Green Energy and Technology

Jefferson Eloy Torres-Quezada *Editor*

Energetic Characterization of Building Evolution

A Multi-perspective Evaluation in the Andean Region of Ecuador

Springer

Green Energy and Technology

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Foreword

The world is facing a global warming crisis, euphemistically referred to as climate change. This extremely serious situation for the perpetuation of life on earth as we know it today is largely due to the problems created by the fossil fuel-based economic and energy model, which originated with the industrial revolution and intensified at the beginning of the twentieth century.

The implications of this model affect how we travel, produce things, air-condition our living spaces, and construct our buildings. The latter part is the one that has the largest hidden and discreet burden of energy consumption on the impact on the environment. Buildings represented 28% of global CO_2 emissions in 2016. This percentage is related to direct emissions, and the energy consumption of buildings. Nonetheless, an extra 11% was produced by indirect emissions, namely, those related to the construction processes and materials used.[1]

Energy-saving issues have been extensively developed from the architectural point of view, by implementing standards that require the establishment of minimum insulation parameters for envelopes and maximum consumption of facilities. Nevertheless, the ecological footprint of the materials we use to crystallize projects is not, for now, a priority issue. We must bear in mind that the life cycle of a material has an environmental impact in the extraction of the raw material, in its transformation, transport, application, and ultimately, in the waste management that it will entail when the building reaches the end of its days. Thus, both the material and the construction system are an issue of tremendous relevance when it comes to a comprehensive analysis of the sustainability of a building.

As of the industrial era and—later on—the dependence on oil, the concept of construction has clearly changed worldwide. This has led to changes in construction systems, new materials, and technologies aimed at reducing construction times and improving the developer's profitability indexes. Furthermore, after the Bruntland report in 1987, building and habitability require new construction conditions to reduce thermal discomfort in interior spaces. Once again, this has resulted in the inclusion of new, much more industrialized materials which, although they require more

[1] "Global Status Report 2017", developed by UN Environment.

energy for their production, seek to reduce the energy demand for air-conditioning. Therefore, the trend in the change of materials in recent decades has been to reduce the energy demand of buildings at the expense of increasing the energy spent in the construction systems employed.

These new materials with an energetic and industrialized approach have initially emerged in high latitudes such as Europe or North America, and applied, of course, to their own economic, environmental, and mainly climatic context. However, other countries have imported and adopted these construction typologies without considering the local context of each country, which may result in an energy expenditure on materials while not contributing to the reduction of the demand for air-conditioning.

This book aims to shed some light on the subject of materiality and its relationship with sustainability, focusing its discourse on Ecuador, mainly in the Andean region of this country. Based on this concept, a multipurpose discussion has been raised about the constructive changes that buildings in this region have undergone. *The Energy Characterization of the Evolution of Buildings. A Multi-perspective Evaluation in the Andean Region of Ecuador*, as we have named this work, gathers the implications of the change of materials in Ecuador and this region in the last decades, through an energetic-thermal look, and at the same time highlights the cause-effect phenomenon in the economic field, as well as the technical-sustainable learning that can be acquired from the constructive genuineness of past architectural structures.

Ultimately, this paper ambitions to characterize the constructive evolution of the building in this region, from an experimental-scientific approach and, at the same time, to establish more conceptual-theoretical viewpoints.

From the experimental point of view, the findings on the quality of the construction systems used in Ecuador show surprising results: we build in a more expensive, less sustainable, and less comfortable manner than it was done 100 years ago. In Andean architecture today, fashion, the reproduction of foreign models, or the pressures of international lobbies for construction materials predominate.

Conceptually speaking, a reflection on the fourth, fifth, and sixth dimensions of materials is proposed, regarding them as atmosphere generators, memory containers, and opportunities to establish transcendental connections with culture and the environment. The retrospective look at vernacular architecture reveals constructive dynamics with an intrinsic attachment to sustainability and is separated by an abyss from current constructions.

This book is meant to be a stimulus for the seasoned and sensitive reader who devours it, leading him or her to irremediably reassess what I build and how I do it, from a material as well as a morphological perspective. We hope from the editorial team that it will be a starting point for responsible and sustainable reflection on the materiality of the things around us, both for students, architects, engineers, and builders, as well as for public and private entities and the general public.

The processes to make a better world are small and may seem trivial, but mountains and deserts are crossed one step at a time. We firmly believe that a grain of sand is the foundation for immeasurable change.

Sevilla, España — Guillermo Casado-López
Cuenca, Ecuador — Jefferson Eloy Torres-Quezada

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About the Editor

Jefferson Eloy Torres-Quezada has a doctorate in architecture and graduated from the Polytechnic University of Catalonia (UPC), obtaining the Cum Laude mention and the international doctorate. He has collaborated as Assistant Professor of the Official MBArch Master Program of the UPC, and as a researcher of the AiEM group since 2015 in Barcelona. He is currently a teacher-researcher at the Catholic University of Cuenca. He registers several scientific articles (Q1–Q4) and participation in different international congresses as an exhibitor. He is the winner of the Extraordinary Prize of DOCTORAL THESIS of the UPC in 2019, and Principal Investigator of the Catholic University of Cuenca. In addition, he has made an international stay at Keio University in Tokyo-Japan, where he was part of the research laboratory of the School of Science and Technology. His research has focused on the energy efficiency of buildings, and sustainable urban and architectural design. As an architect he has participated in different projects of a public and private nature, acquiring experience both in the field of design and construction since 2010.

The Construction Evolution and Their Energectic Impact in Andean Region Buildings

Jefferson Eloy Torres-Quezada and Ana Torres-Avilés

Abstract The constant growth of the building sector has had a deleterious environmental impact across the world. Technological advances, the use of new materials and the replacement of traditional construction systems with industrialized ones have resulted in significant growth in the Total Embodied Energy of buildings in Latin American countries. In the last few decades, Ecuador and its four geographic regions too have experienced this change. In this context, this study focuses on analyzing the change in construction systems in the Andean region of Ecuador from 1980 to 2020, and studying the impact that this change has had on the Total Embodied Energy of residential buildings. The first part of this study provides a detailed conceptual framework of the subject of this study, and discusses the importance of energy, and its production and consumption, in Ecuador in the last decades. The second part analyses the changes in construction systems that this region has witnessed according to national censuses. This information is contrasted in the results section where 40 houses built in the period of analysis in the city of Cuenca-Ecuador are analysed. The growth of embodied energy in dwellings in this region in recent decades has been 2.15 times. Within this increase, the most significant component has been the Structure, followed by the Envelope and the Finishes. Finally, the results show that the changes in materials used have had consequences not only at the environmental level, but also for the thermal mass of the Envelope, which can affect the interior behavior of the building.

Keywords Embodied energy · Construction evolution · Structure-envelope-finishes

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1 An Energy Perspective in the Construction Sector

Climate change- one of the world's greatest concerns today- brings with it a number of repercussions that impact the planet and require immediate action [1]. This phenomenon is defined as the long-term shifts in temperatures and weather patterns, and has a direct relationship with the increase in greenhouse gases (GHG) emissions, specifically of carbon dioxide (CO_2). One of the factors that increases the emission of CO_2 is energy consumption [2]. The beginning of the increase of CO_2 levels on a global scale is recorded in the early nineteenth century, which coincides with the industrial revolution. In the twentieth century, CO_2 levels in the atmosphere grew exponentially with the initial acceleration at the beginning of the century concurring with the discovery of oil, and in the 1960s with the implementation of active air conditioning systems [3]. The current concentration of carbon dioxide present in the atmosphere is 400-410 ppm, which represents an increase of 48% since the beginning of the industrial era, when levels were around 280 ppm, and also represents an increase of 11% since 2000, when levels were at 370 ppm [4], see Fig. 1.

Sectors such as industry, transportation, agriculture, construction, residential, among others, contribute considerably to climate change, through energy consumption, pollution and waste generation [5]. One of the largest consumers of energy is the residential and construction sector. These sectors account for 25% to 50% of the total energy used [6, 7]. The construction of buildings has a significant impact on the environment, as the process of construction requires use of land and raw materials, and generates a large amount of waste. Construction has become the main user of non-renewable energy and consequently a significant contributor to GHG emissions.

Sustainable architecture arises as a response to the significant damage caused by the processes of construction. It proposes passive solutions and the use of environmentally friendly materials to achieve user comfort and reduce energy consumption and thus CO_2 emissions [8].

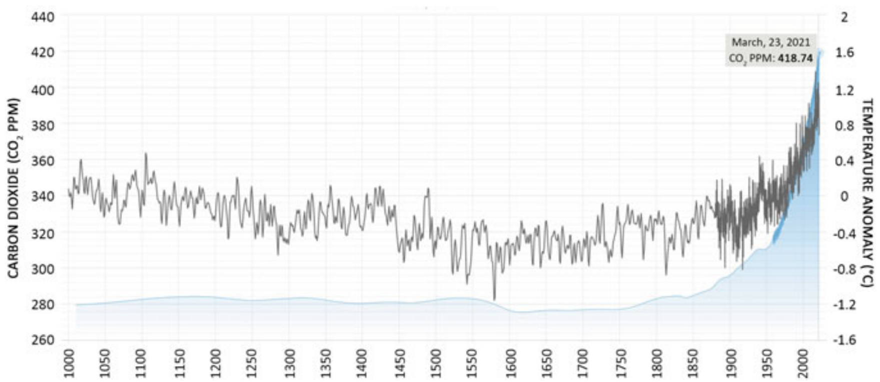


Fig. 1 Variation in the amount of CO2 emitted into the atmosphere. *Source* Own elaboration with data from https://www.co2levels.org/

1.1 Embodied Energy

Besides reducing water consumption and supporting alternative energy generation systems, the sustainability paradigm of the residential sector mainly focuses on reducing the life cycle energy (LCE) of all building. The total building LCE has two perspectives: the energy consumed in the operation stage and the energy consumed in the construction stage, known as Operational Energy (OE) and Embodied Energy (EE) [9].

OE refers specifically to the energy consumed in the dwelling in its use and maintenance. The energy consumption in this stage is due to heating, cooling, lighting and the use of everyday appliances [10, 11]. EE refers to the total energy spent to produce a material, including the energy from the processes of extraction, transportation, manufacture and other services. All of these processes use energy and generate waste- the associated burning of fossil fuels is the main cause of CO_2 generation [12, 13].

Most of the strategies worldwide have focused on the OE, principally on reducing the energy consumption of climatization active systems. With this, the use of insulating materials, double glazed windows, low emissivity glasses, and other innovative technologies have taken a leading role in building design [14]. Nevertheless, in an attempt to reduce the OE, the EE of building materials often tends to increase [15–17]. Furthermore, even though the EE may be equal to or greater than the OE consumed over many years, few strategies or regulations address this issue. Therefore, the scope of this chapter is the EE spent in the construction materials.

All materials go through a series of processes before obtaining their final form, first in the extraction of raw materials phase, then in the production, use and maintenance phases and finally in the abandonment phase. This is the most common process, but it is important to close these cycles, such that the apparent waste has the capacity to become a raw material again and thus start again another cycle without a specific end.

According to several authors, the sum of all direct and indirect energy involved in the processes of construction, maintenance, renovation, repair, and demolition of a building is referred to as the life cycle EE (LCEE) of the building [18, 19]. According to Thomas et al. [20], this energy can be classified into initial embodied energy (IEE), recurrent embodied energy (REE), and demolition energy (DE). The initial embodied energy corresponds to the total direct and indirect energy used during the construction of a building. Direct energy can be defined as the energy used in the processes of raw material extraction, on/off-site construction, manufacture, and transportation; and indirect energy is embedded in the building materials and products installed in the building. By contrast, REE is the energy used in maintenance, repair and renovation activities of the building. Finally, DE refers to the energy needed to demolish and dispose of the building [21]. Figure 2 shows different limits of the processes that a material undergoes throughout its life cycle, from the time it is extracted until it is discarded or recycled.

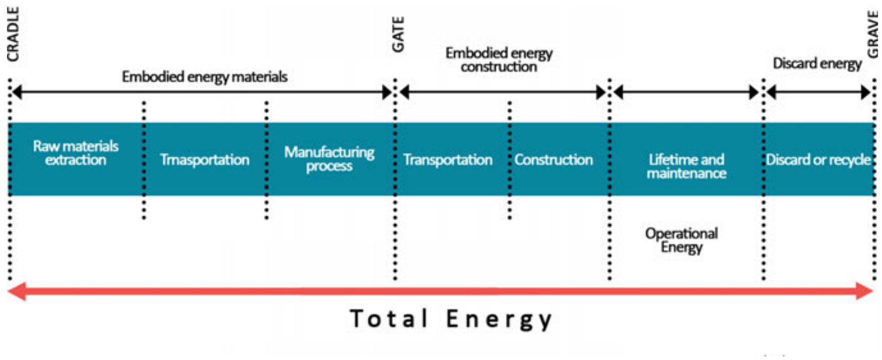


Fig. 2 Process limits in the life cycle of materials. *Source* Own elaboration

1.2 Boundary Conditions

The embodied energy values of any material will depend on the different stages involved. These stages are known as Boundary Conditions, and can be classified into: *Cradle to Gate*, *Cradle to Site* and *Cradle to Grave* [22–24]. These concepts are defined as follows:

Cradle-to-Gate: This concept refers to the energy consumed in the extraction and transportation of raw materials, and their production in the factory.

Cradle-to-site: This boundary condition includes all the energy from Cradle to Gate, plus the energy consumed by transportation until the material reaches the point of use or construction site. In materials with high density and high embodied energy, the difference in values between Cradle to Site and Cradle to Gate is negligible.

Cradle to Grave: This concept refers to the energy consumed from the extraction of the raw material to the end of the products' lifetime, which includes production, transportation, heating and lighting of the factory, maintenance, disposal of materials, etc.

Gate-to-gate: This boundary condition refers to the energy spent only in manufacture and production, and excludes the extraction and transportation. This concept is not usually used- however, some authors use it for specific materials [25].

1.3 Calculation Methods and Uncertainties

With reference to the calculation of EE values, several studies highlight three methods: (i) process-based, (ii) input–output (IO) based, and (iii) hybrid approaches [26, 27].

The first method is a bottom-up approach that collects energy use data from manufacturers and from construction sites, which includes all the direct and indirect energy flows of every upstream process [28, 29]. Since data for all upstream processes are usually not available, this approach excludes certain processes from its calculations-consequently, the results present a certain degree of uncertainty. This method can have some uncertainties related to the unavailability of data of the manufacturing process of materials [30]. The second method, the IO-based approach, applies a top-down approach, and uses macro-economic flows between various industry sectors in the form of an IO model. To calculate the EE value, the economic flows are converted into energy flows with the use of energy tariffs, price of products and energy intensity spent in the manufacture of the product [21]. This method may also suffer from some limitations due to the uncertainty of economic and price data. The third method is the hybrid approach, which improves the reliability and system boundary completeness of the EE calculations of both previous methods. The hybrid approach can be either a process-based hybrid or an IO-based hybrid. The main difference between the two arises due to the EE calculation framework adopted and the type of data used. The process-based hybrid integrates IO-data into the process- based framework, whereas the IO-based hybrid inserts process- data into the IO-model data [31].

Thus, all calculation methods face difficulties in obtaining EE values. Nevertheless, the three of them provide an accurate approximation in order to describe the impact of the construction sector on the environment. The process-based method will be used in the present work.

Furthermore, it is necessary to understand that the values obtained for EE from different research sources or governmental databases will always present certain discrepancies, due to the variations that may exist within the processes inherent to the production of each material. This will depend on the calculation method, the location, factory, type of fuel used, etc. [23]. One of the most important parameters is the temporal consideration, which can affect the quality of EE calculations [32]. This is related to the energy intensities of construction sector, manufacturing improvements, transportation and other sectors, which are constantly changing over time [33]. Moreover, according to results from other studies [22, 34–36], the influence of time on the dispersion of EE values is less than that of other factors such as the origin or content of recycled material. In the case of Ecuador, both the greatest manufacturing changes and the considerations of sustainability (such as the renovation of equipment or the use of alternative energy sources) have occurred in the last decade. Nevertheless, there is limited information on these changes to give an accurate approximation of the EE change [37]. Moreover, EE values are more accurate than the embodied carbon values, because the CO_2 emission indexes are usually estimated based on the types of fuels most commonly used at the place of origin, and are not specific values.

In addition to this, not all countries have a detailed database of these embodied energy and embodied carbon values [38, 39]. Such is the case for many South American countries including Ecuador. However, in this chapter, information on these values has been compiled from other sources and countries, which present production, extraction, and recycling level characteristics similar to those of Ecuador. These values, which are specified in later sections, will be used for the analysis of this study and may serve for future research.

To estimate an entire building's Embodied Energy, it is necessary to calculate the Total Embodied Energy (TEE) of every material used. Therefore, TEE depends on two factors: the specific Embodied Energy of every material (MJ/kg), and the total weight of the material (Kg)- see Eq. 1.

$$\text{TEE} = \text{EE} \times \text{W} \tag{1}$$

where TEE is the Total Embodied Energy of a material within the building (MJ), EE is the specific embodied energy of a material (MJ/kg), and W is the total weight of the material in the building (kg). The total weight of the material can be obtained from the total volume of the material in the building (m^3) multiplied by its specific weight (kg/m^3). According to Eq. 1, the representativeness of a building material's TEE depends not only on its specific embodied energy, but also on its total weight.

Based on the above, this chapter focus on the role of Embodied Energy in the construction sector of Ecuador, specifically in the Andean region. However, first of all, the importance of energy in this country, both its production and consumption, have been discussed in the next section.

2 Production and Consumption of Energy in Ecuador

This section provides an analysis of the current and historical production and consumption of energy in Ecuador.

According to the IPCC (Intergovernmental Panel on Climate Change) report, CO_2 emissions from buildings may reach 16 Gt by 2030, mainly as a result of increased energy consumption in developing countries [40]. In these countries, the main source of primary energy production comes from fossil fuels [41], as is also the case with Ecuador.

In Ecuador, in 2020, 90.6% of the total energy production came from non-renewable sources, namely oil and natural gas; and only 9.4% came from renewable energy sources such as hydro-energy, firewood, wind, photovoltaic, sugarcane bagasse and biogas [42] (see Fig. 3).

The dominance of oil and its derivatives in the energy supply structure has been present since 1972, when Ecuador became an exporter of crude oil from the Amazonian region. Prior to this, the country depended mainly on firewood (and sugar cane) for energy supply, see Fig. 4.

Energy production in 2020 reached 204 million BOE (Barrel of Oil Equivalent) or 343 thousand GWh; while in 2010 it was 198 million BOE (see Fig. 5). In addition, Fig. 5 shows that the energy consumption over this 10-year period was less than the energy production, making the country a net energy exporter. However, Ecuador also imports energy to meet sectoral needs. It is important to note that the reduction in energy production and demand in 2020 as compared to 2019 was due to the COVID-19 pandemic.

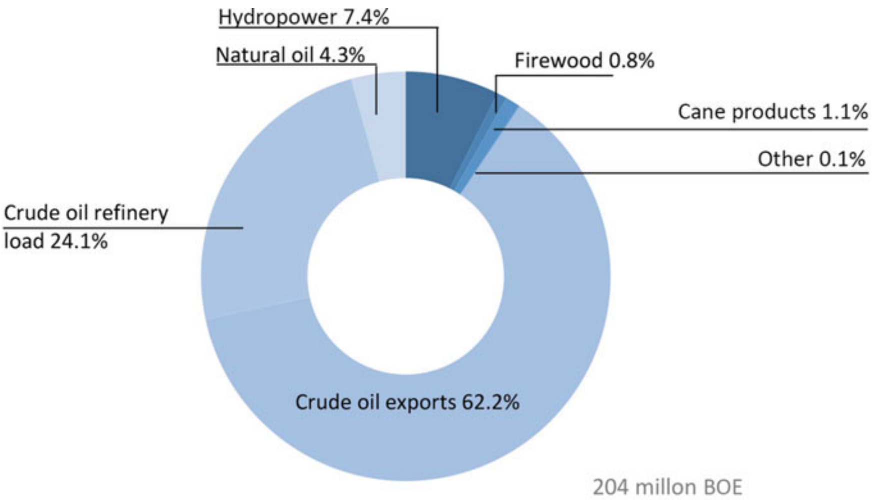


Fig. 3 Primary energy supply (%) in Ecuador in 2020 according to sources. *Source* Own elaboration with data from [42]

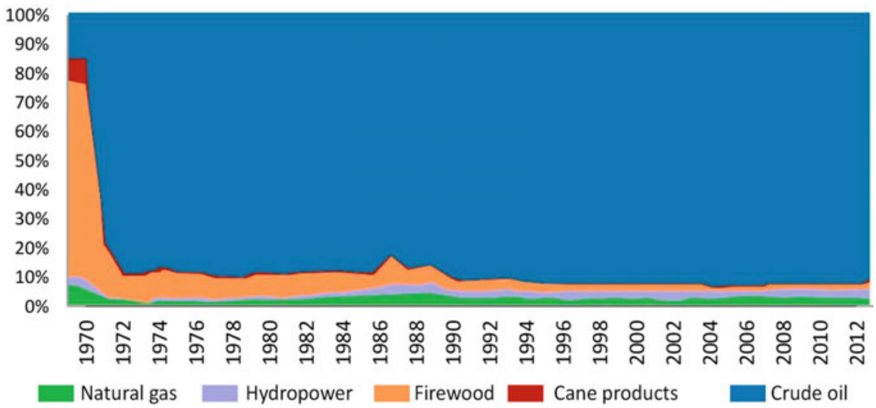


Fig. 4 Structure of the historical energy supply in Ecuador (1970–2012). *Source* Own elaboration with data from [43, 44]

When analysing historical energy production (Fig. 6), it can be observed that Ecuador in 1972 started with energy production of 10 million BOE, which rose in 1980 to 95 M BOE, in 1990 to 147 M BOE, in 2000 to 160 M BOE, in 2010 to 198 M and in 2020 to 204 M BOE. The results show that Ecuador's energy demand since 1972 has been lower than energy production, however, before that, when it was not yet dependent on oil, these two variables had almost equal values.

Although the historical analysis shows a general trend of growth in energy production, several turning points and different rates of growth can be identified. Thus, 1987

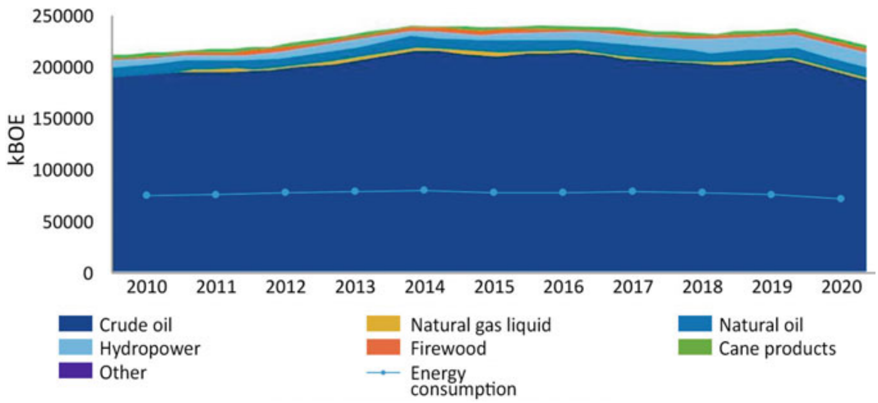


Fig. 5 Evolution of primary energy production from 2010–2020. Own elaboration with data from [42]

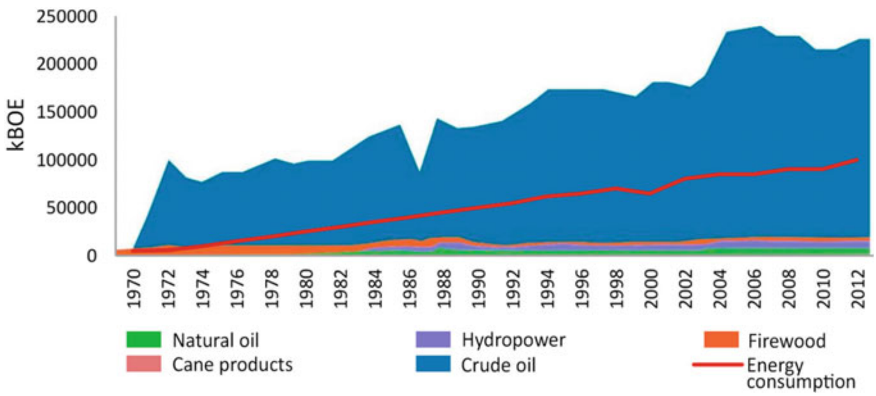


Fig. 6 Evolution of energy supply by source (1970–2012). *Source* Own elaboration with data from [43]

stands out as the year when energy production decreased considerably. After this, energy production maintained a slight growth curve until 2003, when it began to increase with a much steeper slope: production rose from 160 M BOE in 2003 to 210 M BOE in 2006, which meant a growth of 50 M BEP in only 3 years. This growth occurred within the period in which Ecuador began its dollarization, which affected both this sector and the construction sector.

With reference to Ecuador's energy consumption from 1970 till present (Fig. 7), the rise is mainly attributable to the use of transport, which has been increasing in the last decades. The other sectors principally responsible for the rise in energy consumption have been the residential sector and industry, the latter in particular with growth evident over the last few decades. Likewise, the residential sector has seen considerable growth, with consumption rising from 8.5 M BOE in 1970 to 13.5 M

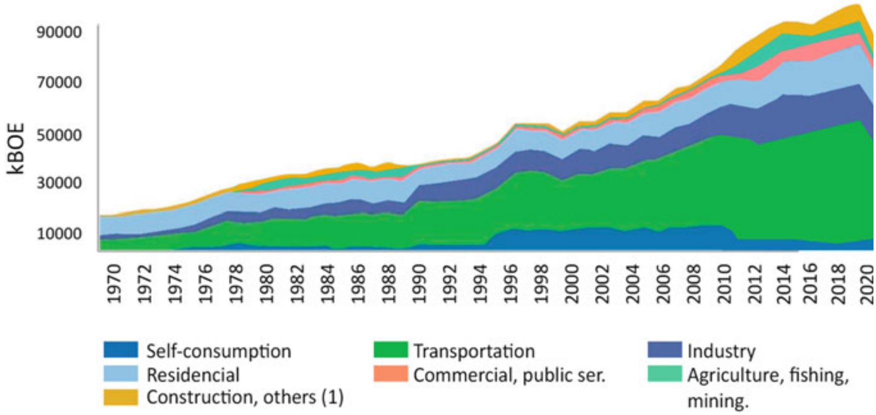


Fig. 7 Evolution of energy consumption by sector (1970–2020). *Source* Own elaboration with data from [42, 44]

BOE in 2010. The share of the construction sector in total energy consumption by contrast is minimal till the 1990s- however, after a sharp reduction in 1999, energy consumption by this sector starts to rise and gain relevance: the sector's consumption rises from 3.4 M BOE in 2010 to reach 7 M BOE in 2020 (these values refer to the construction sector + others). Again, when reviewing the general trend of energy consumption, different inflection points (where the slope of growth changes sharply) can be recognized throughout the period of analysis. For example, in 1976 and 1989, energy consumption experiences significant growth in most sectors, but especially in transport. However, some of the most important growth occurs after 1994, when growth increases considerably until 1996, when initially it levels off and then starts to decline, reaching a low in 1999. After this, the longest growth trend in the last 5 decades is observed in the transport, industry, residential and (as previously mentioned) the construction sectors.

As seen in Fig. 8, transport was responsible for the largest share (45.4%) of Ecuador's total energy consumption in 2020, while the residential sector represented 15.7% of total energy consumption.

Furthermore, it is important to understand the different sources of energy in Ecuador's supply mix. In general terms, Fig. 9 shows the evolution of energy consumption by different production sources. Despite the production of electricity having increased (from 0.8 M BOE in 1970 to 16.5 M in 2019), the energy demand in Ecuador depends mainly on petroleum derivatives. However, the reduction to 16 M BOE in 2020 was due to the health emergency caused by COVID-19. Electricity production has also shown several turning points, such as in 1990, and (one of the most important) in 2005, when production increased considerably.

The energy consumption by source in 2020 is shown in Fig. 10, where the largest source of energy production is Diesel with a share of 31.4%, while electricity has a share of 19.2%.

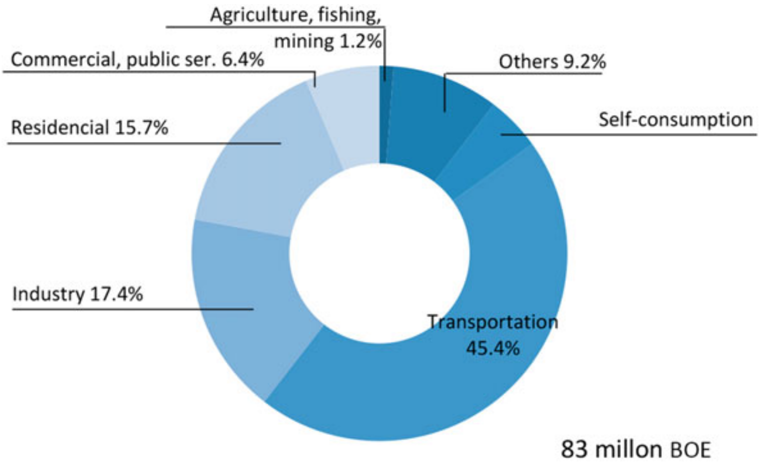


Fig. 8 Energy demand by sector in 2020. *Source* Own elaboration with data from [42]

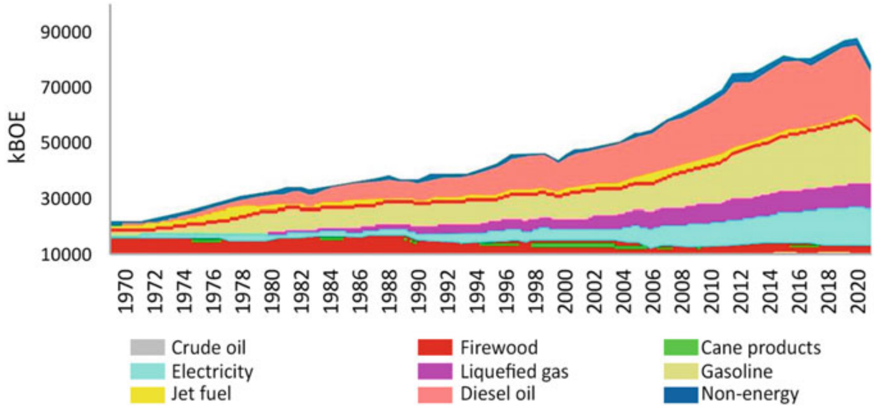


Fig. 9 Evolution of energy consumption by source (1970–2020). *Source* Own elaboration with data from [42, 43]

As shown in Fig. 11, Ecuador's electricity was produced in 2012 from two main sources: 53% from hydraulic generation and 45% from thermoelectricity (composed of turbo gas systems, internal combustion engines and turbo steam). The remaining 2% came from energy imports (1%) and renewable sources (1%) such as biomass, wind and photovoltaic, [44].

However, by 2020 (see Fig. 12), hydroelectric generation had the highest share (at 89.24%), while thermoelectric generation accounted for 8.36%. According to this comparison between 2012 and 2020, the country has moved to using more renewable energy sources, primarily hydroelectricity.

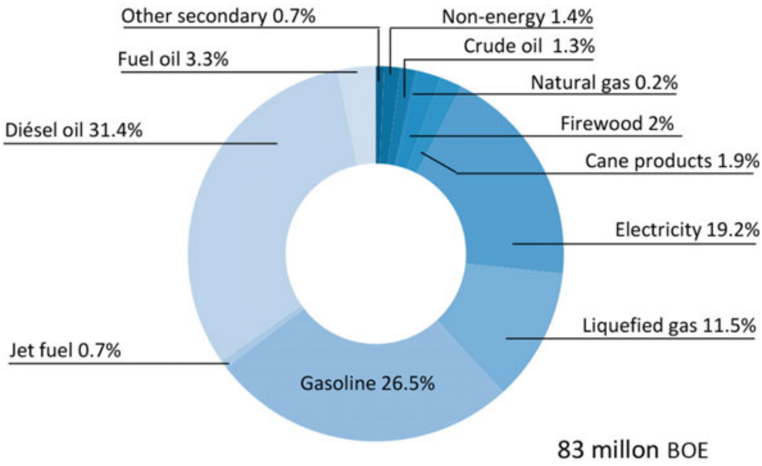


Fig. 10 Energy demand by source in 2020. *Source* Own elaboration with data from [42]

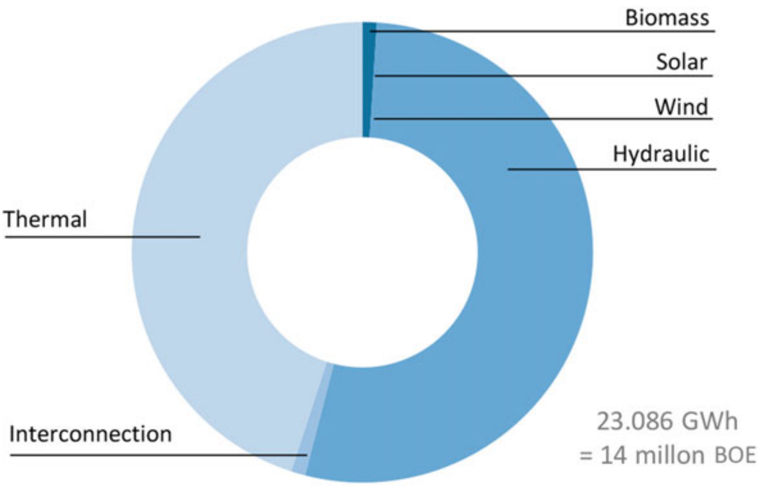


Fig. 11 Type of generation of electricity production_2012. *Source* Own elaboration with data from [44]

Electricity is used in different proportions by the country's various consumption sectors. In 2012 (Fig. 13a) industry was the main consumer of this energy (consuming 42% of total electricity); followed by the residential sector (consuming 29%). The commercial sector together with Public Services were responsible for 29%, and transport accounted for barely 0.001%. These values show a small variation in 2020 over 2012 levels (Fig. 13b), where industry (now at 39.9%) shows a small reduction, while the consumption by the residential sector grows slightly to 31.7%. According

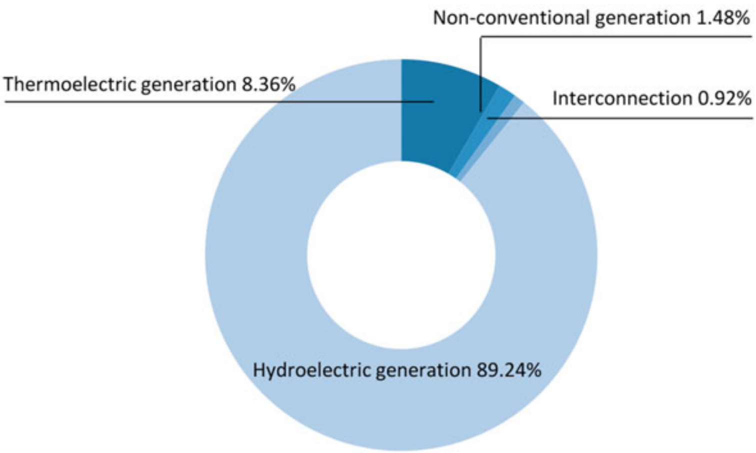


Fig. 12 Type of generation of electricity production_2020. *Source* Own elaboration with data from [42]

to this data, the sectors with the highest consumption of electricity generated in the country are industry and the residential sector.

Although a significant share of the electricity generated is consumed by the residential sector, electricity is not its principal energy source. According to the data obtained for 2020, the main source of energy for the residential sector was liquefied petroleum gas (LPG) (accounting for 51.8% of total energy used), which was mainly used to supply fuel for cooking [42]. It is important to emphasize that 86% of the LPG used by Ecuador is imported.

