Reduced embodied energy. Case analysis of a residential building in Lisbon, Portugal

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Abstract

It is common that when talking about a building's life cycle energy, the only considered aspect is the operational energy. The part that is often left out is called the embodied energy of a building and represents the energy of manufacturing the construction materials and transporting them (initial embodied energy), the energy required for the construction process, the energy required for the maintenance (recurring embodied energy) and the final disposal.

The hypothesis of the thesis is that embodied energy is a crucial part of the total life cycle energy of a building and the objective is the creation of an embodied energy calculation model and testing it on a selected case study. Another objective is to identify if there are possible solutions of reducing the calculated energy.

The calculation model revolved around the Bath University Inventory of Carbon & Energy (ICE) which provides a comprehensive list of the cradle-to-gate embodied energy of the most commonly used construction materials. In order for the model to be complete, the energy for the transportation has also been estimated based on the transport distance and load of the materials, and the construction process embodied energy has been calculated based on initial site preparation works which are the most energy demanding.

Belas Clube de Campo "Lisbon Green Valley" is the selected case study for the calculation model. It represents a residential neighborhood in the northern part of Lisbon, Portugal, in which great effort has been put to minimize the operational energy of the buildings and achieve a very high energy certification. From the neighborhood, the attention will be put on one townhouse situated on lot 307.

The total embodied energy, incorporating the cradle-to-gate values, transportation values and construction process value, has been estimated to be 3378.55 GJ, out of which 52.34% are accounted by steel products, concrete products and lightweight concrete products.

Two possible load reduction solutions were analyzed. The first one estimates the reduction of the embodied energy in the case that all the materials are of national origins, achieving a reduction percentage of 9.82%. The second possible solution analyzes the possibility of replacing certain materials with less energy demanding ones, with the results of a possible reduction of 25% for only five material replacements.

Keywords: Embodied energy (EE); Operational energy (OE); Inventory of carbon and energy (ICE); Life cycle energy (LCE); Primary energy;

Resumo

Ao falar sobre o ciclo de vida energético de um edifício, é comum que o único aspecto considerado seja a energia operacional. A parte frequentemente descartada é denominada de energia incorporada num edifício e representa a energia necessária para fabricar os materiais de construção e transportá-los (energia incorporada inicial), a energia necessária para o processo de construção, a energia necessária para a manutenção energia) e disposição final.

A hipótese da tese é que a energia incorporada é uma parte crucial da energia do ciclo de vida total de um edifício e o objetivo é a criação de um modelo de cálculo de energia incorporado para testá-lo num caso de estudo selecionado. Outro objetivo é identificar se existem soluções possíveis para a redução da energia calculada.

O modelo de cálculo andou em torno Bath University Inventory of Carbon & Energy (ICE), que fornece uma lista abrangente da energia incorporada berço a portão dos materiais de construção mais usados. Para que o modelo seja completo, a energia para o transporte também foi estimada com base na distância de transporte e carga dos materiais, e a energia incorporada no processo de construção foi calculada com base nos trabalhos iniciais de preparação do local que são os mais exigentes em energia.

O Belas Clube de Campo “Lisboa Green Valley” é o caso de estudo selecionado para o modelo de cálculo. Representa um bairro residencial na parte norte de Lisboa, Portugal, onde foi feito um grande esforço para minimizar a energia operacional dos edifícios e obter uma certificação energética muito elevada. No bairro, a atenção será colocada em uma moradia situada no lote 307.

A energia incorporada total, incluindo os valores do berço ao portão, valores de transporte e valor do processo de construção, foi estimada em 3378,55 GJ, dos quais 52,34% são contabilizados por produtos siderúrgicos, produtos de concreto e produtos de concreto leve.

Duas possíveis soluções de redução de carga foram analisadas. O primeiro estima a redução da energia incorporada no caso de todos os materiais serem de origem nacional, atingindo um percentual de redução de 9,82%. A segunda solução possível analisa a possibilidade de substituir certos materiais por outros menos exigentes em termos de energia, com os resultados de uma possível redução de 25% para apenas cinco substituições de materiais.

Palavras-chave: Energia incorporada (EE); Energia operacional (OE); Inventário de carbono e energia (ICE); Energia do ciclo de vida (LCE); Energia primária;

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1. Introduction

1.1. Background

Based on the report of the Global Alliance for Buildings and Constructions [1], globally, the building sector is continuously growing, and it is expected that in the next 40 years another 230 billion square meters of new constructions will be built. Buildings account for 36% of the world final energy consumption and around 39% of the energy-related CO2 emissions. With this in mind, the built sector offers great potential for massive reductions in energy consumption and GHG emissions but it is still not given enough attention in most countries around the world.

However, it is important to notice that progress has been made, with the annual net building-related GHG emissions peaking at 9.5 gigatons CO2-eq in 2013 and decreasing to 9.0 gigatons CO2-eq in 2016 according to the International Energy Agency (IEA) report [2]. Energy efficiency policies for buildings continue to grow and focus on different aspects in different countries of the world. In Asian countries such as Japan and South Korea, the focus was on HVAC systems while in European countries such as Germany or Denmark, there main focus was on policies regarding the buildings envelope. A combination of both efforts is very important, as efficient envelopes offer the possibility of using more efficient heating and cooling systems.

