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# Embodied carbon and economic cost analysis of a contemporary house design using local and reused materials

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A R T I C L E I N F O

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A B S T R A C T

This paper presents a house design that uses adobe in the walls and wood in the roof, a mixed building system that vernacular houses in the region where it is located already use, however it presents a contemporary strategy based on less, more natural, reused, and local materials, implying also less transport. The environmental impact analysis of the Case Study was made considering the Embodied Carbon of the construction materials used and compared with conventional building systems. In spite of presenting a much lower embodied carbon than all the conventional solutions in comparison, it turns to be more expensive.

## 1. Introduction

"For a long time the growth looks insignificant. There appears to be no problem" [1]. However, time ended up revealing that this was not the case. The mentality focused only on the unlimited economic growth, brought with it a wave of excesses in: extraction of natural resources, production, consumption, waste, and, of course, their related pollutant emissions.

The construction industry is one of the sectors with great responsibility for green-house effect gas emissions. Buildings are responsible for more than half of the pollutant emissions responsible for global warming [2], and the consumerist trend that extends to architecture, ends up to contribute for it. Nowadays, architecture is constantly manipulated by the real estate market to match the expected aesthetic trends. Although buildings are, in its physical form, composed of an agglomerate of different materials, each with its own function, many times they end up covered by others, just to be more aesthetically acceptable. Any material production causes environmental impact, so, if materials are added just to hide others, the construction is overloaded with unnecessary impacts. This trend drags on even to coatings that end up being coated [3]. All design stages that precede construction influence, albeit indirectly, the environmental impact of buildings. The decisions related with the shape of the building and its location, allow to control its behaviour, in terms of passive heating, cooling, natural light and ventilation. Naturally, when planned to achieve good behaviour in the most natural way possible, it ends up reducing the energy consumption, thus reducing the environmental impact of building related with its use.

For example, in a first phase of the project it is important to analyze the site, the characteristics of the climate, the recurrent construction practice and the materials available. Choosing local materials and techniques, in addition to adapting to the place and promoting local economy by adopting local labour, reduces the impact caused by their transport. The second phase of the project, in which areas, program content and volume are determined, is when the quantity of material to be used in the building construction is determined. By avoiding using unnecessary amounts of material, whether by reducing the building area or overlapping layers of materials, the impact is further reduced.

Environmental policies in construction sector have been mainly focused on the adoption of energy efficiency measures during the use phase of buildings that, by improving the building's functional behaviour and, consequently, increase comfort, providing less maintenance cost and less impact on environment. This is connected with the fact that national [4] and european regulation [5] is mostly focused on the thermal performance of buildings. However, the option for the use of more sustainable materials in the construction phase of buildings, in terms of their production, has been a strategy relegated to a secondary plane. The material itself implies an associated impact, thus, the judiciously selection of materials to be used has a significant influence on the impact of buildings regarding all phases of its life cycle. This work intends to demonstrate that, by avoiding the use of new and industrialized materials, replacing them as much as possible with reused, natural and locally available ones, such as adobe in the walls, wood in the roof structure and second hand materials found in online selling platforms is

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possible to reduce the environmental impact related with the building envelope, but still being economically feasible. A single-family house whose envelope was conceived according to these principles is presented as a demonstrative case study.

This paper is organized in the following sections: 2 - the methods used are the among the most commonly considered and used on the LCA and cost evaluation; 3 - the case study characterization and implemented strategies to reduce the environmental impact; 4 - the Embodied Carbon Assessment of Case Study House and comparison to commons solutions used; 5 - the Economic Cost Analysis of Case Study House and comparison to common solutions used; 6 – the discussion where both the embodied carbon and economic analysis are summarized and its reciprocal connection; 7 - the major conclusions.

## 2. Methods

It is the selection of the materials that has most significant consequences on the environmental impact of the construction. At the time of its selection some aspects must be taken into account: the amount of material to be used; its nature (because the closer to its natural state, the smaller its processing, and, consequently, the lesser its impact); prefer reused materials (thus avoiding the pollution generated by the production of new materials and also avoiding the production of solid waste, destined for garbage). These were the premises for considered in the design of the Case Study presented and analyzed in this research. Life Cycle Assessment (LCA) is a widely accepted tool to evaluate the potential environmental burdens associated with a product, process, or activity by identifying, quantifying and assessing the impact of the used energy, and materials, and the wastes released to the environment [6]. LCA considers the potential environmental impacts throughout a product's life cycle (i.e. cradle to grave) from raw material acquisition through production, use and disposal.

Although the LCA method was at first oriented to generic products or services [7,8], its application in construction is now widely accepted and considered in specific standards [9,10]. LCA is very important to compare several possible alternative solutions, which can bring about the same required performance but that differ in terms of environmental consequences.

Assessment of buildings lifecycle environmental impacts is often dominated by energy consumption during the operation phase: it is estimated that the operation phase in conventional buildings represents approximately 80% to 94% of the life cycle energy use, while 6% to 20% is consumed in materials extraction, transportation and production and less than 1% is consumed through end-of-life treatments [9]. Nevertheless, with the increasing requirements on energy efficiency, namely in Europe by Energy Performance Building Directive [5] and their regional adaptations, as well as the use of less polluting energy sources, the relative contribution of the material production and end of life phases is expected to increase in the future [11].