In addition, Fig. 14 shows that the transport sector in Ecuador has minimal consumption of electricity, since this sector depends mainly on petroleum derivatives

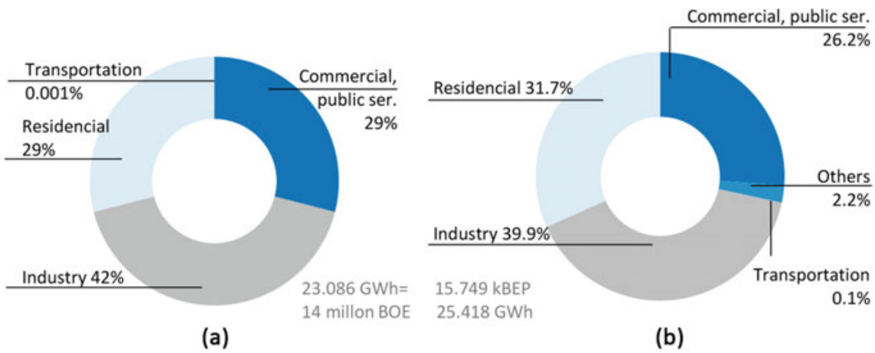


Fig. 13 Percentage of electricity consumption by sector **a** in 2012 and **b** 2020. *Source* Own elaboration with data from [42, 43]

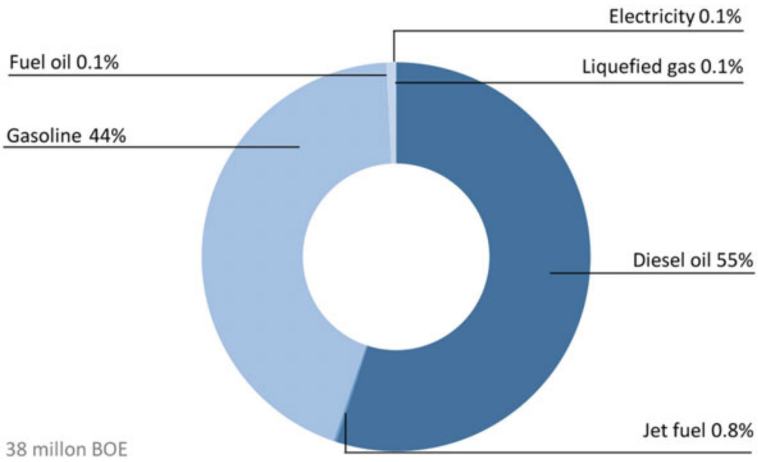


Fig. 14 Percentage of energy consumption by source in the transport sector in 2020. *Source* Own elaboration with data from [42]

such as gasoline and diesel, which were responsible for 55% and 44% respectively in 2020 [42].

The different sources of energy consumption in the transport sector are shown in Fig. 14. The dependence on fossil fuels has a great impact on the CO_2 emissions of this sector. According to this data, most of the energy comes from Diesel, which is mainly used for heavy transport [44]. As in the case of LPG, most of the Diesel used comes from imports (65%). Therefore, in addition to the fact that the energy consumed by the transportation sector has a high impact on the EE of the materials produced in Ecuador, it also has a high impact in economic terms, since the energy source that supplies this sector is primarily imported.

The same happens in industry, although to a lesser extent than in transport: in 2020, one of the main sources of energy in this sector were fossil fuels such as diesel, gasoline, fuel oil, jet fuel, LPG and others (Fig. 15). Diesel is an important energy source for industry, especially in the production of construction materials. Since most of these fossil fuels come from imports (Gasoline, Diesel and LPG), the industry's energy consumption has implications for both the overall economy and the EE of materials produced [42]. However, 43.5% of electricity is also used to supply the total energy consumption of this sector.

This section has highlighted the relevance of the Industry, Transport and Construction sectors in the consumption energy of Ecuador. The energy used in these sectors depends mainly on fossil fuels and it has high correlation with the building field. Therefore, the strategies oriented to reduce energy consumption of building materials, in any phase of their production (extraction, transportation, manufacturing, etc.), will be relevant to reducing the environmental impact. Furthermore, these strategies will probably result in an improvement of Ecuador's national economy by reducing import dependence.

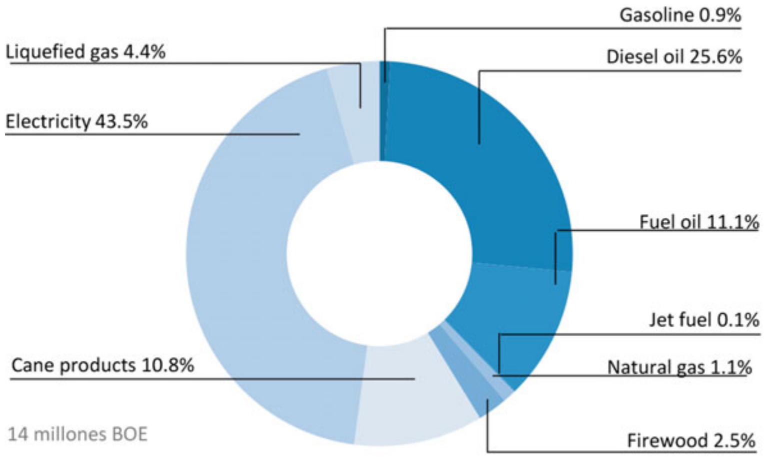


Fig. 15 Percentage of energy consumption by source in the industry sector in 2020. *Source* Own elaboration with data from [42]

3 Change of Building Systems at the National and Local Levels

Despite the significant impact of energy consumption by Ecuador's construction and residential sectors, the need for housing by people from all social and economic spheres has resulted in these sectors becoming fundamental to the country's economic growth. In addition, the construction sector is considered the largest employer in the world [45]. This sector represents around 10% of Ecuador's GDP (Gross Domestic Product), though the value has historically had variations. The largest decrease occurred in the years 2015–2016, coincident with the decline of the national economy [46]. Therefore, the growth of the construction sector in the country depends directly on the country's economy.

Historically, construction processes in the country have been based on the accessibility of different materials, and the requirements and demands of its users or builders. In the beginning, the construction processes and materials used depended on the regional distribution and availability of resources, culture and climatic conditions [47]. These construction and traditional knowledge systems, acquired empirically, lost value over the years. Generally speaking, use of reinforced concrete emerged as a new construction technique in the 1960s, and by the 1970s, steel began to be used, though in very low proportions. These modernization and industrialization processes occurred due to the birth of the oil era in Ecuador. Linked to this, the construction sector saw an increase in the import of new materials, which were used to address technical requirements in some cases and aesthetic whims in others.

In this section, the changes in materials used in Ecuadorian construction will be analysed both at the national level and in the inter-Andean region, specifically in the province of Azuay. For this analysis, statistical information from the National

Institute of Statistics and Census (INEC) has been used, in the form of the Annual Building Surveys (ENED) from 1980 to 2020.

In Ecuador, since 1966, important information on construction processes began to be collected. In the same year, the First Construction Census was carried out, based on the statistical information of construction permits issued by each Decentralized Autonomous Government [48]. These construction permit forms contained, among other aspects, detailed information about the materials used in construction at the national and provincial levels. The data shows the materials considered for the foundation, structure, masonry and roofing.

3.1 Changes in Construction Systems in Ecuador

The analysis focuses on the changes in construction systems in Ecuador in the last four decades (from 1980 to 2020). It has been divided in four periods; from 1980–1990 (Period 1), from 1991–2000 (Period 2), from 2001–2010 (Period 3) and from 2011–2020 (Period 4). Throughout the entire period under analysis, the materials used in the Structure component, at the national level, have been reinforced concrete, cyclopean concrete, metal and wood.

Within the foundation materials, the use of reinforced concrete and cyclopean concrete has predominated in the last four decades. Between 1980 and 1990, 65% of buildings used reinforced concrete as the foundation material, while 32% used cyclopean concrete. In Period 2, an important variation is noticed, as the use of cyclopean concrete increases. However, in the subsequent periods, the use of reinforced concrete increases notably, while the use of cyclopean concrete gradually decreases (Fig. 16a). Regarding the structure of the dwellings, the most used material has been reinforced concrete. The use of this material in these construction elements has remained between 80 and 90% of the total number of permits issued, throughout the analysed periods. By contrast, the use of other natural materials such as wood has tended to decrease (Fig. 16b).

Accordingly, it is possible to determine that in the foundations, the predominant construction system at present is one that uses reinforced concrete, either through continuous or isolated footing foundations. The main variation in the foundations has been the change from continuous stone masonry using cyclopean concrete to reinforced concrete footings. In relation to the Structure, the predominant construction system has been the reinforced concrete porticos- however, there has been a slight increase in the use of the metallic structures and an almost total elimination in the use of wood.

With reference to the Envelope, the predominant materials for walls and roofs have been bricks, Pumice hollow blocks, reinforced concrete, asbestos sheets, tiles, and zinc sheets. Within the materials used in walls, the predominant use of bricks and blocks has been evident in the last four decades. In Periods 1 and 2, the use of bricks represented 51% and 46%, and Pumice hollow blocks represented 46% and 43% of the materials used in Envelopes, respectively. These percentages show that the use

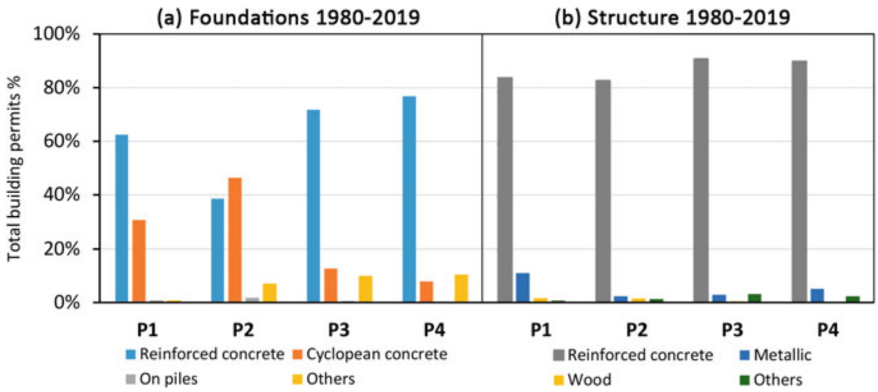


Fig. 16 Materials used in **a** foundations, and, **b** other structural elements, at the national level. *Source* Own elaboration with data from [48–84]

of bricks and Pumice hollow blocks was more or less equitable in these periods; however, for Periods 3 and 4 the trend changes and the use of blocks predominates, while the use of bricks shows a gradual decline (Fig. 17a). As for the roof of the houses, the predominant materials have been reinforced concrete, asbestos, tiles and zinc sheets. In this construction element, in the first period, the most commonly used material was asbestos; however, in subsequent periods, its use has constantly decreased. The pattern can also be seen in the use of tiles, which are used as a second layer over the asbestos sheet. At the same time, the use of reinforced concrete has steadily increased over the periods analysed (Fig. 17b).

Based on this data, it has been possible to determine that, in walls, the use of bricks with cement mortar predominated in the first two periods, which meant heavier construction systems for masonry were used in comparison with the latter

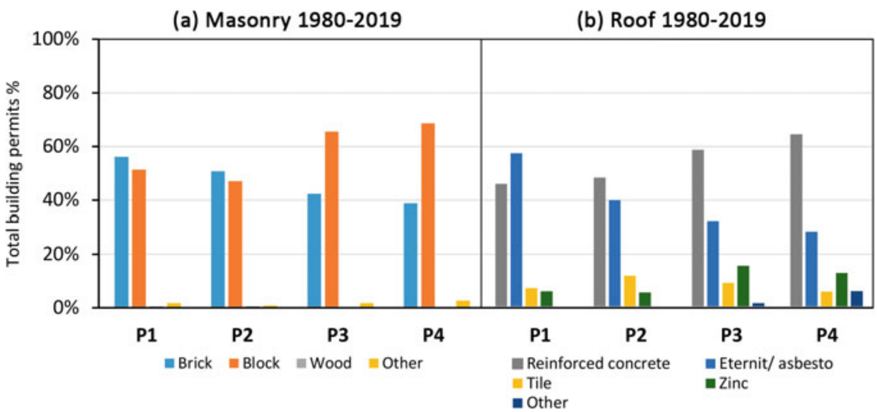


Fig. 17 Materials used in the envelope elements that make up: **a** the masonry, and, **b** roof at the national level. *Source* Own elaboration with data from [48–84]

two periods. In Periods 3 and 4, a lighter construction system was used, composed of Pumice hollow blocks and cement mortar. The opposite is evident in the case of construction systems used for roofing, since in Period 1, the use of asbestos (a light roofing system) predominated, while in the following periods, the use of heavy concrete roofing intensified. Furthermore, these changes show an incremental tendency towards the use of industrialized materials, to the detriment of artisanal and local materials.

3.2 Changes in Construction Systems at Local Level

At the provincial level, with respect to foundations, the use of reinforced concrete and cyclopean concrete have predominated. In Periods 1 and 2, there is a 70% predominance in the use of cyclopean concrete over the use of reinforced concrete. However, in Period 3, the use of reinforced concrete increases, and by Period 4, the use of reinforced concrete exceeds the use of cyclopean concrete (Fig. 18a). Regarding the other structural elements in dwellings, the most commonly used material has been reinforced concrete. The use of this material in these construction elements has remained between 85 and 90% of the total number of permits issued. By contrast, the use of metallic structures has seen variations: their use in the first period was greater than in the second period; and then from Period 3 their use begins to increase and this tendency continues in Period 4 (Fig. 18b).

Based on this analysis, the most commonly used system at present is the construction of footings using reinforced concrete, either continuous or isolated. The main variation in foundations has been the change from continuous stone masonry using cyclopean concrete to reinforced concrete footings. In this case the change is generated gradually, unlike at the national level. In relation to the other structural elements,

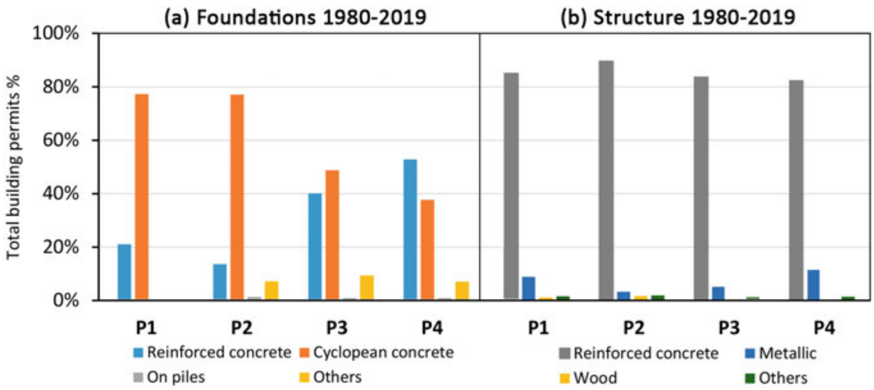


Fig. 18 Materials used in the structural elements that make up **a** the foundation, and, **b** the structure at the local level. *Source* Own elaboration with data from [48–84]

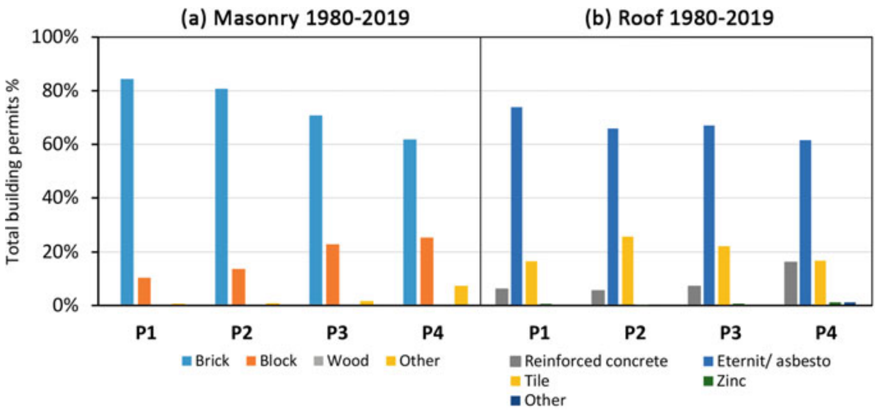


Fig. 19 Materials used in the envelope elements that make up **a** the masonry, and, **b** roof at the local level. *Source* Own elaboration with data from [48–84]

the most commonly used construction system has been reinforced concrete porticoes, while there has been an almost total decrease in the use of wood. This is similar to the situation at the national level.

With reference to the vertical envelope; in the last four decades, the predominant materials for walls have been bricks and Pumice hollow blocks. In all periods, the use of bricks has been greater than that of to blocks, however, it is evident that there is a trend towards an increased use of lighter materials, while the use of heavier materials has steadily declined (Fig. 19a). As for the horizontal envelope, the predominant materials have been reinforced concrete, asbestos sheets, tiles and zinc sheets. In this construction element, the use of asbestos has remained predominant. The second most commonly used material has been tile. In addition, it is evident that the use of reinforced concrete has increased steadily over the years; however, unlike at the local level, the use of reinforced concrete has not increased at the national level (Fig. 19b).

According to this analysis, the use of bricks in walls has predominated, which means that heavy construction systems have been used. However, an increase in the use of the construction system composed of Pumice hollow blocks has also been evident, which is lighter and involves greater EE (since it uses cement in its composition). On the other hand, the use of light construction systems in roofing (such as asbestos sheet), has been dominant in all periods.

In terms of the materials used as Finishes, both nationally and locally, a similar trend is seen: materials of natural origin have been replaced by industrialized ones. In 1980, the use of wood, cane and earth predominated, but they have progressively been replaced by cement, ceramics and agglomerates. Though the data presented in Fig. 20 goes only up to 2010, nevertheless, even in the years after this it is possible to determine that the materials used in the Finishes of residential buildings have had greater variety across all economic and social conditions. This is due to the fact that imports of construction materials has shown a constant increase in the last period of analysis (2010–2020) [85].

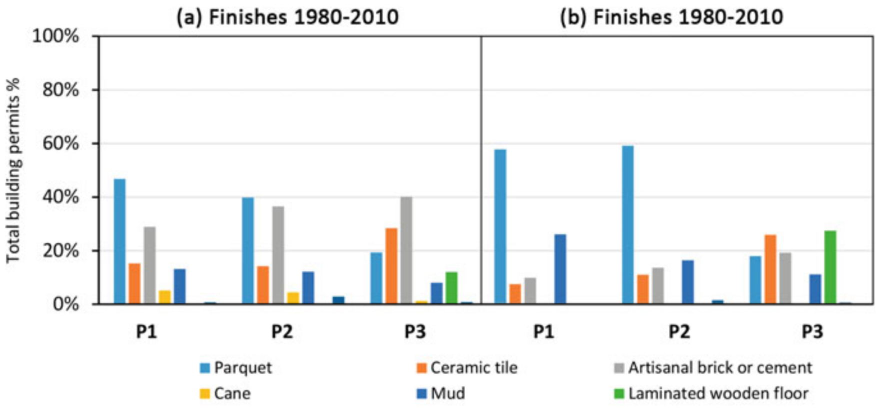


Fig. 20 Materials used in finishes at the **a** national and **b** local level, (180–2010). *Source* Own elaboration with data from [86–88]

Up to this point, the statistical data has been analysed in a general way. This data shows a clear trend in the changing use of materials and construction systems over the years. In order to corroborate this analysis, the following section conducts an experimental analysis of the change in materials and the repercussion on the value of EE.

4 Change of Construction Systems and the Variation of Embodied Energy

Based on the discussion above, this section analyses the impact of the change in materials from 1980 to 2020 in the city of Cuenca on the overall EE. The methodology is based on the field analysis of 40 houses, built over the last 4 decades (1980–2020) in the city of Cuenca. The study assesses the decadal variation for the following periods: Period 1: 1980–1990, Period 2: 1991–2000, P3: 2001–2010, Period 4: 2011–2020. The sample selection begins with the identification of different urban sectors of the city, where the main use of the land is residential. The selected areas must have construction projects from each of the relevant periods. The chosen sectors were Misicata, Ricaurte, and Miraflores. Once the sectors were established, the second step was to randomly pre-select a set of residential buildings based only on the period of construction: this information was obtained from the database of the Municipality of Cuenca [89]. This pre-selection disregarded apartment buildings or multi-family buildings and instead focused on low-rise single-family houses since this is the most widespread urban typology in this region and country [90]. In addition, this selection does not consider the social or economic standing of the building's resident. Nevertheless, all the samples were completed projects and had been approved by the municipality department.

The final but most important step, was the collection of technical information about the buildings through fieldwork. The initial preselection identified 61 samples, however, 21 buildings had to be discarded due to accessibility problems. Consequently, 40 buildings were finally selected.

For each period, 10 single-family dwellings have been analysed, and from each of them the constructive elements have been classified into three components: Structure, Envelope and Finishes. Within each component, the total weight of each material used has been obtained, using the respective specific weights and volume.

The parameter under evaluation for this analysis is the Total Embodied Energy of the building in relation to its construction area (MJ/m^2), termed as Specific Total Embodied Energy (STEE). For this, the values of embodied energy (EE) per unit weight of each material (MJ/kg) are established using previous research [37], using studies where the manufacturing specifications and raw materials are similar with respect to both Ecuador's industry and its boundary conditions (see Table 1). The data considered in this table focused, where possible, on values with Cradle-to-gate (CG) boundary condition. However, 7 materials with Cradle-to-site (CG) condition have also been considered. In addition, 3 values from an Ecuadorian database with a gate-to-gate (GG) condition have been considered, because the energy for the extraction and transport of these materials was minimal, since the extraction was done in the same factory without the use of heavy machinery. Finally, the specific weight values are based on national and local production data and taken from published literature. It is necessary to clarify that, in this study, the impact of industry improvements over time on EE values has not been considered, since this work focuses on the change in construction and design decisions and not on the material improvements. Thus, the EE values used are the same for all four periods.

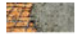
With the data of specific weight and specific embodied energy for each material, it is possible to obtain the STEE of the dwelling and of each construction component, through Eq. 2.

$$\mathrm{STEE} = \sum (P * EI)/S \tag{2}$$

where STEE is the Specific Total Embodied Energy (MJ/m^2), P is the total weight of each material (kg), EE is the specific embodied energy of each material (MJ/kg), and S is the total building surface (m^2). The values of P are obtained by multiplying the total volume of each material by its specific weight.

The calculations focus on the built-up area and omit materials used in courtyards and areas outside the dwellings. Finally, the EE values used in this study do not consider the industry improvements over the time. Nevertheless, according to [37], in Ecuador the change in EE values due to improvements in industry have happened only in the last decade.

Table 1 Specific density and specific embodied energy of the materials considered in this study

Material	Specific Weight (kg/m3)	Weight Source	EE (MJ/kg)	EE Source	EE Country	EE boundary condition	Picture
Concrete	2400	[39]	0.95	[22]	England	GC	
Cement mortar 1:4	2001	[39]	1.34	[22]	England	GC	
Lightweight pumice block	1560	[25]	3.74	[25]	Ecuador	GG	
Structural stone	2700	[91]	0.5	[91]	England	GC	
Artisanal solid brick	1800	[92, 93]	1.33	[92]	Ecuador	GG	
Artisanal hollow brick	1800	[92, 93]	1.33	[92]	Ecuador	GG	
Ceramic tile	1600	[92, 93]	3	[22]	England	GC	

(continued)

Table 1 (continued)

Material	Specific Weight (kg/m3)	Weight Source	EE (MJ/kg)	EE Source	EE Country	EE boundary condition	Picture
Vitrified tile	1600	[92, 93]	8.2	[22]	England	GC	
Vitrified ceramic	4500	[94]	8	[95]	Spain	CS	
Porcelain ceramic	5000	[94]	25.5	[95]	Spain	CS	
Aluminium (primary)	2700	[22]	214	[22]	England	GC	
Steel (40% recycled)	7850	[39]	24.84	[39]	Ecuador	GC	
Stainless steel (42,7% recycled)	8000	[22]	56.7	[22]	England	GC	
Galvanized sheet (primary)	7850	[39]	39	[22]	England	GC	
Glass primary	2500	[22, 96]	16.81	[22]	England	GC	

(continued)

Table 1 (continued)

Material	Specific Weight (kg/m3)	Weight Source	EE (MJ/kg)	EE Source	EE Country	EE boundary condition	Picture
Fibre cement	1500	[22]	10.9	[22]	England	GC	
Vegetable fibre artisanal plaster	1500	[95]	2.5	[95]	Spain	CS	
Plaster	1750	[97]	2.5	[95]	Spain	CS	
Plasterboard	833	[95]	7	[95]	Spain	CS	
Structure for plasterboard	7850	[95]	7	[95]	Spain	CS	
Plastic paint	1400	[98]	20	[95]	Spain	CS	
Laminate wooden floor	650	[99]	36.4	[99]	Germany	GC	
Polyethylene sheet	10	[95]	110	[91]	England	GC	
Timber (wood)	425	[95]	8.5	[22]	England	GC	
Veneer particle board	670	[100]	23	[22]	England	GC	

CC: Boundary conditions. CG: Cradle-to-gate. CS: Cradle-to-site. GG: Gate-to-gate. *Source* Own elaboration with data from: [22, 25, 39, 91–97, 99–101]

4.1 Construction Systems in Each Period of Analysis

Period 1: 1980–1990

In the first period, 2 types of predominant construction systems were identified in the 10 houses analysed (Fig. 21), depending on the materials used in the foundation's elements. The first type consists of a cyclopean foundation that supports double brick walls. The cyclopean foundation is present in the second type as well, but an isolated foundation is also added, with the strip foundation supporting the simple brick walls and the isolated foundation supporting the load of the concrete porches (in a few cases), or mixed, wood and concrete (in most cases).

Table 2 shows the materials used in this period and their recurrence in the cases analysed. The data shows that in the structural elements, the use of wood is still relevant, especially for the first-floor slab, the second-floor slab, roofs and stairs. In the vertical envelope, 100% of the material used is handmade brick, either as a double or a single wall. In the roof, fibre cement is used in all cases, covered by handmade tiles (in most cases), and glass roofing (in 2 cases). In the fenestration (windows), 2 systems have been found: the first uses glass and iron frames (this system is the predominant one) while the second (used to a lesser extent in this analysis) uses glass with wooden frames. In terms of Finishes in this period, the use of wood is greater, and is present in elements of floors, doors, handrails and furniture. In wall finishes, cement mortar is used in all cases-however, there are only 2 cases of the use of plaster. In ceilings, Vegetal fibre artisanal plaster is used more frequently, and wood to a lesser extent.

Period 2: 1991–2000

In the second period the construction systems are similar to those presented in Period 1. However, in Period 2, the type 1 construction system is less recurrent than type 2 (Fig. 22). In addition, in the type 2 construction systems of this period, there is no longer a predominance of mixed use with wood, but instead the use of concrete is more dominant.

Fig. 21 Dwellings analysed in period 1, classified by the types of construction systems found

Table 2 Materials used in each component of the analysed dwellings of Period 1

Structure			Envelope			Finishes		
Elements	Materials	Number of cases	Elements	Materials	Number of cases	Elements	Materials	Number of cases
Foundations	Cyclopean concrete	10/10	Walls	Handmade solid brick + cement mortar	10/10	Floors	Wood	9/10
	Reinforced + cyclopean concrete	4/10					Vitrified ceramic	10/10
						Doors	Steel	4/10
Columns	Reinforced concrete	10/10					Glass	5/10
							Wood	10/10
Beams	Reinforced concrete	10/10					Aluminium	1/10
			Roof	Fibre cement	10/10	Wall finishes	Cement mortar	10/10
First floor	Concrete	5/5					Plaster	2/10
				Artisanal tile	8/10		Painting	10/10
	Wood	5/5					Vitrified ceramic	10/10
Second floor	Reinforced concrete	3/10		Glass	2/10	Handrail	Steel	4/10
							Wood	9/10
	Wood	7/10	Windows	Glass	10/10	Ceiling	Vegetal fibre artisanal plaster	7/10
							Plaster	7/10
Roof	Wood	10/10		Steel	7/10		Painting	9/10
Stairs	Reinforced concrete	4/9					Wood	3/10
	Wood	5/9		Wood	3/10	Fitted furniture	Wood	10/10

Fig. 22 Dwellings analysed in period 2, classified by the types of construction systems found

The materials used and their recurrence in each analysis component in this period are detailed in Table 3. In the foundations, the use of cyclopean concrete continuous foundations decreased and the use of reinforced concrete isolated foundations increased. In this period, the use of wood in the Structure reduces: there are few cases that combine reinforced concrete and wood on the first floor, however, this material has been used 100% for the roof structure. In the Envelope, the use of handmade solid brick continues in all the cases analysed. In the roof, the use of fibre cement still predominates, together with handmade tiles; but glazed tiles are also beginning to be used. In this component, the use of glass for the roof increases and the windows are made of glass with steel, wood or aluminium frames, the latter being the predominant material. Finally, the use of wood continues to predominate in the finishing elements of this period as well; however, there is also a slight increase in the use of other materials such as ceramics and plaster.

Period 3: 2001–2010

In this period, two construction systems were identified, the main difference between them being in the structural elements. Type 1, which predominates (Fig. 23), has a continuous foundation and an isolated foundation of cyclopean and reinforced concrete, respectively. By contrast, type 2 only has an isolated foundation of reinforced concrete. Another peculiarity of type 1 is that its roof uses steel in most of the cases analysed.

Table 4 details the materials used and their recurrence in the analysis of the dwellings of this period. According to the data obtained (and as previously mentioned), the predominant foundation system is composed of cyclopean and reinforced concrete; most of the structural elements in this period use reinforced concrete; and only for the roof has steel been used (and wood to a lesser extent). In the Envelope component, solid brick masonry predominates, though the use of hollow bricks is also seen. For roofs, the use of artisanal tiles disappears and the fibre cement + glazed tiles system is used in almost all the dwellings analysed. In this period there is one case of reinforced concrete roofing, in which ceramic tiles are used as the final covering. In the fenestration (windows), glass with aluminium frames are the only materials used. In the finishing component, the materials which had been used in previous periods have almost entirely replaced by new ones. Although wood and

Table 3 Materials used in each component of the analysed dwellings of Period 2

Structure			Envelope			Finishes		
Elements	Materials	Number of cases	Elements	Materials	Number of cases	Elements	Materials	Number of cases
Foundations	Cyclopean concrete	2/10	Walls	Handmade solid brick + cement mortar	10/10	Floors	Wood	10/10
	Reinforced + cyclopean concrete	8/10					Vitrified ceramic	10/10
						Doors	Steel	2/10
							Glass	6/10
Columns	Reinforced concrete	10/10	Roof	Fibre cement	7/10		Wood	10/10
							Aluminium	4/10
Beams	Reinforced concrete	10/10		Artisanal tile	7/10	Wall finishes	Cement mortar	10/10
							Plaster	6/10
First floor	Reinforced concrete	9/10		Vitrified tile	1/10		Painting	10/10
							Vitrified ceramic	10/10
	Wood	1/10		Glass	5/10	Handrail	Steel	1/10
Second floor	Reinforced concrete	3/10					Wood	9/10
	Wood	7/10		Wood	3/10	Ceiling	Vegetal fibre artisanal plaster	9/10
Roof	Wood	10/10	Windows	Glass	10/10		Plaster	9/10
				Steel	1/10		Painting	9/10
Stairs	Reinforced concrete	10/10		Wood	1/10		Wood	1/10
				Aluminium	8/10	Fitted furniture	Wood	10/10

Fig. 23 Dwellings analysed in period 3, classified by the types of construction systems found

vitrified ceramics are still used on the floors, it is their laminated wood and porcelain ceramic forms which are used; new materials such as stainless steel and aluminium are also used in handrails. In addition to the Vegetal fibre artisanal plaster, plasterboard panels are used for the ceilings; and in the Fitted furniture, the natural wood used in previous periods has been replaced by Veneer particle board.

Period 4: 2011–2020

In this period, 2 construction systems have again been identified (Fig. 24). The main difference between them is found in their structure: in type 1 the elements composed of steel predominate; while in type 2, the elements are composed in greater proportion of reinforced concrete. In addition, there is a particularity in this period, since there are 2 cases that combine the reinforced concrete structure for the first floor and steel for the second floor.

As previously indicated, in this period there is a predominant use of reinforced concrete, steel, and a combination of these, as shown in Table 5. In the Envelope there is another material for walls: the Pumice hollow block. In this component, there is also a combination of systems, since in several cases solid brick is used on the ground floor and hollow brick or pumice block on the upper floor. In roofing, the most commonly used material is fibre-cement, and in fewer cases, it is combined with glazed tile. In this period, the use of reinforced concrete roof covered by vitrified ceramic has increased. In the fenestration (windows), the system of the previous period continues. Finally in Finishes, the use of wood and ceramics decreases even more, which is replaced by laminated wooden and porcelain ceramic. In handrails, the use of glass is observed. In ceilings, Vegetal fibre artisanal plaster is no longer used, and has been replaced entirely by plasterboard panels; while in doors and furniture the use of Veneer particle boards predominates.

Table 4 Materials used in each component of the analysed dwellings of Period 3

Structure			Envelope			Finishes		
Elements	Materials	Number of cases	Elements	Materials	Number of cases	Elements	Materials	Number of cases
Foundations	Reinforced concrete	1/10	Walls	Artisanal solid brick + cement mortar	9/10	Floors	Wood	8/10
							Vitrified ceramic	5/10
	Reinforced + cyclopean concrete	9/10					Porcelain ceramic	7/10
							Laminated wooden	4/10
Columns	Reinforced concrete	10/10				Doors	Veneer particle board	5/10
				Artisanal hollow brick + cement mortar	3/10		Glass	4/10
							Wood	5/10
Beams	Concrete	10/10					Aluminium	4/10
						Wall cladding	Cement mortar	10/10
							Plaster	9/10
First floor	Concrete	10/10	Roof	Fibre cement	10/10		Painting	10/10
							Glazed ceramic	9/10
				Glazed tile	9/10		Porcelain tile	1/10
Second floor	Concrete	10/10				Handrail	Steel	3/10
				Glass	2/10		Wood	5/10
Roof	Reinforced concrete	1/10					Aluminium	2/10
				Glazed ceramic	1/10		Stainless steel	2/10

(continued)

Table 4 (continued)

Structure			Envelope			Finishes		
Elements	Materials	Number of cases	Elements	Materials	Number of cases	Elements	Materials	Number of cases
	Steel	8/10				Ceiling	Vegetal fibre artisanal plaster	7/10
							Plaster	7/10
	Wood	2/10	Windows	Glass	10/10		Painting	7/10
Stairs	Reinforced concrete	10/10					Plaster board	3/10
				Aluminium	10/10		Plasterboard structure	3/10
	Wood	1/10					Wood	1/10
						Fitted furniture	Veneer particle board	10/10

Fig. 24 Dwellings analysed in period 4, classified by the types of construction systems found

4.2 The Impact of Material Changes on the Embodied Energy of Buildings in the Andean Region of Ecuador

The research carried out in the previous sections shows that: first, the changes in materials used have been evident across the periods of analysis at the national and local levels; and second, that the experimental study corroborates the information found in the statistical sources. Therefore, this section focuses on the repercussion of the change of materials on the values of the embodied energy. This section will be divided into three parts; in the first part, the results obtained by components in all the periods will be analysed; while in the second part, the STEE will be estimated for the entire building. The last part will provide a detailed analysis of the most important materials and present some recommendations for the construction and design sector in this Andean region.

4.2.1 Variation of Embodied Energy in Different Components

Structure

Figure 25 shows the Structure STEE results for each dwelling in their respective periods (in Fig. 25a), and the average STEE for each period (in Fig. 25b).

In addition, Fig. 26 shows the results obtained for STEE values of each material of the Structure. The values shown in this figure are an average of the ten buildings analyzed in each period.