The energy efficiency and reduction in the building sector is mentioned and viewed with great perspective in the two key international agreements – The Paris Climate Change Agreement and Montreal Protocol on Ozone Depletion, as mentioned in the IEA report [2]. These actions supported the founding of the Global Alliance for Buildings and Construction (GABC) at the COP21 summit in 2015, that has brought together 24 countries and 72 non-state organizations to collaborate towards a low-carbon global built environment. Through their actions, also private companies have increased their efforts to support awareness and financing models for energy efficiency.

Another organization which is planning to put Europe on the leading seat on energy efficiency in the building sector is the European Union. The most important legislation emitted by the EU was in 2010 with the Directive 2010/31/EU which aims to improve the energy efficiency of both new and existing buildings. Some key requirements of the directive, as described in the European Parliament briefing report [3], are the obligation of developing energy performance certificates for all building advertisements, establishing inspection schemes for the HVAC systems and setting national minimum energy performance requirements. The most important aspect of the directive is the obligation that all new buildings to be Nearly Zero Energy Buildings by 2021 and all public buildings to be Nearly Zero Energy Buildings by 2019.

Another important Directive described in the European Parliament briefing report [3] is the 2012 Directive on Energy Efficiency in which the EU proposed a target of 30% energy efficiency improvement by 2030. In 2015, the resolution "Towards an Energy Union" improved the previous proposed target of 30% to a 40% energy efficiency improvement by 2030.

In 2016, as part of the "EU Strategy on Heating and Cooling", the Parliament enhances the need that the member states should fully implement all the legislations and that the Commission should co-finance the renovations of both public and residential building blocks to achieve a NZEB stock by 2050. The Parliament [3] has pointed out that the energy demand in buildings could be reduced by three quarters if current renovations would be done at a faster pace and that currently around 75% of the European buildings are inefficient energetically and will still be in use by 2050.

Considering the policies mentioned before, it is important to properly define and understand the concept of Nearly Zero Energy Buildings (NZEB). A Nearly Zero Energy Building, as defined by the 2010/31/EU Directive is *a building that has a very high energy performance…The nearly or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby.* According to (Hans and Heike [4]) each EU member state shall issue their national plans in which they need to specify a numerical value of the primary energy demand standard in kWh/m^2/year and the share of energy coming from renewable sources [%].

It is common that in building energy calculation methods the only energy consumption considered is the Operational Energy (OE). The OE is considered the energy consumed by the building during its lifetime after the construction phase until the end of life phase.

The energy demand which is often left out but it is an important part of the life cycle energy consumption of a building is the Embodied Energy (EE). The EE can be defined differently during the life cycle of the building and in Giordano et al. [5], it has the following definitions:

- Initial Embodied Energy, which refers to the energy consumption both on and off site during the building process. The term includes the extraction of raw materials, manufacturing and transportation.
- Recurring Embodied Energy, which refers to the energy demand for renovating and maintaining the building
- End of Life Embodied Energy, which refers to the energy demand of the final disposal.

In Giordano et al. [6] it is described that both OE and EE are based on the Primary Energy Demand (PED), with the difference that OE accumulates during the lifetime of the building, while the EE is considered once at each of the life cycle stages mentioned before. It is also mentioned as important that EE is taken into consideration in the energy performance calculations of a building, and for the value to harmonize with the OE value, the EE must be annualized and expressed on the basis of a floor surface unit. The annualization is done based on the predicted lifetime of the structure.

Dixit [7] points out that when determining the EE, close attention must be paid to the system boundaries of the products involved and to the method of calculation. Further details as well as the objective of the present thesis will be presented in the following chapters.

1.2. Hypothesis and objective

The hypothesis of the thesis is based on the fact that embodied energy is a crucial part of the life cycle energy of buildings and that it should be managed properly.

The objective of the thesis is to quantify the embodied energy by developing a model and testing the application on a selected case as well as research on sustainable solutions for demand reduction throughout the life cycle of the building. By doing this, it can be determined if EE represents a significant part of the life cycle energy demand of a building and if there are feasible solutions for lowering it.

1.3. Methodology and working plan

According to Richard [8], the main elements of the embodied energy are the following:

- Energy for the primary resource extraction
- Energy for the transport of the unfinished product
- Energy for the processing and manufacturing of the final materials
- Energy for the transport of the final materials
- Energy for the assembly and construction process
- Energy for the maintenance
- Energy for the demolition/recycling processes

When analyzing each of these elements it is important to define the correct system boundaries which offer accurate results and in the same time do not over-complicate the analysis with none or negligible added value.

There are four different calculation methods for EE available with each of them having advantages and disadvantages and with many literature studies supporting one or the other. They are described in Hamilton-Maclaren et al. [9], as follows:

i. Input-Output Analysis

This method uses country specific data tables which illustrate how many units of input from one or more processes are required for one unit of output of a specific process

The main disadvantage of this method is the high potential for data errors in the energy and material prices.

ii. Process Analysis

The process analysis method utilizes the direct data for energy demand from the manufacturer and it is usually considered to be faster and simpler than the input-output method. The danger of using this method is the fact that some energy streams may remain unaccounted for and a loss of detail in the calculation may occur.

iii. Hybrid Analysis

This method combines the previously mentioned methods in order to achieve maximum accuracy. Hybrid analysis utilizes the data tables of the input-output analysis and combines it with process analysis results.