LCA is essentially an iterative process that includes the following major stages [7]: (i) Goal and Scope Definition; (ii) Life Cycle Inventory (LCI); Life Cycle Impact Analysis (LCIA) and interpretation of the results. In the first stage, the purpose of the work, the audiences, the system boundaries (temporal, geographical and technological), the sources of data and the environmental impact categories to be used are identified. LCI stage includes collecting data for each unit process regarding all relevant inputs and outputs of energy and mass flow, as well as data on emissions to the air, land and water. The Life Cycle Impact Assessment (LCIA) phase evaluates potential environmental impacts. The purpose of this phase is to estimate the importance of all environmental burdens obtained in the LCI by analyzing their influence on selected environmental loads. The interpretation may be described as the systematic procedure to identify, qualify, check, and evaluate the results of the LCI and LCIA stages [11]. The modules considered in the analysis of this case study were those mentioned in EN 15978:2011 related only with the production of materials (modules A1-A3). The embodied carbon assessment is based in the first parameter: (i) Global warming. The other parameters that were not evaluated are: (ii) Ozone depletion; (iii) Acidification for soil and water; (iv) Eutrophication; (v) Photochemical ozone creation; and (vi) Depletion of abiotic resources-fossil fuels [8].

The first step in the quantification of the environmental impacts is the inventory analysis [12]. Taking into consideration the aims of the study, it was only considered the production of materials and its transportation. The end-of-life scenario was not considered.

The calculation of the environmental indicators (Life Cycle Impact Assessment - LCIA) demands specific knowledge of life cycle inventory datasets, in particular, how these are composed and what is included, i. e., the system boundary and allocation rules are crucial [13]. Nowadays, there is still a considerable lack of specific environmental information for the major part of the construction products, i.e., Environmental Product Declarations (EPD). Since the development of specific environmental information for products is very time and cost consuming, initial LCA studies, which main goal is to de-fine the design alternative to be further developed, are normally based in generic (average) data. This study is based in one of the internationally accepted generic Embodied Carbon databases, the ICE Database [14].

The economic cost analysis should be based in the whole life-cycle costs of the building system. At this stage, this study considered just one economic indicator: construction materials cost (CC).

## 3. Case study characterization and implemented strategies

The case study is a single-family house design (Fig. 1) developed during an academic research carried out by the second author under supervision of the first author and another supervisor, presented with more detail in [3], which aims to counteract a whole set of trends in contemporary architectural design: it minimizes itself in its area, seeks to optimize natural resources, and, above all, it has as a basic principle to optimize the selection of materials. The design options, thought out from the initial stage and which ended up influencing the materials to be selected, were based on four strategies in order to guarantee the minimum impact of the materials used in the building envelope: Less, More natural, More reuse, Less transport, More local.

### 3.1. *Less*

“It's that simple: reduce the amount of materials in a building” [3]. The best way to avoid pollution is not to pollute. Thus, in the case study design, only the needed materials were used. The structural materials are apparent, where possible, and coatings were added only when strictly necessary - it is essential to waterproof the roof, for example. The solution here implemented was reused galvanized steel panels. The moisture outside, or even in spaces such as the kitchen and bathroom, would end up damaging the structural materials. And it is only in these cases that coatings were added, just to preserve essential materials, not as aesthetical camouflage.

### 3.2. *More natural*

Each material represents an environmental impact, which can be illustrated by the carbon emissions that this material generates since it is extracted from nature until its applied in the building [13]. Therefore, choosing materials as close as possible to their natural state is always the simplest way to reduce the environmental impact of architecture. Furthermore, the more artificial, the more industrial procedures involved, the more toxic that material will generally be. And "(…) in fact, a toxic material can never be good, neither for the environment nor for human beings." [3] So, one way to reduce the environmental impact was precisely to opt for natural materials [15]. The structural walls are in double pane of adobe masonry, using the most primitive technique: the earth is extracted from the ground at the construction site, and the blocks are moulded in wooden moulds and placed to dry in the sun. The