The average STEE of the Structure component in Period 1 is 721 MJ/m^2, which is the lowest of all the analysed periods. This is mainly due to the higher use of wood as a structural element in this period, since this material has a lower EE (8.5 MJ/m^2) and specific weight (425 kg/m^2) than reinforced concrete. Of the construction systems analysed in this period, dwellings with Type 1 showed lower STEE values. Sample 3 (which has a Type 1 construction system and a structural system predominantly made of wood) had the lowest STEE value of 513 MJ/m^2; while Sample 8 (which

Table 5 Materials used in each component of the analysed dwellings of Period 4

Structure			Envelope			Finishes		
Elements	Materials	#		Materials	#	Elements	Materials	#
Foundations	Reinforced concrete	3/10	Walls	Artisanal solid brick + cement mortar	7/10	Flats	Wood	4/10
							Vitrified ceramic	4/10
	Reinforced + cyclopean concrete	7/10					Porcelain tile	10/10
							Laminated wooden	10/10
Columns	Reinforced concrete	7/10		Artisanal hollow brick + cement mortar	7/10	Doors	Veneer Particle board	9/10
							Glass	2/10
	Steel	5/10					Wood	1/10
Beams	Reinforced concrete	7/10					Aluminium	2/10
						Wall cladding	Cement mortar	10/10
	Steel	5/10					Plaster	10/10
First floor	Reinforced concrete	10/10		Pumice hollow block + cement mortar	3/10		Painting	10/10
							Vitrified ceramic	3/10
Second floor	Reinforced concrete	4/10					Porcelain ceramic	7/10
						Handrail	Steel	1/10
	Steel + galvanized sheet	5/10	Roof	Fibre cement	7/10		Wood	3/10
				Vitrified tile	4/10		Aluminium	2/10
Roof	Steel	7/10		Glass	4/10		Stainless steel	4/10
				Vitrified ceramic			Glass	3/10
	Reinforced concrete	2/10			4/10	Ceiling	Plaster	10/10
							Painting	10/10
	Steel + galvanized sheet	1/10	Windows	Glass	10/10		Plasterboard	10/10
Stairs	Reinforced concrete	6/9					Plasterboard structure	10/10
				Aluminium	10/10	Fitted furniture	Wood	1/10
	Steel	3/9					Veneer particle board	9/10

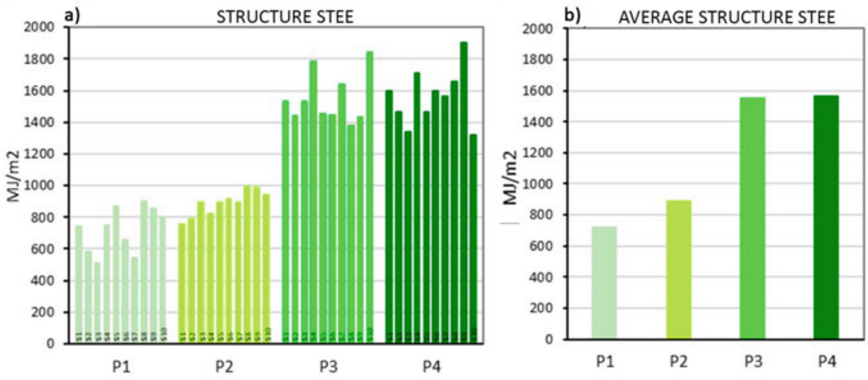


Fig. 25 STEE of the Structure component of **a** the 10 dwellings analysed and **b** the average, in each period

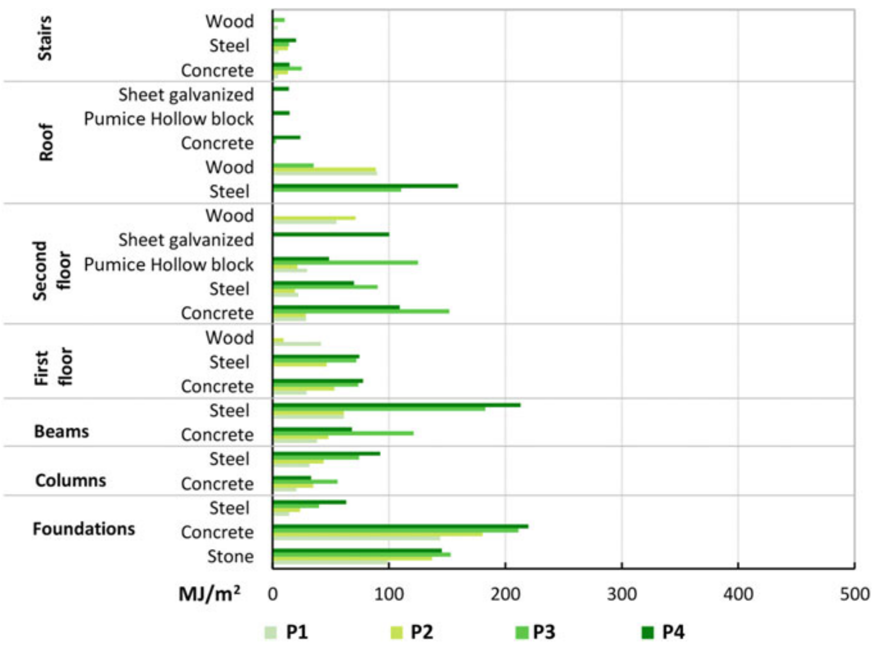


Fig. 26 STEE (MJ/m^2) of every material used for the Structure component of each period

has a Type 2 construction system which used reinforced concrete for its structure) had the highest STEE value of 901 MJ/m^2.

In Period 2, the average STEE was 893 MJ/m^2. Despite the types of construction systems in Periods 1 and 2 being same, the type 2 system (which uses more reinforced concrete in its elements) was more common in Period 2. This resulted in the increased

STEE of 172 MJ/m^2 in Period 2 in relation to period 1. Similar to the results obtained in Period 1, the minimum STEE in Period 2 is given by a type 1 house (S1 which has a STEE of 756 MJ/m^2), while the maximum STEE is given by a type 2 house (S9 which has a STEE of 987 MJ/m^2). Since wood was still considered for some structural elements (such as the second floor slab and roof) in Period 2, even though the proportions reduced compared to the previous decade, the STEE values largely did not differ.

Unlike the relationship observed in the first 2 periods, Period 3 sees a significant jump in STEE values in comparison to Period 2, (an increase of 173%). The average STEE value in P3 is 1548 MJ/m^2, with a minimum of 1381 MJ/m^2 (S8) and a maximum of 1845 MJ/m^2 (S10). These values correspond to the type 1 dwellings of this period. The significant increase in this period is mainly due to the almost complete replacement of wood by concrete in the horizontal structural elements (such as the first floor slab, the second floor slab and the beams); and the replacement of wood by steel in the roof.

Finally, between Periods 3 and 4 there is no marked increase: the average STEE value in P4 is 1562 MJ/m^2, representing a 14 MJ/m^2 increase over P3. This is because the most frequently used system in this period is composed of reinforced concrete, similar to P3. Nevertheless, despite the similar average STEE values between P3 and P4, architectonic differences result in some samples showing a marked difference-principally due to the increased use of steel and a change in the construction system of the roof. The maximum value (S9: 1903 MJ/m^2) of the 10 samples analysed in Period 4 corresponds to a Type 1 house which uses steel as the predominant material. Besides the use of steel, the highest STEE increases in P4 (in samples S1, S4, and S8) are due to the replacement of wood and steel in the pitched roofs by reinforced concrete horizontal slabs.

Based on the above results, it is possible to determine that the Total Embodied Energy in the Structure component over the last four decades has tended to continuously increase, though more significantly between Periods 1–2 and 2–3, than Periods 3–4. Due to the changes in materials used in the structural elements from 1980–2020, the embodied energy has risen 2.2 times. It should be emphasized that the difference in embodied energy between P1 and P2 is not due to a change in materials, but due to the differential distribution of construction typologies between the periods: there is a prevalence of type 1 in P1 and type 2 in P2.

Furthermore, Fig. 27 shows the Specific Total Weight (STW) of each of the 10 dwellings analysed in the four periods (Fig. 27a) and the average STW of each period (Fig. 27b). These results are important to understand that the changes shown in the STEE analysis are directly correlated with the weight of Structure component. Therefore, the STW generally tends to increase in the period of the analysis, though this correlation does not apply in the last period (as subsequently discussed). Like in the STEE analysis, the most representative change is shown between P2 and P3, when there is a total replacement of wood by reinforced concrete. However, the STW between P3 and P4 decreases from 1048 kg/m^2 to 916 kg/m^2 because of the increased use of steel in some P4 samples (S1, S6, S7, and S9). Even though the weight of these samples is lower than those that use reinforced concrete, steel has a much higher EE (24.84 MJ/m^2) than concrete (0.95 MJ/m^2), which results in the increase of the STEE, as seen in Fig. 25.

In addition, Fig. 28 shows the results obtained for STW values of each material of the Structure. The values shown in this figure are an average of the ten buildings analyzed in each period.

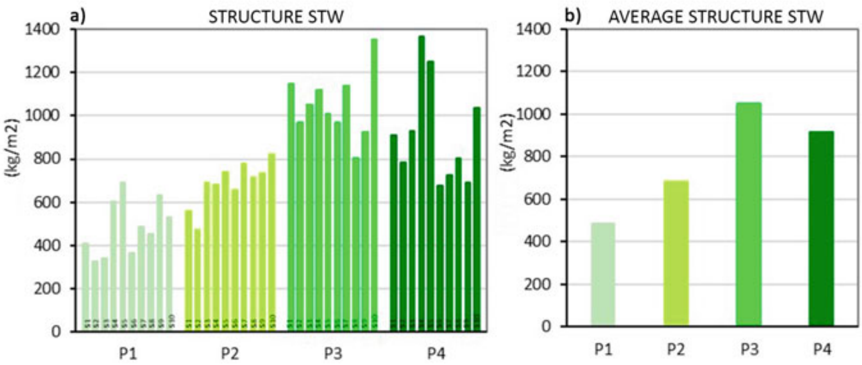


Fig. 27 STW of the Structure component of **a** the 10 dwellings analysed in every period, and **b** the average in each period

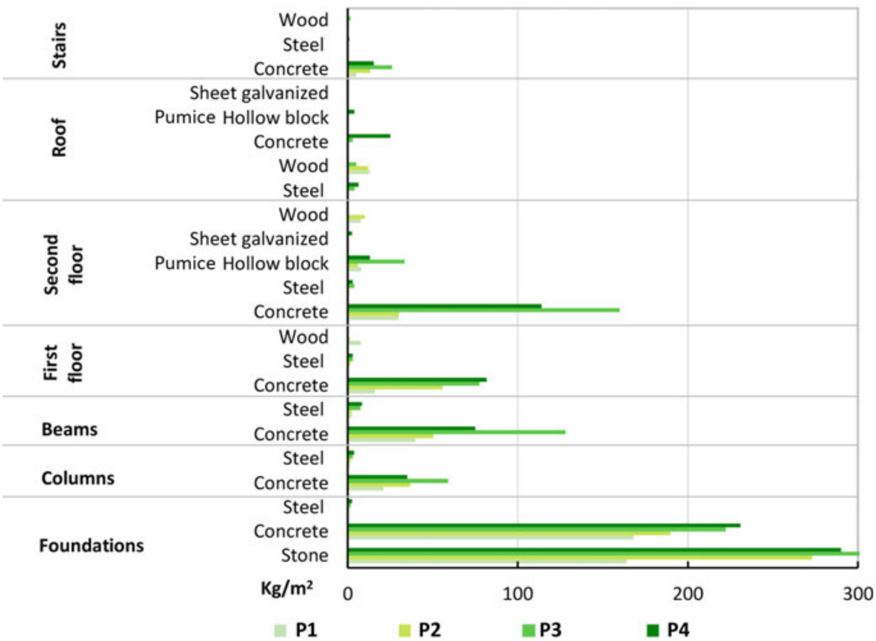


Fig. 28 STW (Kg/m^2) of every material used for the Structure component of each period

Envelope

The STEE results for each dwelling and the average STEE for each period in this component are shown in Fig. 29.

In addition, Fig. 30 shows the STEE results for each material of the Envelope. The values shown in this figure are an average of the ten buildings analyzed in each period.

Period 1 shows the lowest average STEE value (707 MJ/m^2) of the 4 periods analysed, with a maximum of 805 MJ/m^2 (in S3: which has double solid brick walls) and a minimum of 572 MJ/m^2 (in S4: which has single solid brick walls). In this component, the most significant element is walls followed by the roof elements and finally the windows, which responds to the use of 30 cm thickness walls. In this

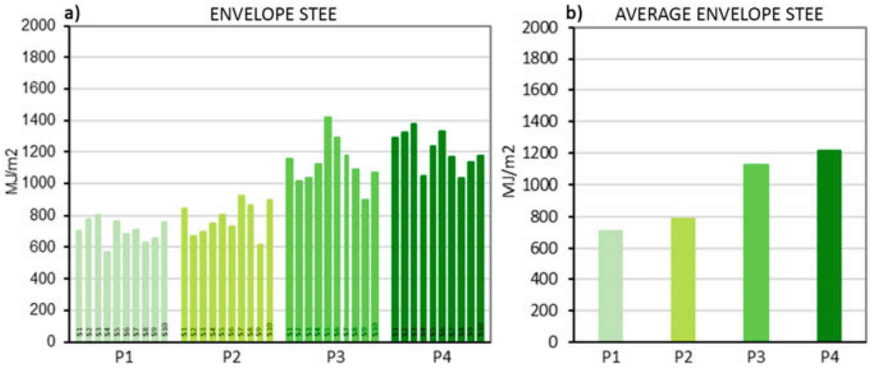


Fig. 29 STEE of the Envelope component of **a** the 10 dwellings analysed in every period, and **b** the average in each period

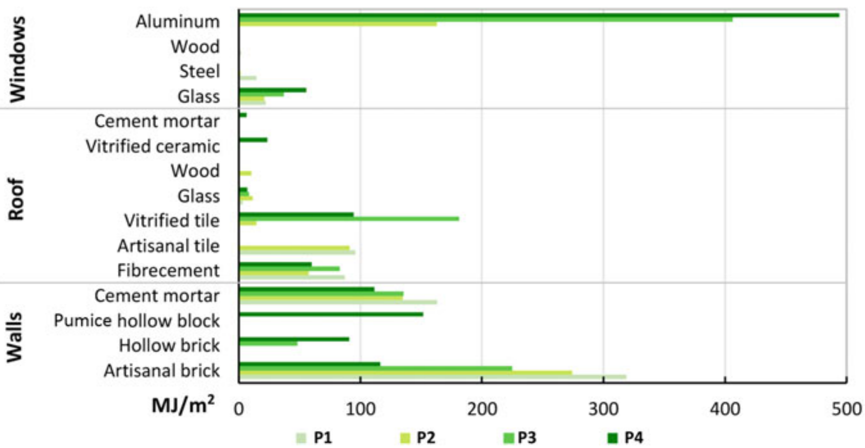


Fig. 30 STEE (MJ/m^2) of every material used for the Envelope component of each period

period, the window elements generate the least impact. This is because they use wood and iron for their frames, and and since windows occupy only a small proportion of the envelope, the use of glass is low.

In Period 2, the average STEE value shows a small increase (of 75 MJ/m^2) in comparison with Period 1. The average STEE value in P2 is 780 MJ/m^2, with a maximum of 916 MJ/m^2 and a minimum of 610 MJ/m^2. The modest increase between these periods is due to the fact that, although the double brick wall has completely been replaced by a simple wall, aluminium, which has a higher EE (214 MJ/m^2) than wood (8.5 MJ/m^2) and steel (24.84 MJ/m^2), is also being used. In addition, since the surface area of windows in relation to the vertical envelope in P2 increases, requiring greater amounts of material, there is a consequent increase in the STEE. In both P2 and P1, the most representative element is the walls. However, in terms of STEE, the windows are more representative than roof element in P2.

Similar to the Structure component, the greatest change in the STEE of the Envelope of the analysed periods is from P2 to P3. In Period 3, the average STEE value is 1126 MJ/m^2, which represents an increase of 45% when compared to Period 2. In P3, the maximum STEE value is 1417 MJ/m^2 and the minimum is 897 MJ/m^2. Despite the similarity of materials used in both P2 and P3, the significant rise in STEE in P3 is due to both the replacement of artisanal tiles by vitrified tiles, and (more importantly) due to the substantial increase in the surface area of the windows (thus requiring a greater use of aluminium and glass). In addition, the increase of the window/wall ratio makes aluminium (406 MJ/m^2) the most significant material in the STEE of the Envelope, followed by solid brick for Walls. Thus, in contrast to the previous periods, windows are the most representative element in Period 3, followed by the walls and the roof.

Finally, in Period 4 an average STEE value of 1211 MJ/m^2 is obtained, with a maximum of 1380 MJ/m^2 and a minimum of 1032 MJ/m^2. Despite the introduction of new materials and construction systems in P4 (especially for the wall elements), the variation in STEE between Periods 3 and 4 is not very large. This is due to several factors: the first is that although new materials (such as Pumice hollow block and artisanal hollow brick) with higher EE have been used in the walls, they have lower weights. Second, although horizontal slabs are included as new construction systems for the roof, the use of tiles over the fibre-cement sheet is reduced, and so the STEE of the roof element sees a reduction. Third, Period 4 sees an increase in the window proportion that is even greater than in previous periods, which results in an increase of STEE of this element. These factors reduce the variation between P3 and P4. As a result of the increase in the window/wall ratio, the window element is again the most representative in this period, and is responsible for 45% of the STEE of the Envelope component.

Based on these results, the least marked change in the four analysed periods is between P3 and P4, while the greatest increase occurs between P2 and P3, similar to what was observed in the Structure component. The overall results of the Envelope component show that its STEE has increased 1.71 times in the last four decades, both due to changes in the materials used and because of changing architectural preferences that have resulted in an increase in the glazed surface.

Figure 31 shows the Specific Total Weight (STW) of the 10 dwellings analysed in each period, and the average of each period. In contrast to the Structure, the Envelope's STW experienced a reduction in the last four decades. This is due to the insertion of new materials with lower weight (like hollow bricks); the elimination of other materials (like tiles); and the incremental increase of the glazed surface proportionate to the vertical envelope. According to this data, a dwelling built in the first period could have a STW around 500 kg/m^2 (such as in S2 from P1), which corresponds to a building with double solid brick walls, a pitched roof with fibre-cement sheet covered by artisanal tile, and a window/wall ratio of 36%. By contrast, a building from P4 could have a STW around 216 kg/m^2 (such as in S10 from P4), and be built with single hollow brick walls, with only with a fibre-cement layer without tile for a roof, and a window/wall ratio of around 76%. Despite the P4 dwelling having a lower STW than the P1 dwelling, its STEE is much higher (P1:780 MJ/m^2 vs. P4: 1180 MJ/m^2). Further, this decreasing STW can have repercussions for the thermal conditions of the buildings, since the thermal mass of the buildings also reduces, resulting in greater daily thermal oscillations in the interiors. Moreover, according to the technical characteristics in the construction systems of the analysed samples, the use of insulation has been neglected- the use of lightweight materials or the elimination of layers can therefore also increase the thermal transmittance of the envelope, which can in turn increase heat loss.

In addition, Fig. 32 shows the results obtained for STW values of each material of the Envelope.

Finishes

The STEE results for each dwelling and the average STEE for each period in this component are shown in Fig. 33.

In addition, Fig. 34 shows the STEE results for each material of the FInishes. The values shown in this figure are an average of the ten buildings analyzed in each period.

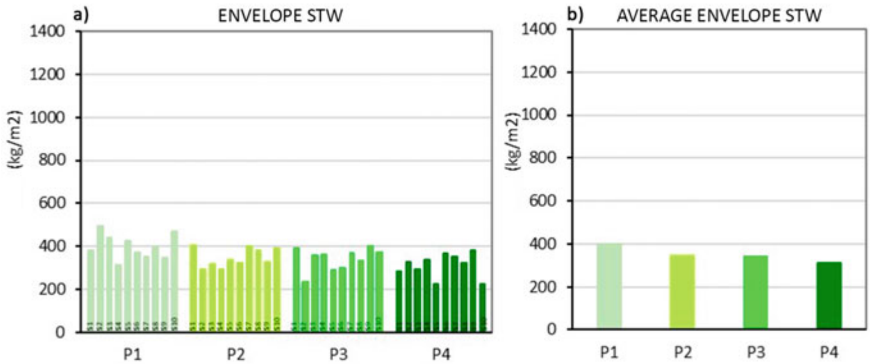


Fig. 31 STW of the structure component of **a** the 10 dwellings analysed in every period, and **b** the average in each period

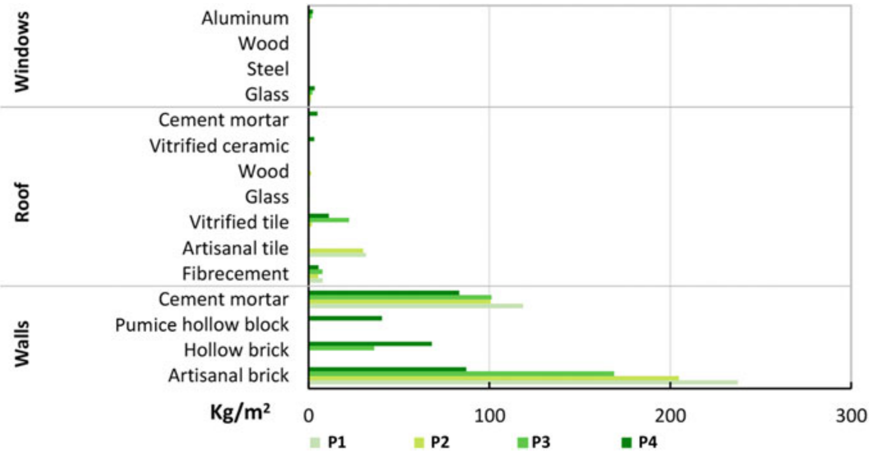


Fig. 32 STW (Kg/m^2) of every material used for the Envelope component of each period

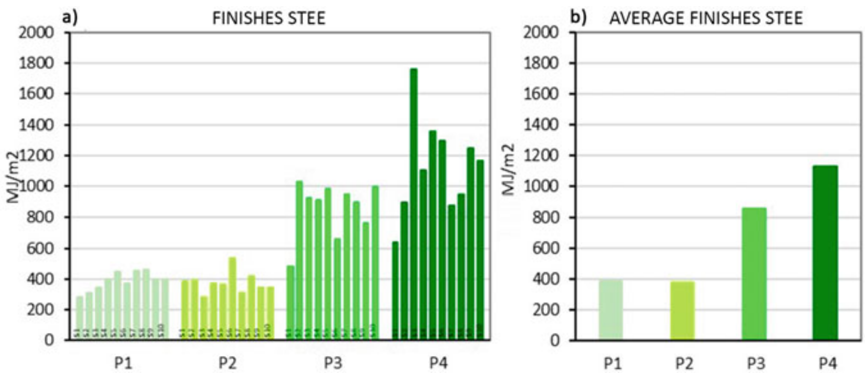


Fig. 33 STEE of the Finishes of **a** the 10 dwellings analysed in every period, and **b** the average in each period

In Period 1, the average STEE value of the Finishes component is 386 MJ/m^2, with a maximum of 461 MJ/m^2 and a minimum of 280 MJ/m^2. The most representative elements in this period are those used in wall and floor finishes. The cement mortar used for plastering and the vitrified ceramics are the most significant in terms of STEE, and they are also the materials with the highest weight among the Finishes. The materials used in this period do not have a high EE, but they do have a high weight, which makes them the materials with most repercussion on STEE. Nevertheless, due to the predominance of artisanal materials and other materials of natural origin, the STEE value is one of the lowest in the four periods analysed.

In Period 2, the average STEE value is 376 MJ/m^2, with a maximum of 536 MJ/m^2 and a minimum of 282 MJ/m^2. In relation to Period 1, the average STEE value of

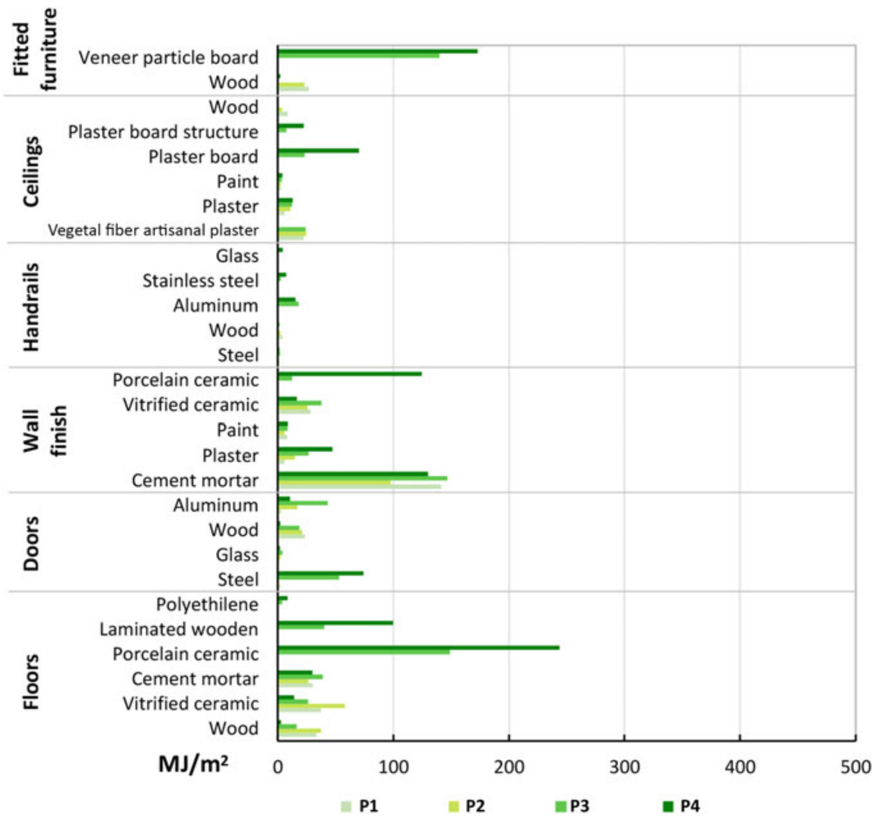


Fig. 34 STEE (MJ/ m^2) of every material used for the Finishes component of each period

P2 shows a slight decrease, despite several elements (such as doors and ceilings) showing an increase in their STEE. The overall decrease is because the STEE of the wall finishes elements reduce significantly, as 2 of the samples do not use any type of finish (such as mortar or plaster) on their walls, but instead leave only brick as the final finish. The use of handmade and natural materials (wood) predominates in P2 as well, however, these have begun to be replaced by other materials with higher EE, such as aluminium.

Period 3 has an average STEE value of 857 MJ/m^2, with a maximum of 1026 MJ/m^2 and a minimum of 481 MJ/m^2. As with the other two analysed components, the largest increase of STEE in the four periods occurs between Periods 2 and 3, because Period 3 sees a large number of new finishing materials being incorporated. P3 shows an increase of 128% over P2, which is principally due to the replacement of natural wood with processed wood and other industrialized materials. Such is the case of fitted furniture, that has replaced the use of wood with veneer particle boards, which for this analysis has been considered as a domestically produced material. However, in several cases this material is imported. Other cases of new materials are laminated wooden and porcelain ceramic which have replace the use of wood. These changes make the flooring element the most incident in the increase of STEE.

In period 4, the STEE average value is 1129 MJ/m^2, with a maximum of 1903 MJ/m^2 and a minimum of 1319 MJ/m^2. In this period the STEE increases 272 MJ/m^2, with respect to P3, this is due to the fact that the materials that began to be used in P3, in P4 are totally consolidated. This means that the use of natural and handmade materials has been totally replaced. In the case of the floors, wood is replaced by laminated wooden and porcelain ceramic in 100% of the cases; while in the ceilings, vegetal fibre artisanal plaster is replaced by plasterboard panels in all the samples. Therefore, the STEE of all the elements in this period has increased. In P4, the most representative element is the floors, followed by wall finishes, and ceilings.

Based on these results, similar to the trend seen in the other components, STEE in the Finishes component has increased over the last 4 decades- in this case with an increase of 2.92 times from 1980–2020. Again, the largest increase is generated between P2 and P3.

Figure 35 shows the STW of the 10 dwellings analysed in each period, and the average of each period. According to these results, the STW of this component has seen a slight increase in the last four decades, from 157 to 190 kg/m^2, which represents an increase of 21%. Again, the highest increase is also shown in the transition from Period 2 to Period 3.

In addition, Fig. 36 shows the results obtained for STW values of each material of the Finishes.

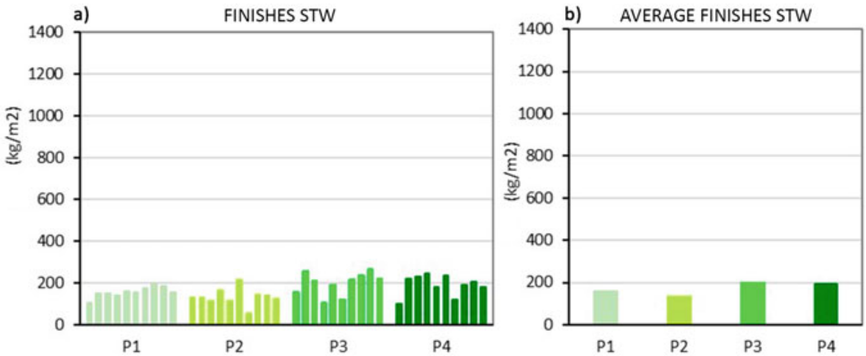


Fig. 35 STW of the Finishes component of **a** the 10 dwellings analysed in every period, and **b** the average in each period

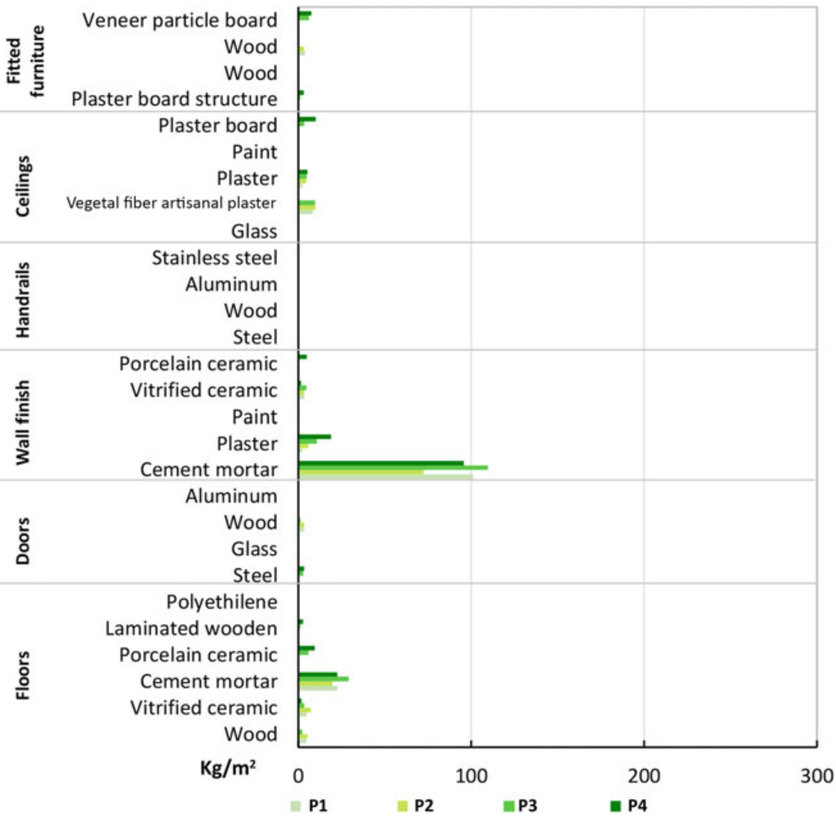


Fig. 36 STEW (Kg/m^2) of every material used for the Finishes component of each period

4.2.2 Variation of the Embodied Energy in the Entire Building

So far, the independent results of each component have been analysed. In this section the STEE of the entire building in each period is analysed, with the percentage of each component. These results are shown in Fig. 37.

According to the results obtained, the change in construction systems over the last four decades has resulted in an increase in the STEE of the buildings. As in the analysis of the components, the largest increase recorded has been in the transition from Period 2 (2045 MJ/m^2) to Period 3 (3531 MJ/m^2), which has corresponded to an increment of 73%. The other transitions- from P1 to P2, and from P3 to P4- have seen smaller increases, corresponding to 13% and 11% respectively. Consequently, the STEE of dwellings in the last four decades has increased 2.15 times, from 1815 MJ/m^2 to 3902 MJ/m^2. In addition to this, the impact of each component on the overall result has seen variations throughout the analysed periods.

The component with the highest impact on the STEE of residential buildings in the Andean region of Ecuador is the Structure, followed by the Envelope and

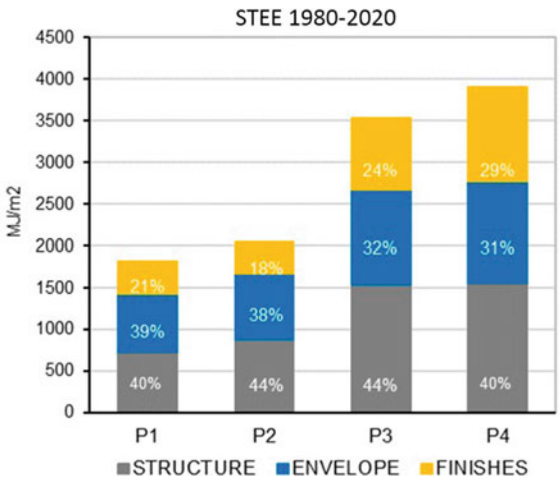


Fig. 37 Average values of STEE in the periods of analysis and their percentage of impact in each period

finally the Finishes. The Structure component has maintained an share between 40 and 44% of the total STEE throughout the periods of analysis, which means that the share of this component has been maintained throughout the last four decades. The second component with the highest impact has been the Envelope, which has a representativeness between 39 and 31%. In the analysis of the components, it is evident that the Envelope STEE has increased in the last four decades. However, the relevance of this component across the periods of analysis has reduced, since the representativeness of the other two components has significantly increased, especially the Finishes. Finally, the component with the lowest overall impact has been the Finishes, though its relative impact within the STEE of the entire building has shown a clear tendency to increase, since it has gone from 21 to 29%. So, Currently, the role of this component in the STEE of the building has a value almost equal to that of the Envelope.

5 Conclusions

The development of this chapter has focused on analysing the impact of the change of building systems on the Embodied Energy of buildings and their components in the Andean region of Ecuador from 1980 to 2020. Based on the results obtained in this study it has been possible to draw the following conclusions.

First, the sectors with some of the highest energy consumption in Ecuador has been the construction and residential sectors. This trend has been gradually increasing and the solutions that have previously been presented do not address the problem in a comprehensive manner.

Secondly, official records have shown that as the years go by, new materials and new ways of building are introduced, and that natural and handcrafted materials are displaced by these new industrialized materials. This fact has been confirmed by the analysis carried out in this chapter.

According to this premise, the change in building systems over the years has had a negative impact on energy consumption as per this study (with the disclaimer that it does not consider industry improvements over time), the embodied energy of materials from 1980 to 2020 has increased 2.15 times. Within this increase, the most significant component has been the Structure, followed by Envelope and Finishes. However, while the embodied energy of the Structure and Finishes have shown a tendency to increase (due to the insertion of new materials with higher embodied energy), the embodied energy of the Envelope has tended to decrease. This has been due to the fact that in the Envelope the weight of the materials used in masonry and roofing has significantly decreased, and the window surface has progressively increased. This fact could have negative repercussions on the interior temperature of the dwellings, as their thermal mass is reduced, which can cause an increase in the daily temperature oscillation. This repercussion of the change of construction systems on the interior temperature will be analysed in later chapters.

Another conclusion, that can be addressed in further investigations, is the change of the size of the buildings. According to the analysed data, the gross area of residential buildings in Cuenca has greatly reduced, specifically, the houses built in the last decade have on average had 60% of the area of the houses built in the 1980s.

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The Constructive Evolution of the Envelope. The Impact on Indoor Thermal Conditions in Andean Regions

Jefferson Eloy Torres-Quezada and Ana Torres-Avilés

Abstract The introduction of new technologies and materials in recent decades has significantly reduced construction times around the world. These changes have brought about a standardization of construction systems, which don't account for different cultural, social or even climatic contexts. Ecuador, and all its regions, have conformed to these changes, leaving behind their vernacular architecture which had been made of mud or guadua cane, and replacing them with industrialized systems which use materials such as concrete or metal. However, it is not clear whether these changes have been advantageous or disadvantageous for the interior thermal performance of the buildings. In this context, this chapter presents a thermal analysis of the different construction systems used in housing projects built in the last 4 decades, viz. 1980–1990, 1990–2000, 2000–2010 and 2010–2020, taking as a case study the Andean region of Ecuador. For this purpose, 10 dwellings from each period have been analyzed, and the average characteristics of their materials (Envelope weight) and the building morphologies (window/wall ratio) have been established. The impact of these variables on the interior temperature has been measured through energy simulations with the Design Builder program and its calculation engine Energy Plus, which has been configured to a base model for the four periods, in order not to bias the results. The study establishes that residential buildings in this region have, on the one hand, seen considerable reduction in the weight of their envelope, and on the other hand, seen considerable growth in the proportion of the glazed surface. These changes have had repercussions the thermal oscillation in the most recently built buildings tends to be greater than in the older ones, as the morphological and material changes results in a reduction in thermal mass and an increase in thermal transmittance.

Keywords Thermal mass · Materials · Thermal transmittance · Thermal oscillation

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1 Traditional Architecture and Climatic Conditions

Historically, the built environment around the world has evolved, on the one hand, around indigenous knowledge (through techniques learnt either by trial-and-error or through intergenerational experience) and, on the other, to the local availability of materials [1]. This meant that construction styles were defined by cultural norms, traditional practices and environmental considerations. Traditional architecture thus developed in response to the regional variations in both climatic conditions and the distribution of natural resources. In other words, the construction processes were adapted to the conditions of the environment in which they were located.

This feature has presented repeatedly around the world, with several texts establishing the different traditional housing typologies for each climatic condition. In general, the world's climate is classified into different groups according to the latitude in which they are located, viz. equatorial zone, tropical zone, temperate zone and cold zone. In the equatorial zone, with latitude 0°, there is a warm-humid climate, which is characterized by periods of diurnal heat and intense rainfall. The climate of this region tends to become more comfortable as the elevation increases. The traditional architecture in this region is distinguished by being lightweight, with screened enclosures, an emphasis on protection from solar radiation, natural ventilation and sloping roofs [2–5].