It is the most complex of the methods and involves longer calculation times but achieves greater accuracy.

iv. Embodied Energy Coefficients

This method involves using pre-defined embodied energy coefficients for materials expressed in MJ/kg or MJ/m^2. The databases cover materials on a cradle-to-gate approach, which means that the rest of the embodied energy elements must be considered separately.

By using the already existing coefficients, this method is by far the fastest to implement, but it is important to pay attention to the data compatibility.

For the present thesis, the embodied energy coefficients for different types of materials will be utilized for determining the manufacturing energy. In addition to this, the embodied energy for the transportation to the construction site will be assessed based on the origin of each material, and the embodied energy of the construction process itself.

The recurring embodied energy and the embodied energy for final disposal will not be assessed.

The main steps and organization of the thesis is the following:

- Extensive literature review in the field of embodied energy and building life cycle energy demand. (Chapter 2)
- Construction of the embodied energy calculation model (Chapter 0)
- Analysis and application of the model on a selected case study (Chapter 5)
- Discuss the results and the weight of embodied energy in the life cycle of the selected case study, and solutions for the reduction of the demand (Chapter 5.4)
- Conclusions based on the previously mentioned results, determining if the original hypothesis was correct or wrong. (Chapter 6)

2. Literature review

2.1. Embodied energy

In the construction industry there is a very high demand for resources which determines a significant consumption of energy and the release of pollutants in the atmosphere. Hammond and Jones [10] explain that each material must be extracted, processed and transported for its final use, with each of these stages consuming an important amount of energy. That amount of energy is defined as embodied energy and represents the quantification of the energy demand for the considered materials .

In the paper of Dixit et al. [11] it is emphasized that embodied energy interpretations have a great variation as the available databases suffer from big incompatibilities. Due to the differences in parameters, the values for embodied energy greatly vary from study to study. Some studies follow the international Life Cycle Assessment (LCA) standards while others do not follow any international standards.

The LCA guidelines can provide a good structure for the embodied energy analysis but it has several issues that must be addressed much more elaborately, as augmented in the paper of Dixit et al [12]. Feedstock energy and primary energy together with system boundary selection and the calculation method are the biggest issues for the analysis. The most influential factors for the parameters are the temporal, technological and geographical representation of the energy data used in the analysis.

Robert and Graham [13] explain that the embodied energy of a material is made of both direct and indirect energy. The indirect energy is used for creating the inputs needed for the main process, while the direct energy is used for the main process itself, whether it is the product assembly, manufacturing or construction.

2.2. Life cycle analysis. Weight of embodied energy

Until recently, many studies considered that the operating energy has the largest share in the life cycle energy bill of a building, consisting of 90-95% even when taking into consideration only the demand for heating according to the article by Sartori and Hestness [15] . However, in the recent years, the increased importance of environmental problems has led to more strict and complex building processes, more energy efficient operations as well as updated and better Life Cycle Assessments methodologies, changing the importance of both operational and embodied energy.

In the paper of (Sartori and Hestness [15]), an analysis of 60 literature case studies has shown that the biggest share of energy demand in a building is the operating energy. The second conclusion of the analysis was the direct relationship between the operational energy and the total energy, which refers to both operational and embodied energy, demonstrating that low-energy buildings are more efficient than conventional ones even though their embodied energy is higher due to increased used of materials (Figure 1). As it can be seen, the graph in Figure 1has a linear development, with the total energy increasing proportionally with the increase of the operational energy. The gap between values is a result of the values collected from the case studies discussed in the paper, with the top-right point representing a case study in which operational energy accounts for over 1,100 kWh/m^{2}y.

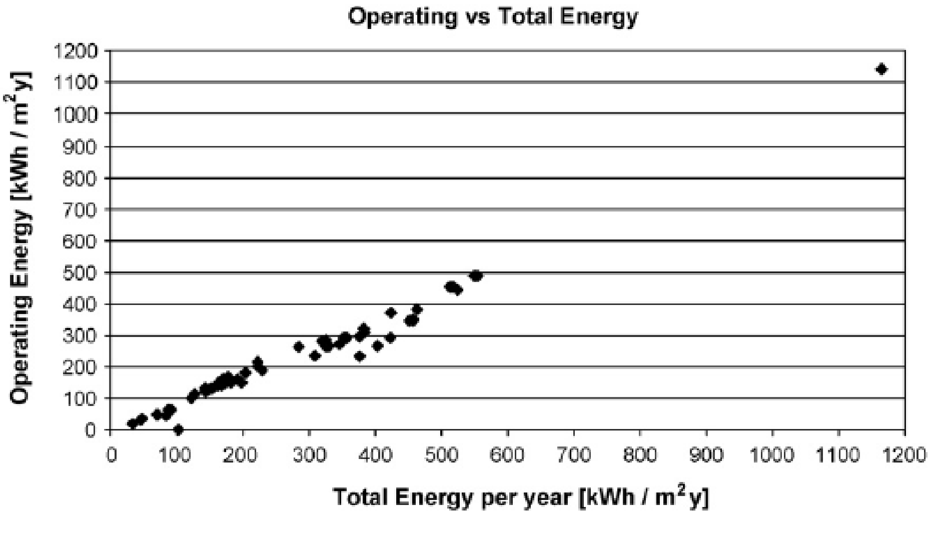

Figure 1. Operating Energy vs Total Energy in 60 different case studies [15]

(Ramesh et al. [16]) state that although embodied energy only represents approximately 10-20 % in the context of the life cycle energy, the opportunities for its reduction should not be ignored and one of the potential solutions is the use of materials that require less energy during manufacturing. In this case, attention must be paid on the material's life expectancy and parameters in order for them to not have an energy impact on a later stage.