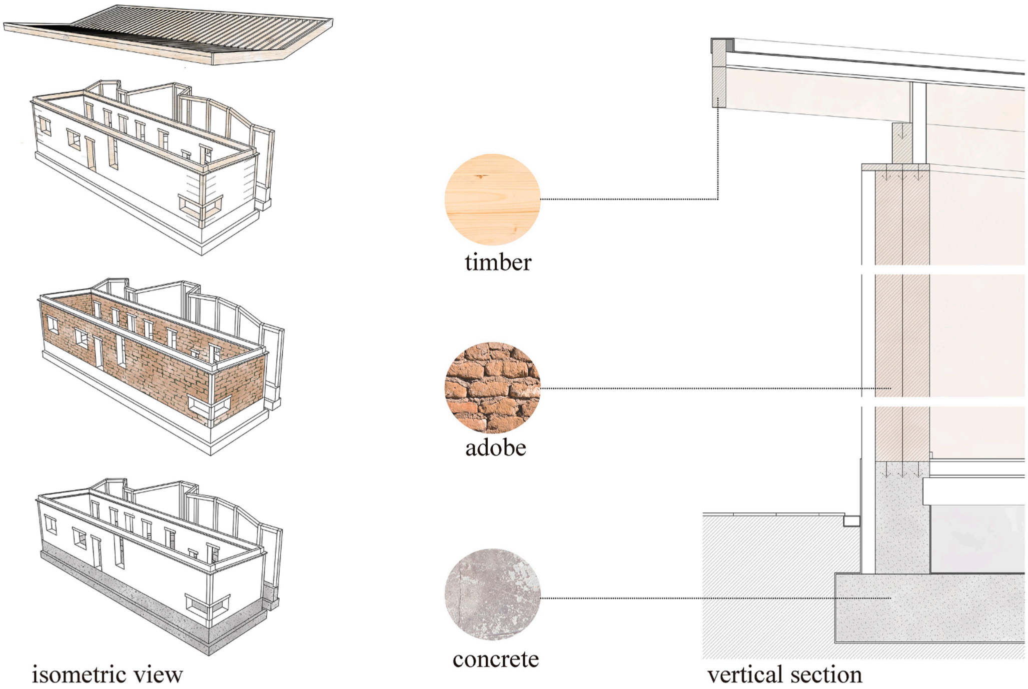

**Fig. 1.** Isometric view and vertical section of the Case Study House.

covering and structural reinforcement of the masonry walls - pillars at the intersection of the wall panels, to avoid disconnections; and a wooden plank at the top of the wall, for a correct distribution of the roof weight - are made of local pine wood. The use of concrete, which does not fit the Case Study principles, comes from the impossibility of using adobe to perform the structural function of foundation. In the past, it was often used stone, to support the structure, but with the structural instability that this represented, it ended up not being allowed its use in such an important role as the foundation of the buildings. Thus, a lean concrete would be applied, with the highest possible percentage of inert material. Another material necessary for the proper functioning of the house is thermal and acoustic insulation. Although they are not the most common or cheaper insulation solutions, we can look for natural materials with low conductivity, which allow to perform this function, such as cork, a natural resource that Portugal has in abundance, being the largest producer in the world. For this purpose, an Expanded Cork panel assumes the outer layer of the walls as an External Thermal Insulation Composite System (ETICS), allowing the interior temperature and humidity to be more effectively regulated by the wall elements in earth.

### *3.3. More reuse*

"Although all these material options minimize most of the impact, reusing is preventing these impacts from happening." [3] Since there are materials needed for the proper functioning of the house, at least they should not produce significant impact! Most of the coatings to be applied in the Case Study are reused from dismantled buildings, or simply result from stock discontinuation. The materials used are: granite slabs, for the exterior pavement to access the house; galvanized steel panels for covering the roof; wood recovered from pallets, which covers the entire interior floor; OSB boards, which cover the outside of the service bathroom; antique tiles covering the damp area of the kitchen; discontinued ceramic tiles for cladding in both bathrooms; wooden beams that line the entrance area. And finally, the window frames, which are all reused. Through an intensive survey of their availability on various internet platforms, window frames were adapted and integrated in all facades that otherwise would probably be destined to garbage or recycling. In Figs. 2 and 3 can be seen the window frames selected by this process and their position in the Case Study House facades.

### *3.4. Less transport, more local*

"It would be ironic if the transport of a natural material would pollute more than the sum of the production and transport of an industrial alternative" [3]. All reused materials were selected considering a maximum distance of 50 km from the house location site (Fig. 4), 50km south of Porto, the second biggest city in Portugal, and the most far location of the materials considered in the design. Adobe, the most significant material in terms of weight applied in this case study, was produced from local soil, therefore without transport impact. Adobe construction is a recurrent practice in Aveiro, the capital city of a Portuguese district, and where the Case Study is located [16]. In fact, this very natural construction, which is part of the building heritage of the place, has been disappearing, reducing its practice. Earth construction represents nowadays only 1% of buildings throughout the country [17]. Pine wood and cork are natural materials of national origin, lightweight and produced locally.

## 4. Embodied carbon assessment of case study house and comparison to commons solutions

The materials used in the exterior walls and structure on housing buildings in Portugal are generally heavyweight [18]. Concrete and brick are used in the conventional construction system that allows high thermal inertia and acoustic insulation. Following a previous study by Mendonça [19], it could be concluded that brick accounts for almost 40% of the Embodied Energy (EE) and consequently also of the Embodied Carbon (EC) of the conventional building construction, and especially on exterior walls. Thus, for obtaining more environmentally sustainable building solutions, the consideration of materials with less EC than brick and concrete should be pondered. The use of more lightweight and prefabricated solutions [17], even when associated to conventional heavyweight solutions in what can be called as mixed weight solutions, has proved to present less embodied energy and be at least equally efficient in terms of functional performance [19]. Combining the traditional materials used in traditional construction in

**Fig. 2.** Reused window frames in south facade and vertical section of the Case Study House.

the region of the Case Study House – Earth and Wood, allows to obtain a Mixed Weight solution, such as the one here proposed and analysed in comparison with conventional construction (Concrete and Brick) and with Lightweight prefabricated building systems (Light Steel Frame and Wood Frame solutions). In terms of thermal and acoustical insulation the Case Study solution considered the use of Expanded Cork, following a previous study by Mendonça [19]

"If we invented concrete today, nobody would think it was a good idea (…) It's liquid, needs special trucks, takes two weeks to get hard and doesn't even work if you don't put steel in it. Who would do that? — Nobody!" (Ramage cit. on [20]). Concrete has been associated with significant environmental impacts of construction and, even so, its use remains widespread and characteristic of conventional construction [21]. In conventional concrete and brick system, the components are almost always permanently fixed, composing an inseparable unit, which causes components with short useful life to condition components with longer useful life. A fundamental principle for efficient reuse of building components is the differentiation between the building components. Systems that pretend to be easily disassembled should allow dry assembling, with components prepared to be mechanically fixed and not