The tropical zone has a hot-dry climate, characterized by intense solar radiation, large daily temperature oscillations, dust storms and low ambient moisture. In these zones, traditional architecture consists of walls with small openings, large eaves, light colors and light materials [4, 5]. The temperate zone is typical of cold-humid climates, characterized by periods of low temperatures and cold nights. Finally, the cold zones have a cold-dry climate, with extremely low temperatures. In the last two zones, architectural styles seek to protect inhabitants from the cold outside through solar gain and materials with high thermal inertia [4], Fig. 1.

Accordingly, each area sought to make buildings adapted to their climatic conditions and to the materials available in each zone.

Based on the previously described climatic classification, Ecuador (being at latitude 0°) should have a warm-humid climate throughout its territory—however, since the Andes Mountain range crosses through the country, its territory has been classified into 4 regions: Coastal, Andean (Sierra), Amazonian and Insular region (Galápagos), Fig. 2.

In the Coastal region of Ecuador, the climate is warm-humid, so the traditional construction processes used light materials of natural origin (such as bamboo), in order to enhance natural ventilation to interior spaces.

The prototypical traditional house in the Coastal region is essentially responsive to the climatic conditions of this region. The dwellings are raised above the ground level, in order to avoid possible flooding [6]. In addition, several strategies are applied to meet the primary design objective for buildings in this region: ventilation. The construction of reed walls with small slits allows cross-ventilation in the dwelling, which in turn favors the dissipation of heat, that otherwise tends to rise. High ceilings

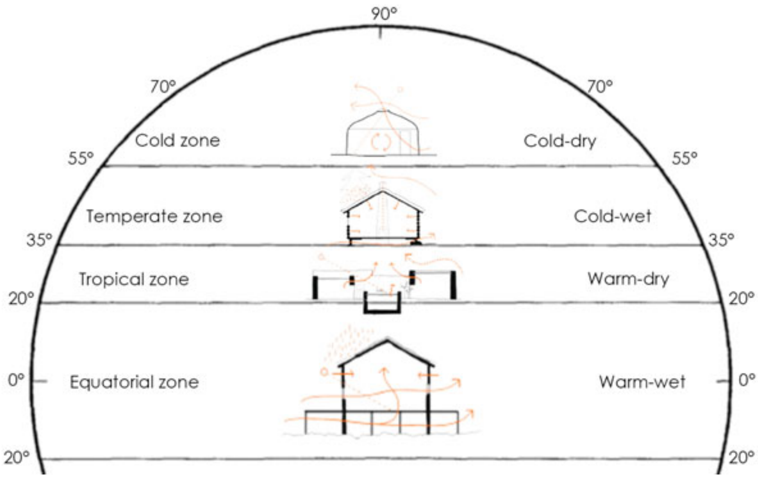

Fig. 1 Climatic zones and traditional building typologies. *Source* Own elaboration with data from [4, 5]

Fig. 2 Map of Ecuador with its 4 natural regions. *Source* Own elaboration edited from https://ecuador1b106.wordpress.com/ecuador/

and the use of natural materials also improve interior ventilation. The raised elevation of the houses, done primarily to avoid flooding, also contributes to improving indoor thermal conditions because the increased elevation also improves the airflow [7]. The roof design also plays a key role in building for this climate due to the large amount of solar radiation received in this region [8]. Light colors, light materials and

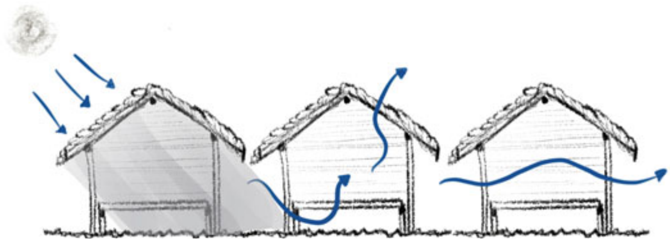

Fig. 3 Strategies to improve the indoor thermal conditions of traditional housing in the Coastal region of Ecuador. *Source* Own elaboration

large eaves block the prolonged incidence of the sun on the walls of the house [9]. In addition, the openings of the house remain open most of the time, which favors constant ventilation of the interior space (Fig. 3).

These strategies are applied to the building conception, however, there are other strategies that contribute to improving interior climatic conditions in urban spaces for example, the orientation of the house. In this region, the facades with the largest surface area are oriented either to the north or the south as this reduces the area of direct solar incidence. In addition, vegetation is planted near houses to provide shade and increase ventilation, thereby improving indoor thermal comfort [6] (see Fig. 4).

Dwellings in the Insular as well as the Amazonian regions of Ecuador apply similar strategies to those in coastal regions. In these regions, the building designs incorporate the elevation of the structure and the use of light, natural materials to ventilate the interior spaces, since (as previously mentioned) these constructive traditions have been used in regions with warm and humid climates [10].

The Sierra region, which is the primary subject of this chapter, is framed within the subclimatic map of Ecuador by INAMHI (the National Institute for Meteorology and Hydrology) as a sub-humid climate, cold temperate Mesothermal. The settlements belonging to this zone are located in areas with altitudes in the range of 1900 m.a.s.l. (meters above sea level) to 3200 m.a.s.l.; while the average annual temperature ranges

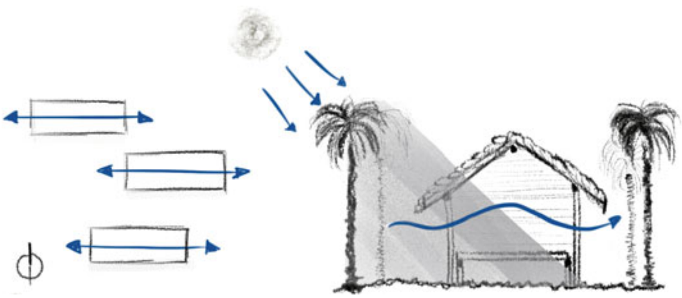

Fig. 4 Strategies at the urban level to improve the indoor thermal conditions of traditional housing in the Coastal, Amazonian and Insular regions. *Source* Own elaboration

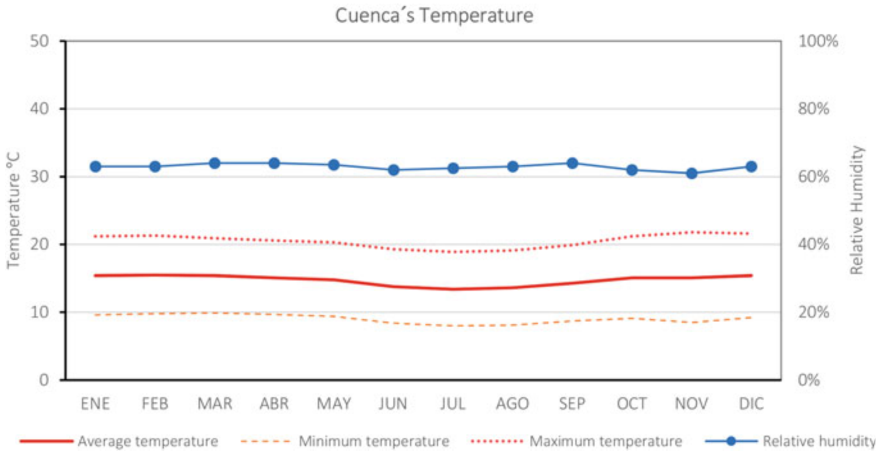

Fig. 5 Monthly average of the maximum, average, and minimum temperature; and the average relative humidity in the city of Cuenca. *Source* Own elaboration based on data from [11]

between 12 and 20 °C, the relative humidity ranges between 65 and 85%, and the annual rainfall fluctuates between 500 and 2000 mm [11].

The city of Cuenca is located in the Andean region of Ecuador at an altitude of 2560 m.a.s.l., so its climatic conditions are similar to those previously mentioned. The average annual temperature is 15.7 °C, with an average daily oscillation of 9 °C and an average annual oscillation of 2 °C. The months with the highest temperature are June, July and August. Regarding humidity levels, the annual average value is 62.9% [11], (see Fig. 5).

Considering this Andean city's climate, the aim of building design was to reduce thermal oscillations that is, to reduce temperature variations in the building interior. The traditional architecture in this region therefore had compact units, with reduced number of openings and used materials with high thermal inertia [2, 5].

Unlike in regions with warm climates, heavy materials such as earth were used in Cuenca, because the masonry of this material is able to absorb, retain and return heat to the interior of the house [12]. Therefore, the main strategy used in traditional construction in this region has been the use of heavy materials with high thermal inertia, especially in making the walls and roofing. The façade has small openings, which reduces both heat loss at night and excessive gains during the day. This implies that with larger glass surfaces, there will be greater heat gains in the daytime, while at night the heat captured will be also be lost more rapidly (see Fig. 6).

In addition, unlike in the layout of houses in hot climates, houses in this region have facades with the largest surface area oriented towards the east and west in order to capture the greatest amount of solar energy both directly through windows and indirectly through opaque surfaces.

It is thus evident that for both Ecuador and the rest of the world, building in warm and cold regions require opposite approaches. This marked heterogeneity arises out

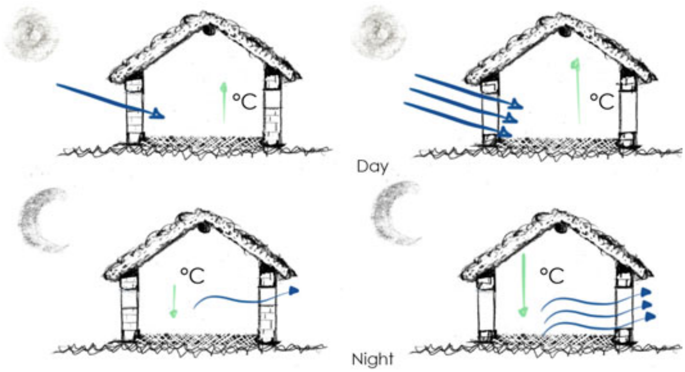

Fig. 6 Relationship between window area and heat gains and losses. *Source* Own elaboration

of the need to design optimal shelter in widely differing climatic conditions and with differential resource availabilities. In spite of all the thermal advantages offered by the use of these materials and construction systems, architecture in Ecuador has seen morphological changes, though mainly in the materials used. Starting in the 1960s, reinforced concrete emerged as a new construction technique, and by the 1970s steel began to be used [13]. The changes in construction systems and the use of new materials were mainly due to the emergence of Ecuador's oil economy [14, 15], which resulted in new materials being imported, in order to meet technical requirements in some cases and aesthetic whims in others.

Thus, little by little, the new materials and construction methods displaced the traditional techniques [15], and all the environmental considerations described above became secondary. Today in Ecuador there is standardization of architecture, such that construction characteristics are similar across the coastal, Amazonian or Andean regions, regardless of the climatic variations. Thus, the materials used are largely the same, and there is a tendency to reduce the weight of the materials used in construction, especially in the envelope. While this trend can be productive for buildings in hot climates (as it allows for faster heat dissipation), it is counterproductive for cold climates for the same reason (as it reduces the mass of the materials and leads to greater interior temperature swings). Consequently, 35% of the residents in the city of Cuenca do not have thermally comfortable conditions inside their homes [16], even in the case of houses that comply with the Ecuadorian construction standard [17].

2 Thermal Comfort and Materials in Traditional Housing

2.1 Thermal Comfort in the Andean Region

"Buildings are barriers to rain, wind and sometimes subtle filters to light and heat" [2].

Architecture is based on the premise of offering a space of shelter for the user, a feature that is undoubtedly met by any type of construction. However, not all are conducive to the thermal comfort of the inhabitant.

Thermal comfort is a concept that emerged from the modern movement, one made relevant at the time by the insertion of new air conditioning systems in architecture, resulting in scientific interest in comfort [18]. Thermal comfort has been approached from three main directions: rational, physiological and psychological [19]. This means that thermal comfort depends not only on the climatic conditions, but also on the adaptation of the individual inhabitant to their environment [20], a premise that makes the quantification of thermal comfort subjective and variable [21]. Several authors consider that the maximum air temperature that man can withstand is 55 °C, and by contrast, the minimum temperature that he can withstand is at the freezing point (0 °C) [2, 22]. According to the above, the ideal temperature should be somewhere in the middle of these two extremes [22]. In the search for the range of ideal or comfortable temperatures, several authors have formulated methods that consider different climatic parameters or factors.

On the one hand, Olgyay [22] established in his climatic chart that in areas with a moderate climate, the inhabitants would be in the 'comfort zone' at temperatures between 18°–24 °C in winter and between 21°–27 °C in summer, when the relative humidity is between 30 and 65%. This method considers the outside temperature, solar radiation, air velocity and relative humidity to determine the hygro-thermal comfort in outdoor conditions [23]. On the other hand, Givoni [24] established a comfort zone as being between 18°–25 °C in winter and 20°–27 °C in summer: he considered the average temperature and relative humidity to develop "The Building Bio-Climatic Chart", a climatic chart that seeks to focus more on the internal conditions of buildings, which have been represented in a psychrometric abacus. This tool also establishes four zones in which architectural corrections (such as solar gains, cooling or ventilation strategies) can be used to counteract thermal discomfort and create extensions to the comfort zone, (see Fig. 7).

As discussed, thermal comfort depends not only on climatic characteristics but also by the user's perception, and is influenced by social, economic and cultural conditions [24], so the feeling of comfort varies in each geographical area. However, there are several comfort ranges that have been established by different researchers. For example, Lopez [25] suggests a comfort range between 21 and 26 °C, with small fluctuations admissible depending on air humidity and user activity. The Spanish technical building code states that the comfort zone is around 20 °C [26]. The Ecuadorian construction standard establishes a comfort range between 20 and 24 °C for the study area [27].

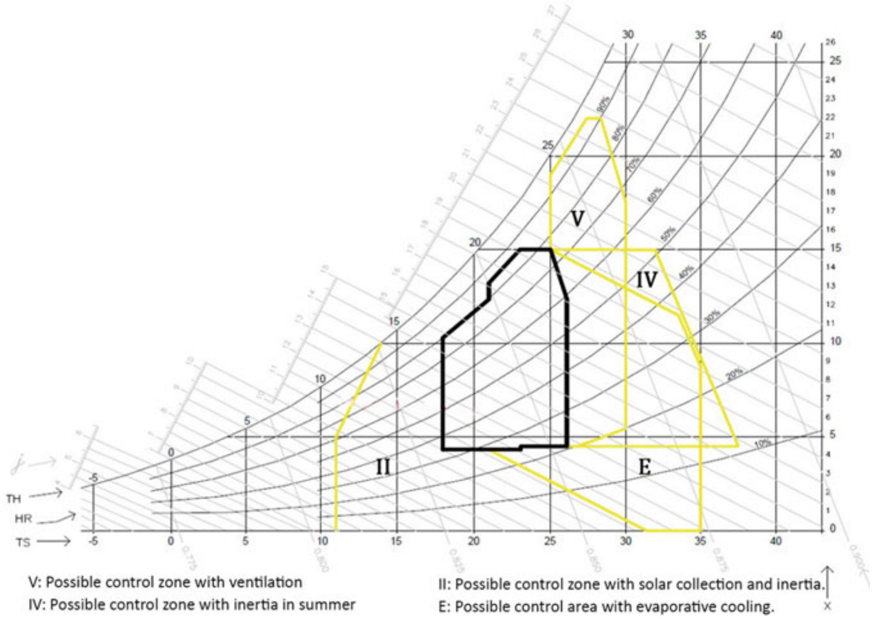

Fig. 7 Psychrometric abacus of Givoni at an atmospheric pressure of 1013 hPa (0 m.a.s.l.). *Source* Own elaboration based on [24]

According to this comfort range, the temperatures in the Andean region (specifically in Cuenca), which oscillate between approximate temperatures of 12 and 21 °C throughout the year, do not reach thermal comfort conditions, except in the months of October to February (when maximum temperatures are reached)—see Fig. 8.

When analyzing Cuenca's average annual temperature (15.7 °C) and average annual relative humidity (62.9%) and placing it on the Givoni psychrometric abacus, it is found that the city is located in a thermal discomfort zone. The possible architectural solutions proposed are solar gain and thermal inertia. The importance of these strategies can be confirmed by comparing with other studies conducted in more extreme climates than that of Cuenca. For example, in Barcelona-Spain, the use of thermal mass along with solar gain offers greater thermal advantages than the use of insulation [28].

At this point it is important to note that the traditional architecture used in this region of Ecuador was well-adapted to the local climatic conditions, because it sought to capture as much solar radiation as possible, absorbing it in the dwelling's large walls, retaining it and returning it to the interiors of the houses. However, the use of these empirical techniques and natural materials have gradually ceased in local construction. This, along with the fact that Ecuador does not have sustainability policies for buildings or urban spaces, has resulted in uncontrolled changes in the architectural and construction practices of the country [29].

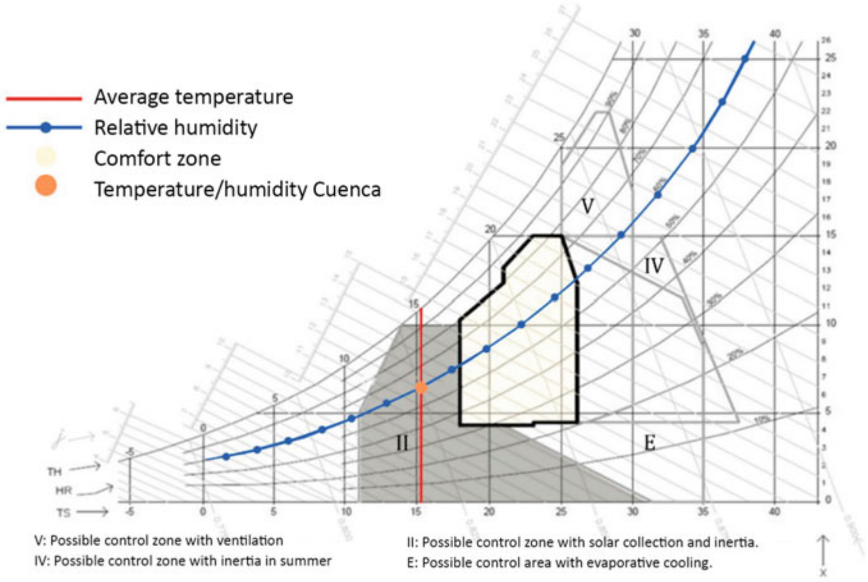

Fig. 8 Psychrometric abacus of Givoni, with mean temperature and relative humidity of the city of Cuenca

2.2 Materials in the Andean Region

One of the most popular materials in traditional construction has been raw earth, which was used in different construction techniques such as tapial, adobe, and bahareque, among others [1]. These techniques were used not only in the cities of the Sierra region of Ecuador, but also in other Andean regions, as well as around the world [30].

Earth as a building material has been used for thousands of years in traditional architecture practices across the world [31]. The U.S. Department of Energy estimates that more than half of the world's population lives in dwellings made with it [32]. Researchers evaluating its advantages have catalogued it as a thermoregulatory material that provides a warm internal environment in winter and a cool internal environment in summer [33, 34]. In addition to also having good acoustics (due to thick walls), it is a sustainable material due to its low embodied energy and high reusability [35–37]. The estimation of the embodied energy of an adobe house found that the use of earth in construction can save 370 GJ of energy per year, which in turn reduces CO_2 emissions by 101 tons each year [38], due to its low embodied energy and smaller ecological footprint. Thus, construction with this type of natural material allows buildings to be more environmentally friendly.

For this reason, several studies have proposed to validate the thermal performance of traditional earthen construction in various parts of the world. Michael et al. [39] evaluated the thermal stability of adobe, and estimated its ability to conduct and retain heat through two dynamic indicators: the time lag and the decrement factor. The time lag refers to the time needed for a thermal wave to propagate from the outer to the inner surface of a wall; while the decrement factor represents the ratio of the decrease of the amplitude of the thermal wave during heat transmission. The high time lag ($\geq$5 h) and low decrement factor (<0.05) values reported in their study confirms the thermal stability of adobe in interior environments, quantifying its ability to gradually expel the heat captured in the day into the interior environment during the night.

Adobe has been used in many parts of the world for example, in Peru, where approximately 6 million people live in the rural Andean regions, and where minimum temperatures range from −20 and −1 °C. In this cold region the main bioclimatic design strategy is passive solar heating, so traditional construction in these spaces used materials that could capture and store energy during the day and release it to the interior of the house during the cold nights. In general, the materials used were adobe, tile and ichu (a natural fiber native to the region), which fulfilled the requirement of passively heating a house with solar energy. However, some natural materials were replaced by industrialized ones, which do not contribute to indoor thermal comfort. In this context, Molina et al. [40] analyzed (using digital simulations) the significance of using materials with high thermal inertia on thermal comfort in buildings in these regions. The study found that the main heat gains were from the adobe walls (48.4%) and the skylights (21.8%), which absorbed heat during the day and released it at night. It concluded that the use of this construction system with adobe masonry contributed to the improvement of indoor comfort in this Andean region.

Another earthen construction system which predominated in other regions is the bahareque, which uses earth and different types of wood for structure. This technique has been replaced by hollow brick masonry and hollow concrete blocks, which use standardized building materials made by mass production processes. However, unlike traditional construction systems, these processes do not consider thermal comfort. Roux [41] conducted a thermal comparison of the three mentioned construction typologies, and found that the bahareque wall presents a time lag of 4.25 h, a value much higher than that obtained by the hollow brick and concrete walls, which had a lag no longer than 30 min. The paper concluded that natural construction systems offered better interior thermal conditions than standardized ones.

Another study compares the behaviour of wattle and daub masonry with concrete block masonry in an Andean region with a cold climate and large recorded temperature fluctuations. The study observed that when exposed to temperature variations, the wattle and daub construction witnessed lower temperature oscillations, which allowed the house to remain at a comfortable temperature 22% of the day by contrast, houses with block masonry were able to maintain a comfortable temperature for only 12% of the day [15]. This study too positions traditional construction as a more viable option when compared to globalized construction techniques.

The aforementioned studies have focused on validating the thermal behaviour of traditional earthen constructions in cold climatic regions. However despite this evidence, builders and users have largely rejected these construction system because they consider them unsafe and obsolete [42]. This is largely due to a lack of awareness and scarce information. What is clear is that construction systems have changed worldwide and traditional systems have consequently suffered, especially in Latin American cities [43] due to an emphasis on reducing costs and construction times [44–47].

These changes result in the loss of cultural identity as territories adopt imported trends. Additionally, by ignoring regional resource availability and constraints, they result in deterioration of environmental conditions. Andean cities have experienced the highest transition from traditional to modern construction systems, in response to the presence of new construction solutions and architectural styles or due to economic fluctuations [48].

This has been the experience of Cuenca, a city in the Andean region of Ecuador that has replaced traditional construction with new construction systems. Most of the natural and traditional materials have been gradually supplanted by new technologies and imported materials [49], in order to meet the new requirements of the sector and adapt to new architectural trends.

3 Weight Reduction in Construction Materials

Despite solar gains and thermal inertia being the main recommendations to improve thermal comfort in this city, houses in Cuenca have seen the mass of the materials in the building envelope progressively decrease.

Through the analysis in the previous chapter, where 10 dwellings from each period between 1980 to 2020 in Cuenca were studied (P1: 1980–1990, P2: 1991–2000, P3: 2001–2010, P4: 2011–2020), it has been possible to observe that the weight of the envelope has been reduced (masonry and roof elements are considered within this component). Over the time range analyzed, there have been varying fluctuations in the weight of the envelope; however, the greatest reductions were seen in period 4 (see Fig. 9).

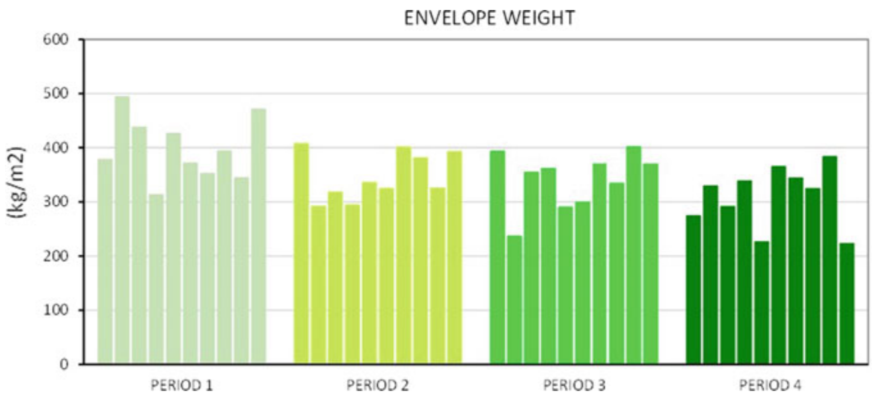

Fig. 9 Weight of the envelope component of the 10 dwellings analysed in each period

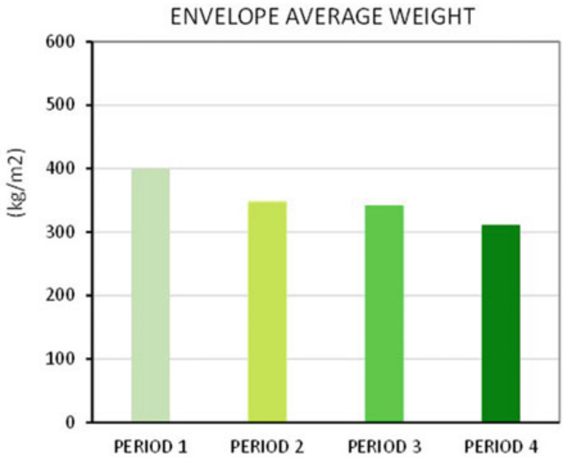

Fig. 10 Average weight of the Envelope component in each period

On averaging, the weight of the envelope in the 4 periods goes from 398 to 310 kg/m^2, a reduction of 22% (Fig. 10). This is mainly due to changes in the materials used, which substantially affected this component.

The reduction in the weight of building materials over the periods analyzed results in a reduction of their thermal mass. As shown in Fig. 11, traditional architecture sought to build thick walls with natural materials. In the first period analyzed, this type of construction was replaced by one with thick walls of handmade solid bricks, which still focused on maintaining the thermal inertia of the envelope. However, over the years, the rising demand for housing and the need to save money and construction time, led to reductions in the thickness of these walls, though they still used solid bricks. In the subsequent periods, the use of solid bricks began to decline, replaced first by concrete blocks and later by hollow bricks. These materials are lighter thus enabling reduction in construction times and lowering of costs. The problem with these materials is that they greatly reduce the thermal mass of the vertical envelope of the house. In these types of walls, heat transmission is greater (and so heat gains and losses increase); and since they have less thermal mass, the oscillations occur more quickly.

A similar trend is evident in the horizontal envelope (Fig. 12). Traditional construction sought to protect the user from low outside temperatures, and so the roofs used wood, a layer of earth with natural fibers, and on top of this, handmade tiles (cover and channel). Later, the layer of earth was eliminated, and only wood and tile were used both as a cover and as a channel to insulate the roof. In subsequent periods, fiber cement sheets began to be used with a single layer of tile on top (1991–2000). Finally, in the last period, the roof only used fiber cement as a single layer.

This analysis effectively demonstrates that the weight of the materials used in the envelopes of houses in Cuenca from 1980–2020 has reduced. This fact has impacted in the reduction of the thermal mass of the envelope. However how much does this reduction affect the thermal behaviour of the dwelling?

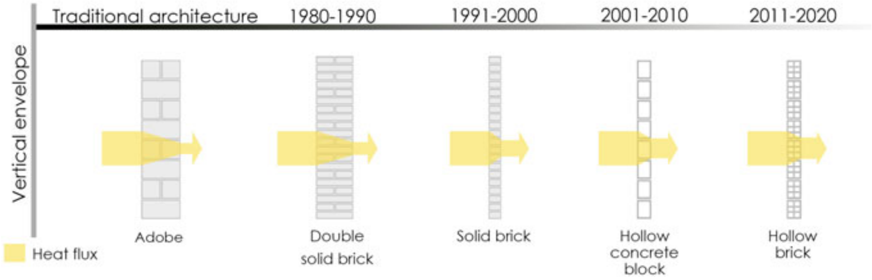

Fig. 11 Heat transmission in walls with different materials and thicknesses over time in the city of Cuenca

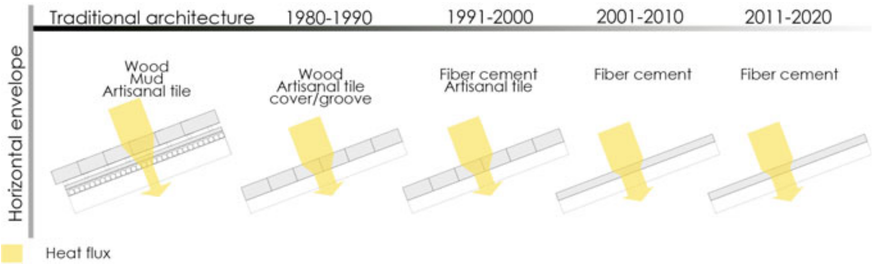

Fig. 12 Scheme of roof heat transfer through different construction system during the last decades in Cuenca-Ecuador

4 Thermal Impact of the Construction Systems Change

This section addresses the impact of the changes in building materials over the years on the thermal behavior of the dwellings in Cuenca, for which the indoor air temperature was taken as a reference parameter. The methodology implemented in this study was based on digital simulations. The software used was Design Builder, and its calculation engine EnergyPlus. The climate model configuration was performed with an EPW file specific to the city of Cuenca (ECU/_AZ/_CuencaLamar.Intl.AP.842390/_TMYx.2004–2018), which was obtained from the Energy Plus database. The comfort zone used to evaluate the results was 21 to 24 °C, as specified in [27]. This same range was used to calculate the air conditioning loads for both heating and cooling.

In order to provide an integral analysis of the interior temperature of the houses in Cuenca in each construction period, the predominant characteristics of 10 houses analyzed in each period were taken. These characteristics were applied to a base model, with the purpose of objectively analyzing the repercussion of the change in materials on the interior temperature, without generating morphological disadvantages from one period to another. The model was configured using the most representative typologies of the city under study. This base module was composed of two

Fig. 13 Base model for simulation

floors with a living-dining room, and kitchen on the first floor and bedrooms on the second floor. The building was attached on its east side and the glazed surfaces were oriented to the west. The space used for the analysis was the intermediate bedroom (8) located on the second floor, see Fig. 13.

The analysis day used for the simulations was August 11, representing an average cold day in the city under study. This day recorded a minimum and maximum temperature of 8 °C and 20 °C, respectively, with a relative humidity of 60%. The day was chosen based on air temperature values and not on solar radiation. Due to the geographic location of Ecuador, the solar paths do not vary greatly throughout the year; however, in August there is a decrease in air temperature, and this month registers the lowest values throughout the year.

The main characteristics that were considered to establish the calculation models for each period were the materials (mainly of the envelope), and the average window ratio. The results the model obtained for each period from the main characteristics identified from the initial analysis are specified below.

Period 1: 1980–1990

Based on the initial analysis of the 10 houses built in this period, two predominant construction typologies were identified. The greatest discrepancy was found in the materials used in the structure of the houses-while wood was the dominant material, some houses had already started using reinforced concrete as a complementary material. In the envelope component, the predominant material was solid handmade brick (used in most houses as a double wall, and in a small percentage of houses as a single wall). On the roof, fiber cement and handmade tiles predominate as the final covering. The proportion of glazed surface (windows) in this period corresponded to 41%, while the solid surface was 59%. See Fig. 14 for a visualization of the morphological and material characteristics.

The typology that was considered for the simulation (Fig. 14) was the one that used wood in its structure, since wood predominates in most of the houses analyzed for this period. In the case of the envelope, double masonry was considered on the first floor and the second floor, since it was the most commonly used construction system. In the case of the roof, a layer of fiber cement plus handmade tiles was used. Finishing materials were also considered in the simulations since they were part of the elements exposed to heat gains and losses. In the first floor, second floor, and in the ceiling, the predominant material was wood. Finally, in the vertical envelope, cement mortar plaster with paint was used as the final finish.

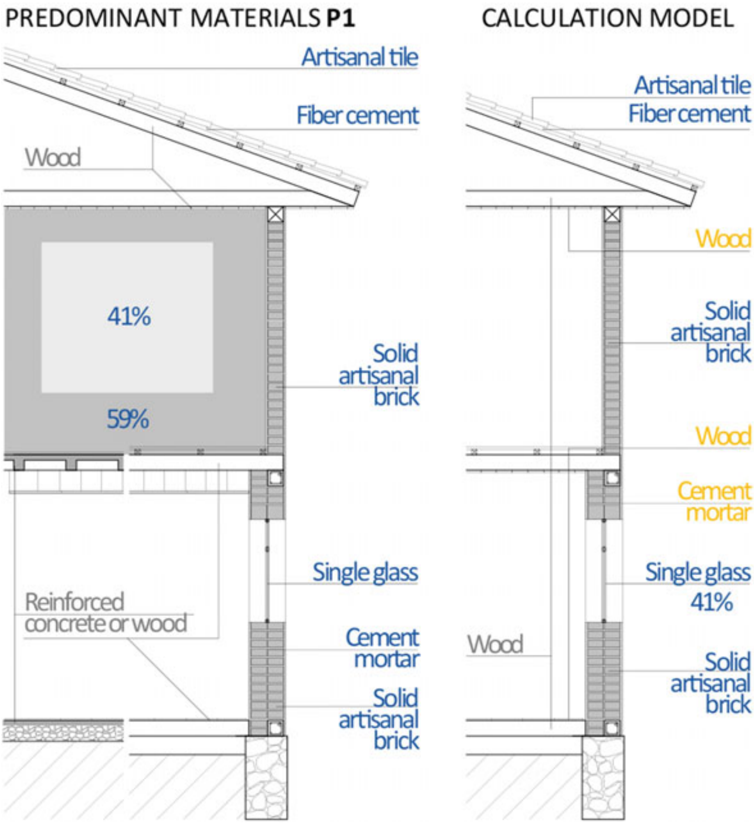

Fig. 14 Predominant morphological and material characteristics in the analyzed dwellings of Period 1

Period 2: 1991–2000

The characteristics of the dwellings in this period are similar to those found in the previous period. However, in this period, most of the structural elements used reinforced concrete and the use of wood was less frequent. In the vertical envelope, solid handmade brick was used as a simple wall, and in the horizontal envelope, fiber cement and handmade tiles were used. In this period the window area increased to 44% while the solid area reduced to 56%, Fig. 15.

In this period, the calculation model used for the simulation (Fig. 15), incorporated a reinforced concrete structure, both on the first floor and on the second floor; the wooden structure was maintained on the roof. In the envelope component, simple masonry of solid handmade brick was considered throughout the house; and in the roof, fiber cement and handmade tiles were used. Finally, the finishing materials required for the simulations were ceramic tile and wood for the floors, cement mortar and plaster for the masonry, and stucco plus plaster for the ceiling. This construction

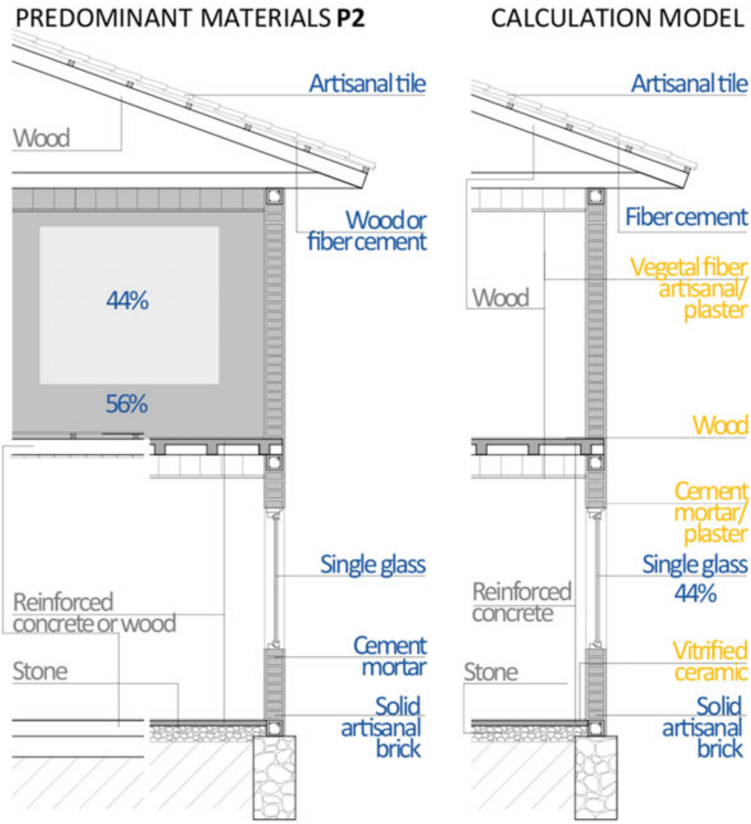

Fig. 15 Predominant morphological and material characteristics in the analysed dwellings of Period 2

typology was considered together with the average window ratio of the 10 houses analyzed in this period: this calculation model was represented by the predominant characteristics found in this general analysis.