Another possibility that (Ramesh et al. [16]) identified in literature for reducing embodied energy is the use of recycled materials. Comparing two cases, one building which was built with a large proportion of recycled materials and one which was built with new materials, revealed that more than 50% can be saved by using this method.

Both papers of (Sartori and Hestness [15]) and (Ramesh et al. [16]) have pointed out the importance of differentiating between end use energy and primary energy. This has been emphasized due to the fact that life cycle assessment case studies found in literature can be presented in either one form or the other. End use energy represents the energy measured at final use stage and it can also be called delivered energy. The primary energy is the one used to produce the end use energy and it includes the extraction, transformation and distribution losses from the process.

As there is no clear definition as to which type of energy is the embodied energy expressed, it can be assumed that it refers to primary energy. In this case, in the context of a life cycle energy analysis, the operational energy expressed in end use energy terms has to converted into primary energy and this has to be done depending on country-to-country basis, as each country utilizes different ways of obtaining their end use energy.

One of the case studies review by (Ramesh et al. [16]) presents the case of a self-sufficient building which is consuming no operational energy compared to low energy buildings which are designed to minimize their demand. It was observed that the self-sufficient home has a higher life cycle energy than the low energy houses due to the very high embodied energy requirements for obtaining the self-sufficient status (Figure 2). This proves the importance of embodied energy and its inclusion in the life cycle analysis.

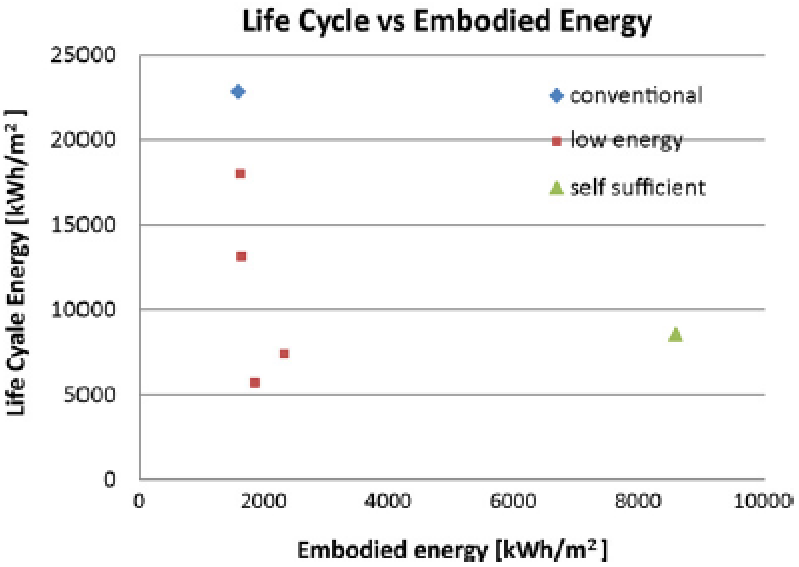

Figure 2. Life cycle energy vs embodied energy in different types of housing [16]

The importance of the location and climate of the building is also mentioned in (Ramesh et al. [16]) and (Sartori and Hestness [15]) papers, as it directly affects the results of the life cycle energy. Different indicative figures for energy consumption have to be taken into consideration and the comparison between similar buildings in hot and cold climates adjusted accordingly.

In the analysis presented in the paper by (Zabalza et al. [17]) the variation of the embodied energy weight can be seen in different case studies. In sixty studies from nine different countries including Sweden, Germany, Australia, Canada and Japan the proportion of embodied energy varies between 9% and 46% of the overall life cycle energy when analyzing low energy buildings and between 2% and 38% in conventional buildings when considering a lifetime of 50 years. It is emphasized that in other studies the values account only for 10-20% but also the lifetime considered is bigger, reaching up to 75 years. This proves again the importance of the parameters such as lifetime, geographic location and climatic conditions.

In the life cycle analysis report of high and low density residential dwellings done by (Norman et al. [18]) it has been identified that the most important construction materials contributing to embodied energy of the manufacturing part are bricks, windows, drywalls and structural concrete. The study suggests that these four combined account for around 60-70% of the total embodied energy of the production process.

In the paper of (Zabalza et al. [17]) a series of LCA studies of different common building materials has been done, including bricks and tiles, insulation materials, cement and concrete, wood products and some other common materials.

In the group of bricks and tiles, it was discovered that ceramic floor tiles possess the highest primary energy demand, due to the very high consumption of natural gas in their production stage. Due to this fact, the use of quarry tiles is recommended which can save up to 13.45 MJ-Eq/kg of primary energy and 0.57 kg CO_2-Eq/kg of emissions. In the case of bricks, the use of light clay bricks or silico-calcareous is recommended in order to reduce their embodied energy in the context of the life cycle.

