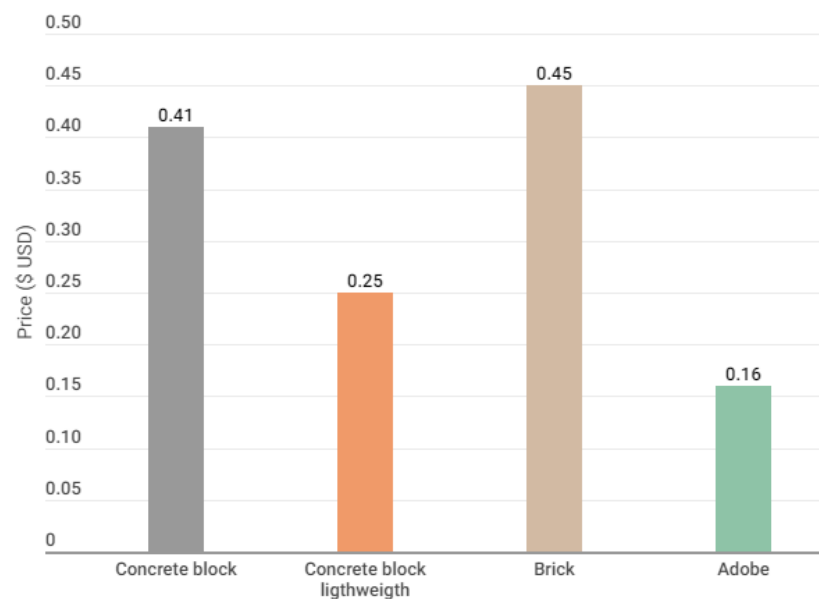


Figure 8. Comparing construction materials and prices, concrete block, concrete block lightweight and brick prices from *Cámara de la Industria de la Construcción* from Ecuador [45] (graph by authors).

As shown in Figure 9, the highest incidence occurred during the extraction and utilization of raw materials. This process is costlier than the manufacturing of prefabricated concrete because it necessitates extensive industrial production of cement, such as the use of industrialized bricks that employ cementitious composites in their production.

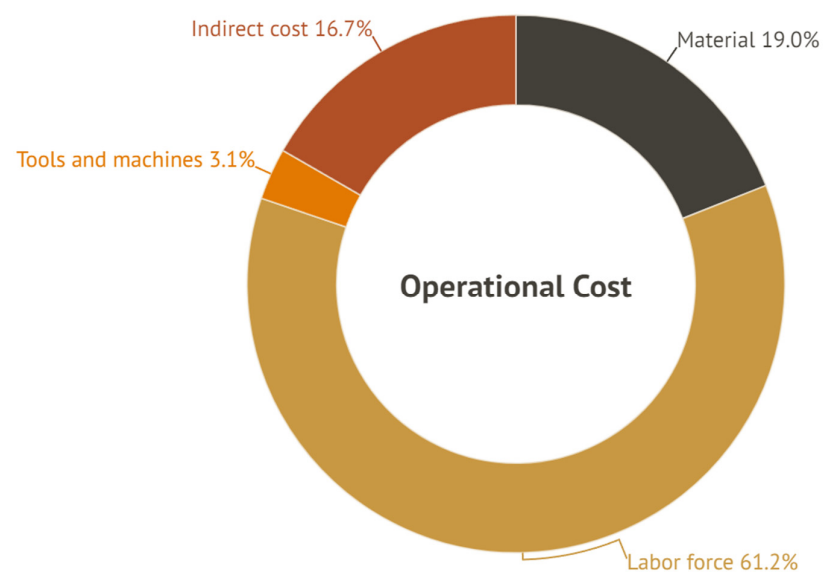


Figure 9. Percentages of incidence in operational cost of adobe bricks (graph by authors).

One drawback of the adobe block production process is the need to produce a large quantity of specimens, as it is a traditional, handcrafted material that has been eclipsed by the industrial production of concrete. Researchers such as Alvarado [7] and Barreto [36] have pointed out that adobe producers typically produce items on a per-order basis rather than keeping inventory.

5.2. Operational Cost

The total cost of installing 1 m² of adobe block masonry was approximately 11.53 USD, as can be observed in the attached chart (Figure 9). Labor has a significant impact on the total cost, accounting for 61.2% of the total cost compared to 19.1% for materials. This suggests that labor is the main factor that increases the cost of installing masonry because the performance will be the same for masonry composed of concrete blocks as for adobe blocks. Therefore, the result is higher because of the characteristics of the materials used for adobe block production and the mortar, which does not contain cementitious components.

The installation of a masonry wall in Ecuador using pressed concrete blocks measuring 40 × 20 × 10 cm is priced at 14.68 USD [44], with labor accounting for 34.7% of the cost. This significant difference is because although the installation process is similar, specialized labor does not possess the same level of expertise as prefabricated concrete, resulting in lower productivity levels.