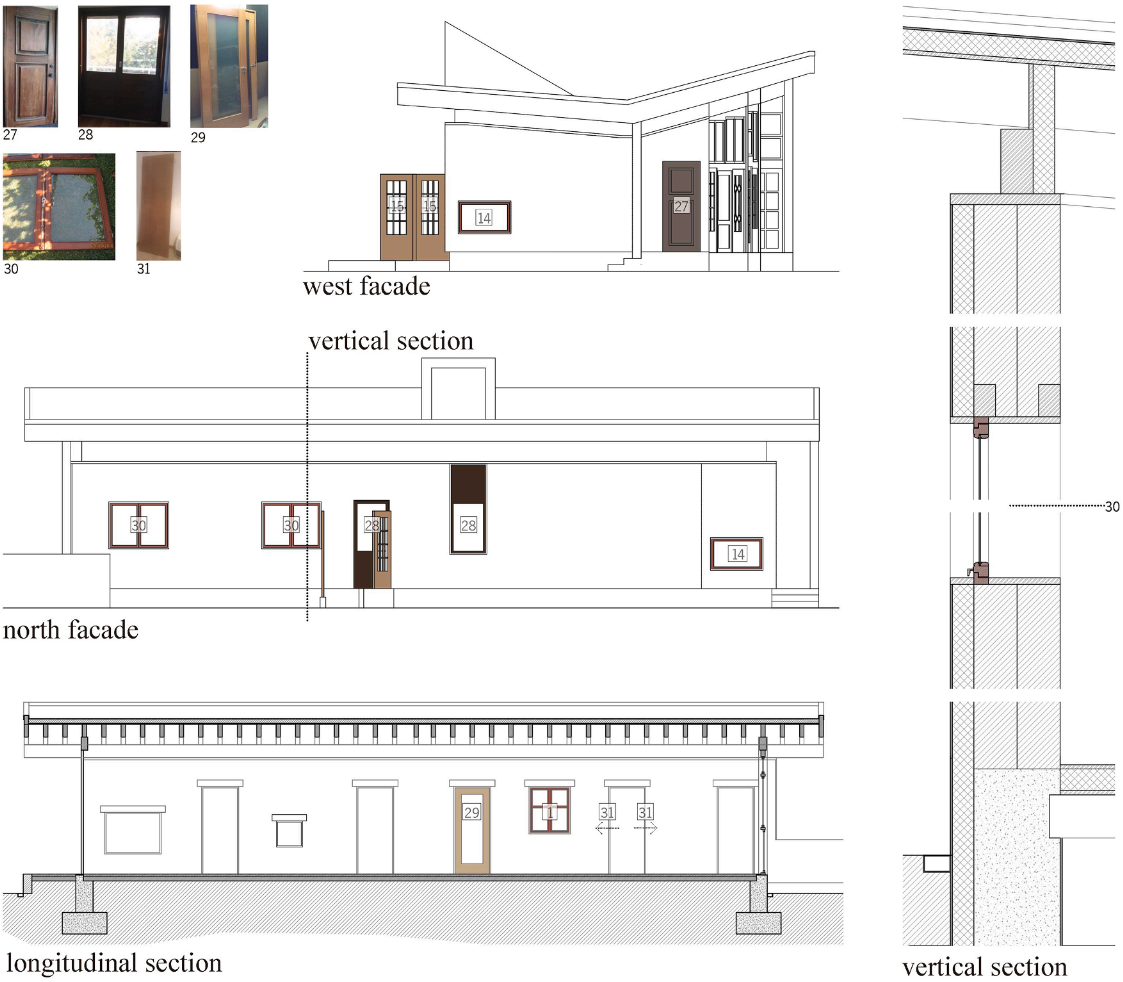

**Fig. 3.** Reused window frames in west and north facades and vertical section of the Case Study House (adapted from [3]).

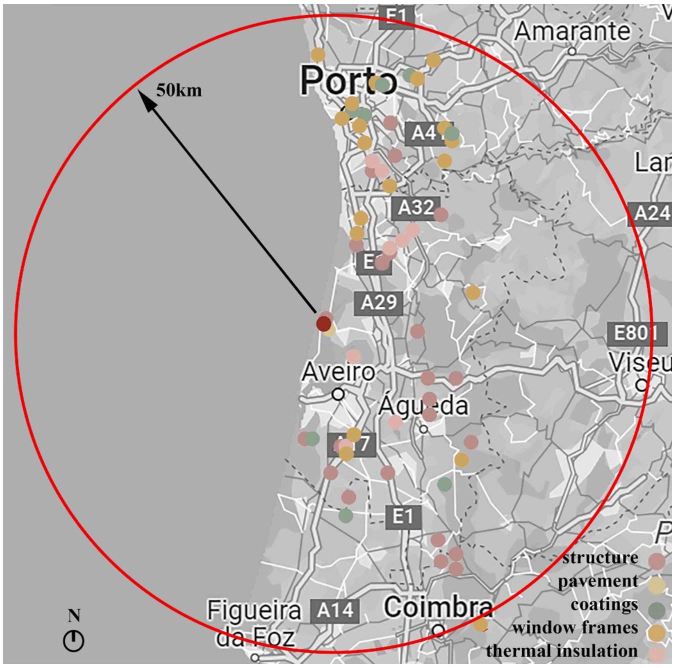

**Fig. 4.** Origin location of the materials used in the Case Study House, available within a maximum radius of 50 km from the site.

glued in a permanent and irreversible way. Modular buildings start to be common in Portugal, mainly for single family houses. The most common materials used in this type of buildings are timber and steel [21]. As exterior cladding materials, these buildings preferably use wooden solutions (strips, agglomerated or plywood panels), metal (profiled sheets and sandwich panels), in ventilated façades, in addition to the ETICS solution which is not very suitable for disassembly and transport.

Oliveira et al. [22] studied the viability of four constructive systems used in South European countries (France, Greece, Italy, Portugal, Spain) in terms of economic and environmental costs, considering the cost of materials, shipping cost and labour cost. From this study, were selected three of the constructive systems analysed for a current Portuguese typology of a single family housing dwelling: Conventional System (CS) made with non-structural hollow brick and structural reinforced concrete frames; Light Steel Framing (LSF) and Wood Frame (WF). These were compared with the case study system, called as A+W, based on Adobe walls and WF roof. All systems were analysed without foundations, as these were assumed to be equal for all the solutions.