For the insulation materials, as expected, the results show that using natural materials such as cork, wood fibers or sheep's wool can save up to 98% in emissions compared to conventional insulation such as EPS. The biggest impact in the case of insulation was found in expanded polystyrene and rigid polyurethane foam.

In the case of cement, it was pointed out that the impact of cement (gypsum and limestone) is much higher than that of cement mortar (cement and sand) and that of concrete (cement, gravel and water). This is due to the fact that mixing cement with low-impact materials is able to reduce its general impact. If the concrete is reinforced, then, as the analysis says, its impact increases drastically over normal concrete, by 63% for primary energy demand and 31% for the emissions due to the inclusion of steel.

The analysis of the wood products reveals that in general, they all have a much lower impact than the rest of the materials. Their primary energy demand comes from biomass and their balance for the equivalent CO_2 emissions is neutral. However, it is still pointed out that there is room for improvement, specifically related to the advisable replacement of conventional urea-formaldehyde and melamine-formaldehyde resins with natural ones.

Another number of materials were analyzed such as steel, aluminum, copper, PVC and glass, all of them being highly used in the construction industry. The study points out, that of all of these, aluminum has the highest energy demand for manufacturing in the form of electricity. For the PVC case, the water footprint is very high due to the numerous cooling processes needed.

In the paper of (Iddon and Firth [19]) a life cycle analysis of a typical four-bedroom detached house in the UK has been done. Based on the results, the operational energy has a share of 77.7% while the embodied energy has a share of 22.3% of the total life cycle energy. The distribution of the embodied energy is represented in the figure below (Figure 3):

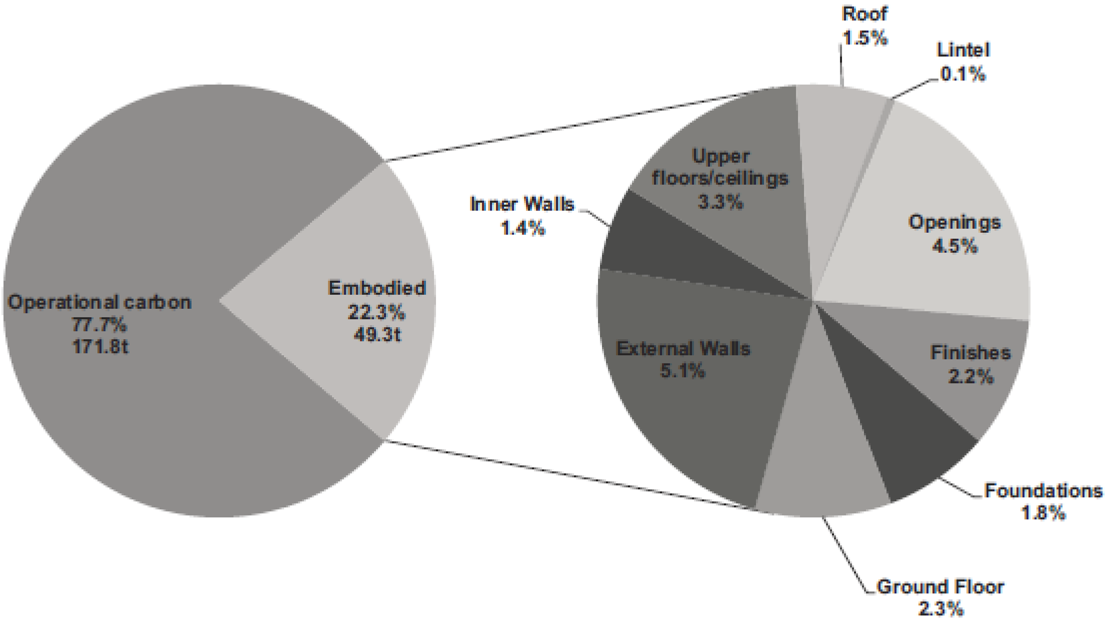

Figure 3. Share of OE and EE in a typical 4-bedroom house in the UK [19]

As can be seen in Figure 3 the biggest shares of embodied energy are for the external walls and the openings. This is due to the bricks used for the external walls and for the windows used to cover up openings, both having a high embodied energy consumption. Another big contributor is the reinforced concrete used in the foundations and ground floors [19].

One interesting aspect of the analysis done by (Iddon & Firth [19]) is the comparison of operational and embodied energy proportions based on different construction techniques:

I. Traditional masonry construction: Utilizing aerated concrete blocks for the external walls and medium dense concrete blocks for the internal walls, both with gypsum boards added.
II. Heavyweight construction: Utilizing dense concrete blocks for both external and internal walls without gypsum boards.
III. Closed timber frame construction: Utilizing closed timber frames and expanded polystyrene insulation with the addition of foil backed plasterboard.
IV. Structural Insulated Panels: Utilizing Kingspan TEK and Plasterboard for both external and internal walls.

In the list above only the materials that differentiate the scenarios have been mentioned, both internal and external walls having extra materials which remain the same.