Periodo 3: 2001–2010

In period 3, two predominant construction systems were identified. In this case, the main difference was in the materials used in the vertical envelopes of the houses. In this period the materials used in the structure were reinforced concrete and steel, and wood was used in specific cases (only for the roof elements). In the case of the envelope, the predominant masonry was solid handmade brick and light brick or a mixture of the two. In the vertical envelope, fiber cement and vitrified tiles were used as the final finish. Finally, for this period, the glazed surface (windows) area rose to 55%, while the solid masonry surface area dropped to 45%, (see Fig. 16).

The calculation model adopted for this period (Fig. 16)was composed of the predominant materials in the structure, such as reinforced concrete for most of the elements and steel for the roof. For the envelope, solid handmade brick was used for the first floor and light brick for the second floor masonry; and for the roof, fiber

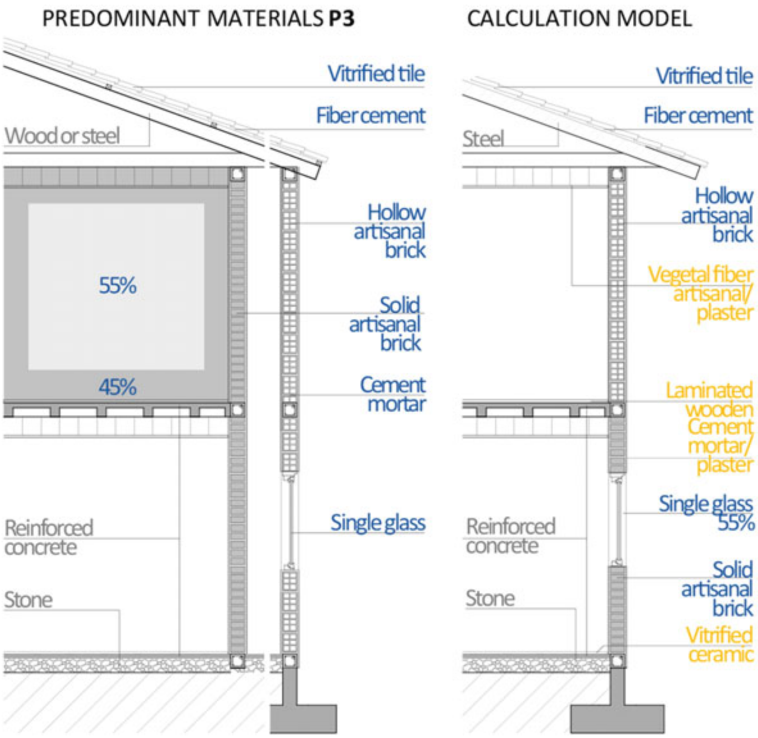

Fig. 16 Predominant morphological and material characteristics in the analysed dwellings of period 3

cement and glazed tile. The finishing materials exposed to heat gains and losses in the floors were ceramic tile on the first floor and laminated wood on the second floor; the coating used for the masonry was cement mortar plaster and filler; and finally, for the ceiling, stucco and filler were used. As mentioned above, the typology mentioned is the result of the general analysis of 10 houses built during this period.

Periodo 4: 2011–2020

For this period, three construction systems were identified, with the main differences being in the structural elements, since reinforced concrete, steel, or a mixture of these two materials were used in all the elements. In the envelope, different materials were also used, such as light brick, solid handmade brick and pumice block. In general, solid handmade brick was used in the first floor masonry, while light brick or pumice block was used in the second floor masonry, in order to reduce the weight of the construction. In this period, flat concrete roofing was introduced in the horizontal envelope and the use of fiber cement and tile reduced. Finally, the average glazed surface in this period corresponded to 73%, while solid masonry dropped to 27% (Fig. 17).

For this period, the design model (Fig. 17) was composed of reinforced concrete and steel structural elements, solid brick masonry on the first floor and light brick on

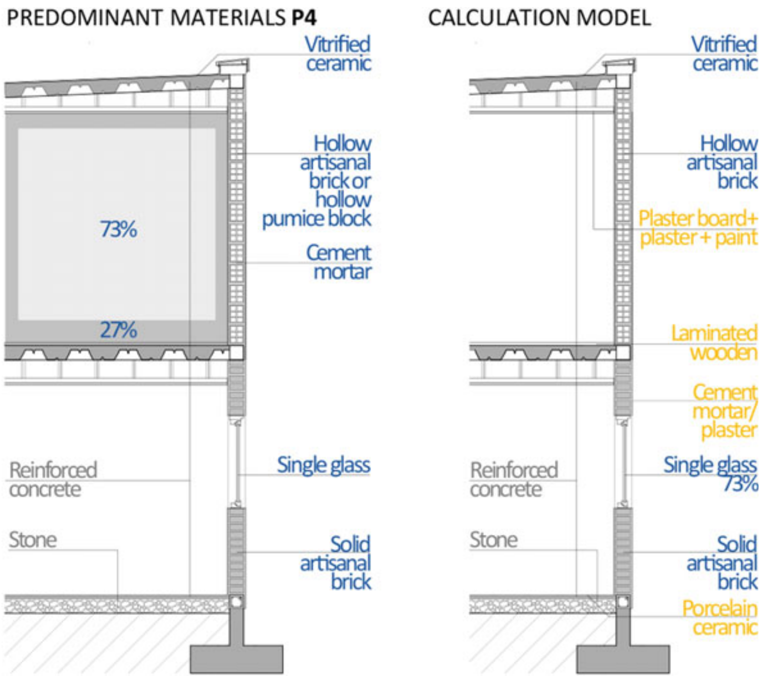

Fig. 17 Predominant morphological and material characteristics in the analysed dwellings of period 4

Table 1 Summary of the thermal parameters of the materials configured in the simulation software

Material	Thickness	Thermal conductivity (W/m.K)	Density (kg/m3)	Specific heat (J/kg.K)
Solid brick	0.13	0.72	1920	960
Hollow brick	0.13	0.72	1920	840
Fiber cement	0.01	0.25	1400	840
Tile	0.02	0.72	2000	840
Cement mortar	0.015	0.72	1650	920
Concrete	0.05–0.10	1.16	2400	1000
Wood	0.02	0.12	1380	510

the second floor, and reinforced concrete roofing with ceramic tile covering. Finally, the finishes included porcelain tile on the first floor and laminated wood on the second floor, the walls were covered with cement mortar plaster and plaster, and the ceiling was plasterboard plaster, finished with plaster. Once again, the calculation model represented the main characteristics found in the general analysis of the houses built in this period.

Table 1 shows the thermal characteristics of the materials used in each of the construction elements of the envelope.

Table 2 shows a summary of the parameters configured in the simulation software for the simulated environment based on the characteristics of each of the periods. In addition, this table shows the occupancy, infiltration and lighting values configured for the model. Regarding the occupancy values, a constant use of one person in the analyzed room was considered, this with the objective of evaluating the space 24 h a day as if it were a weekend day. Regarding the lighting, a schedule of use was configured from 6:00 pm to 11:00 pm, where a single LED luminaire was turned on. Finally, the infiltrations were configured with a value of 1.5 ach obtained from the study of [50] according to measurements taken in situ.

5 Results

The results obtained from the simulations were developed in two phases: in the first, each period was detailed and in the second, a comparison was made between the 4 periods analyzed. The comfort range used to evaluate the results obtained was from 21 to 24 °C as specified in [27].

Table 2 Summary of the parameters configured in the simulation software

Parameter	Period 1	Period 2	Period 3	Period 4
Window wall ratio (%)	41	44	55	73
Window U-value (W/m^2.K)	5.4	5.4	5.4	5.4
Wall U value (W/m^2.K)	1.67	2.50	2.8	2.5
Wall thermal mass (kJ/m^2.K)	160	148	148	133
Roof U value (W/m^2.K)	2.00	2.7	2.6	3.1
Roof thermal mass (kJ/m^2.K)	121	115	101	81
Occupation (24/7) (hab/m^2)	0.05	0.05	0.05	0.05
Infiltrations (24/7) (ach)	1.5	1.5	1.5	1.5
Illumination (18h00–23h00) (W/m^2)	2	2	2	2

5.1 Results by Periods

Period 1

Through the configuration of materials and average glazed surface in this period, the maximum interior temperature reached was 24.0 °C, while the minimum reached was 20.7 °C. This generates a daily temperature oscillation of 3 °C. According to the results obtained for this period, the typical house built between 1980 and 1990 has a comfort period of 16 h, from 12:00 pm to 4:00 am, which represents 67% of the day. Given the high thermal mass of the masonry in this period, the temperature reaches the comfort range in the afternoon hours and remains there until 4:00 am. In the morning period the house is less than 0.5 °C outside the comfort range (Fig. 18).

Period 2

In this period, several wooden elements were replaced by reinforced concrete, and the materials used in masonry decreased in weight, because the double masonry of solid brick used in period 1 was replaced by a simple masonry of solid brick. In this period the window surface also varies in Period 2 it increases by 3% in relation to Period 1.

The interior temperature of the calculation model for this period showed that there was a maximum temperature of 24.8 °C and a minimum of 19.6 °C. This generates a daily oscillation of 5 °C. According to the results obtained, the typical dwelling in this period remained within the comfort range from 1:00 p.m. to 2:00 a.m., that is, a total of 13 h, which represents 54% of the day.

In this period, similar to the pattern seen in period 1, the temperature reaches the comfort range in the afternoon hours and is maintained until 1:00 a.m. After that, from the early morning hours till mid-day, the house is outside the comfort range (Fig. 19).

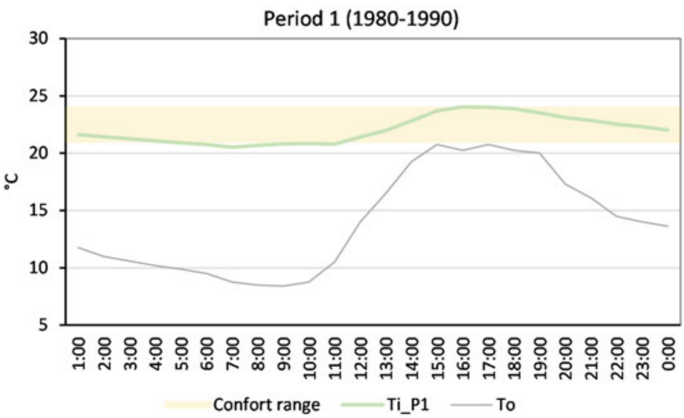

Fig. 18 Indoor temperature in the bedroom of the period 1 dwelling (Ti_P2), outdoor temperature (To) and comfort range

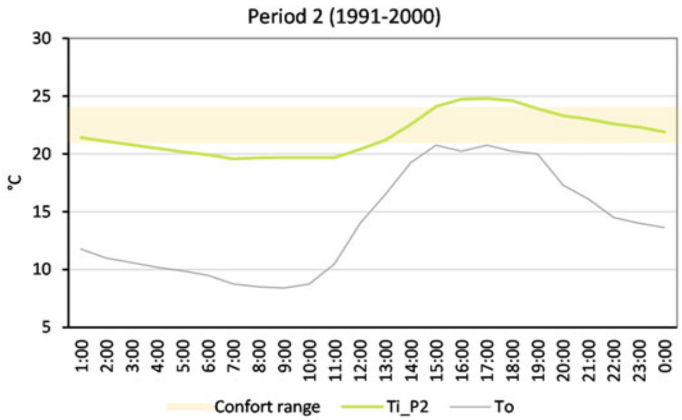

Fig. 19 Indoor temperature in the bedroom of the period 2 dwelling (Ti_P2), outdoor temperature (To) and comfort range

Period 3

In this period, the use of wood in the structural elements decreased, and was replaced by steel for the roof and reinforced concrete for the other structural elements. The walls used a different type of brick, which had a lower weight. Therefore, the vertical envelope in this period has a lower thermal mass than in the previous periods.

The change of materials, and the increased surface occupied by the windows, resulted in a maximum interior temperature of 27.0 °C and a minimum of 19.7 °C in the typical dwelling of this period, which translates into a daily oscillation of 7 °C (Fig. 20). In this period there is no longer a continuous period of thermal comfort on the contrary, there is an initial period of comfort from 01:00 pm to 02:00 pm; after

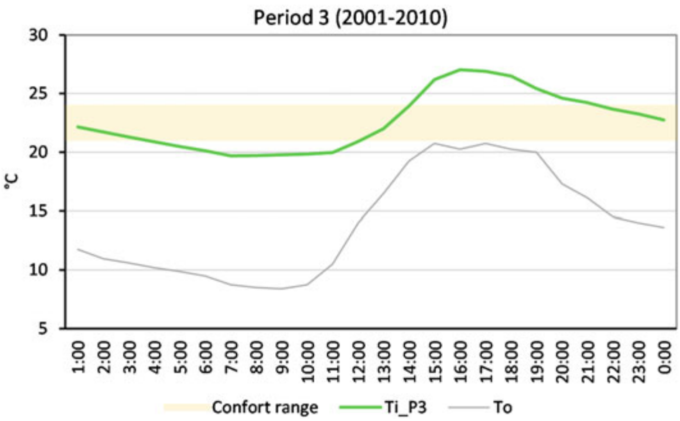

Fig. 20 Indoor temperature in the bedroom of the period 3 dwelling (Ti_P3), outdoor temperature (To) and comfort range

which the room warms up significantly (exceeding the comfort range from 02:00 pm to 09:00 pm); the temperature then drops again to the comfort zone from 09:00 pm to 03:00 am. After this, from the early morning hours till mid-day, the temperature is again in outside the comfort range. The total number of comfortable hours per day is 8 h, which represents 33% of the day.

In Period 3, the greater temperature oscillations are mainly due to the increase in the glazed surface (which occupies more than half of the wall area) and the reduction in the mass of the materials used in the envelope.

Period 4

In this period, the mass of the materials used in the roof increases. However, they do not seem to present thermal advantages over the previous periods. Through these results, it is possible to deduce that the increase in the glazed surface generates greater temperature variations, despite the fact that, in certain elements, their thermal mass increases. The glazed surfaces are principally responsible for the heat gains and losses, and so the calculation model for this period is outside the comfort zone for longer durations.

The results recorded a maximum indoor temperature of 29.3 °C and a minimum of 19.8 °C (Fig. 21). This generates a daily oscillation of 9 °C. The periods of time in which the temperature is in the comfort zone are similar to those observed in Period 3: after an initial short period of thermal comfort, the temperature increases and results in the overheating of the room. After this, as the temperature falls the comfort range is reached again, however, in the early morning hours the temperature decreases and the rooms goes out of the comfort zone again. As per this analysis, the indoor temperature remains within the comfortable range for 8 h, i.e. 33% of the day. Once again, the large temperature variations presented in this period were due to the

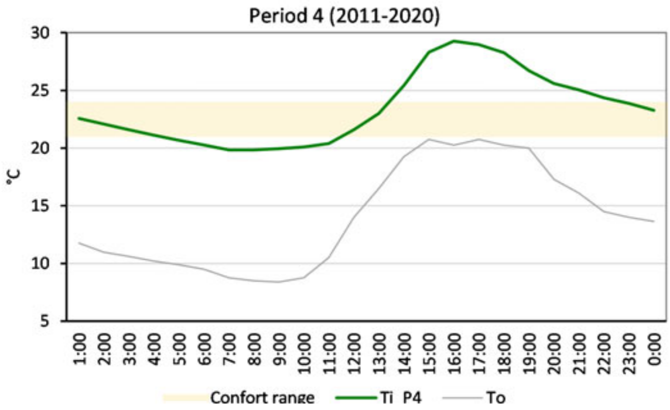

Fig. 21 Indoor temperature in the bedroom of the period 4 dwelling (Ti_P4), outdoor temperature (To) and comfort range

increase in the glazed surface of the façade and the reduction of the solid masonry surface.

5.2 *Overall Results*

Figure 22 groups the indoor temperatures obtained in each period to provide an overview of the results, from which two trends can be observed (Fig. 22).

In houses built in Periods 1 and 2, the temperature drops below the comfort zone and reaches a minimum of up to 19 °C; after this, the temperature increases

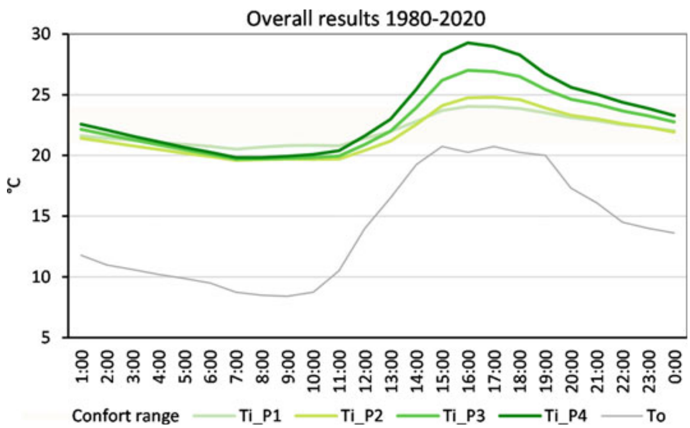

Fig. 22 Indoor temperature of the 4 periods analyzed in relation to the comfort zone

and remains within the comfort zone. This is because the materials used in these dwellings have a higher thermal mass and are able to retain heat for longer periods of time. In addition, the surface area of the windows, that varies between 41 and 44%, does not allow large heat losses as seen in the later periods.

Houses built in Periods 3 and 4, by contrast, show a different trend, since in this case, the temperature rises above the comfort zone until it reaches a maximum of 29 . After this period, as the temperature drops initially the comfort zone is reached, and then it continues to fall till it reaches a minimum of 19 °C. These high temperature variations are principally due to the heat flux through the vertical and horizontal envelope. On the one hand, since the vertical envelope is mostly made of glass, during the day there are heat gains large enough to lead to overheating of the room. Additionally, this glass has no insulation and when it cools down, the temperature tends to drop and there are substantial heat losses. On the other hand, in these two periods the horizontal envelope uses fewer layers than in previous periods, which significantly increases the thermal transmission of this surface. In addition, since in equatorial regions the roof is the most exposed surface of the envelope to the solar radiation and it is the surface with most heat interchange with the sky [51], this element is one of the most responsible for the heat gains in the day and the heat loses in the night.

Throughout this chapter we have discussed several factors affecting thermal comfort and how traditional architecture adapted to the climatic conditions of each geographical area. Thus, based on the results obtained in this study, it is possible to state that the change in materials and the increase in the glazed surface (or in other words, the insertion of new architectural trends), have caused large oscillations in the interior temperature of dwellings.

Morphological and material variations have repercussions for the interior thermal behavior of the dwelling. The heat gains from solar radiation, internal inputs (lighting and occupancy) and the large thermal mass can allow a space to reach an interior temperature within the comfort range (as seen in Periods 1 and 2), even when the outside temperature reaches 9 and 20 °C. However, solar radiation inputs rise due to the increased glazing area (as seen in Periods 3 and 4) resulting in the indoor temperature rising above the comfort range. These results imply that the interior space of modern buildings in Cuenca would additionally require the use of cooling strategies, or even the use of active cooling systems.

In this context, an analysis of the active cooling and heating requirements are made below, based on the degree-hours. This allows us to identify the periods of thermal comfort and discomfort in which each of the simulated dwellings is located. As mentioned above, the periods of time in which the temperature falls or rises above or below the comfort zone (21–24 °C), respectively, are considered as periods that require energy for cooling or heating (Fig. 23).

In this study, the housing model of Period 1 presents the lowest energy requirement, in relation to the other periods, i.e. this model is closest to being completely within the comfort zone. In Period 2, the energy requirement increases 12 times. In this period the highest energy demand is for heating systems, due to the fact that

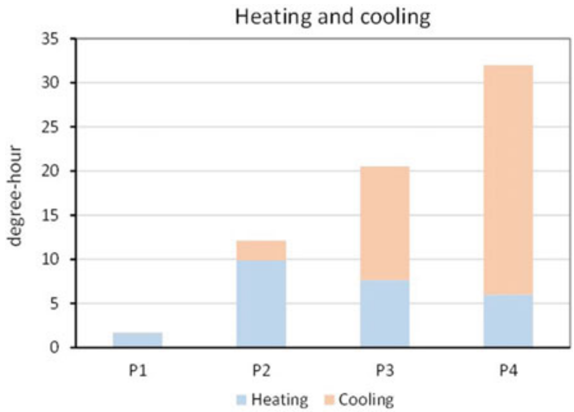

Fig. 23 Heating and cooling requirements for the 4 periods analyzed as a function of comfort degree-hours

in the early morning hours and in the later morning periods the temperature of the house drops below the comfort zone.

In the subsequent periods, the energy requirement increases substantially due to the need for cooling systems to counteract the overheating of the room in the day, which occurs due to the increased window surface in these periods, which allow greater heat gains and losses.

It is thus evident that, in general, as indoor thermal comfort has decreased in Cuenca's dwellings, the energy demand has increased over the years. Therefore, the change in materials and the use of new architectural trends over the years has not resulted in improvements in indoor thermal conditions, but rather a reduction in thermal comfort. Therefore, modern construction and design changes create habitability inconsistencies such as the possible need for cooling systems in temperate climates, such as that of the city under study.

6 Conclusions

This chapter has focused on analysing the repercussions that the change in materials and construction systems had on the interior temperatures of the dwellings in Cuenca built between 1980 to 2020. These repercussions, in addition to impacting the indoor temperatures, also influence the operational energy consumption of houses. The aim of the results presented here is to raise greater awareness to the requirements of regional architecture, such that it can meet the needs of its users, generate interior comfort and remain environmentally friendly. Several conclusions can be drawn from the results analyzed in this chapter.

First, architecture has undergone a global standardization, which means that attention is no longer paid to the context in which buildings are built, but instead greater prioritization is given to economic considerations, and in several cases, to aesthetics and comfort over concern for the environment. For these reasons, traditional materials have been replaced by more modern, lighter ones, which allow reductions in the time and costs of construction.

Second, the results obtained show that the change in materials together with the increase of the window surface have had a negative and deteriorating impact on the interior comfort of the dwellings over the years. In addition, an increase in the glazed surface directly determines the reduction of thermal comfort as it is the area most sensitive to heat gain and loss. The progressive increase of this surface area generates increasingly longer periods of discomfort, and contrary to what might be expected in this climate, the use of cooling systems becomes necessary due to the high heat input from solar radiation.

This chapter shows the tendency of the construction sector to use new materials, and assesses the impact of these materials with interior thermal comfort. It provides a possible approach for determining future guidelines to promote the use of materials which are responsive to the climatic conditions of the local environment, and encourage adaptations that can both satisfy the needs of the user and maintain the balance with the environment.

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Construction Development, Economic Evolution, and Environmental Impact in Ecuador

Jefferson Eloy Torres-Quezada, Tatiana Sánchez-Quezada, and Gilda Vélez-Romero

Abstract The construction industry has for many years been a cornerstone in the world economy, and serves as a reliable indicator of a country's economy since its evolution is pro-cyclical, i.e., it behaves just as the total production does. This chapter focuses on the impact of the Ecuadorian construction sector's performance on the GDP, as well as its possible relationship with the energy consumption. Hence, this study examines construction, economic, and environmental variables in the Ecuadorian context. With this objective, different indicators such as the GVA, energy demand, and electricity consumption have been considered and compared, during the period from 1997 to 2020. The analysis uses Pearson's correlation coefficient to measure the statistical relationship between the variables. The results confirm that the increase in Ecuador's economy is directly related to the increase in the construction sector, which in turn has a direct influence on the energy expenditure and consumption by different sectors, and specifically, by residential buildings, which shows a directly proportional dependence. In other words, the increase in the country's economy generates a greater amount of construction, which in turn consumes more energy and therefore, is more environmentally polluting.

Keywords Construction development · Economic evolution · Energy consumption · GVA · GDP

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1 Introduction, Concept, and Process

1.1 Introduction

Economic reliance on the construction industry, and vice versa, has been a recurring phenomenon for many years in countries around the world, see Fig. 1.

Construction systems are an essential contributor to economic development, as they not only meet social and developmental requirements, they also boost production in other related sectors. The importance of the construction sector in the evolution of a country's economy can be seen in many countries- for example, in the case study of China [1]. However, resource consumption and emissions by this sector have also raised concerns about its sustainability. In China, the construction sector's increasing role as the 'power engine' for the Chinese economy also led to growing carbon emissions by this sector [2]. Similarly, according to Tatari and Kucukvar [3], the construction sector in the United States of America is an essential contributor to economic development, given that it protects social development and can also boost the production of other related sectors.

The economic reliance on this sector is echoed in different countries across Asia [4], Europe [5], and America [6]. Nonetheless, the extent of this relationship, according to Wilhelmsson and Wigren [7], depends on the diversity of each country and the period it is going through.

In Ecuador too, there are indications that growth in the construction sector is related to economic development [8]. Furthermore, this connection is likely associated with variations in embodied energy, consumption and CO_2 emissions of buildings.

Torres-Quezada et al. [9] assert that the Embodied Energy (the energy consumed for the production of a material) of dwellings saw a growth trend in the last 4 decades, with the largest increase occurring in the transition from the 1990s to the 2000s, most likely due to the globalization of the construction sector and the change in

Fig. 1 Figurative illustration of the relationship between the economic sector and the construction sector. *Source* Own elaboration

the monetary system that Ecuador underwent when transitioning from sucres to US dollars.

In Ecuador, as in other parts of the world, economic recovery from the recession caused by the COVID-19 pandemic is likely to boost the construction sector, a growth which will almost certainly lack awareness about the environmental impact of the materials used and the impact of the construction system on thermal comfort inside homes. However, it is necessary to address economic concerns though a sustainable and environmentally friendly development approach.

In this context, this chapter examines the relationship between Ecuador's economic evolution and the development of the construction sector. The specific objective of this study is to analyze the evolving relationship between the country's construction sector, economy, and energy consumption. The chapter begins with a discussion of the different economic concepts needed to evaluate the economic changes in the country.

1.2 Concepts

GrosS Domestic Product (GDP)

Vascones Gavica and Villena Izurieta [10] state that "Gross Domestic Product is comprised of the total of the monetary values of the final demand goods and services that were produced by the country in one year" (pp.19–20). According to Parkin et al. [11] not only does the GDP measure the value of total production, it also calculates total income and total expenditure. It is of paramount importance that there exist a symmetry between the values of total production and total income because it then shows a direct relationship between productivity and people's standard of living. The productivity then increases as incomes do, thus enabling the acquisition and production of more goods and services, and showing a direct relationship between the increase in income and the growing value of production.

Similarly, the Central Bank of Ecuador [12] defines Gross Domestic Product as "The value of goods and services of final use generated by economic agents during a period. Its calculation—in global terms and by a branch of activity—is derived from the Input–Output construction, which describes the flows of goods and services in the productive apparatus, from the viewpoint of producers and end-users".

Hernández [13] in his book *Introduction to Economics*, discusses three different ways of calculating GDP:

1. The expenditure method: In this method, independent calculations are made of the GDP component variables: household consumption (personal consumption), government consumption, variations in inventories, gross fixed capital formulation, and net exports.
2. The production method: This method calculates gross value added by deducting intermediate consumption from the gross value of production. Calculations of the

gross value of production are made at basic prices, while intermediate consumption is valued at market prices (since these inputs entail transportation and marketing costs). The gross value added, for each branch of economic activity, is expressed in basic values, since, in addition to deducting the margin of transport and trade, it also deducts the net indirect taxes on products.

3. The payment to factors method (income method): The method of payment to the factors of production consists of calculating and adding the components of the value added: remunerations, capital consumption, and the net operating surplus that includes the income of self-employed workers, interest, royalties, profits and remunerations to entrepreneurs, among other concepts.

Larraín and Sachs [14] state that the production of an economy is measured through its GDP, which can be measured in two ways. Nominal GDP measures the value of a country's production of final goods and services at current market prices. Real GDP measures the value of output at base-year prices. Since real GDP holds prices constant to the base year level (that is, adjusts for inflation), it gives us an idea of how much the overall economy is growing as a result of increases in the number of goods and services produced, and not due to increases in prices (p. 43).

As discussed above, the GDP is an extremely well-studied index, which has been used as a variable to describe the economy of a city, state or even a country [15]. This index is one the reference parameters used in this study to describe the economic evolution of Ecuador.

Gross Value Added (GVA)

Gross Value Added, also known by its acronym GVA, is a macroeconomic indicator that calculates the total value generated by a specific sector, region, or country. It refers to the value of goods and services produced in a particular territory during a specific period after deducting indirect taxes and intermediate consumption. Pereira et al. [16] point out that GVA is important for analyzing the economic growth of a country, being an indicator that demonstrates the economic evolution and the primary income sources of a nation.

Relationship Between GDP AND GVA

GDP refers to the total market value of final goods and services produced in a country during a given year, while GVA is the value created by subtracting intermediate consumption from GDP. The relationship between the two is as follows:

GVA = GDP–intermediate consumption

In this regard, Salinas Campuzano et al. [17] note that GDP is the complement of the aggregate values of the different stages of production and the various sectors of the economy. GDP is obtained from a country's GVA since the two have a very close relationship. GVA is obtained by subtracting intermediate consumption from the total output of a country. From a country's point of view, the GVA is one of the most important macro-level indicators of a nation's economic growth and production development, since it can give perspective of a specific sector and its influence on the GDP.

1.3 Methodology

To attain the proposed objectives, the methodology of this study is divided into two phases. In the first phase, a bibliographic and analytical review of the evolution of Ecuador's economy and its construction sector is conducted. This review focuses on the GDP and the GVA of the different sectors that constitute the total GDP. The data are collected from 1965 to 2020 in the case of GDP, and from 1997 to 2020 in the case of GVA. The analyzed periods are based on the data available in the annual bulletins obtained from the Central Bank of Ecuador [12]. All these values are expressed in thousands of dollars, and data before the year 2000 have been converted from Sucres to Dollars according to the exchange rate of the year 2000 [12].

These data were analytically assessed to describe the behavior of the country's economy in relation to the construction sector and its representativeness over the last decades. Furthermore, the evolution of the construction sector was analyzed through the change in the built-up area (evaluated as square meters of constructed area) in the 3 most important cities of Ecuador (Guayaquil, Quito, and Cuenca) from 1997 to 2020, according to the construction permits issued. These values are expressed in thousands of square meters and were taken from the database of the Central Bank of Ecuador.

In the second stage, a statistical correlation study was performed to analyze the relationship between the economic, construction, and energy sectors in Ecuador. To this end, Ecuador's GDP, GVA of construction, energy demand, and electricity consumption were used as variables. Along with these variables, the GVA values of other productive sectors were compared to the construction sector's GVA to analyze its impact on other sectors (manufacturing, commerce, and transportation) that contribute to Ecuador's economy. The data taken for this correlation were the annual values of these variables from 1997 to 2020, i.e. 24 correlation points, which were previously evaluated in the first phase of this study. The correlation index between these variables was evaluated through the coefficient of determination (r^2).

2 Economic Evolution of Ecuador

As mentioned above, in this first stage GDP was taken as a parameter for measuring the country's economy. In Fig. 2, the evolution of GDP over 5 decades (from 1965 to 2020) is shown, according to information collected from the Central Bank of Ecuador [12].

Based on these data, several points can be highlighted in Ecuador's economic history. Ecuador's GDP from 1965 to 1972 had a fairly horizontal trend and marked

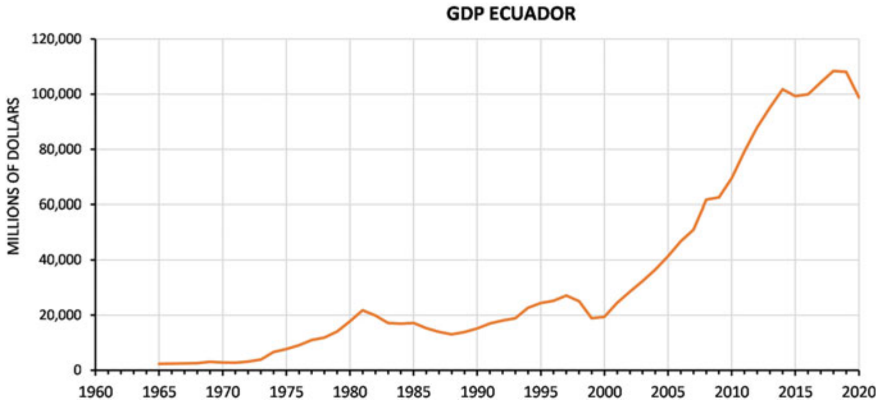

Fig. 2 Evolution of the Gross Domestic Product in Ecuador from 1965 to 2020. *Source* Author's own work with data taken from [12]

the period with the lowest values in this time series. From 1973, the GDP started to rise, coinciding with the beginning of oil extraction in Ecuador, which according to [18] started in the same year. From this year onwards, this economic indicator showed positive trend growth, however, the graph itself exhibits both negative and positive slope changes.

The first inflection point came in 1981, when the slope of the graph turned negative, a trend which continued till 1988. According to Montalvo [19], the 1980s were memorable as a long period of successive tax and balance of payments crises, where Ecuador's old currency, the Sucre, was devaluated 3,857%. After 1988, the trend again reversed as GDP growth increased. This increase coincided with several factors which propelled growth such as the industrialization of the shrimp sector [20]. In 1997, another inflection point was reached as the slope turned negative, though this time for a much shorter duration. This decrease was due to the economic problems that the country suffered at the end of the millennium, when uncontrolled inflation and depreciation of the Sucre led to the dollarization of Ecuador in 1999. As of this event, the GDP had a much more pronounced growth, rising from around from around 20,000 million dollars in 2000 to roughly 102,000 million dollars in 2014, an increase of approximately 500%, as shown in Fig. 2. Thereafter, a considerable decline was observed in 2015, when due to the drop in oil prices, revenues generated by this sector also declined- as discussed in the following section.

The latest reduction in this economic index (and the largest after Ecuador's dollarization) was in 2020 and due to the pandemic caused by COVID-19, an event that also adversely affected the world economy. As a result of this health emergency, Ecuador's GDP reduced from around 108,000 million dollars in 2019 to an approximate 98,000 million dollars in 2020, a reduction of approximately 10% [12].

The economic evolution of Ecuador has had different behaviors according to the development of the country's GDP, where different trends are shown in this process.

These abrupt variations in GDP are influenced by different productive events, where the construction sector has a great influence.

For a deeper analysis of the influence of different sources of income on the Ecuadorian GDP, an analysis of the GVA of different sectors have been carried out. Information was taken from the Central Bank of Ecuador's database from 1997 to 2020 [12]. The bulletins collected have 45 items from different sectors that contribute to GDP grouped into 18 categories. For a more synthetic analysis, the different categories were grouped to obtain 10 sectors for the purpose of this analysis, while all the remaining uncategorized elements which contribute to the GDP were classified as a separate grouping called Other Elements (OE). The grouping of the different sectors analyzed is shown in Table 1. The data collected for these 11 categories from 1997 to 2020 are shown in Fig. 3.

According to this information, the different GVAs show quite varied behaviors throughout the analyzed period. In the 1990s, the sectors with the highest contribution to Ecuador's GDP were S1_Agriculture, aquaculture and fishing; S8_Financial, professional and domestic activities; S6_Commerce, accommodation and food; and S9_miscellaneous. The sectors with the next highest GVA values were S3_Manufacturing; S2_Oil and Mines; and S7_Transportation. Meanwhile, the sectors with the lowest values were S5_Construction; S10_Other services; and S4_Electricity and water. The latter (S4) remains the sector with the lowest contribution to the GDP during the entire analysis period. At the beginning of this period, the GVA of construction, manufacturing, and even petroleum and mining were among those that contributed the most to Ecuador's GDP.

After 1997, the GVA for all the sectors- except for oil and mining—showed a decreasing trend until 2000, when Ecuador's financial crisis (mentioned above) occurred. The oil and mining sector showed a fairly steep growth curve during this period, increasing in value from 950 million dollars in 1998 to 4,800 million dollars in 2000 (approximated values) [12]. Oil prices are quite volatile and depend mainly on external agents, making them a high-risk export for export-oriented, oil-dependent economies. As a consequence, the GVA of this sector in Ecuador was very erratic, experiencing several abrupt expansions and contractions after 2000 [21]. In the early 2000s, it first decreased sharply and then entered a growth trend, rising to a GVA of approximately 10,000 million dollars in 2008, when the price of this fossil fuel reached its highest value in the last few decades (120 dollars per barrel), which meant higher revenues to the fiscal coffers through oil collection by the Ecuadorian State [22]. In 2009, the GVA of this sector decreased sharply again however, it rose soon after to reach its highest value of 12,000 million dollars in 2013. From 1999 to 2013, S2_oil and mines remained one of the sectors with the highest contribution to the country's economy. After this period, the contribution of this sector to Ecuador's GDP significantly, reaching approximately 4,750 million dollars in 2016. Although it has since managed to raise its value, it does not count as one of the sectors with the highest GVA in recent years.