The analysed solutions were defined to have in common the same heat transfer coefficient for opaque horizontal elements 0,26W/m$^{2}$.°C and vertical opaque elements 0,30W/m$^{2}$.°C (Table 1). These coefficients respond to the required demands for the more severe climatic zone as mentioned in the Portuguese thermal regulation [4]. The compositions and U-values of the simulated solutions are shown on Table 1. The thermal conductivity of the materials considered were presented in detail in Oliveira et al. [23], with exception for the adobe, that was considered as 0,215W/m$^{2}$.°C, based on Binici et al. [24]. The layers are listed from the outdoor to the indoor in the envelope and partition walls,

**Table 1**
Composition and U-values in W/m$^2$.°C of the analysed solutions.

| | Envelope | mm | Partition | mm | Roof | mm |
|---|---|---|---|---|---|---|
| **Conventional Solution – CS** | | | | | | |
| | **Envelope** | **mm** | **Partition** | **mm** | **Roof** | **mm** |
| 1 | Hollow Brick | 150 | Plaster | 15 | XPS | 140 |
| 2 | Air Gap | 40 | Hollow Brick | 110 | Pot and Beam | 240 |
| 3 | XPS | 90 | Plaster | 15 | Plaster | 15 |
| 4 | Hollow Brick | 110 | | | | |
| U | 0.30 | | | | 0.26 | |
| **Light Steel Framing - LSF** | | | | | | |
| | **Envelope** | **mm** | **Partition** | **mm** | **Roof** | **mm** |
| 1 | OSB | 18 | Plaster board | 13 | OSB | 20 |
| 2 | Air Gap | 35 | Rock wool | 80 | Rock wool | 130 |
| 3 | Rock wool | 110 | Air Gap | 40 | Air Gap | 50 |
| 4 | OSB | 18 | Plaster board | 13 | OSB | 20 |
| U | 0.30 | | | | 0.26 | |
| **Wood Frame - WF** | | | | | | |
| | **Envelope** | **mm** | **Partition** | **mm** | **Roof** | **mm** |
| 1 | OSB | 18 | Plaster board | 13 | OSB | 20 |
| 2 | Air Gap | 35 | Rock wool | 80 | Rock wool | 130 |
| 3 | Rock wool | 110 | Air Gap | 40 | Air Gap | 50 |
| 4 | OSB | 18 | Plaster board | 13 | OSB | 20 |
| U | 0.30 | | | | 0.26 | |
| **Adobe + Wood Frame – A+W** | | | | | | |
| | **Envelope** | **mm** | **Partition** | **mm** | **Roof** | **mm** |
| 1 | Adobe | 300 | Plaster board | 13 | OSB | 20 |
| 2 | Expanded Cork | 80 | Expanded Cork | 80 | Expanded Cork | 160 |
| 3 | | | Air Gap | 40 | Air Gap | 50 |
| 4 | | | Plaster board | 13 | OSB | 20 |
| U | 0.30 | | | | 0.26 | |

and from the top to the bottom on the roof.

In Oliveira et al. [23] four environmental parameters were considered: Embodied Energy (EE), Global Warming Potential (GWP), Acid Production Potential (APP) and Photo-chemical Ozone Creation Potential (POCP). In the present study the only environmental parameter considered was the Embodied Carbon (EC). The EC was estimated both for the production of materials as well as the transport. The Embodied Carbon assessment was based on EN 15978, regarding only the building production phase and adopting the average values available in the ICE Database [14]. In Table 2 are presented in detail the evaluation of EC for the 4 analysed solutions. In this study was considered just the envelope and dividing walls as well as the roof. The envelope walls and roof present similar properties in terms of U value in all the solutions and are adequate to Portuguese thermal regulations [4]. The foundations were not considered, as these were assumed to be equal for all the solutions and depending on the type of soil. All other common specifications, such as technical installations, were not evaluated as these would be equal in all compared solutions. The methodology considered in the weight evaluation of the CS, LSF and WF solutions are described in detail in Oliveira et al. [23].

In the definition of the transportation flows, assessment assumed an average distance from the manufacturer of each material to the building site of 200 km, with exception to the case study where the reused products were considered with the accurate distance, within a radius of 50 km from the site. For the Adobe used in external walls, composed by soil extracted and moulded in the site, the transport considered was of 0 km. The potential Embodied Carbon of the transportation are assessed according to the expected type of transportation (by truck) and distance.

By the analysis of Fig. 5, it can be concluded that A+W Case Study solution using adobe in the exterior walls and wood in the roof allows a reduction of 86% in Embodied Carbon of materials production and