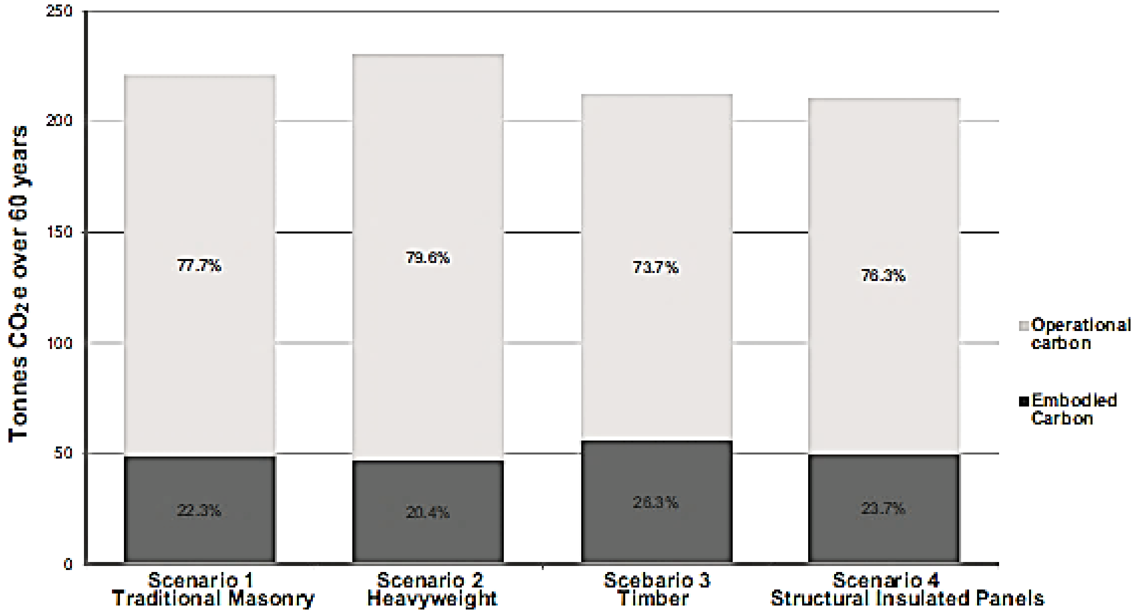

Figure 4 OE and EE for different construction scenarios for a four-bedroom house in the UK [19]

In Figure 4 the results of the different scenarios are presented in terms of percentage of operational and embodied energy. As can be seen, the lowest embodied energy percentage is found in scenario two, which can be surprising due to the dense concrete blocks used. The low value is due to the fact that the walls do not have any other type of boards or insulation, thus lowering the embodied energy.

Scenarios four and three perform better overall in the CO_2 emissions for a period of 60 years (Figure 4) and the total life cycle energy due to their lower operation energy as a consequence of their insulation. As well, due to the insulation, their embodied energy is the highest, but in this case, this does not affect the life cycle energy in a bad way, the scenarios still having the lowest life cycle CO_2 emissions.

It is important to mention that in the scenarios presented before from the paper of (Iddon and Firth [19]), there were very small differences in embodied energy and operational energy percentages between the different construction types. The purpose of mentioning them, was to illustrate the impacts of adding certain types of construction materials to the increasing or decreasing of the embodied energy and its relationship with the operational energy.

An analysis of the two types of residential buildings in Hong Kong has been done in the paper of (Chen et al. [20]) in which they accounted for the energy use in producing, transporting, installing and finishing of the building materials. One of their findings was the percentage of energy uses in different life cycle processes and the results can be seen in Figure 5:

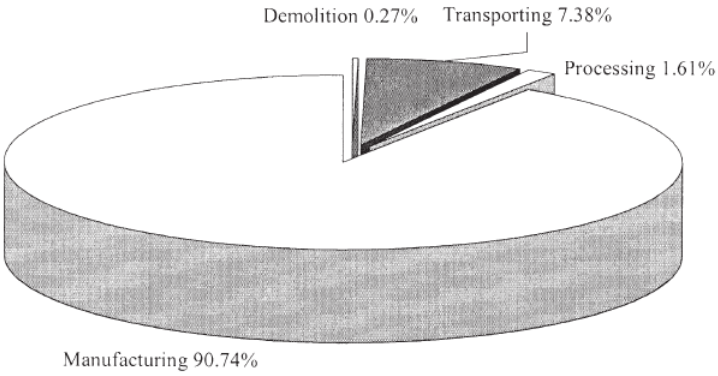

Figure 5. Percentage of energy intensities of different processes for materials in a residential case study in Hong Kong [20]

As it can be seen, the majority of the energy goes into the manufacturing stage while the rest is distributed among demolition, transportation and processing. The low value for the transportation embodied energy could be caused by the fact that the vast majority of materials originated from close sources.

Another important find in the paper of (Chen et al. [20]) is that steel has the highest embodied energy impact among all the materials. This is exemplified in Figure 6:

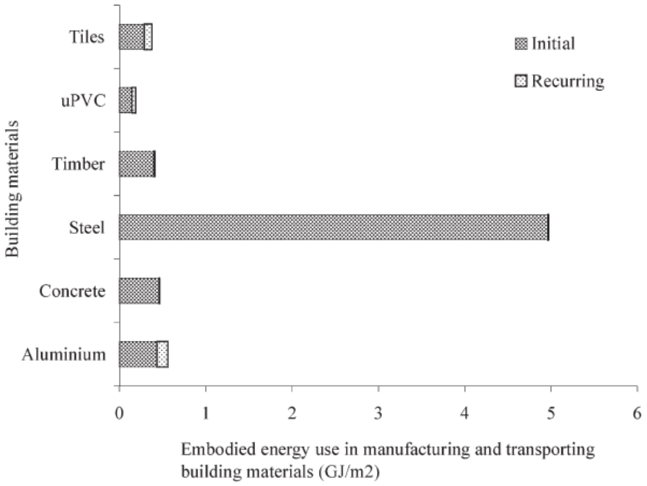

Figure 6. Different materials embodied energy in the case study of a residential building in Hong Kong [20]

It is mentioned that steel and aluminum account for approximately 77% of all embodied energy present in the selected building and suggest this as an opportunity for improvements.