Similar to most other sectors, the GVA of S5_construction decreased near the end of the millennium; nonetheless, its fall was much milder than that of other sectors. From here, the sector entered a growth trend, expanding progressively it

Table 1 Grouping of sectors considered for the GDP analysis

A	**Agriculture**	S1_Agriculture, aquaculture, and fisheries
001	Banana, coffee, and cocoa cultivation	
002	Flower cultivation	
003	Other agricultural crops	
004	Animal husbandry	
005	Forestry, timber harvesting, and related activities	
B	**Aquaculture and shrimp fishing**	
006	Aquaculture and shrimp fishing	
C	**Fishing (except shrimp)**	
007	Fishing (except shrimp)	
D	**Oil and mining**	S2_Oil and mines
008	Oil, natural gas extraction, and related service activities	
009	Mining and quarrying	
E	**Petroleum refining**	
024	Manufacture of refined petroleum products and other products	
F	**Manufacturing (except oil refining)**	S3_Manufacturing
010	Meat processing and preservation	
011	Shrimp processing and preservation	
012	Processing and preservation of fish and other aquatic products	
013	Processing of vegetable and animal oils and fats	
014	Dairy product processing	
015	Milling, bakery, and noodle products processing	
016	Sugar processing	
017	Cocoa, chocolate, and confectionery processing	
018	Processing of other food products	
019	Beverage processing	
020	Tobacco processing	
021	Manufacture of textile products, and apparel; manufacture of leather and leather goods	
022	Production of wood and wood products	
023	Manufacture of paper and paper products	

(continued)

Table 1 (continued)

025	Manufacture of chemicals and chemical products	
026	Manufacture of rubber and plastic products	
027	Manufacture of other non-metallic mineral products	
028	Manufacture of base metals and metal products	
029	Machinery and equipment manufacturing	
030	Manufacture of transportation equipment	
031	Furniture manufacturing	
032	Manufacturing industries NCP	
G	**Electricity and water supply**	S4_Electricity and running water
033	Electricity and running water supply	
H	**Construction**	S5_Construction
034	Construction	
I	**Trade**	S6_Trade, lodging, and food services
035	Wholesale and retail trade; and repair of motor vehicles and motorcycles	
J	**Lodging and food services**	
036	Lodging and food services	
K	**Transportation**	S7_Transport
037	Transportation and storage	
L	**Financial services activities**	S8_Financial, professional and domestic activities
039	Financial services activities and insurance scheme financing, except social security	
M	**Professional, technical and administrative activities**	
040	Professional, technical and administrative activities	
N	**Domestic service**	
044	Private households with domestic service	
O	**Mail and communications**	S9_Miscellaneous
038	Mail and communications	
P	**Public administration, defense; compulsory social security plans**	
041	Public administration, defense; compulsory social security plans	
Q	**Education and health and social services**	
042	Teaching	

(continued)

Table 1 (continued)

043	Health and social services	
R	**Other services**	S10_Other services
045	Other services	
OE	**Other elements of GDP**	OE_Other elements

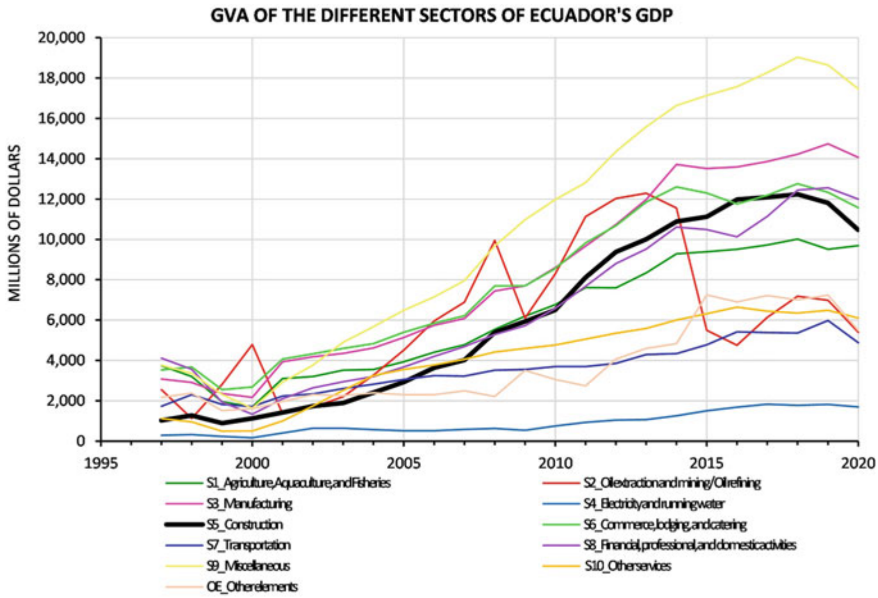

Fig. 3 GVA by sector to Ecuador's GDP. Author's own work based on [12]

reached a peak in 2018 (at 12,000 million dollars). In the last two decades, steady growth has seen this sector become one of the largest contributors to Ecuador's economy, contributing between 10 and 12% of total GDP since 2010. Indeed, as of this year (2010), S5_construction has had higher representativeness than S1_agriculture, aquaculture and fishing and S8_financial, professional and domestic activities, and is only below S3_manufacturing, S6_trade, accommodation and food, and S9_miscellaneous, the latter of which includes several sectors such as social security plans and mail-communications (see Fig. 4).

An analysis of Fig. 3 identifies three moments when a significant detrimental impact on the GVA of the sectors under study can be seen. The first was in 2000-the confluence of several factors in the late 1990s (including the 'El Niño' phenomenon in 1998, the concurrent fall in oil prices and the international financial crisis), led to destabilization of Ecuador's economy and high inflation in the local currency. The consequent political, financial and social difficulties, and the threat of hyperinflation,

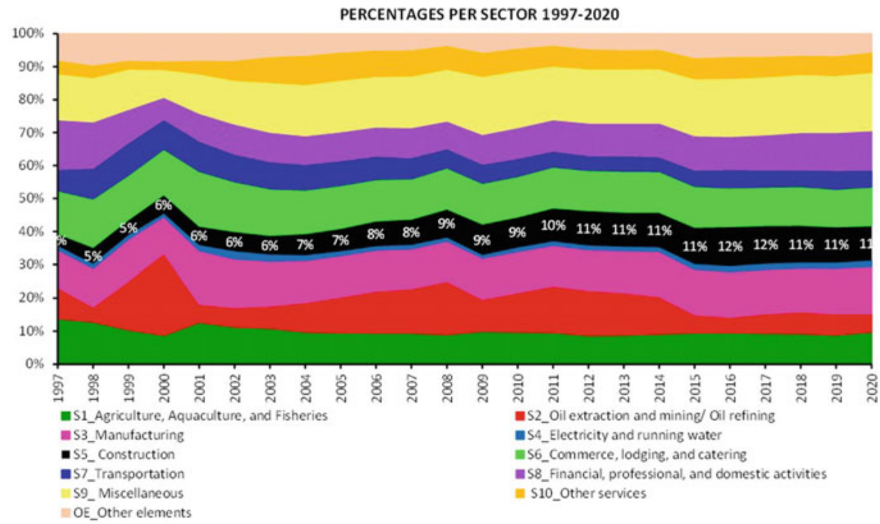

Fig. 4 Percentage of GVA per sector to Ecuador's GDP. Author's own work based on [12]

lead the Ecuadorian government to adopt the US dollar as legal tender in 2000 (dollarization) [23].

The second was in 2016, when the Pedernales earthquake caused considerable damage to homes, buildings and productive infrastructure in the rural and urban sectors; damaged the agricultural sector; and lead to decreased exports, and losses of formal and informal labor sources, resulting in a strongly negative impact on the economies of the region and the country [24]. The third and latest, was in 2020, with the pandemic caused by COVID-19. The construction sector has maintained a fairly steady GVA growth and did not experience the declines seen by the other sectors in most of the periods mentioned above (the exception being the pandemic year of 2020). In 2020, the fallout from the global pandemic meant all the sectors suffered a decrease, except S1_agriculture, aquaculture, and fishing, which showed a small increase.

3 History of Construction at the National Level

The real estate and construction sector in the main cities of Ecuador have experienced changes that have impacted in the development of the industry in the last 25 years. As shown previously, while the GVA of the construction sector (S5) saw a significant decline at the end of the millennium, after this, it has increased due to the economic stability achieved by the country after dollarization. Several authors state that this event strengthened realty companies due among other factors to the inflow of foreign currency from migrants focused on acquiring real estate [25, 26]. Similarly, the

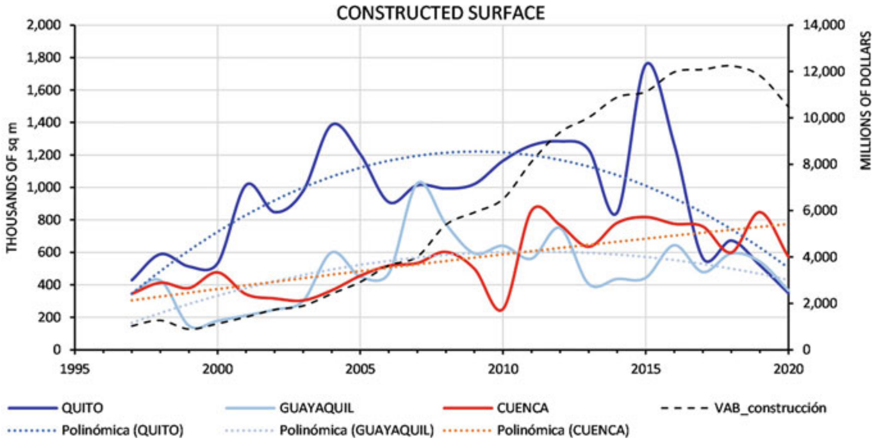

Fig. 5 Constructed surface in the 3 largest cities in Ecuador from 1997 to 2020 [12]

introduction of long-term loans (with an average tenure of 15 years) for the purchase of housing, which was handled entirely by the traditional financial sector (banks and mutual funds), further consolidated the development of this market. These conditions prompted developers and builders to take advantage of the economic circumstances and to increase the number of real estate projects. This was evidenced by the amount of constructed area in different cities of the country, as shown in Fig. 5. This figure describes the construction area each year from 1997 to 2020. Additionally, this graph shows the GVA values of the construction sector, measured on the secondary Y-axis.

This graph shows that the 3 cities did indeed see a reduction in construction in 1999- as reflected in the GVA of construction (dashed line). Moreover, if we compare construction values in the periods before and after 2000, a significant increase is visible in all 3 cities, especially in Quito.

The growth of constructed surfaces in these three cities showed irregular behavior in the two decades since 2000, with each city showing different trends. In Quito, the constructed surface increased from 500 million (M) m^2 in 2000 to 1000 M m^2 in 2001, and reached a maximum peak in 2015 (at 1800 M m^2). Nevertheless, construction in this city has also had decreases, the largest of which was in 2017, when construction area went from 1800 to 580 M m^2. This was probably due to the aftermath of the 2016 earthquake on the Ecuadorian Coast, since a natural disaster slows down the economic development of homes [27]. After this, the lowest value of the area under construction in the analyzed period was observed in this city in 2020 (385 M m^2), as a result of the COVID-19 pandemic. Guayaquil also shows a growth in area under construction after the end of the millennium; however, the area under construction does not rise as high as Quito's. Guayaquil's highest peak is registered in 2007 at 1000 M m^2, falling sharply in the subsequent year to 600 M m^2 (2008). From then, the trend stays more or less constant at around 500 M m^2 of construction area, until reaching 400 M m^2 in 2020. Lastly, the city of Cuenca's growth trend starts in 2003 (3 years later than that of the other cities), when it increases the area under construction from 300 M m^2 to 600 M m^2 in 2008. The highest value reached in this city is 870 M m^2 in 2011—after that, its value remains constant at around 800 M m^2. Just like the other cities, Cuenca also suffers a decrease in 2020 (reaching 600 M m^2 of area under construction in 2020) [12].

As per the collected data, at the nationwide level, the construction sector's constructed surface shows its highest increase at the end of the millennium, while at the end of the decade from 2010 to 2020 it does not show a considerable change. In fact, according to the polynomial trend lines in these 3 cities, it is shown that their peak values occur around 2009. Although the city of Cuenca does not show a trend line with a peak, it is evident that there is a change in the slope of the growth line around 2010. This trend is similar to that shown in the Chap. 1, where the increase in embodied energy consumption is significant in the transition from the 1990s to 2000, whereas the energy values are quite similar in the transition from the 2000–2010 decade to the 2010–2020 decade.

4 Relationship Between Economic Evolution, Construction, And Energy Sector

4.1 Results

In this second stage, the correlation results between the economy, construction, and energy variables are shown through the r^2 correlation of the determination index. According to the literary analysis, the country's energy demand from 2004 to 2014 had a direct relationship with the national GDP. Furthermore, it is evident that electricity consumption increases when the economy expands [18] (see Fig. 6).

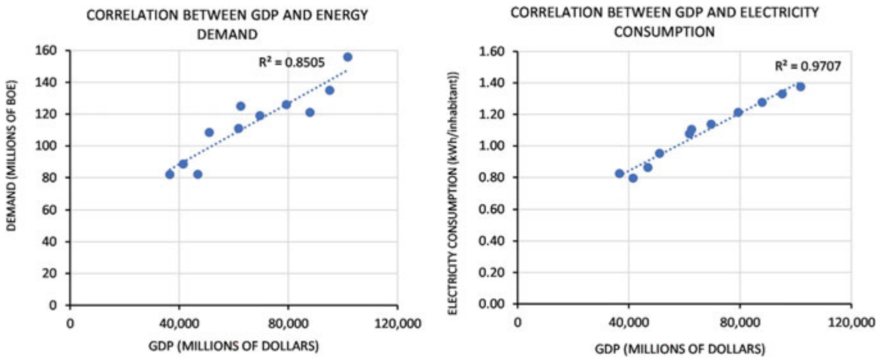

Fig. 6 Correlation of GDP with the country's energy demand and per capita electricity consumption from 2004 to 2014. *Source* Authors' own work based on [18]

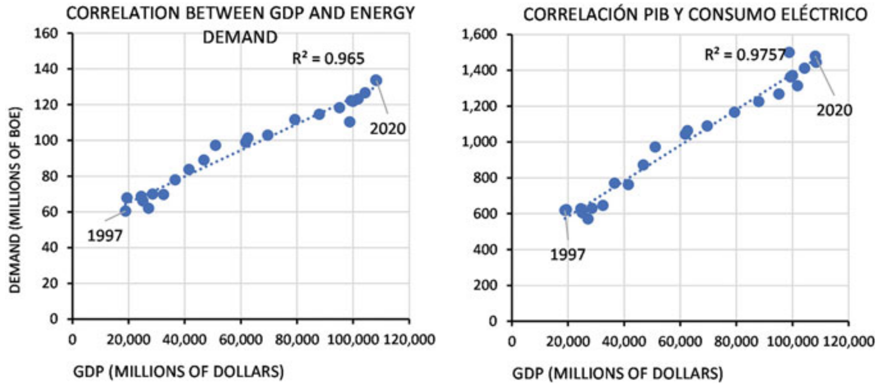

Fig. 7 Correlation of GDP with the country's energy demand and per capita electricity consumption from 1997 to 2020. *Source* authors own work based on [12]

Figure 6 shows that GDP (expressed in millions of dollars) has a high correlation with the country's energy demand (expressed in millions of barrels of oil equivalent-BOE) and with per capita electricity consumption (expressed in kWh/inhabitant). Nonetheless, since this information pertains only to data from 2004 to 2014, it means that there are only 10 points of correlation. For a more thorough analysis, we have taken the data for these variables for the period from 1997 to 2020, from the database of the Central Bank of Ecuador (see Fig. 7).

These data confirm the relationship shown in the period from 2004 to 2014 in the National Energy Balance [18] and show an even higher correlation than in the previous one. Therefore, from 1997 to 2020, GDP and energy demand have a correlation index r^2 of 0.965, and GDP and electricity consumption per capita have a correlation index of 0.9815. These two values indicate that the country's energy demand and the electricity consumption per inhabitant have a growth directly related to the increase in GDP, i.e., the higher the GDP, the higher the country's average energy consumption per inhabitant.

Ecuador's economy can thus be described as having a proportional relationship with both energy demand and residential consumption. In order to compare the economic and energy variables with the construction sector, as well as their effect on other productive sectors of the country, different correlations were made between these parameters. In the first place, we evaluated the impact of the construction sector on the country's economy, correlating the GVA of construction with the national GDP, as shown in Fig. 8.

According to the data collected for the 24-year period shown in Fig. 8a, these two variables have a correlation index very close to 1 ($r^2 = 0.9904$). Thus, Ecuador's GDP is highly dependent on the construction sector.

As in other countries, construction is one of the most influential flows in the Ecuadorian economy. As shown in Fig. 8b, the trend of the country's GDP curve is very similar to that of construction GVA. The trend of these curves after the

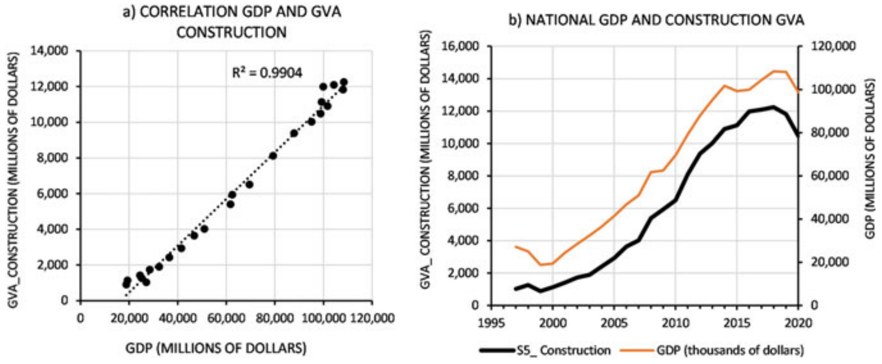

Fig. 8 **a** Statistical correlation and **b** graphical correlation between GDP and GVA of the construction sector from 1997 to 2020. *Source* Author's own work based on [12]

turn of the millennium, when the country becomes dollarized, shows practically only growth. Nevertheless, several changes in slopes can be seen that are coincident between these two curves. For example, both curves reach their minimum point, and after dollarization, change to a growth trend, though with different slopes. The slope of the GDP was greater than that of construction GVA. This higher increase was probably due to the impact of another productive sector of the country. Moreover, in the passage from 2007 to 2008, when the price of oil increases considerably, both the construction sector and GDP values can be seen to increase with an almost identical slope until 2014. Then in 2015, an inflection point is observed in both curves, but one that is more pronounced in GDP (probably due to the economic recession in that year).

In 2016, even though the construction sector grows, the GDP remains practically stagnant- this can be attributed to the earthquake experienced in the same year. In 2018, both curves reach their peak and then decline in 2020 with the steepest negative slope seen in the entire period analyzed, due to the global pandemic. It is worth noting that the construction sector can also have a high impact on other dynamic sectors of the economy, such as manufacturing, transportation, or trade. The correlations between construction GVA and these sectors are shown in Fig. 9.

Based on this, construction appears to be highly correlated with these 3 sectors, especially with the index $r^2 = 0.9857$. On the other hand, contrary to what might be assumed, out of these 3 relationships, the one with the lowest correlation is that of construction GVA with transportation/warehousing GVA (Fig. 9b).

The manufacturing sector in particular demonstrates high growth after 2000, with a highly positive slope during almost the entire analyzed period (Fig. 9a). As with construction, from 2008 onwards, this sector shows a very steep growth curve, until 2015 (when it reduced in value). In 2020, the GVA value of manufacturing declines as a result of the impact caused by the COVID-19 pandemic. Graphically, the two curves remain closely parallel in the analysis period, although the manufacturing

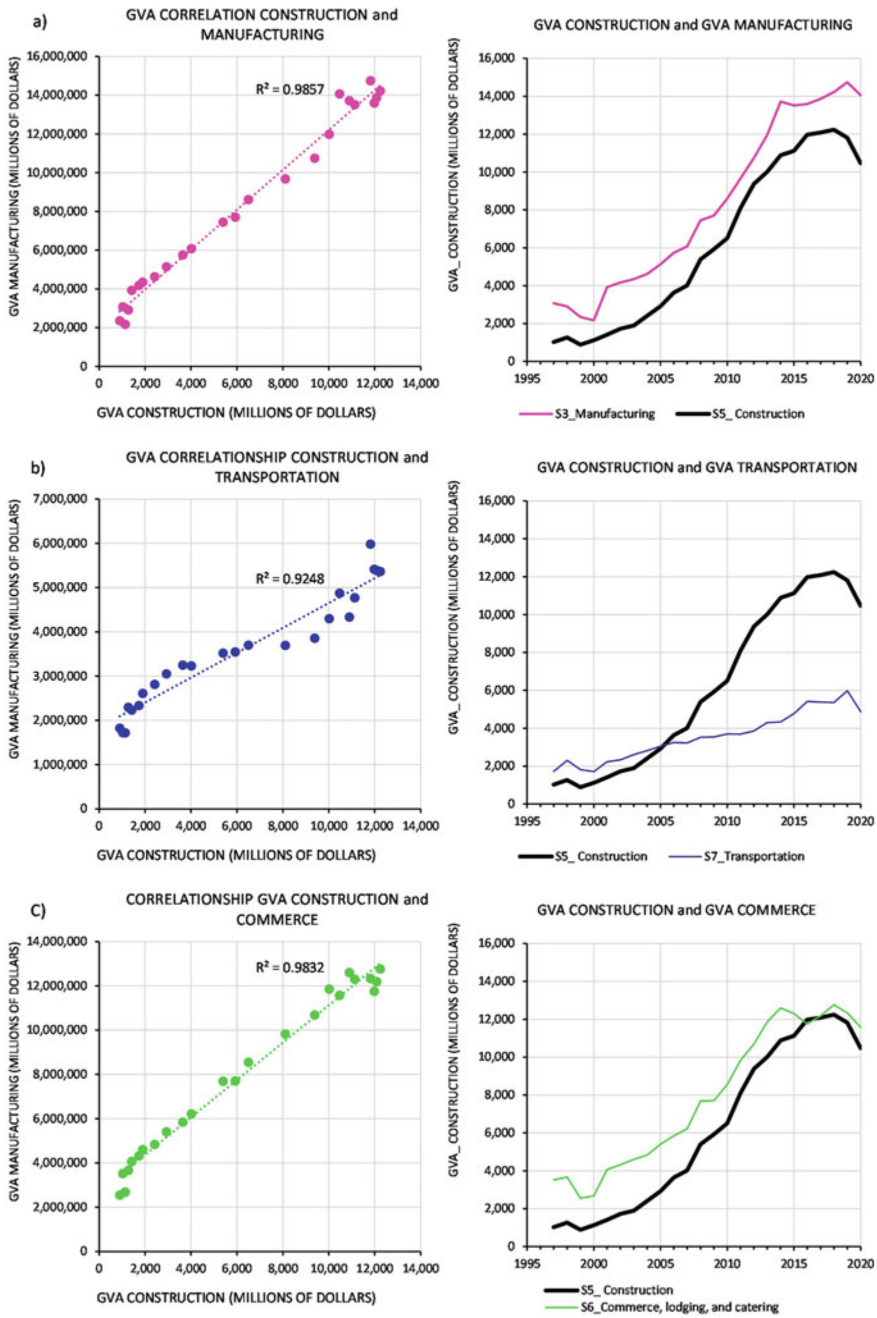

Fig. 9 Statistical correlation (left) and graphical correlation (right) between **a** GVA Construction and GVA Manufacturing, **b** GVA Construction and GVA Transport, and **c** GVA Construction and GVA Trade, from 1997 to 2020. *Source* authors own work based on [12]

sector shows more accentuated slope changes and has higher values than those of construction.

Figure 9b shows the relationship between the construction and transportation/warehousing sectors- despite showing a high statistical correlation ($r^2 = 0.9248$), the trend of the curves is quite far from each other. Before 2005, the construction sector plays a less important role than transportation. However, the sharper rise in construction's growth compared to that of transport results in the former eventually assuming a larger role in the economy than the latter.

The third relationship (Fig. 9c), between the construction and commerce sectors, shows an r^2 index of 0.9832, a higher correlation than that of construction with transportation. Moreover, the GVA curves of these two sectors present great similarity in most of the period analyzed, except between 2014 and 2017. On this basis, it can be assumed that the construction sector has been a major driver of the various subsectors of this sector, including wholesale and retail trade, accommodation and food services.

Lastly, Fig. 10 shows the analysis of the relationship of construction in dollar terms with the country's energy demand and consumption. To this end, the GVA of the construction sector has been compared with the country's total energy demand and electricity consumption per inhabitant.

Figure 10 confirms that as construction grows, so does the country's energy demand. The relationship between these two variables reaches a correlation index of 0.9522. In terms of the relationship between construction and per capita electricity consumption, the correlation is higher with a value of 0.9658.

4.2 Discussion

Several correlations between the economic, construction, and energy variables can be made through the results shown. First, through the correlation analysis between GDP and energy demand, and GDP and electricity consumption, it can be inferred that as Ecuador's GDP increases, so does its general energy consumption, which implies an increase in the different component sectors (such as industry, transportation, and commerce, construction, and residential). Additionally, the relationship between GDP and electricity consumption shows that the increase in GDP is directly proportional to the increase in Ecuador's domestic consumption, since the main source of energy in this sector is electricity.

Secondly, Ecuador's economy is highly dependent on the construction sector at the national level as shown by the correlation between the GDP and the GVA of construction. The increase or decrease of the economy, in this case, GDP, over the last 24 years depends largely on the ups and downs of the construction sector. Although the country's economy also depends on other productive sectors, this GDP-construction reliance has been growing in the last few years, as shown in the results above.

These relationships also show that not only does the construction sector have considerable influence on Ecuador's GDP, but it also influences other productive

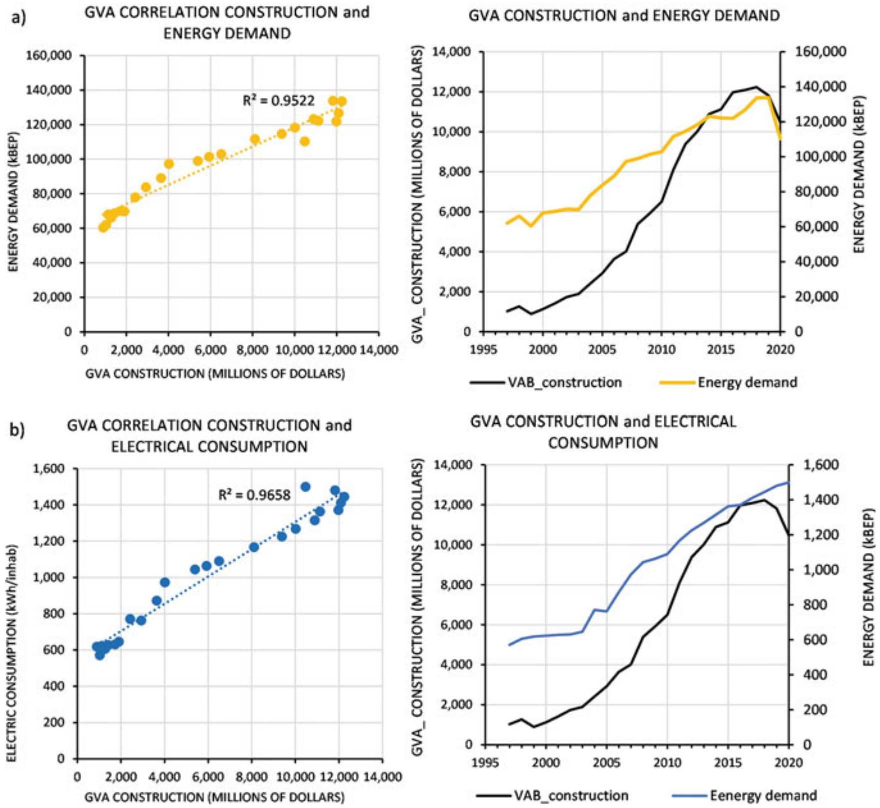

Fig. 10 Statistical correlation (left) and graphic correlation (right) between **a** GVA Construction and energy demand, and **b** GVA Construction and electricity consumption, from 1997 to 2020. *Source* authors own work based on [12]

sectors, which, in turn, impact the behavior of the country's economy. The results show that the activity of the construction sector, due to its dynamics, is directly related to production subsectors such as manufacturing and transportation, and to the country's economic activity like commerce and lodging.

Construction's close relationship with the manufacturing sector is mainly because one of the most influential production subsectors within manufacturing is the production of base metals and metal products, which is directly related to the structure, masonry, and finishing components of building construction. As for its relationship with commerce and lodging: the increase in the construction sector stimulates the purchase and sale of materials, equipment, and food (i.e., commerce activities) at the local level and, consequently, at the national level, which in turn can stimulate the lodging sector. Ultimately, the relationship between construction and the transportation sector lies in the potential increase in the mobilization of raw materials (aggregates, minerals, etc.), construction materials (structural or finishing materials), and even the mobilization of labor. The impact of construction on transportation is evident; however, this dependence is not as high as in the manufacturing or commerce sectors, contrary to what one might think.

Third, the results of the relationship between construction and energy demand indicate that as the construction sector grows, so do other sectors such as manufacturing and transportation, thereby generating greater demand for energy in the country. If these data are related to those of the first chapter of this book, it can be said that the greater demand for construction materials involves a greater production of these materials by the industry. As we have seen, the industrialization of the construction processes and the abandonment of artisanal materials production has also meant that production of construction materials requires a larger amount of energy. The change of the millennium has been an essential inflection point in this growth, where all sectors, and certainly the construction sector, have grown very rapidly compared to previous years. Regarding energy demand, although there has been growth since 2000, the biggest change occurs in 2003, when the construction sector and other productive sectors consolidated after the crisis of the fall of the Sucre and the change to dollarization. Later on, in 2015, the energy demand reduced due to the economic recession of those years. Finally, this curve has its latest decrease in 2020, which is directly related to the global pandemic.

To conclude, the relationship between the construction sector and electricity consumption shows that as the construction sector grew, so did the consumption of electricity per inhabitant, mainly represented by the residential sector. This may indicate that the successive construction projects that are being built tend to consume more energy in the operational stage. On the one hand, this is associated with the greater reliance on modern construction systems in housing in recent years, but it is also associated with the fact that buildings tend to consume energy more to meet thermal comfort needs, as discussed in Chap. 2. Again, the increase in electricity consumption shows an inflection point in 2003, and from then on, the trend is only upward. Even in the year of the pandemic, this sector maintained its positive slope, unlike any other sector.

It is important to mention that all these analyzed variables both in economic and energy terms are related to the different events, recessions, and catastrophes, that Ecuador has undergone, all of which are reflected in the inflection points in the analyzed curves. The most interesting point in this period has been the year 2000, which marks the dollarization of Ecuador's economy. This year can be seen as a turning point for all the variables: when construction, as well as the other productive sectors begin to grow, and consequently, the economy increases. This is, however, and regretfully, also reflected in higher energy consumption at the country level.

5 Conclusions

This chapter addressed the influence of Ecuador's productive construction sector on the behavior of the national GDP, and in turn, its relationship with the country's energy consumption. To this end, different parameters, such as GVA, energy demand,

and electricity consumption of the country have been interrelated from 1997 to 2020. Several conclusions could be drawn from this analysis.

Firstly, the data confirms that the growth of Ecuador's economy is directly proportional to the growth of its construction sector, and this, in turn, has a direct impact on the energy expenditure of different sectors, specifically residential buildings. In other words, with a larger economy, the construction sector grows, but without any environmental awareness.

This research has allowed the analysis of the importance of the GVA in the economy of Ecuador, as well as highlighted that the contribution of the construction sector to the GDP is significant, having become one of its five highest contributors. This boosts and promotes the economic growth of Ecuador through the invigoration of several productive sectors such as manufacturing, commerce, and transportation.

The relationship that exists between the construction sector and the environmental impact of a country is evidenced by the increase in energy demand and electricity consumption when the demand for construction and, therefore the country's economy, grows. The analysis shows that the change of the millennium, which is associated with the dollarization of Ecuador, has had a high impact on the country's construction demand and energy consumption.

Lastly, the Ecuadorian construction sector has shown sustained growth in the last twenty years, despite most economic, political, and social crises, constantly maintaining its GVA, unlike other sectors of the national economy (the only exception being the year 2020 for obvious reasons due to the COVID-19 pandemic). In a similar manner, the analysis shows that the correlation between GDP and GVA of construction, as well as the correlation between GVA of construction and manufacturing are positive, obtaining correlation results of 0.9904 and 0.9857 respectively, maintaining a directly proportional dependence, which shows the need to promote the construction activity as a sector integral to the development of the nation. Notwithstanding this, this stimulus must be associated with environmental sustainability policies that moderate the energy impact that may be generated from this probable growth of a productive construction sector.

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Constructive Sincerity and Bioclimatic Architecture

Guillermo Casado López

Abstract The materiality of architecture is an inescapable issue when it comes to building, however, throughout history there have been few examples that focus on its expressive possibilities. Materials can be seen as the 'pixels' of architecture, and are what allow us to create spaces, geometries and textures, but at the same time they are also elements with mechanical and physical characteristics that generate structural systems and thermal comfort in interiors. In addition, the environmental implications of the costs of extraction, transformation, end use and disposal are enormous, since the wrong choices can saturate the planet and, in some cases, affect health. Industrial modernity has produced a huge number of new materials from the oil and chemical industries, relegating traditional—and much more sustainable—materials to the background. The study of ancestral vernacular systems allows us to appreciate the development of techniques through trial and error that allow buildings to adapt and interact with their environment. The teachings contained in the examples that still survive allow the modern designer to be inspired towards a more sustainable approach, and can also generate modern interpretations. This has increased with the contemporary development of new systems and materials within the field of bioconstruction, a field that, though still in its infancy, has already resulted in some innovations of great interest. Integrating sustainable materials in modern projects is an exercise in responsibility, which offers the opportunity to investigate its sensory possibilities through its exposed and solid use, without coatings. Therefore, working with constructive clarity and using bioclimatic materials allows the building to connect with memory, the context and respect for the environment, as well as generating evocative atmospheres full of meaning.

Keywords Material · Bio-construction · Architecture · Sustainability

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1 Introduction

Although bioclimatic architecture has been developed since the dawn of time, in recent decades it has been conceptually interpreted through what is generally called sustainable architecture. While the former is based on more natural resources, the latter has much more materialistic and capital-related connotations, although it is promoted through an idea of survival. Bioclimatic architecture has cultural, traditional and local connotations, while sustainable architecture paradigms are, in most cases, global in nature. The emerging need to save energy and conserve the environment, not as a moral commitment but as a necessity, has led to modern models being established on the basis of measurable and scientific parameters. Energy certifications, embodied energy assessments or green building seals are along these lines. This makes it possible to determine energetically, environmentally and economically the strategies and results they produce, but the aspects of utmost relevance that underlie ancestral architectures are left aside.

This marked global character of everything that is developed in the modern world, which has in its principles replicability, mass production and economic performance, makes the proposals that arise become inextricably linked to the chemical and petroleum industries, using in a large number of cases the waste they generate to produce building materials. An example in this direction is the Passivehaus standard, which prioritizes energy savings over other concepts such as the life cycle assessment, the health of materials and the ingenuity of bioclimatic architecture. This method that prioritizes the insulation systems-based approach for energy saving, has its complement with another product of globalization: the use of machines. The applicability and replicability of these systems generate effective solutions from their perspective, but produce disconnections with the vernacular and with human health. Although such systems are not at odds with the possibility of being included within the framework of the vernacular through good architecture, they certainly do not favor a design process that connects with memories, transcendence and the most essential principles of architecture.

The general normative perspective places serious difficulties on designers who try to meet its parameters and at the same time generate an architecture within the bioclimatic and vernacular framework. There is also a gap between the sustainable and the conceptual within architecture, which encourages proposals that are disconnected from the place, history and culture. This situation affects the design of the building itself and, to a large extent, the choice of materials and their construction systems.