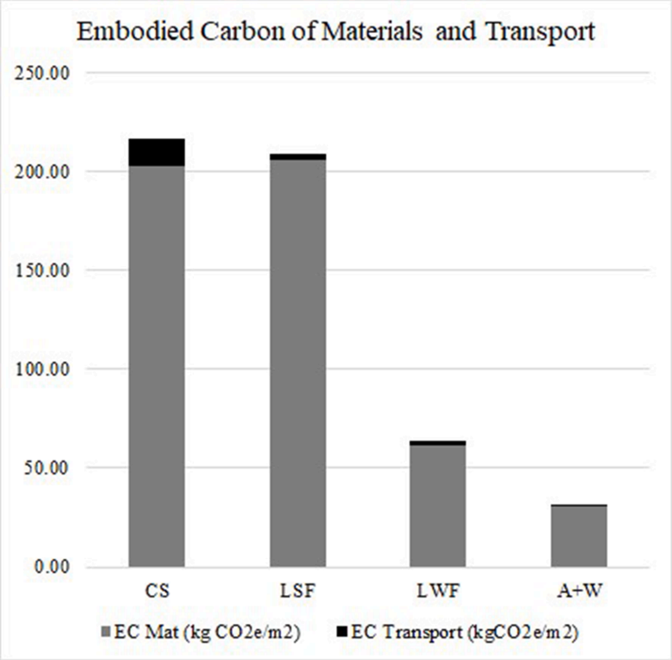

**Fig. 5.** Materials Production and Transport Embodied Carbon of the analyzed solutions.

**Table 2**
Embodied Carbon assessment of the analysed solutions.

| Total | Materials | Weight (kg) | Weight (kg/m$^2$) | Embodied Carbon (Kg CO$_2$e/Kg)* | Embodied Carbon (Kg CO$_2$e) | Embodied Carbon (Kg CO$_2$e/m$^2$) |
|---|---|---|---|---|---|---|
| CS | Concrete | 48033.6 | | 0.13 | 6244.4 | |
| | Clay Bricks and Blocks | 32929.8 | | 0.21 | 6915.3 | |
| | Steel rods | 7002.0 | | 1.71 | 11973.4 | |
| | Mortar | 4579.2 | | 0.20 | 915.8 | |
| | XPS | 945.9 | | 3.29 | 3112.0 | |
| | **Sum** | **93490.5** | **649.2** | | **29160.9** | **202.5** |
| LSF | Profiled steel | 7744.6 | | 3.03 | 23466.1 | |
| | OSB | 5931.1 | | 0.46 | 2698.7 | |
| | Rockwool | 2368.3 | | 1.12 | 2652.5 | |
| | Plasterboard | 2217.6 | | 0.39 | 864.9 | |
| | **Sum** | **18261.6** | **126.8** | | **29682.1** | **206.1** |
| WF | Local timber | 6380.0 | | 0.49 | 3145.3 | |
| | OSB | 5931.1 | | 0.46 | 2698.7 | |
| | Rockwool | 2375.6 | | 1.12 | 2660.7 | |
| | Plasterboard | 907.2 | | 0.39 | 353.8 | |
| | **Sum** | **15593.9** | **108.3** | | **8858.5** | **61.5** |
| A+W | Adobe | 66120.0 | | 0.02 | 1520.8 | |
| | Expanded cork | 5820.0 | | 0.19 | 1105.8 | |
| | Local timber | 3685.0 | | 0.49 | 1816.7 | |
| | **Sum** | **75625.0** | **525.2** | | **4443.3** | **30.9** |

Legend: CS – Conventional solution; LSF – Light Steel Frame; WF – Wood Frame; A+W – Adobe+Wood mixed solution; *Values based on reference [14].

transport, in relation to the conventional hollow brick solution, and still present 50% of reduction in relation with the second best solution, the Light Wood Frame. Regarding the EC, the exterior wall system using natural material come out as more sustainable than the Conventional Solution as well as the Light Steel Frame and Wood Frame solutions, considering both the EC of materials production and transport.

The embodied carbon of the envelope materials in the Case Study in A+W is of 30.9 kg $CO_2e/m^2$. Assuming an LSF envelope EC would be of 206.1 kg $CO_2e/m^2$. In literature review presented in [18], the values are typically in the 63–864 $CO_2e/m^2$ ranges. Assuming a LWF envelope the EC reaches 61.5 kg $CO_2e/m^2$. In literature review [17], these values are about 26–630 kg $CO_2e/m^2$ for WF houses. Assuming a conventional Concrete and Brick envelope (CS), the EC would be of 202.5 kg $CO_2e/m^2$. For CS in literature review these values are about 215–752 kg $CO_2e/m^2$ [19].

## 5. Economic cost analysis of case study house and comparison to common solutions

Economic cost is one of the most important factors to take into account when designing a building. When comparing the cost of each material, for example, wood tends to loose, because the cost exceeds that of concrete [23,25]. Although the final price is one of the main factors for those who invest in real estate, it is important to realize that the cost of materials will always depend on the market in which it operates, and that is how the lower price of concrete is justified. Otherwise why would it make sense for a material with more manufacturing process to be cheaper? It is always the adhesion that determines the market price.

However, there is always a way to ensure that the price of construction does not rise: equilibrium. If wood takes an initial high price, use wood only in the quantity needed and don't forget that in the end of its useful life, the selective dismantling of a wood building is much cheaper and less impacting than the dismantling of a concrete building. The most appropriate strategy is to reduce the price of materials whenever possible and look for a compromise between environmental impact and cost.

Controlling the prices of each material applied allowed the budget of the Case Study House to be around 323.4 €/$m^2$, as it can be seen in Table 3, excluding foundations, glazing, installations and finishes.

By the analysis of Table 4 it can be concluded that A+W Case Study solution is 51% more expensive than the Conventional Heavyweight solution and 10% more expensive than the Light Wood Frame solution, however it is 13% cheaper than the Light Steel Frame solution. The economic cost estimations for the reference solutions (CS, LSF and WF) were based on a previous study where the author was also involved [23].

Despite not having been accounted for in this study, since the reference solutions did not include these components in the comparative analysis, the reuse of coatings and frames would significantly reduce the cost of these components, by 30%.

## 6. Discussion

In the analysis of the envelope solutions studied, considering its EC, the most polluting solution is the conventional system (CS), if we include transport in the analysis, since the LSF solution, even though it is the one with the greatest EC in its production, it becomes slightly less polluting than the CS if transport is included, as it is much lighter. The WF and A+W solutions are the least polluting. With regard to economic cost, the conventional solution turns out to be the cheapest, however, as it requires more transport, adding the associated costs, it ends up becoming more expensive, depending on the distance at which the materials have to be purchased, being considered an average of 200 km in Portuguese reality [23].