Steel is regarded as having a very high embodied energy content as well in the paper of (Reddy and Jagadish [21]) where is it also mentioned that for such high-energy demand materials, the transportation embodied energy is negligible.

Another embodied energy study for a normal 3-bedroom semi-detached house in Scotland was done in the paper of (Asif et al. [22]). It is interesting to mention that in this study, the biggest embodied energy content is given by concrete instead of steel (Figure 7).

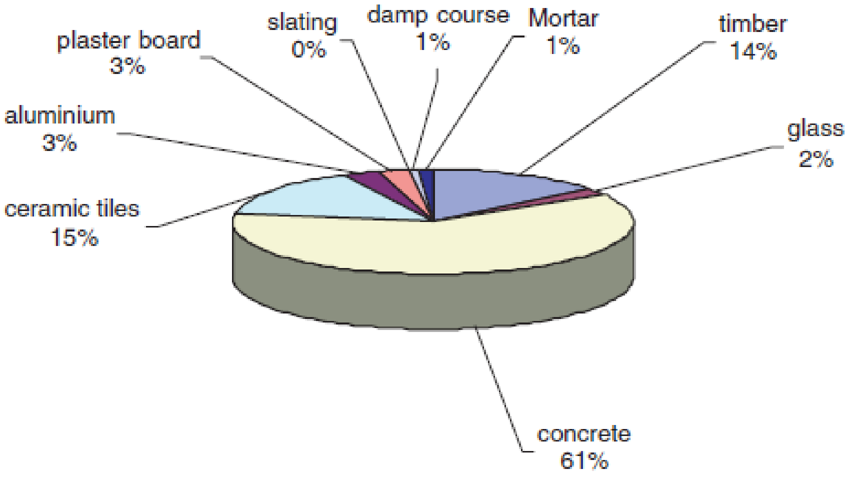

Figure 7. Embodied Energy Percentages in a case study building in Scotland [22]

Figures indicate that concrete accounts for 130,000 MJ in embodied energy, while aluminum accounts only for 5870 MJ. This case study highlights again the uncertainty in the literature results for embodied energy of different materials and buildings.

In the paper of (Treloar 1998 [23]), it is hypothesized that the top nine materials categories account for 90% of the total embodied energy of a building. These categories are represented in Figure 8:

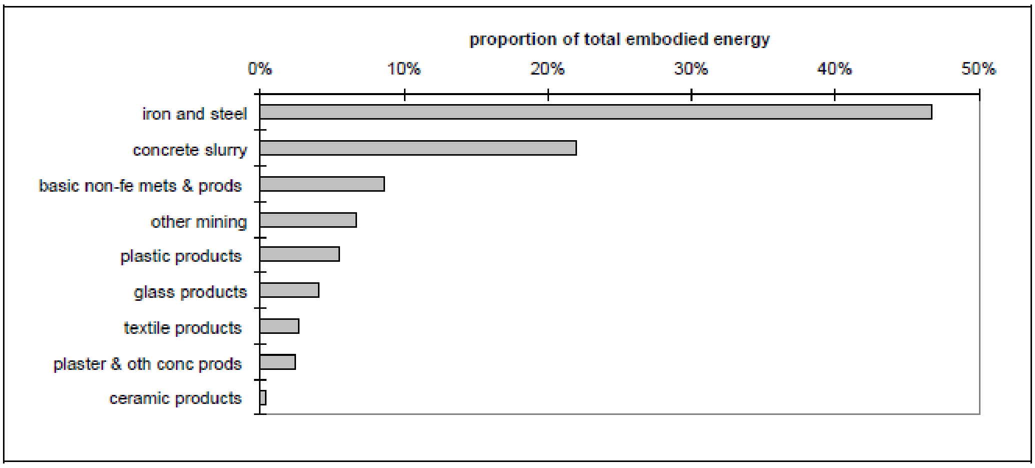

Figure 8. Proportion of embodied energy materials categories [23]

These results are confirming the findings in the papers of (Chen et al. [20]) and (Asif et al. [22]) with all three of them confirming that steel and concrete are the major contributors of the embodied energy of a building.