5.3. Replacement/Repair Costs

Similarly, in the previous section, labor costs constituted 78.1%, as shown in Figure 10, with a total cost of 5725 USD. Labor is the most expensive aspect of the repair and maintenance process because the coating can be applied with the same material used to establish the adobe blocks. Similarly, the fact that materials derived from cement were not used makes the product more cost-effective, in addition to the ease of obtaining the material in large quantities.

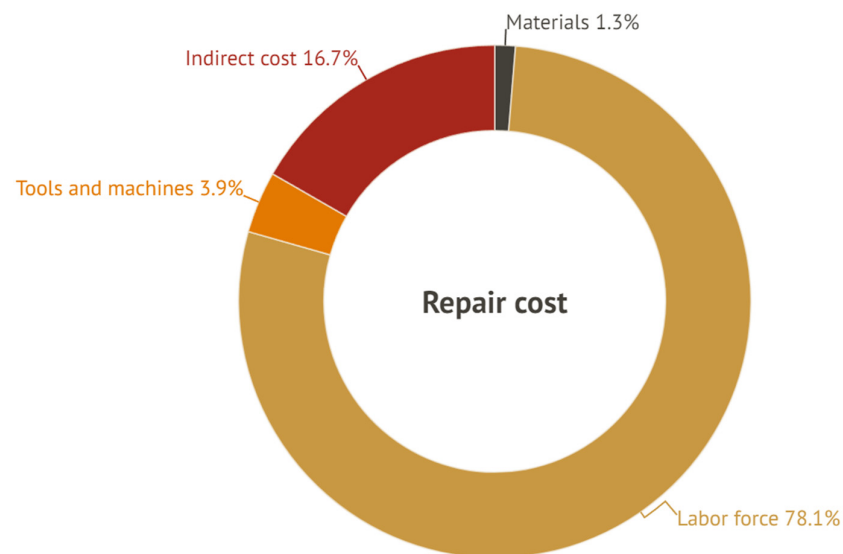


Figure 10. Percentages of incidence in repair costs of adobe bricks (graph by authors).

The installation of a masonry wall in Ecuador using pressed concrete blocks measuring 40 × 20 × 10 cm is priced at 11.17 USD [44], with labor accounting for 59.5% (Figure 11) of the cost. This difference is due to the fact that although the installation process is similar, the specialized labor does not possess the same level of expertise with adobe as they do with prefabricated concrete, resulting in lower productivity levels.

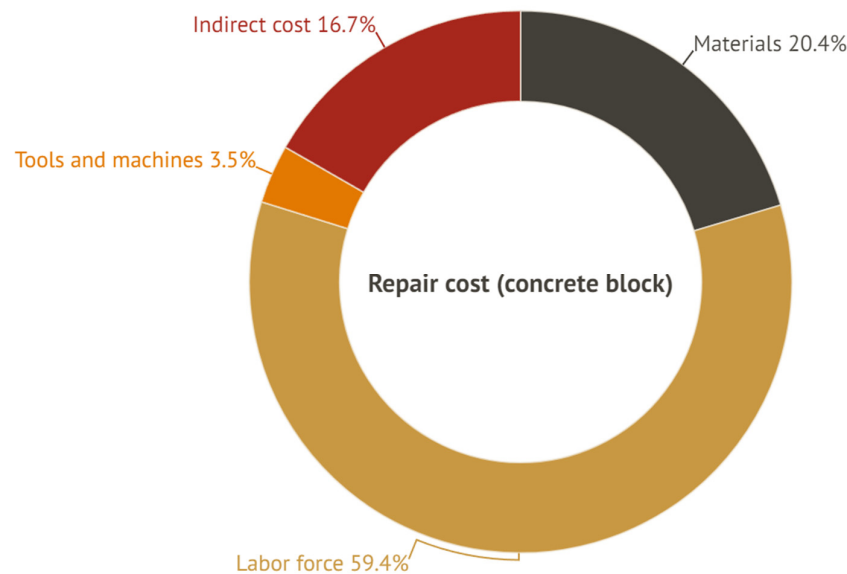


Figure 11. Percentage of incidence of repair cost of concrete blocks [45] (graph by author).

5.4. Disposal Costs or Resale/Recovery Value

In this section, traditional masonry methods are compared with the adobe block system in various aspects.

Adobe bricks are considered more environmentally friendly because they are made from natural and locally sourced materials. The production of adobe bricks consumes less energy than that of concrete blocks, which require cement production. Concrete production is a significant source of carbon emissions [51].

Robles et al. [49] confirmed that adobe bricks exhibited excellent thermal insulation properties owing to their composition. They can regulate temperature effectively, keeping the interior cooler in hot climates and warmer in cold climates. On the other hand, concrete blocks have lower insulation properties and may require additional insulation materials for thermal effectiveness.