The WF is the second cheapest solution, as it doesn't need a lot of transport (like the LSF) it ends up gaining even more advantage in its price. The LSF solution is the most ex-pensive solution due to the high cost of steel. The A+W proposal is slightly more expensive than the WF one. The embodied costs excluding foundations and installations are about 373 €/$m^2$ for LSF, 295 €/$m^2$ for WF, 214 €/$m^2$ for CS and 323 €/$m^2$ for Case Study (A+W), In literature, the embodied costs typically range from 400 €/$m^2$ to 1400 €/$m^2$ [26,27], considering the foundations.

**Table 3**
Prices of each material applied in the Case Study House (excluding foundations).

| MATERIALS | Area ($m^2$) | Cost/$m^2$ (€/$m^2$) | Total cost (€) |
|---|---|---|---|
| STRUCTURE | | | |
| Pine wood (Roof) | - | - | 9452.00 |
| Adobe (Walls) | 546.00 | 7.27 | 3 972.30 |
| Concrete (Foundations) | - | - | 30 182.90 |
| INSULATION | | | |
| Expanded Black Cork (ETICS) | 267.20 | 33.50 | 8 950.00 |
| PAVEMENT | | | |
| Compacted earth | 39.05 | 8.46 | 330.40 |
| COATINGS | | | |
| Reused | | | 2 607.82 |
| Marine Plywood | 30.00 | 8.00 | 240.00 |
| Gray tiles | 21.34 | 2.10 | 45.00 |
| Galvanized sheet panels | 247.50 | 3.43 | 850.00 |
| Wooden bars | 15.60 | 158.46 | 690.00 |
| OSB boards | 20.00 | 11.00 | 220.00 |
| Old tiles | 1.82 | 1.00 | 1.82 |
| Pallet slats | 100.00 | 4.81 | 481.00 |
| Non-slipery granite slabs | 22.80 | 3.50 | 80.00 |
| New | | | 1 303.00 |
| Pine planks | 16.65 | 17.70 | 294.70 |
| OSB boards | 170.90 | 5.90 | 1 008.30 |
| WINDOWS | | | |
| Reused | (varies) | (varies) | 2006.40 |
| **TOTAL COST (excluding foundations)** | | | **23933.00** |
| **COST BY $m^2$ of Gross Area** | | | **323.42** |

**Table 4**
Construction cost of the analysed solutions (CS, WF and LSF values based on [23]).

| | Construction cost (€/$m^2$) |
|---|---|
| CS | 214.3 |
| WF | 295.1 |
| LSF | 372.8 |
| A+W | 323.4 |

Legend: CS – Conventional solution; LSF – Light Steel Frame; WF – Wood Frame; A+W – Adobe+Wood mixed solution.

## 7. Conclusions

Although the reduced environmental impact of the Case Study solution was a somewhat predictable conclusion, due to the fact that Adobe and Wood are used, materials close to their natural state; the fact that it could be a solution less expensive than that of the Wood Frame was not that predictable. In fact, there is always a tendency for the most current practice to be the most accessible due to the demand-supply law, however, what is not normally expected is that an intensive and unconventional labour solution may still have a competitive cost.

As mentioned above, the case study intended to make a compromise between environmental and economic costs, and hence the balance between Adobe structural walls together with a Wooden structure. Only the building materials production phase was considered. This balance turns out to be very visible in this analysis: as the Wooden structure is found, for the most part, in the roofing solution, we realize that its increased cost in comparison to Conventional construction in concrete and hollow brick is due to the Wooden roof solution. The double-wall adobe walls present a low cost of construction, comparing it with the other wall solutions, it turns to be the cheapest, however, the Adobe+Wood solution ends up being the second most expensive essentially due to the cost of the roofing solution.

This research aimed to analyse the relation between environmental impact and economic cost on a Case Study house. In this House, only the pollution generated by the transport of materials was considered, but not the economic cost. It was pre-defined that only local materials would be used in the Case Study, with a maximum distance of 50 km from the site. The building material used in more quantity, Adobe, would be manufactured in the site, manually and by hand, using the land extracted during the foundations execution phase. Although the economic costs of transport were not accounted for, as this is usually already included in the final cost of the product, if it could be independently accounted it would only benefit the Case Study solution.

The simplifications and assumptions considered in this case study analysis may led to limitations and potential uncertainties. The free accessible ICE database considered for assessing the EC of the envelope materials in the case study was created from a large re-view of the literature, however it does not reflect the specificities of the case study location and proposed materials in the Adobe+Wood building envelope system, similarly for all comparison conventional building envelope alternatives. Use phase impacts were not evaluated, as well as end of life; however, differences are expected to be limited, as the proposed and reference envelope configurations should have similar energy performances. End of life scenario will always be more advantageous for the proposed envelope solution, that presents the higher possible recycling rates, even easy reuse. This case study is focused on a specific house and specific location, although results may not represent different building sizes and locations. The strategies proposed in this case study envelope design, identify improvement opportunities that can be easily implemented on other single-family houses but also in diverse types of housing buildings, however this last scenario was not evaluated. The implementation of less, more natural, reused, and local materials in the external envelope of buildings, may be used to improve the circularity in construction sector, however the economic cost can still be reduced in order to be competitive with the conventional building solutions, namely for the external envelope.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## References

[1] D.L Meadows, D.R.J. Meadows, The Limits to Growth: The 30-Year Update, 1st ed., Chelsea Green Publishing Company, USA, 2004, p. 22.

[2] S. Roaf, Ecohouse:. A casa ambientalmente sustentável: Sue Roaf, Manuel Fuentes, Stephanie Thomas; trad. Alexandre Salvaterra, 3a edição, Bookman, Porto Alegre, 2009. ISBN 978-85-7780-361-3.

[3] C. Vieira, O projeto de uma casa humilde: num contexto de sensibilidade ambiental, Escola de Arquitetura da Universidade do Minho, Guimarães, 2020 outubro deAvailable online, http://hdl.handle.net/1822/69246. accessed on 05/07/2021.