Obviously, if the industry put its efforts into the development of much more ecological and local building materials and systems, amazing results would be obtained, both in their technical performance and in their economic and environmental balance. There are already insulations based on cork, hemp fibers or sawdust from lumberyards. There is also an incipient development (or rather recovery) of lime technology, raw earth and silicate paints, to give just a few examples. All these materials not only have a lower impact on the environment and on health, but also improve the properties of conventionally modern ones. However, their low production and demand mean that they are not competitive against chemical derivatives, cement, steel or zinc.

The trend of bioconstruction within architecture can be seen as a vindication of these ancestral and natural materials, but it must have a normative support that sustains it. It is not even necessary for these materials to prevail over others, since it is would be enough if there were legislation that allows them to be used as a structure or as an envelope, through the characterization of their physical and chemical properties.

As an example, in the world there are several countries that have regulations regarding the use of raw land as a building material. However, most deal only partially with the different existing construction systems, generally focusing only on one or two techniques. For example, in Spain, France and Colombia only the compressed earth block (CEO) system is permitted for walls, partitions and facades; in Brazil and India, the CEO and Tapial; while the USA and New Zealand are among those whose regulations include rammed earth, adobe and CEO [1]. Ecuador does not have any regulations in this regard, and there are few countries in the region that regulate these systems. In addition to this lack of regulations at a global level, in many cases the raw earth system is justified through the inclusion of cement in its composition, which detracts from the result from a bioconstruction perspective.

The issue of materiality is the great challenge of modern sustainable architecture, being inextricably linked to the local development of materials and construction systems, an idea which is diametrically opposed to the global paradigms of standardization and simplification.

Therefore, an opportunity arises to involve sustainable materiality within the scope of architecture, thus generating proposals that allow a leading role for the material beyond its purely practical application. The most forceful ways of working with material in architecture always obey a solid use of it, that is, without coatings or intermediate layers, according to two of Banham's three principles in his definition of New Brutalism: the use of materials in their inherent form; and the evident display of the structural system [2]. This has been applied throughout history in many cases, but it was with the modern movement when reflections on the material and its place in the project became more relevant, especially thanks to Le Corbusier and his great discovery: brutalism.

The methodology of this chapter is based on a critical review of the issue of materiality, establishing two very different points of view. On the one hand, the constructive sincerity and the phenomenology associated with it, developed through history and presented in a more literal way in some cases of the modern movement. On the other hand, materiality from a bioclimatic perspective, which is much more pragmatic, based on the resources available in the environment, and on the search for comfort conditions. It is based on the hypothesis that both approaches can be included in a project, though they have different origins, and can create a way of creating architecture that allows the results to be in line with both the pragmatic and the conceptual, and always with the focus of materiality.

The objective of this chapter is to carry out a critical reflection on the relationship between the most conceptual parts of architecture and the principles of bioclimatic architecture, through the perspective of materiality, extrapolating the conclusions to the Ecuadorian case.

2 The Material in Architecture

> The achievements of war engineering in concrete, steel and wood have given signs of sufficient maturity to guide the conception of these new buildings. The gigantic structural skeleton has established its right to be seen. You no longer need any disguise to please. New envelopes made of transparent, translucent or opaque materials, with exciting textures and colors, can be suspended from their members. Painted friezes will articulate the circulations between the large enclosures and sculptures will embellish their interior.

Louis Kahn: Essential Texts. Edited by Robert Twombly: 2003. W. W. Norton and company. New York–London.

The history of construction technologies is linked to the history of materials. In architecture, both are presented at the same time, the material never being prior to the technique, since the latter configures the former. Although the stone existed before the building, it does not become a construction material until it is tamed through a construction technique. As an example of proto-architecture, the dolmen is configured through a lintel concept, which requires stones with a certain geometry. The stones go from being rocks that rest on a mountain to becoming a structure that is stressed through compression and flexo-traction. But this is actually secondary, because the primary goal of its builders was to create a space related to an environment and the cosmos. The complex and holistic relationships that exist in architecture are similar to those in sculpture. Space and form are materialized by stone, clay or wood. Therefore, when the materials endow the object with a dimension, the shape is affected, since the properties of matter provide textures, volumes and geometries and, ultimately, a certain energy.

What is interesting about the example of the dolmen is the humility and sensitivity with which the creators approach the act of construction. The stone plays a leading role, telling a story with its composition, fracture points and cracks. In addition, its relationship with the environment is totally natural, since it is presented in its stable state in the place where it is located. Its transformations have been due only to carving work, without applying chemical or physical treatments. This stone allows and supports the growth of moss, moisture stains and cracks due to thermal oscillations. These processes, which from a modern view would be pathologies, actually give life to this material, which has a not insignificant persistence over time.

Architecture at the beginning was composed of materials from the ground, known as "technogenic materials" [3], which were transformed through simple processes. Technical advances throughout history would begin to produce increasingly complex systems. It was in the Neolithic when the first structures of wood and skins began to appear, which would later evolve as humanity developed metallurgical processes [4]. Initially, the drying of the earth in the sun gave rise to adobes, (see Fig. 1), which would the first architectures built by series production to be generated. The same

Fig. 1 Adobes (photography). *Source* Author 2013

happened with the carving of ashlars. The high point (from which the concept of modern materials arises to a large extent) appears with the firing of the earth and the first bricks, as well as with the firing of limestone to create lime. This marked a transition from taking advantage of materials in their natural qualities to transforming them to obtain others with better performance. But these transformations come at a price, as the natural stability of raw materials is broken, allowcreating new materials that are susceptible to degradation, rust, fracturing or disintegration. Only Roman concrete can be considered a material with the pretense to eternity, since its chemical and processing lead it to absorb the CO_2 lost in cooking and return to the original limestone, with improved properties conferred through the addition of additiphysicalves of volcanic origin [5]. The vast majority of the rest of the materials made from physical and chemical transformations, are doomed to disappear in a few decades if there is no maintenance work.

However, very soon coatings and plasters would begin to be applied. Greeks and Romans already covered stone walls with mortar or lime mortar. Classic Arab culture covered its buildings with finely carved plaster and earthen plaster. But we do not find systems more complex than these schemes. That is to say, basically the bare adobe or stone wall was changed to walls with a layer for decorative purposes and, in some cases, for protection of the system. These first architectures did not conceive of envelope systems by grouping layers of different materials, with the exception of roofs. The challenge of generating a waterproof space was superimposed on the purely structural one, with the need to create the support on the one hand and the waterproof system on the other. In the case of rainy climates, this problem has generally been solved through waterproof elements geometrically arranged in such a way that drainage occurs. This system initially used branches and leaves, which were placed in such a way that they allowed the evacuation of water by gravity, before being improved through the use of tiles or stone slabs, which allowed greater durability.

The development of complex construction systems, composed of various materials and with an elaborate technique, emerges according to contemporary concepts throughout the twentieth century. This is due to the appearance of new materials derived from petroleum, fundamentally plastics in various forms. Industrial research began to produce materials with great thermal insulation capacity, waterproofing capacity, plasticity and/or hardness. This allowed materials to specialize in a certain property, so that the construction systems that arose was made up of several layers.

Analyzing this historical process from an ecological point of view, it can be affirmed that prior to the first modern oil well, drilled by Edwin Drake in Pennsylvania in 1859, all architecture was sustainable from the perspective of materiality. The materials were sourced locally, they were very minimally processed and after their useful life they were easily absorbed by the environment. The appearance of oil as cheap energy led to industrial development and the advancement of transport technologies, which has been the seed of the current environmental and climate crisis on our planet. In the purely architectural context, the industrial development propitiated by this fossil fuel resulted in the appearance of air-conditioning machines, which allowed the bioclimatic aspects of buildings to be neglected. This twentieth century model, in which appliance technology prevails over design ingenuity, generates an increase in energy consumption through air conditioning, with consequential pollution. But oil also resulted in the creation of new materials from refinery waste, which generate pollution in their production and transformation process, and are also not acceptably biodegradable.

There are now attempts being made to try to reverse the dynamics of the last century of the last century, but commercial interests and the globalization paradigm do not leave much room for serious and comprehensive development. Another important obstacle is the fact that in order to obtain a system that meets the requirements of thermal insulation in materials within bioconstruction, elements with greater thickness are usually necessary. This supposes a loss of useful space in a building, a situation that can be challenging with land and real estate speculation.

Therefore, in order to deal with the problem of the globalization of materials and the decline of traditional materials, a profound change in the general conception of what architecture and habitability is necessary. For this reason, this chapter approaches materials from a more conceptual perspective, through a series of reflections on constructive sincerity in architecture and brutalism, two similar positions that focus on the use of bare materials.

3 Pure Positions in Front of the Material

Throughout history there are many examples of the application of construction materials in their pure state. However, during the modern movement these positions acquired special relevance. Architects such as Alvar Aalto, Louis Kahn, Mies Van der Rohe and Le Corbusier took this direction of constructive sincerity, but with conceptual nuances in their interpretation. There is also a much more pragmatic architecture that reproduced this material paradigm of nakedness and honesty: the architecture of the industrial revolution. Unlike in the case of modern architects, it was structured through constructive sincerity for economic reasons, not aesthetic or conceptual ones. For this reason, our attention is focused on those proposals that are loaded with a theoretical reflection within architecture, since this chapter does not have aesthetic pretensions, but rather conceptual ones.

When reviewing the concept of constructive sincerity in the modern movement, it can be observed that architects associated with this approach were usually from Protestant environments, for whom perhaps moral precepts (such as sincerity) influenced conceptual understanding of the material [6]. There are two prominent positions in the modern movement regarding the way of understanding the pure use of the material. On the one hand, we find Mies van der Rohe, who had a rationalist and dominating interpretation of the material. On the other side, there is Le Corbusier, whose brutalism proposed a freer and more expressive way of understanding the material, allowing it to have certain degrees of freedom. Both endow material and technology with a conceptual meaning, expressing their qualities through their solid exposure in the project, however, their personalities and ideologies produced disparate approaches. They have in common the search for authenticity (which is a more appropriate quality for a material than that of sincerity), and the emphasis on the material being central to the design of a project.

This way of understanding the material through its inherent qualities, generates a conceptual architectural position that is not linked to space or understood geometrically, but instead to Peter's concept of "atmosphere" [7]. This idea, closely linked to that of Steven Holl's "phenomenology" [8], results in a theoretical revolution in the understanding of architecture. Both coincide in understanding the project from a perspective that prioritizes the viewers and their experience, through resources such as sound, touch or temperature. For them, what is relevant is not spatiality through a coordination of geometry and light, but the sensory experience. However, this does not mean that form and volume are ignored, on the contrary, a whole is created that enlarges the holistic system of architecture.

Although these principles have been widely used in history—a clear example is classical Arab architecture- they had not been explicitly described until now. This development, carried out through praxis and not theory, had its break from the phenomenology of the modern movement, which laid a series of conceptual foundations that were based, to a large extent, on geometrical, technical investigations and on the inclusion of state-of-the-art technological materials. In the vast majority of modern examples, memory, history, culture and the environment were ignored, as was as the recreation of the senses through architecture. The phenomenological themes were hardly developed, with focus instead on the lavish exhibition of technical, volumetric and compositional achievements. The senses were not the central theme, although many architects, such as Frank Lloyd Wright, Luis Barragán and Óscar Niemeyer, worked on these issues in a heterogeneous and personal way.

This situation has not been analyzed in the main treatises of the modern movement, since the euphoria and admiration for the new architectural model left little room for this type of criticism. But the its basis was created around two thousand years ago, through the most modern of antique cultures: Rome. Vitruvius exposed through his treatise some very positivist and materialist principles, which are still studied in architecture schools: firmitas, utilitas and venustas [8] or 'solidity, utility and beauty'. It seems like a comprehensive description of the pretensions of contemporary architecture, where themes such as the social, the poetic, the phenomenological or the symbolic are conspicuous by their absence. The recovery of the treatise "The Ten Books of Architecture" [9] during the Renaissance, caused the development of all subsequent architecture in Europe and America to abandon the principles of phenomenology that had been applied, for example, in Gothic or in Arabic architecture. In addition, the canon of beauty from the classical orders was considered valid and exclusive, through deep geometric and mathematical studies, which have an irrefutable value, but which cannot be considered in a unique way.

The modern movement was presented as a break from all these aesthetic orders established in the Antiquity and the Renaissance, which had been evolving throughout history through styles such as baroque, neoclassicism or picturesque. This split occurred, as in most artistic historical changes, through a denial of a general quality of the former. In this case it was denying styles as a paradigm, symmetry and ornament. However, this denial continued to work within the same concepts as the previous one: firmitas, utilitas and venustas, only modifying the concept of what is now beautiful, which nevertheless continued within aesthetic, compositional and geometric concepts.

The great innovation produced by the modern movement was the inclusion of the conceptual as an element in the creation and formalization of buildings. When the concepts transcended, connections with the phenomenological were produced, but which were not subsequently reflected upon or discussedby their authors, as if the achievement obtained escaped the need for any explanation. This was the case with the Barcelona Pavilion by Mies van der Rohe, a pure expression of poetry by the quintessential rationalist of the time. Memory through sculpture, spatial silence, theatrical dialogue between materials, the water. An act of artistic expression sprang from a paradoxical discourse, in which the supremacy of the human and the meticulousness of the technique prevailed, and in which there was no room for sensory or experiential reflections. On the opposite side, we find another example of extreme expressiveness that produces phenomenological experiences, despite the rigidity and rationalism of its program: Le Corbusier's Unité d'Habitation in Marseille. With an unbridled and revolutionary force, Le Corbusier proposed the first brutalist building, in which he riskily experimented with a completely new and expressive conception of the material, enclosing profound reflections on what architecture is in its essence and connecting it with sculpture. In this case, there was no theoretical discourse on the part of the author about this discovery, and practically none by subsequent critics and historians.

These "coincidences" obey deep impulses of the soul, which are not easy to rationalize or explain, and even less at the time that they occurred. However, Zumthor and Holl enter fully into these topics. They begin to be interested in aspects of architecture seen from their perceptive self, and not from an erudition based on references and comparisons that is, from a simple delight in form. This phenomenological and atmospheric vision is adequate to understand the conceptual consequences of materials in architectural projects, which amplify their role through the symbolic messages they can transmit and the sensory experiences they can generate.

Thus, the material is not a means to build a space, but it is one of the great themes of architecture.

4 The Material in Bioclimatic Architecture

Bioclimatic architecture has its essence in traditional architecture, as well as in the trial-and-error methods. The absence in antiquity of rapid means of transport and production conditioned those systems to develop through the use of locally available materials. However, the evolution through empirical developments were generating optimal solutions for a place and its conditions. In this sense, the material becomes relevant through its thermal properties, (a crucial factor for comfort), or its geometric or mechanical qualities (for sun protection or ventilation solutions). Sometimes the earth provides the conditions of insulation and thermal inertia (such as in very hot and dry or cold climates), other times it is materials like bamboo that allow the creation of models that prioritize ventilation in hot and humid climates. As has been said before, the architectures prior to the industrial revolution, which have evolved over time, were optimal for their environment.

The appearance of globalization restricted the use of traditional systems in developed countries, further fueled by a theoretical position of the modern movement that denied these systems. Eurocentric cultural concepts were applied to construction materials, dismissing the vernacular as weak, perishable and characteristic of a lower class. This generated a dynamic of downplaying ancestral architectural knowledge, which ended up putting all vernacular architecture in serious crisis.

Globalization generates materials that can be replicated throughout the world, produced in large quantities and at low economic (but not environmental) cost. This relegates traditional materials to underdeveloped areas and, in the case of developed countries, to almost complete extinction. This means that knowledge of vernacular techniques and production methods is lost in the latter, thus becoming a product of low or no demand, which in turn makes it difficult to execute a modern building with traditional techniques. Suddenly, building with natural materials from the environment becomes a luxury product, which requires great economic effort for its execution.

Tradition shows us wisdom of great value through vernacular models, in which the properties of the materials used in the area and the design itself are connected. One and the other conform, resulting in an optimal interior environment for the climate where they are located. The adobe houses of the Sahara Desert cannot be conceived of with any other material, since its thermal inertia allows it (through a correct dimensioning of walls and openings) to exchange the energy of the day (very hot) and that of the night (very cold) in the interior through thermal delay. If the material is changed, this exchange does not work; and if the geometry of the spaces and the thickness of the walls are not correct, it does not work either. This relationship is lost in modern models, in which there are insulation and optimization strategies designed for air conditioning systems.

There are incipient industries recovering some of the traditional techniques and materials, and in many cases interpreting them in a modern way- the question of heritage forces the actors involved in the interventions to confront these technologies, though not always in the right way.

The industrial material predominate over the natural, though only due to its economic advantages (Fig. 2). On moving past the primacy of monetary materialism, natural materials assume immense value, such as through the benefits for health, since traditional materials do not generate harmful products or diseases. This is not the case of industrial materials, especially those derived from petroleum, which, apart from the large amount of embodied energy, in some cases produce volatile substances and residues in their degradation that are polluting and harmful to health. For example: cooler wall surfaces can facilitate emissions from chemical wall paints; while moisture in concrete allows alkaline degradation of di-ethyl-hexyl-phthalate (DEHP) (the plasticizer of vinyl flooring) [10]. In-depth studies are needed on the health implications of the chemical envelopes that our modern living spaces create- but of course history and empiricism have already shown that earth, wood or lime have no harmful effect.

All vernacular architectures have managed to develop models adapted to their environment with the raw material found there. Regarding the bioclimatic adaptations, at times the thermal inertia is used, in others the insulation, and in some the

Fig. 2 Byo-contruction system through compressed earth block and hemp insulation (photography). *Source* Author 2011

capacity to create ventilation or solar protection systems. Currently there are means to further optimize the benefits of these materials and create new ones, through certain industrial processes or construction systems. However, the large investments in research necessary are not directed in this direction, but rather toward chemical development through petroleum residues and chemical industries. Gama-Castro et al. [4] affirmed, referring to technogenic materials, “the scarce theoretical-practical knowledge that the Earth Sciences have about their composition, characteristics and properties is surprising”.

But not all the advantages are from a scientific and measurable point of view. There is a subtle background and pertaining to the field of lived experience that influences the atmosphere of a living space. Being in an adobe room is not the same as being in a concrete room. Materials have their own energies and evocations that influence the observer’s perception. The natural material tells its story and is alive. Adobe buildings have a characteristic odor that is given by the land of the area used. The character of wooden or bamboo constructions show in the pieces, the knots, the rings or the chromatic differences of the organic fibers. Stone constructions show veins, color differences, porosity and differential hardness. All this participates in the construction of the aforementioned idea of “atmosphere”. That is to say, it is not only the form and the aesthetics, but also the silent messages that the matter transmits. And in the case of natural materials, this message is full of life, of atavistic recognitions that are embedded in our existential DNA.

5 Constructive Authenticity and Bioclimatic Architecture

Constructive clarity has been applied in bioclimatic architecture in an irregular way. There are examples that are clearly ascribed to it, such as igloos, stilt houses or houses in the Atlas Valley in Morocco. In these cases, the material is solid, without any kind of coatings or paint. But there are also numerous cases of vernacular architecture that work with coatings or paints. The cultural aspects or the protection requirements of the base material generate these solutions. Earth plastering, lime plastering, and ceramic coverings are a few examples. However, they do not normally aim to improve the thermal behavior of the system, so for bioclimatic purposes they are dispensable.

The possibility of working with efficient construction systems that at the same time develop constructive sincerity, is limited by the climatic conditions of the environment and the available material. Extreme climates do not allow for the creation of this type of solution, since modern regulations dictate that different layers and components are necessary to obtain acceptable comfort. This is largely due to the reduction in tolerance and social acceptance for certain living conditions, which are seen from a contemporary perspective as an attack on the fundamental human rights. This would be the case in the example of the aforementioned igloo, which is a successful solution in extreme cold weather that manages to create an internal environment of up to 40 degrees Celsius more than the outside, but never at a temperature higher than 10 °C, so for decent housing purposes it does not seem like an acceptable option. The development of global dynamics, consisting of the application of space heating and cooling technologies—such as air conditioning or fossil fuel boilers—has focused the issue on energy saving, assuming that a machine is necessary to obtain comfort. This is what happens in the Spanish standard of the Technical Building Code (CTE), where the checks required for compliance with the DB-HE (Energy Efficiency) require, through simulation programs, the placement of an air conditioning system, without giving the option to manage comfort through bioclimatic strategies.

The possibility of applying constructive authenticity to bioclimatic architecture depends on several factors, but if it is considered that in many climates it is necessary to include an air conditioning system to obtain comfort, then following the strategy of thermal insulation and inertia can require going against popular consensus.

In order for a material to be applied according to its constructive authenticity and meet the comfort requirements, it is necessary that it meets the structural, insulation and inertia conditions of being self-supporting and that it meets the requirements of insulation or thermal inertia, as well as being capable of mechanically supporting the environment.

The 3 fundamental materials without industrial transformation that have been used most profusely throughout history have been raw earth, stone and wood.

In terms of material properties, it is raw earth that has the greatest advantages of the three. Earth is available in 90% of the inhabited areas of our planet, and can be associated with other materials that complement it to create the construction and structural system that will make up the building. Adobe or rammed earth walls do not require cladding if they are properly protected from contact with water and humidity; however, they do not work in very hot and humid climates due to their great hygroscopic capacity. But there are modern techniques that can stabilize these systems, through natural materials such as lime. Earth is a good insulator, even better when combined with straw, and it also has very good thermal inertia. Its texture, its chromatic possibilities and its touch make it an ideal material to generate phenomenological experiences, while in many cultures it is a symbol of the ancestral construction tradition.

Stone can be used in its inherent materiality as long as the climate is not too cold or too hot, since its great thermal inertia capacity also makes it a conductor when the difference in temperature between the inner and the outer surfaces is very large. With appropriate thickness of the walls and control of the permeability of the enclosure, a very suitable solution for temperate climates can be obtained. Its properties of solidity, permanence and hardness had fascinated ancient cultures, making it the material of choice to raise the great historical buildings. As with earth, stone exists in a great variety of textures, colors and densities, which gives it great expressive possibilities when applied in architecture, since it also allows different forms of carving and modeling.

Wood has very good thermal insulating properties, although the direction of the wood fibers in relation to heat flow must be taken into account. The thermal conductivity of the woody substance in the longitudinal direction of the fibers is $h = 5.62$ kcal/m h °C and in the perpendicular direction $h = 0.362$ kcal/m h °C [11].

It is not a suitable material to create isolated spaces in hot and humid climates. Being a living material gives wood a specific and particular character, as well as much more limited durability than the stone and earth, even with maintenance. For expressive purposes, wood provides warmth and a welcoming atmosphere to human habitations.

In all three cases, thickness is essential for insulation and thermal inertia requirements, which are greater than if we use mixed systems with chambers or layers of highly insulating materials. Therefore, in the vast majority of cases, the significant space requirements of natural materials, when compared to the use of insulating layers of other materials, becomes a problem in built up areas.

Modern bioclimatic trends are excessively focused on achieving the objective parameters of sustainability, while ignoring in the most cases the expressiveness and commotion that architecture can create. We also find false bioclimatic buildings, in which some sensational resource has been applied such as green facades, terraced gardens or a huge number of solar panels neglecting the fundamental parameters of material sustainability in building components. However, they are still sold as green and environmentally friendly architecture.

But there are honorable examples of projects that have worked along the two lines described, seeking a bioclimatic strategy and at the same time managing to extract expressiveness and phenomenology through the material. A case in point is the Toro Pool in Spain, by VIER Arquitectos. A brutalist approach was taken through an interpretation of the rammed earth system and vernacular material of the area, which interacts with another much more contemporary one- exposed reinforced concrete. The dimension of the purely bioclimatic, both in the recyclability of adobe and in its thermal properties, transcends through the exhibition of the material without any coating, showing the layers and evidencing how it was built. There is in this a sensory experience that connects with the nature of the land that makes up the wall, but also with history and memory, through the construction method it represents. The concrete provides the counterpoint. It is not a bio material, but it has mechanical characteristics that can hardly be obtained with other materials, even more so due to the scale of the building. This concrete is presented in the Le Corbusierian manner, just like the rammed earth, establishing between the two a magnificent debate on what is modern and what is traditional. The skill of these architects has led to a result that works, that is not radical and that transcends through the use of the material.

Another example of raw earth is the Hotel Tierra Atacama, in which a rammed earth construction system is developed, inspired by an old ruin existing in the desert where it is located, an area with the lowest annual rainfall in the world. The architectural interpretation is also made from a modern vision, through the geometrical prisms where the rooms are. The adobe is presented without coating and without rain protections, since the rainfall regime is null, and the risk of water absorption does not exist. The architects of this project took advantage of the climatic conditions and the available material to create an optimal high temperature insulation system, and at the same time proposed an unusual construction solution, in which the raw earth was exposed to the environment. As in the Toro Pool, modernity and ancestry converse, generating a stimulating result that blends the future and the past.

Ecuador has climatic characteristics that allow, in most of the inhabited areas, comfortable conditions to be attained through the use of natural materials and bioclimatic strategies. For the Sierra region, raw earth is the most suitable, since its climate (temperate with cold periods and a general drop in temperatures at night), allows the establishment of strategies of thermal insulation and inertia with sensible wall thicknesses. In addition, there is a tradition, pre-Columbian in some cases and colonial in others, of building with this material, which is abundant in the environment. Therefore, in the collective memory, adobe has a meaning, it is a known material that survives in some heritage buildings. The climate of cities in the mountains, such as Quito, Cuenca or Loja, allows the surrounding system to be solved only with this material, without the need for superimposed insulating layers. The use of this material in a solid way and without coatings represents a great opportunity for architects, since its expressive and symbolic possibilities will open projects towards more ambitious goals in the conceptual and bioclimatic aspects.

In the coastal and Amazonian regions of Ecuador, characterized by a tropical, humid-warm climate, the materials that work best are guadua cane and wood. In this case, insulation strategies are counterproductive, since the internal thermal loads of the house would cause overheating. The only plausible strategy is ventilation, so that the thermal loads dissipate. And so it has been for centuries in these areas, through stilt (or semi-stilt) solutions that promoted ventilation under the floor and under the roof. These constructions have been developed using wood and guadua cane, without the need for coatings or extra layers. In the eastern Ecuadorian area, buildings are built in many cases with brick or concrete block, keeping the chamber ventilated between the roof and a false ceiling that covers the habitable area. For thermal purposes, brick or block do not contribute to comfort, so the recovery of wood construction techniques would not mean a reduction compared to the previous ones. This material is very abundant in the area and offers excellent properties if it is properly protected from xylophages. Its exposure in its natural texture does not offer any technical problem in its durability, so it becomes an option with great possibilities for design.

Therefore, both in Ecuador and in the rest of the world, vernacular architecture can show us what to build with and how to build.

6 Conclusion

The challenge of taking advantage of the expressive properties of materials through a solid conception of the material and at the same time obtaining a comfortable building is possible. That is, the shortcomings of modern buildings that applied constructive authenticity, whether Miesian or Le Corbusier, in terms of climate and comfort can be remedied by opening these concepts to natural and traditional materials. This supposes the appearance of bioclimatic brutalisms, as in the case of the two buildings discussed in the preceding section, and also opens for investigation the processes of degradation and naturalization that these materials can suffer. This is another conceptual aspect of great importance, since, if the interpretation of the material is in its natural state, maintenance interventions must be carefully designed and carried out, since its alteration would cause a loss of meaning in the building.

The Ecuadorian case, from the perspective set forth in this document, offers a great and valuable opportunity to work in both directions of the material's discourse: the conceptual and the sustainable. History and memory help feed the desires of the new project, providing the guidelines of the traditional wisdom accumulated in times past, but also allow the interpretation and investigation of new models, which maintain the identity and meet the requirements of comfort and sustainability.

Ultimately, everything comes down to the effort of creating good architecture, in all dimensions, since if we focus on just one part, the other parts suffer. Either the building doesn't work well with the weather, or the building misses the opportunity to create a sensory, emotional, and intellectual experience.

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Materials from a Heritage Perspective

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Abstract Historical materials can be studied from various technical, symbolic, artistic, health-related and other perspectives. This process points to a constant versatility, in which conservation goes beyond the conventional spheres of its management, such as inventory. In the case of the buildings in the Historic Center of Cuenca (HCC), construction materials are studied for historical and architectural perspective, to ensure maintenance and even to inform contemporary design. Thus, the type of material becomes the analytical axis to study the architecture of buildings that trace their origins to the Cañari, Inca, European and American influences through social and cultural interactions. Through the study of three materials (adobe, stone and brick), it is possible to define the energetic implications of their production and use, as well as understand the requirements for their architecture conservation or rehabilitation, thus making it possible to assess the relevance of the interventions and management policies in force. Therefore, a solely historical-artistic, physical–mechanical or chemical vision is not sufficient, as the interest comes from perspectives of resource efficiency and articulation of cultural meaning. Today, this interest is positioned within the framework of the Sustainable Development Goals.

Keywords Historical material · Heritage architectural · Energy and heritage · Energy and conservation

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1 A General Level of Valuation Perspectives

Historically, research on and knowledge about building materials has included analytical and conceptual approaches [1] that encompass both the pragmatic, technical, and functional requirements and the symbolic ('personality') dimensions of the construction [2]. The very definition of architecture also stems from this, so this bimodal nature allows its transcendence [3].

The links between a material's technical functionality and aesthetics (just as those between technical objects and art object) [3], arise through the properties of the former. Understanding this material heritage requires going beyond merely the application of an art, the structural stability, the resource availability in an environment, the productive processes, contemporary and accumulated environmental affection, economic accessibility, and even cultural identity and attachment. The complexity of this understanding lies in the sum of these and other interacting variables.

In historical terms, since the emergence of the first treatises on architecture, multiple works have dealt with building materials' role, function, and participation in architecture, engineering, and city building. Guerra García in [1] highlights Theodor Mommsen's *History of Rome* for its contributions to the understanding of the evolution of ancient Rome from its architecture. García extends the analysis towards later texts, in order to broaden the vision of the material as both a theoretical-practical category in the art and science of building, and as an object of historical concern. Also, current observations evidence that even on the most iconic contributions (such as those of Vitruvius in *De architectura*), there are difficulties in understanding the theory and practice of architecture in antiquity [4], but studying building materials, as an external factor, can help in unraveling such complications.

In the context of Ecuador and Cuenca, the panorama is less broad. Evidence on the means and resources for understanding materials in pre-Hispanic times is scarce, while descriptions associated with chronicles or travelers' notes prevail. Other investigations have provided information on cultural material or *sherds*, that is, mainly utilitarian and ceremonial artifacts typical of socio-cultural and productive activities.[1]

The truth is that materials are a constant in history and architecture, though their descriptors may vary. In English, associations would be with the terms 'ancient material', 'cultural heritage material', 'archaeomaterial', 'archaeological material', or 'old building material'; while in Italian, it would correspond to 'materiale antico'. In the same way, the specialized bibliography does not refer to more specific definitions for these terms; they usually operate as descriptors of research in subjects such as architecture.

According to Lambourn [5] "the central place of materials in architecture, and the subsequent construction of architectural history is so obvious that it is easily taken for granted. The idea that architectural traditions are conditioned by the materials

[1] For more information on this topic, consult Ernesto Salazar, Florencio Delgado, Karen Olsen, Francisco Valdez, and other in Apachita, the archaeological bulletin prepared by the Centro de Investigaciones Socioculturales (CIS) of the Universidad San Francisco de Quito (USFQ). Also in the Arqueología Ecuatoriana portal managed by the Colegio de Arqueólogos del Ecuador.

available for construction is axiomatic, as is the notion of hierarchies of materials, determined both by the economics of supply and demand and by cultural factors". These factors, in turn, influence and determine patterns of architectural survival, and with it, the analysis and argumentation about construction and architecture quality.

In this sense, any material which has survived till the point of analysis can be used to decipher and decode the meaning of architecture and integrate it with economic, social and environmental history. Thus, Milleto [6] indicates that historical materials are those that define the authenticity and permanence of architectural entities, and in turn, of the history of the city as a whole, not only by accumulating anthropic traces, but by facilitating the socio-cultural compression of proper and characteristic of a territory [7], i.e., collecting and synthesizing values.

From this perspective, materials are objects of interest mainly in the humanities and social science related academic fields such as archaeology, art history, and the history of sciences and techniques [8]. It is interesting to note that distinctions between different academic divisions can often be more due to institutional classifications than any real ontological differences- as Bertrand et al. [8] highlight regarding the difference between environmental science at INEE and Humanities at INSHS in France's CNRS. Also, according with the same author, *ancient materials* can be envisaged as sources of knowledge for understanding cultural behaviors, environmental and material sciences, and can be analyzed using optimized scientific procedures to acquire historical information such as the origins of an artifact, its use, alterations, and other particulars; therefore, they are part of a larger set of materials that are studied from the point of view of their historicity.

In a large scenario, the use, conservation, and evolution of materials denote their transcendence on the territory. Authors such as Tanac Zeren and Yilmaz Karaman [9] discuss the role of earth, wood, and stone in traditional Turkish houses; examining the earthquake resistance of this vernacular architecture and how it compares with the requirements of the Turkish Seismic Code. They also discuss the historiography of these houses as societies and building cultures evolved. On the other hand, Lambourn [5] describes the architectural history of Gujarat (India), suggesting that even though the surviving structures are made predominantly of stone (with fewer surviving examples of brick construction), the historiographical evidence indicates a more complex use of materials across the centuries, consistent with the region's geology and geography. Synchronic and diachronic perspectives can be used to differentiate between monumental and domestic architecture-moreover, while the latter is usually representative of locally available resources, monumental architecture often includes materials sourced from distant places. In the latter case, Muiños Barros [10] for example indicates that the particular color associated with Mexican architecture is due to the use of *tezontle*, a type of volcanic slag used since pre-Hispanic times (such as in buildings in the ceremonial precincts of Tenochtitlán) till the present day, due to the abundant presence of tezontle outcrops and its widespread presence in local construction traditions.

The Historical Center of Cuenca (HCC) includes materials (both modern and historical) coming from the Cañari, Inca, and Spanish (including Moorish) building traditions, as well as French-influenced, modern, and even contemporary ones, to support of the architecture of miscegenation [11]. In some cases, they make connection to other territories (periphery and rurality), and their belonging to the most significant set of building materials that in the past gave shape to cultural heritage of the present, and in turn, allow cultural evolution. As such, historical materials can be seen as a form of ancestral knowledge, and as a source of inspiration for material sciences (through their physical, chemical, and mechanical properties and behaviors). Their study can also enable the incorporation of archaeo/palaeo-mimetic properties into modern materials [8].

In this way, architectural history can be viewed through the lens of materials history [2]. Two considerations are therefore of interest. The first is 'how can a material be identified as being historical?' and, therefore, 'how can that status be defined?'. Initially, the theoretical category of 'historical materials' corresponds to all those inputs or resources that allow narratives of past events to be constructed, including not only texts, inscriptions, relics, photographs, and films, but also ancestral knowledge and experience, which contribute to this task (that is, primary sources). In this way, historical materials are notably located outside architecture and its related disciplines.

The second consideration develops around the question- 'what is a potential route for the holistic understanding of these so-called historical materials?' Starting from medieval archaeology and Italian research in the 1990s, Architectural Archaeology (AA) was delineated as an area of knowledge and technical discipline for the conservation of built heritage, and represents a propitious path in historical, constructive, social, and territorial terms. No less significant is the role of Archaeometry, which applies scientific methods and technologies to archaeological study. The association of this quantitative methodology with Architectural Archaeology is advantageous for the study of building materials [1, 12–14]. Therefore, neither only the historical-artistic, physical–mechanical or chemical vision of materials is sufficient- it is the convergence of these approaches that allows for the creation of contrasting information and effective knowledge.

In the last few decades, the interest in materials has expanded from cultural and historical archeological perspectives, especially in urban landscapes. Also, the maintenance and conservation of architectural heritage is a complex and expensive process. The prolonged exposure of the built structures to often harsh outdoor environments can result in decay, requiring careful restoration and maintenance. The restoration treatments, which work with the aim of improving conditions, substantially alter the equilibrium of materials, and can themselves potentially risk incompatibility with the substrate (resulting in further damage) [15], highlighting the complex nature of heritage conservation.

In order to promote the process of integrating knowledge it is necessary to involve a wide spectrum of institutes, universities, and international research centers. It should be noted that in Ecuador, the interest in and research on the *science* around materials, does not have the academic depth seen in Europe or the Unites States. The interest in building materials as objects of construction, innovation and technological development is mild.

2 Cuenca City: Architecture, Building Materials, and Historical Process

Historically, humans have used their skills and knowledge to modify their environment to meet to their own interests and comforts [16]. The growth and evolution of cities of cities has brought with it diverse guidelines [17]; in the case of HCC the exploitation and use of resources is linked to economic, political, social, technical, and cultural dynamics. This process of adaptation and development is also closely connected through the historical, cultural and geographical links. Thus, architecture was one of the first activities that resulted in significant changes to the morphological-spatial configurations of the city [18]. Here we speak of not only the modern or the neoclassical (French influence) styles, but of all the ways of defining architecture (and particularly the interaction, coexistence, and relationship of construction materials), which give it form and meaning. This is particularly clear in the case of traditional architecture.