Concrete blocks are stronger and more durable than adobe bricks [29]. Concrete has high compressive strength, making it suitable for load-bearing structures. However, adobe bricks may be more prone to weathering over time, particularly in wet climates, and proper maintenance can extend their lifespan [26].

Adobe bricks are generally weaker than concrete blocks. Although they can withstand normal loads and provide sufficient stability, they are more susceptible to water damage over time and may require maintenance. Concrete blocks are known to have superior strength and durability. They can withstand higher loads and fire, and are more resistant to water damage than adobe bricks [52].

6. Conclusions

In conclusion, the initial challenge that a decision maker must confront is the manual production of adobe bricks in most factories, which is associated with a lower efficiency than the industrialized process of prefabricating concrete. Furthermore, the decision maker must also consider that adobe bricks may not be readily available, necessitating the precise measurements of materials and careful consideration of waste. Adobe's cost is roughly 0.16 USD per adobe brick ($10 \times 20 \times 40$ cm), which presents a considerable advantage over the price of concrete blocks, which is around 0.41 USD.

One issue that can be identified is the shortage of experienced personnel in the workforce owing to the limited use of adobe in construction. Consequently, a decision maker who opts to use adobe bricks must consider hiring skilled professionals, which increases costs and reduces productivity compared to techniques that employ concrete.

Although research has shown the environmental and sustainability benefits of adobe, its use has been restricted owing to industrialization and preference for materials such as wood, metal, and concrete. However, a decision maker may choose to use adobe to preserve the architectural heritage of a structure, or if the challenges presented in this document have been evaluated considering the project conditions and it is determined to be more cost-effective than other materials.

In the future, there may be a shift in the choice of materials used in construction processes, particularly with a growing focus on environmental management involving concrete. However, concrete, wood, and metal remain the preferred options because of factors such as availability, durability, and strength.

Moreover, this analysis may offer valuable insights into suitable locations for construction and sources of material extraction, thereby minimizing environmental impacts, particularly in relation to energy consumption. It is essential to acknowledge that merely enhancing structural behavior is insufficient; interdisciplinary integration must also be considered. There is already significant interest in the environmental impact of the building sector.

It is recommended that future research efforts focus on multidisciplinary projects that aim to improve structural properties in the rural areas of developing countries to achieve cost-effectiveness and minimize environmental impact.

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Appendix A

These values were obtained from the Research and Testing Database of the esteemed Laboratory of Materials Resistance, Soil Mechanics, Pavements, and Geotechnics [53] at Pontificia Universidad Católica del Ecuador.

Table A1. Fine soil compacted densities in Ecuador.

Material	Extraction Site	γ_d compacted (g/cm ³)	SUCS Classify
Fine soil	Guamaní, Quito, Ecuador	1.396	CL
	Las Naves, Bolívar, Ecuador	1.536	ML
		1.692	MH
	El Ejido, Quito, Ecuador	1.724	CL
	Arajuno, Pastaza, Ecuador	2.022	CL
	Itchimbia, Quito, Ecuador	1.409	CL
	Nayón, Quito, Ecuador	1.597	ML
	Angamarca, Quito, Ecuador	1.277	CL-ML
	Macas, Ecuador	1.877–1.927	CL

Table A1. Cont.

Material	Extraction Site	γ_d compacted (g/cm ³)	SUCS Classify
Fine soil	El Bosque, Quito, Ecuador	1.476	ML
	Cumbayá, Quito, Ecuador	1.443	ML
	Puembo, Quito, Ecuador	1.485	ML
	Ferrovial, Quito, Ecuador	1.702	CL
	Santo Domingo, Ecuador	1.074	ML
	Quinindé, Esmeraldas, Ecuador	1.372	ML
	El Triunfo, Guayas, Ecuador	1.296	CL
	Morona Santiago, Ecuador	0.896	MH

Table A2. Fine sand compacted densities in Ecuador.

Material	Extraction Site	γ_d compacted (g/cm ³)	SUCS Classify
Fine Sand	Carcelén, Quito, Ecuador	1.453	SM
	Machachi, Pichincha, Ecuador	1.528	SM
	San Antonio, Pichincha, Ecuador	1.793	SP-SM
	La Floresta, Quito, Ecuador	1.807	SM
	Tulcán, Carchi, Ecuador	2.158	SM
	Machala, El Oro, Ecuador	1.862–2.083	SC
		1.636	SM
	Río Coca, Sucumbios, Ecuador	1.528	SM
		1.526	SW
	Imbabura, Ecuador	1.714	SM
	Pifo, Quito, Ecuador	2.077	SM
	Valle de los Chillos, Quito, Ecuador	1.790	SM

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