[4] A. Passer, H. Kreiner, P. Maydl, Assessment of the environmental performance of buildings: a critical evaluation of the influence of technical building equipment on residential buildings, Int. J. Life Cycle Assess. (2012), https://doi.org/10.1007/s11367-012-0435-6.

[5] REH - Portuguese Regulation for the Energy Performance of Housing Building, Decree-Law 101-D/2020 of 7th December, Portugal.

[6] Directive (EU), /844 of the European Parliament and of the Council of 30 May 2018 Amending Directive 2010/31/EU on the Energy Performance of Buildings and Directive 2012/27/EU on Energy Efficiency, 2018.

[7] ISO. ISO 14040, Environmental Management — Life cycle Assessment — Principles and Framework, International Organization for Standardization. ISO, Geneve, 2006.

[8] ISO. ISO 14044, Environmental Management — Life cycle Assessment — Requirements and Guidelines, International Organization for Standardization. ISO, Geneve, 2006.

[9] CEN. EN 15804, Sustainability of Construction Works - Environmental Product Declarations - Core Rules for the Product Category of Construction Products, CEN, Brussels, 2012.

[10] CEN. EN 15978, Sustainability of Construction Works - Assessment of Environmental Performance of Buildings - Calculation Method, CEN, Brussels, 2011.

[11] R. Mateus, S. Neiva, L. Bragança, P. Mendonça, M. Macieira, Sustainability assessment of an innovative lightweight building technology for partition walls – Comparison with conventional technologies, Build. Environ. 67 (2013) 147–159, https://doi.org/10.1016/j.buildenv.2013.05.012. ISSN 0360-1323.

[12] X Li, Y Zhu, Z. Zhang, An LCA- based environmental impact assessment model for construction process, Build. Environ. 45 (2010) 766–775.

[13] M.J. González, J.G. Navarro, Assessment of the decrease of CO2 emissions in the construction field trough the selection of materials: practical case study of three houses of low environmental impact, Build. Environ. 41 (7) (2005) 902–909.

[14] Circular Ecology. Embodied Carbon - The ICE Database. Available online: http://www.circularecology.com/embodied-energy-and-carbon-footprint-database.html (accessed on 06/07/2021).

[15] S.M. Khoshnava, R. Rostami, R. Mohamad Zin, D. Štreimikienė, A. Mardani, M. Ismail, The role of green building materials in reducing environmental and human health impacts, Int. J. Environ. Res. Public Health 17 (2020) 2589, https://doi.org/10.3390/ijerph17072589.

[16] D. Silveira, H. Varum, A. Costa, Rehabilitation of an important cultural and architectural heritage: the traditional adobe constructions in Aveiro district, in: A. Kungolas, C.A. Brebbia, E. Beriatos (Eds.), Sustainable Development 2007, WITPress, 2007, pp. 705–714. ISBN 978-1-84564-103-0, Carvoeiro, Algarve, 25 a 27 de Abril de 2007.

[17] J.B. Pedro, Habitação em Portugal: Evolução e Tendências, LNEC, Lisboa, 2013, 12 de novembro.

[18] P. Mendonça, J.P. Couto, A.P. Reis, Economic and construction analysis of lightweight membranes in housing in temperate climates, Environ. Eng. Manag. J. 10 (10) (2011) 1485–1493.

[19] P. Mendonça, Living under a second skin - Strategies for Environmental Impact Reduction for Solar Passive Constructions in Temperate Climates (in Portuguese), PhD Thesis in Civil Engineering, University of Minho, 2005.

[20] Harper, P. Our dependency on growth, like on concrete, must be abolished. Available online: https://www.dezeen.com/2019/09/25/oslo-architecture-triennale-architecture-degrowth-phineas-harper/(accessed on 05/07/2021).

[21] V. Tavares, N. Soares, N. Raposo, P. Marques, F. Freire, Prefabricated versus conventional construction: comparing life-cycle impacts of alternative structural materials, J. Build. Eng. 41 (2021), 102705, https://doi.org/10.1016/j.jobe.2021.102705. ISSN 2352-7102.

[22] F. Oliveira, P. Mendonça, J.P. Couto, A. Camões, Environmental impact and comparative economic analysis among different building constructive systems used in Portugal, WSEAS Energy Environ. Struct. Eng. 29 (2014).

[23] F. Oliveira, P. Mendonça, J.P. Couto, A. Camões, E. Silva, Comparative environmental and economic analysis of South European building constructive systems, WSEAS Trans. Environ. Dev. 10 (2014) 509–528.

[24] H. Binici, O. Aksogan, M.N. Bodur, E. Akca, S. Kapur, Thermal isolation and mechanical properties of fibre rein-forced mud bricks as wall materials, Construct. Build. Mater. 21 (4) (2007) 901–906, https://doi.org/10.1016/j.conbuildmat.2005.11.004. ISSN 0950-0618. Available online:accessed on 06/07/2021.

[25] A. Hafner, S. Schäfer, Comparative LCA study of different timber and mineral buildings and calculation method for substitution factors on building level, J. Clean. Prod. 167 (2017) 630–642, https://doi.org/10.1016/j.jclepro.2017.08.203. ISSN 0959-6526. Available online:accessed on 27/12/2021.

[26] A. Atmaca, N. Atmaca, Comparative life cycle energy and cost analysis of post-disaster temporary housings, Appl. Energy 171 (2016) 429–443, https://doi.org/10.1016/j.apenergy.2016.03.058.

[27] C. Dara, C. Hachem-Vermette, G. Assefa, Life cycle assessment and life cycle costing of container-based single-family housing in Canada: a case study, Build. Environ. 163 (2019), 106332, https://doi.org/10.1016/j.buildenv.2019.10633.