Regarding the historical architecture of Cuenca and its vicinity, there is little known or recorded about the materials and construction techniques associated with the pre-historic and ancient cultures, such as the occupation of the Chobshi and Cubilán caves in 10,000 B.C., the agro-pottery cultures of Narrío (2,300 B.C.), Tacalzhapa (500 B.C.) and Cashaloma Cañari (500 A.D.) [19], or even of the Cañari and Inca tradition. The knowledge method has emphasised the bibliographical recompilation or the description of the cultural material with inductive methods [20], but the constructive materials have not been considered as scientific inputs. In short, as Páez [21] indicates, "*the pre-Hispanic architecture of the Historic city of Cuenca is a latent and open subject, a tangled quipu of which many loose ends have yet to be tied, and many knots to be interpreted. One and all of them go deep into our streets and houses, as well as into our souls"*. Although researchers such as Idrovo [22] approach the subject from the archaeological point of view, most of them have used the city of Tomebamba, its architecture and construction materials, in comparative analysis with cities such as Cuzco and Macchu Picchu. However, according to Espinoza [23], they have generally been historical elucubrations that pretend to tell the truth or are simply the product of the fantasy of some researchers.[2]

In this sense, it is true, for example, that the supply of natural stones such as andesite, travertine, and others from sites like Cojitambo, Baños, or Sinincay, is not a current problem; in the same sense, it is no less true that Ingapirca, Paredones and Pumapungo show the extensive use of andesite and other stones not precisely identified, which is consistent to some extent with the appearance of consolidated settlements of the Cañari and Inca periods. The knowledge of basic geometric configurations supports the above assertions. Undoubtedly, the most significant thing to understand about the evolution of native architecture is the natural tendency to move up the hierarchy of materials as soon as technology allowed it [24]. Fraser points out that under this premise the architectural hierarchization according to the hierarchy

[2] For more on this, see Espinoza (2010). The author describes extensively the details of the Inca city of Tomebamba and the segment of Pumapungo.

a) b)

Fig. 1 Colonial Cuenca. **a** Illustration of the city of Cuenca by Guamán Poma de Ayala ca. 1936. **b** Colonial house on Calle Larga ca. 1975. Colonial house on Calle Larga around 1975. *Source* Manosalvas [27]

of materials is logical, however, "low" quality materials could be used in some very important contexts, and the use of rare materials was not merely an economic issue. Indeed, it is often the symbolic rather than the economic value that conditions the precise use of a given material at a given time.

The impact of the Spanish conquest produced the next leap in the configuration of urban space and regional architecture, since the conditions for the development of the pre-capitalist territory of the European matrix were imposed on the Cañari-Inca territory, [21] In this way, a *new order* was established which reused the pre-existing infrastructure of the Cañari and Inca cities; streets, canals, and squares. The Cañari-Spanish alliance resulted in the foundations of the new city expanding around the indigenous city instead of on it [25] (Fig. 1). This was one of the most important arguments made to achieve the declaration of the HCC as a world heritage site. Despite this, even the most advanced existing structures of the time were razed or underwent a transformation in their forms and techniques, giving insight to the intensity of change witnessed, and the ability and skill of the Cañari builders and artisans to adapt to it. The latter category included goldsmiths, potters, carpenters, and weavers of plant and animal fibers, among others. Between 1530 and 1557, local artisans rose from relative obscurity to became progressively more important in the colony [26] the diversification of the craft trades[3] (weavers, blacksmiths, etc.) also increased during this period.

Modesty remained a fundamental characteristic of Hispanic architecture for at least 250 years (Fig. 1). Initially, there was a clash between the dry walls of unworked stone and wattle and daub, as opposed to the plumbed walls of adobe and fired brick.

[3] For more information on the dynamics of learning the trade, see Arteaga [27]. Also, to frame it in the national situation review Webster (2012) who describes extensively the case of Quito.

The earthen envelopes were made with the addition of natural fibers (usually straw) to guarantee that the element would last and not easily disintegrate; the same straw acted as a waterproofing material for the roof; and and the floor was made simply of compacted earth [28].

This architecture, which was the result of crossbreeding, used Euclidean mathematics and geometry applied to practical knowledge, but also the cañari abacus, such that the norms and forms of the time in Europe were coupled with the local resources and their constructive determinants (as in the case of the Baroque). This process continued till the end of the nineteenth century and the beginning of the twentieth century, when a new transformation occurred-the rise of the neoclassical of French influence. This style brought to the table the constructive versatility of andesite, travertine, earth, plaster, lime, and their combinations with brick and tile. In other words, all these construction materials began to define the architectural image and the historical urban landscape of Cuenca, even beyond the historical and heritage areas.

Although the historiographic account is common and made from multiple authors and levels of depth, the contributions of materials and local construction techniques frame a limited number of researchers. According to Jaramillo [29], the clear presence of craftsmanship in the buildings of Cuenca was a form of architecture in itself; with this assertion, he compared the historical work of local artisans with architectural production, and therefore positioned the handling of materials as an artistic work[4] which could be perfected in time in the hands of the gifted. Multiple reports [30–37] indicate that the artisan's work increasingly spans both the decorative and the constructive.

According to Bermeo and León [38], before the creation of modern engineering and architecture institutions, it was the great master builders who, with the artisan labour, built structures based on ideas of common sense and with locally available materials such as adobe, brick, stone and wood. Juan Luis Lupercio Chumbi is the most famous of this group. From another perspective, Muñoz [39] and his vast unpublished archive have contributed to the study of vernacular architectural models through examples such as the Church of El Sagrario or Old Cathedral, and the small buildings in the provinces of Azuay and Cañar.

Similarly, Pesántez and Gonzáles [40] discuss and describe the beliefs, practices, construction techniques, processes, and other forms of traditional knowledge associated with vernacular architecture. From these investigations, it was found that the use of stone, wood, earth, straw and other plant species predominated as building materials before they were systematically replaced- most significantly in the case of straw for tile; and earth and lime for Portland cement. This architectural modernization was also influenced by the international styles, the modern movements, the artistic avant-gardes and nineteenth-century historicisms, see Fig. 2. While each one had core invariant elements, they also together came to define what became known as 'Estilo

[4] The author includes in the research other information about constructive activity and their influence on the material.

Fig. 2 Collage of historical architecture between 1937 and 2016. **a** Intersection of Tarqui and Simón Bolívar streets. **b** Intersection of Benigno Malo and Sucre streets. *Source* Manosalvas [27]

Cuencano' or Cuenca's architectural style. As a consequence, the study of construction materials in Cuenca and its surrounding areas has been primarily approached from the symbolic, empirical or artisanal perspectives as technical support. Therefore, also the architecture, whose different material realities have been a product of the imaginary of the cuencano as a way of forgetting the past, and in turn, historical mentalities have positioned the materials as a cultural referent of progress [41]. Thus, the architectural style of Cuenca is the product of both material realities and the loss of traditional memories and construction styles- historical thinking therefore used the building materials as reference points to mark cultural progression [41].

Whether indigenously developed or imposed, architecture and building materials can reveal patterns of syncretization and resistance, as seen in the buildings of the HCC which reflect varying degrees of assimilation of technologies, techniques and designs [21]. Building materials are thus an important focus of academic study, both in their current usage and historical value, as can be seen from research at local and international levels. The breadth of this scope means that the interest in materials transcends any single discipline, and is instead multidisciplinary and multidimensional [42]. It allows us to define their meta-comprehension.

The previous context includes landmarks. The Artisan Neighborhoods is a representative case. These neighborhoods, which were in strategic sectors of the foundational center, wove networks of work, exchange and production with the rural sectors. Today rural sectors are the peri-urban and peripheral areas of the city [43]. For its part, vernacular architecture of pre-Hispanic origin prioritized the architectural conception joined with and defined by the considerations and constraints of the geographical and geological environment [40]. The Cañari and Inca settlements opted for the use of stone, earth, wood and straw, even before the Iberian influence on vernacular architecture [41] (which continued with the same material resources). The structuring of the buildings depended on social rank, and the materials used were

Fig. 3 Graphic synthesis of materials and construction stages. *Source and Elaboration* Aguirre Ullauri, Castillo Carchipulla & López León [77]

an important determinant of the same. No doubt that the permanence of materials, despite the morphological variations in architecture, describes their solvency and versatility (Fig. 3).

The materials, techniques and technology employed in cities can be used to mark not only defining transitions (such as the development of carpentry) but also the hybridization of astronomical and geographical knowledge for the exploitation of raw materials. The use of brick and lime, though introduced in the mid-sixteenth century, was not significant in the historical urban landscape until well into the next century due to its high cost; and only boomed during the last years of the nineteenth century [40, 41]. It is important to note that the colonial period extended in Ecuador until 1822; by 1830, the republic had gained political and administrative independence [44]—though through this period Cuenca's architecture continued to reflect vernacular characteristics. Minimal variations in materials, construction systems, and aesthetics would be evidenced until present times (houses would continue to favor centralized courtyards, orchards, porches and other elements characteristic of Spanish architecture) [41].

Between 1880 and 1930, thanks to the economic prosperity driven by exports of toquilla straw hats and husk, architectural designs saw a marked transition from Spanish to French influence, the latter being seen as representative of modernity and progress. This change resulted in constructive styles, spatial forms and materials with greater embellishments as both residential and monumental architecture began favoring the French neoclassical style, with decorations used in façades and interiors. While adopted initially by the public administration and economic elite, neoclassicism soon became more widespread, as elements were incorporated to develop a new, local variation of the style. These motifs, in contrast to the sobriety and simplicity of the earlier style, defined the new architectural and urban aesthetics [28, 45], and were positioned as being 'modern'.

> After some years of importing the building materials that were necessary to create the new style, the region started producing its own construction materials, particularly bricks, for which the area is now known nationwide and which is considered to be an authentic local building tradition. Today, the neoclassical architecture forms part of the protected cultural patrimony in the city center, an area that is officially defined as the "Centro Historico" [46].

That is, as in Europe, the style and location of architecture '*served the upper classes both as an instrument for and as a symbol of universal civilization'* [47]. In fact, Cuenca sought to project itself into modernity, and overcome the heavy burden of its colonial and pre-Columbian past. Architecture, art, music, poetry and other cultural products were the means identified for the implementation and strengthening of this legitimate need. This highlights the historical tendency of Cuenca and other Ecuadorian and Latin American cities to use existing resources for local development, while the architecture evolved by adapting and imitating techniques [78]. The city developed slowly, due to permanent migration, low technification and inadequate provisioning of planning tools until the late twentieth century.[5] The rise of French influence enhanced the use of materials such as travertine (pink, green, yellow and grey), exposed brick and andesite stone; polychrome brass, glass and colored glass, wrought iron and tin, ceramics and tiles, plasterwork and others. This diversity and the relative ease of access typifies to the recognizable imitation and to the adaptation as natural constructive acts. The embellished superficial facades [48] show the greatest incorporation of these materials, followed by the interior decorations and furniture.

For its part, while vernacular architecture in the city continued to disappear and deteriorate, its building materials continued to be in use in the twenty-first century. They even surpassed modern and postmodern materials such as concrete, iron and glass, which implied that there were new ways of conceiving local architecture. Also, the influence of styles such as Art Nouveau, Art Deco and others increased the overhaul of many (potentially heritage) buildings which are impossible to recover today [42] (Fig. 2). Also, the material innovations brought with them new building methods, but only ceramic materials (tile and brick) were integrated until they became iconic materials in the city. Metropolitan Cathedral of the Immaculate Conception of the Virgin Mary, commonly called the New Cathedral [49], is a colossal example which became an icon for the urban, industrialized and progressive future of the city, too. The ceramic materials reached its highest development with the previous building [50].

As can be seen, the identification and analysis of materials and their links to architectural elements, heritage conservation, and urban planning are necessary in order to understand the architecture of the HCC, and its physical, social and cultural reality. It is no less important, in the face of the inevitable need for both documentation

[5] It is noteworthy that the extensive literature that addresses the artisanal neighborhoods of Cuenca is limited to the context of the HC, disregarding the potential of the adjacent spaces. This situation results a lack of knowledge and with it a lack of empowerment among the citizenry, both of the sites and of their productive activities.

and conservation, to characterize and study the historical-constructive relationships, and understand environmental contexts the buildings are located in [51].

In subsequent years, the developments in architecture were reflected not only through the emergence of material variants but also through the progressive technical growth, which gradually optimized services, infrastructure, urban landscape and productivity of Cuenca, resulting in its current status as a cultural, academic, technological, economic and industrial center in the South of Ecuador. Also, despite the succession of styles, the need to recover the local identity, will not leave aside the architectural typical features. That is to say, despite the significant impacts of the changes in the architectural styles, industrialization, and the economic policies on construction practices in the region, a historical analysis of the built environment shows that materials such as travertine or andesite stone have been continually used through the ages (Fig. 3).

Thus, from the historical account, it is possible to synthesize the characteristics of the architecture of Cuenca and its historical urban landscape. The evident permanence and persistence in the use of certain materials, in addition to empirically denoting their high performance and technical qualities, also indicates their cultural importance to the people of Cuenca. As a result, heritage inventories [52] show, though not systematically, the categories of value for buildings that highlight by their unique forms and contrasts of the local constructive culture through a group of materials.

It can be seen how materials take a leading role not only in the stylistic definition at different architectural scales (Fig. 2), but also in the evolution of construction techniques and processes linked to the improvement of workmanship. Using these particulars, a review of the existing heritage inventories shows the remarkable almost-recurrent increase of assets [27] (Fig. 4). It also allows for the identification of potential historical trends in the region. A closer study of the materials used in the structural elements, architectural elements and finishes over the years (Fig. 3) shows that between 1975 and 1978, brick, marble (possibly travertine), stone (surely andesite), wood (of various species), earth and multiple mortars were the predominant materials used, though materials made from modern manufacturing processes were also present (Fig. 5).

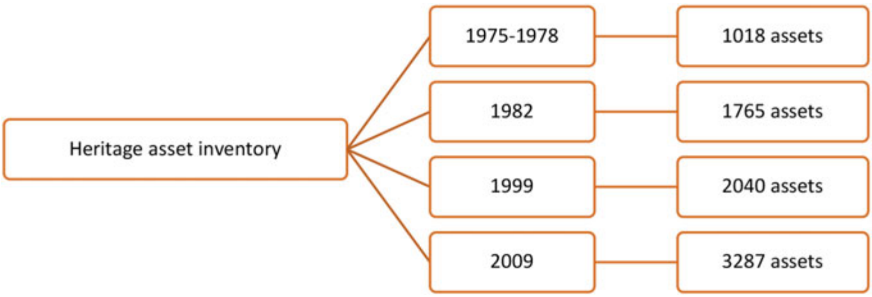

Fig. 4 Summary of local inventories. *Source* Manosalvas [27]; Aguirre Ullauri [53]

Fig. 5 Material report of the inventory carried out between 1975 and 1978. *Source* Aguirre Ullauri [53]

In the case of the inventory for the period 1980–1982, it was determined that the general decrease of inventoried, or rather registered, assets acted as a trigger for the identification of materials. Nevertheless, it is possible to identify adobe, wood and brick as the predominant materials (Fig. 6). Others, such as tile, are absent, possibly due to the lack of registration or systematic recording. On the other hand, in the 1999 inventory, the records of materials used are maintained, and the report of the use of others from the 1975–1978 inventory is recovered; it is also true that, as time goes by, the introduction of new materials becomes more evident. In this sense, Portland cement and its derivatives play a leading role in the 1999 inventory (Fig. 7).

Finally, in the 2009 inventory (Fig. 8) the situation is the same as for previous inventories. Thus, there is constant presence of materials such as earth or Portland cement and numerical growth of heritage assets, but there are important materials excluded, too.

3 City of Cuenca: Energy and Life Cycle Approximation of Three Historic Materials

The old material constitutes the urban core of the historical present of the city, that is why this energetic proximity, aims to make known the environmental advantages in the approach to heritage conservation [54]. In addition to the preservation of cultural heritage, the conservation of historic buildings can also be a way to avoid the energy consumption and carbon emissions associated with demolishing and rebuilding them.

Improving energy consumption in buildings was a key component of the global call by the Sustainable Development Goals (SDGs) to reduce the ecological footprint of buildings. As a result, there emerged strategies, approaches and tools which supported the development of new education systems, economic frameworks, and building standards aimed at energy conservation, as well as different ways of thinking about the reuse of heritage buildings [55]. Current regulations support the development of technical knowledge about historical or old materials and their intrinsic characteristics. This is advantageous when generating interventions to conserve and maintain heritage buildings, as it can help ensure compatibility between the new materiality and old materials and avoid damage [56], which in turn can help extend the service life of buildings.

In addition to being heritage, historical materials are adapted to the immediate natural environment and therefore energy consumption is reduced by reusing them. This is why sustainable reuse and regeneration helps not only the conservation of heritage, but also the environment [57]. Research aims to provide an insight into the energy characteristics of historical materials (such as thermal transmittance and thermal conductivity) which can be an introduction to further analysis, and evidence of thermal improvements in an indoor environment.

It is clear that building materials can be seen through a historical lens [58]. The evolution of constructive materiality corresponds to the human need to improve

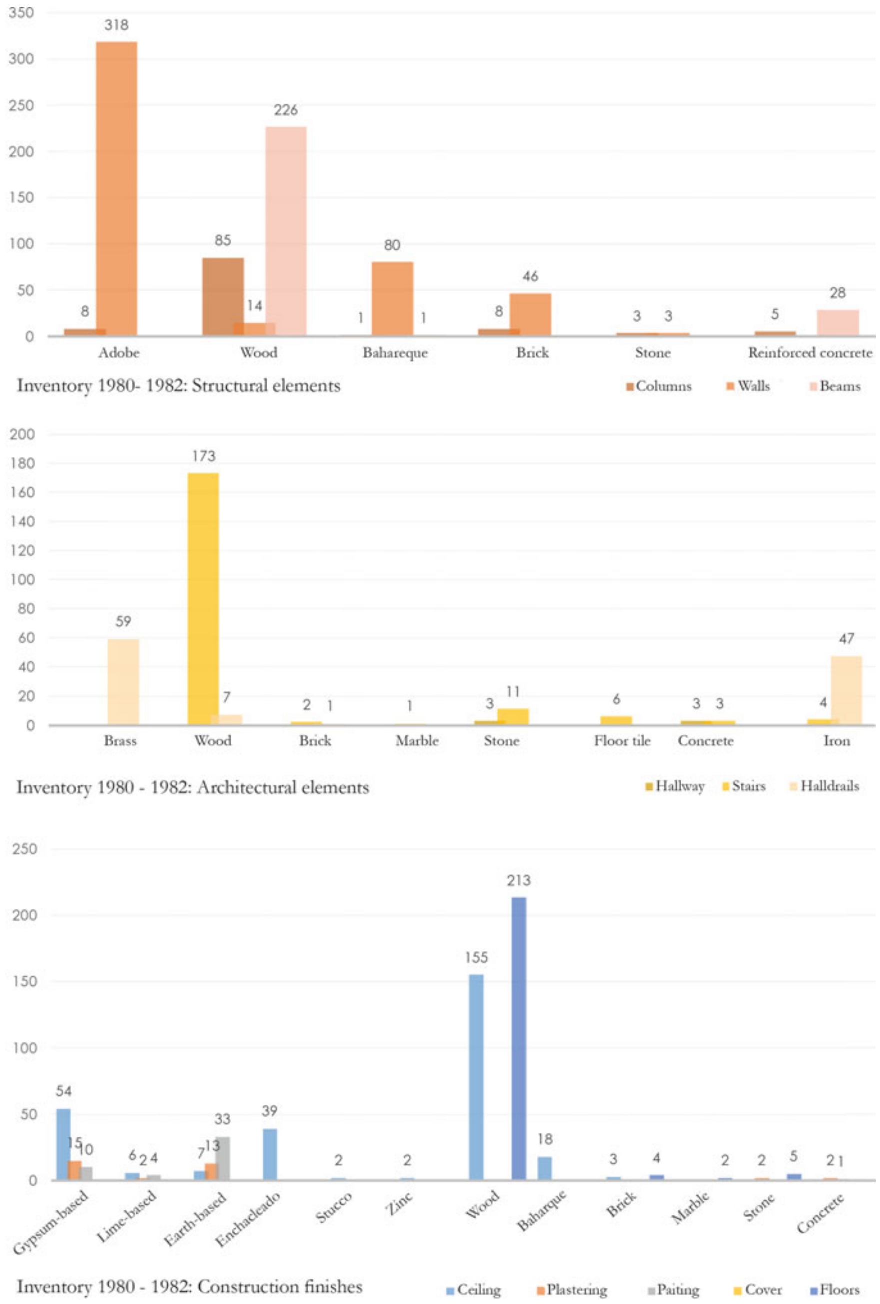

Fig. 6 Material report of the inventory carried out between 1980 and 1982. *Source* Aguirre Ullauri [53]

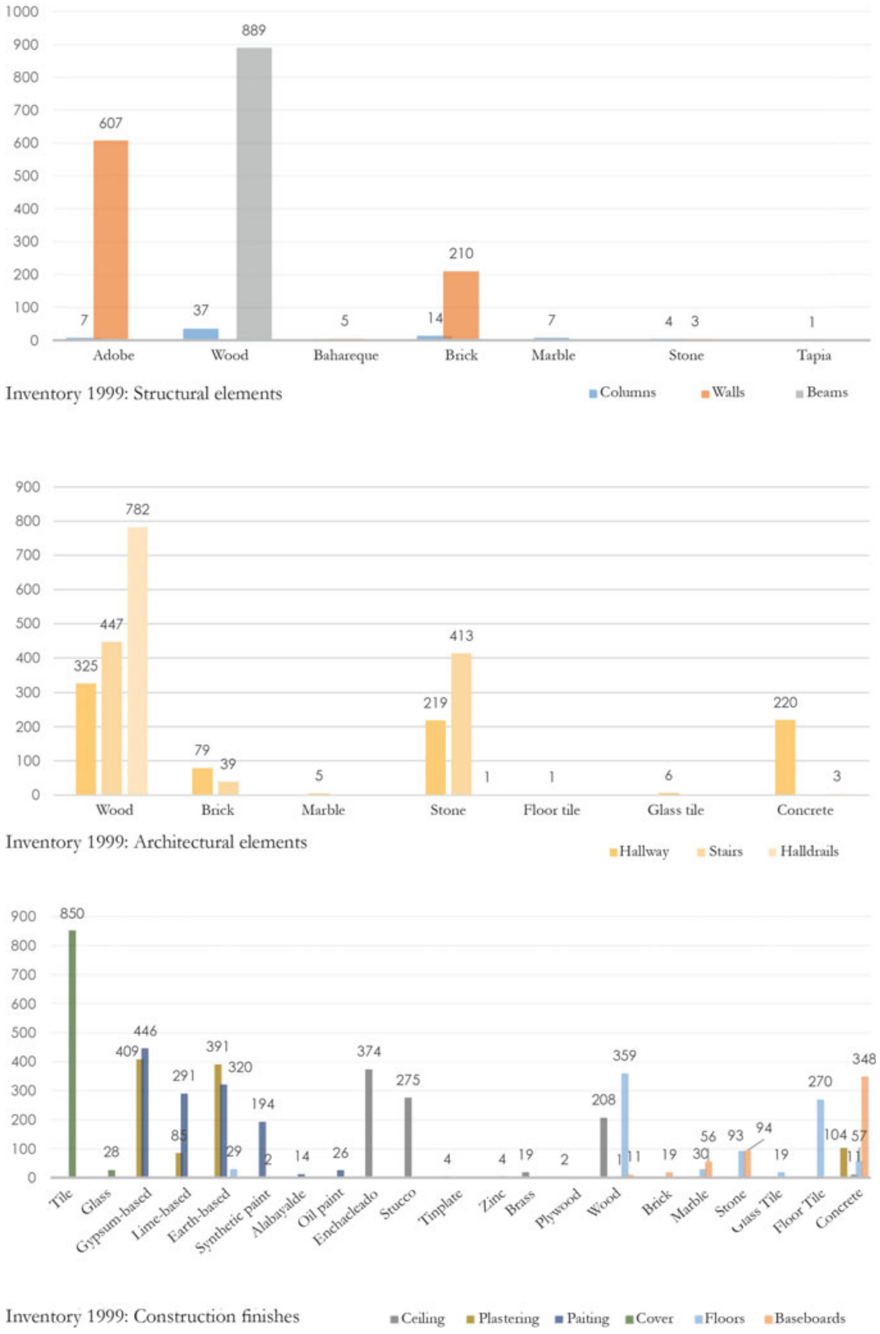

Fig. 7 Materials report of the inventory carried out in 1999. *Source* Aguirre Ullauri [53]

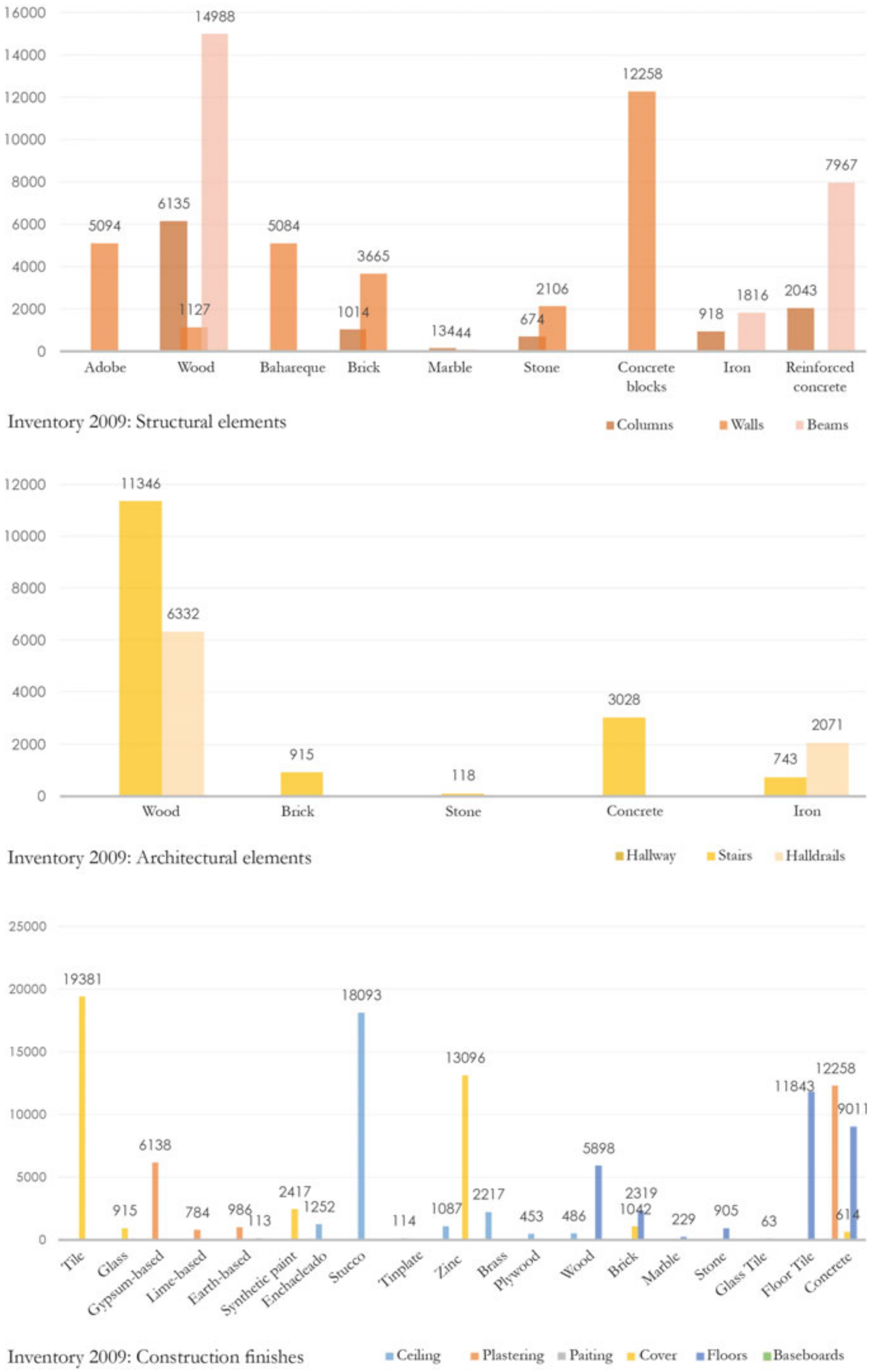

Fig. 8 Report of materials of the inventory carried out in 2009. *Source* Aguirre Ullauri [53]

shelters that were initially built to ensure survival. Thus, there has been a constant improvement in habitation, as well as in the materiality that constitutes it. For millions of years mankind has found the solutions to housing requirements through the extraction of resources from the surrounding natural environment, without considering the potential problems of progressive consumption of natural elements.

An economically viable alternative is to promote the use of local materials with good energy efficiency characteristics [59]. Subsequent sections review the energetic characteristics and comparative materiality of historical materials- primarily adobe, rocks and brick as they are materials most commonly used in the façades of heritage buildings [53]. It is important to mention that these materials are locally extracted and have a good energy performance, and therefore reduce the ecological footprint.

3.1 Adobe

Materials such as adobe are used in many of the HCC buildings (Fig. 7). Adobe is made up of sand, clay, water, and natural fibers that help prevent shrinkage and improve physical and mechanical characteristics [60]. Thermal conductivity averages at 0.22 W/m K, although the values may change due to the variations in densities of the materials and the techniques used in the manufacturing process. Studies show that by using adobe on a building façade, thermal comfort is improved and energy consumption is reduced by 10% [61].

Thermally, adobe is capable of absorbing and conserving heat in the day when exterior temperatures are high and releasing heat to interiors at night when exterior temperatures fall [62]. It is a uniform material, so its heat propagation is homogeneous [63]. As it is produced by hand, adobe blocks have no fixed dimensions. Additionally, the blocks lack compaction as adobe is not tamped, resulting in the final material having highly variable porosity and hygroscopicity. To prevent the absorption of moisture from the environment, a coating is typically required.

In addition, one of the benefits of using this material can be seen from the durability of heritage buildings the use of adobe in building envelopes and structures allows buildings to show a plastic response and reduced deformation even after several seismic events [64].

Under Peruvian standard E-80 the composition of an adobe is: 50–70% sand, 5–18% clay and 10–28% vegetable fiber for flexibility. The water used for this process must be potable and free of organic matter, oils and acids [64]. The sand and clay used must be free of coarse granular material and foreign matter, and the final adobe should be free from cracks, splits and other defects that can lead to low compressive and flexural strength, and, consequently low durability.

Adobe is a good acoustic insulator, has a low environmental impact, can be reintegrated into nature, has high fire resistance and permits a ‘do it yourself’ (DIY) approach . A review of its characteristics (density, thermal conductivity and thermal transmittance) at different thicknesses are described in Table 1—based on this analysis by several authors, it shows good thermal behavior. The thermal conductivity

Table 1 Thermal characteristics of adobe

Materials	Sources	Density ρ (kg/m^3)	Thermal conductivity (W/mK)	Thickness (m)	Thermal transmittance K (W/m^{2}K)
Adobe	Evans et al. [65]	1500	0.58	0.35	–
	Evans [66]	–	–	0.15	2.89
	Espinoza et al. [67]	–	0.85	0.38	2.23
	Bestraten et al. [68]	1200	0.46	0.3	1.43
	Heathcote [69]	1650	0.82	–	2.73
	Arancibia [70]	1600	0.95	–	–
	Daudon et al. [71]	1600	0.81	–	–
	Moevus et al. [72]	1200–1700	0.46–0.81	–	–

Source Various authors

of dry adobe depends mainly on its density and porosity. It varies between 1.5 W/m K for dense adobe (2200 kg/m^3), and can go down to 0.10 W/m K for mixtures of adobe and hemp or adobe and straw (500 kg/m^3) [72].

3.2 Stone

Another historical material considered in this study and present in heritage buildings is stone; it has been used by humans for thousands of years and will likely be used by subsequent generations as well. The main reason for this is its robustness and long service life. Predecessor civilizations such as the Incas predominantly used stone in their buildings. Since buildings in the colonial period used stone for the substructure, large parts of Inca masonry were incorporated into colonial buildings, with the result that currently there are very few heritage buildings that preserve this unique construction process. At the end of the nineteenth century and by the beginning of the twentieth century, there was greater versatility in construction materials used, with the inclusion of andesite, travertine, plaster, lime, as well as others such as brick and tile [53].

The water vapor permeability of a building material defines the moisture exchange capacity between the interior and exterior of a building, with higher permeability allowing easier exchange. Stone is impermeable [72]. The thermal conductivity of stone additionally depends on its mineral composition, texture and degree of crystallization–crystalline structures show higher heat conduction than amorphous and glassy rocks of the same composition [73, 74].

Table 2 Thermal characteristics of stone

Materials (Type)	Sources	Density ρ (kg/m³)	Thermal conductivity (W/mK)	Varied thickness (m)	Specific heat capacity (c) (KJ/kg K)
Crystalline stone	Norma UNE-EN 1745 [75]	2800	3.5	–	1.00
Sedimentary stone		1500	0.85	–	1.00
		2600	2.3	–	1.00
Porous natural stone (e.g., volcanic materials)		1600	0.55	–	1.00
Igneous (andesite)		2000–2700	1.10	–	1.00

Source Standard UNE-EN 1745 [75]

Table 2 summarizes the thermal conductivity of andesite and other rocks according to their formation- with higher density the degree of thermal conductivity increases gradually. These considerations need to be accounted for when planning interventions for the maintenance or renovations of heritage buildings to avoid damage to the stone.

3.3 Brick

Among the materials commonly used in the Historical center of Cuenca's construction is burnt clay bricks, which have an embodied energy of 1.2–4.05 MJ/kg [79]. This high value is the amount of energy consumed in the manufacture of this ceramic material, with a pollution of 0.2 kg of CO_2 for each kilo of brick made. The use of bricks was incorporated under Iberian influence and continues till this day. The density and water absorption characteristics of this material in three regions in Cuenca are shown in Table 3. The density of bricks in these regions ranges from 1.51 to 1.65 g/cm^3, with a (relatively high) water absorption of 17.06 to 19.96%.

Table 3 Density and absorption of the analyzed bricks

Brick	UNE-EN 772 -13	INEN 296
	Density (kg/m³)	% Water absorption
Sinincay	1510	19.23
Racar	1330	19.96
Tejar	1650	17.06

Source Aguirre Ullauri [53]

Table 4 Thermal characteristics of brick

Material	Sources	Density ρ [kg/m^3]	Thermal conductivity l [W/mK]	Thickness [m]	Thermal transmittance K [W/m^{2}K]
Solid mansory wall	Arancibia [70]	1800	0.87	0,12	–
	IRAM 11,601: 16	1800	0.91	–	–
	Evans [66]	–	–	0.15	2.77
	Evans [66]	–	–	0.10	2.36
	Muñoz et al. [39]	–	0.29	0.12	–

Source Various authors

Table 5 Thermal characteristics of the brick of the city of Cuenca-Ecuador

Raw materials	Coarse and fine aggregate (%)	Silt and clay (%)
Sinincay	62.71	37.39
Racar	73.13	26.87
Tejar	75.66	24.34

Source Aguirre Ullauri [53]

The characteristics in Table 3 are from an analysis of different parts of Cuenca-by contrast Table 4 describes the results of different researchers in analyzing the thermal characteristics of brick.

The composition of the bricks in the different sectors of Cuenca is described in Table 5, which shows the percentage of coarse and fine aggregates, as well as the percentage of silt and clay [76]. Therefore, the higher the density of the material, the lower the thermal conductivity, and its transmittance varies according to the various tests carried out by different authors (Table 4).

As a conclusion of the energy analysis of these historic materials, it can be said that the measures taken to reduce greenhouse gas (GHG) emissions of historic buildings are aimed at improving their energy efficiency by insulating the building envelope and improving their heating, cooling and lighting systems. This allows these buildings to be used for longer, and can be an option to reduce resource wastage and the unnecessary expansion of the city. It should be considered that much of the energy embodied in each historic material has already been expended in the case of heritage buildings, and the continued use of these buildings (instead of demolishing and building anew) would reduce a percentage of the overall energy consumption of materiality.

The increase in embodied energy of these buildings will then only correspond to the new materials that are added for thermal upgrading. An option for the city and its HCC then is to renovate, as renovation generates less embodied energy and less energy expenditure. The reuse of historical materials, regeneration, and conservation of traditional building techniques would promote a circular economy of craftsmanship and permanence over time.

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