The value of 7.83 GJ/m2 has been obtained in the embodied energy analysis done in the paper of (King 2004 [24]). The values was in range with different sets of values that they found in literature and are presented in Figure 9:

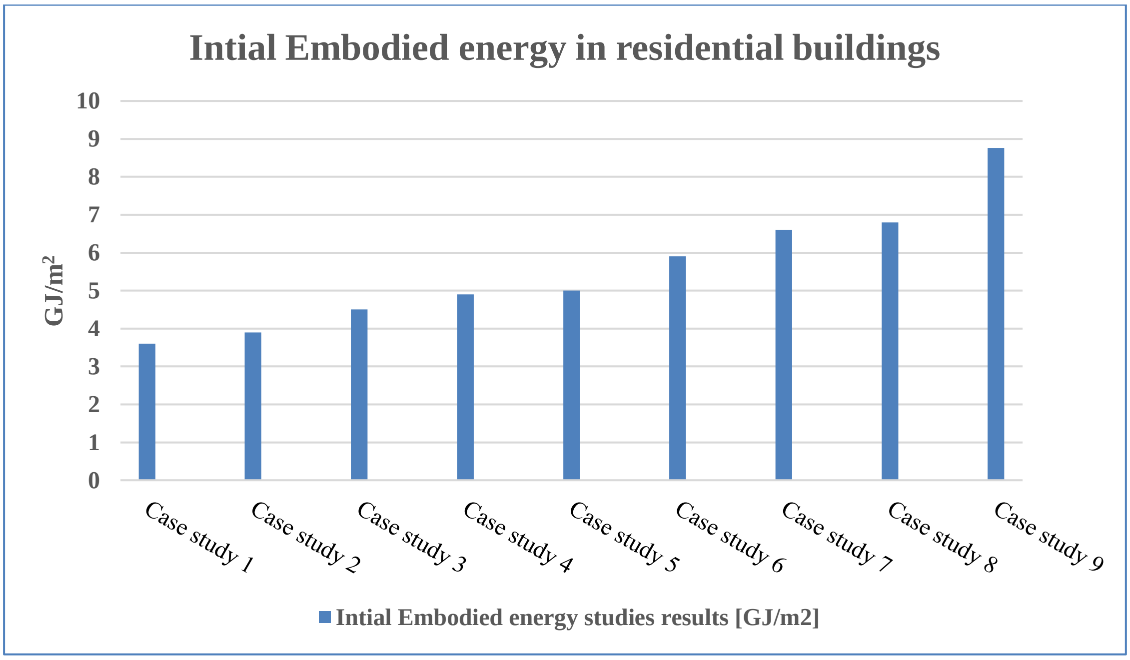

Figure 9. Embodied Energy Values of different residential building types (Graph adapted from [24])

As it can be seen from the different literature studies cited above, the values and conclusions regarding embodied energy analysis vary from case to case. Even so, similarities and common conclusion can be found in all of them. The literature review done will be used as confirmation for some of the outcomes of the present thesis.

A summary of the cited studies and their main findings will be presented in Table 1:

Table 1. Literature review – Main findings

Literature Study	Main findings
M. K.Dixit, J. Fernandez-Solis, S. Lavy and C. H. Culp, "Need for an embodied energy measurement protocol for buildings: A review paper," Renewable and Sustainable Energy Reviews, vol. 16, no. 6, pp. 3730-3743, 2012.	Embodied energy interpretations have a great variation as the available databases suffer from big incompatibilities
S. I. and H. A.G., "Energy use in the life cycle of conventional and low-energy buildings: A review article," Elsevier - Energy and Buildings, vol. 39, no. 3, pp. 249-257, 2007.	The biggest share of energy demand in a building is the operating energy. Low-energy buildings are more efficient than conventional ones even though their embodied energy is higher due to increased used of materials
T. Ramesh, P. Ravi and S. K.K, "Life cycle energy analysis of buildings: An overview," Elsevier - Energy and Buildings, vol. 42, no. 10, pp. 1592-1600, 2010.	A self-sufficient home has a higher life cycle energy than the low energy houses due to the very high embodied energy requirements for obtaining the self-sufficient status
B. I. Zabalza, C. A. Valero and U. A. Aranda, "Life cycle assessment of building materials. Comparative analysis of energy and environmental impacts and evaluation of eco-efficiency imprevement.," Elsevier - Building and Environment, vol. 46, no. 5, pp. 1133-1140, 2011.	For ceramics, ceramic floor tiles possess the highest primary energy demand, due to the very high consumption of natural gas in their production stage For the insulation materials, using natural materials such as cork, wood fibers or sheep’s wool can save up to 98% in emissions compared to conventional insulation such as EPS. The impact of cement (dinker, gypsum and limestone) is much higher than that of cement mortar (cement and sand) and that of concrete (cement, gravel and water). Wood products have in general a much lower impact than the rest of the materials.
J. Norman, H. L. MacLean, M.ASCE and C. A. Kennedy, "Comparing high and low residential density: Life-cycle analysis of energy use and greenhouse gas emissions," Journal of Urban Planning and Development, vol. 132, no. 1, pp. 10-21, 2006.	The most important construction materials contributing to embodied energy of the manufacturing part are bricks, windows, drywalls and structural concrete (60-70% of total embodied energy).

T. Chen, J. Burnett and C. Chau, "Analysis of embodied energy use in the residential building in Hong Kong," Elsevier - Energy, vol. 26, no. 4, pp. 323-340, 2001.	The majority of the embodied energy goes into the manufacturing stage while the rest is distributed among demolition, transportation and processing Steel has the highest embodied energy impact among all the materials
B. V. Reddy and K. Jagadish, "Embodied energy of common and alternative building materials and technologies," Elsevier - Energy and Buildings, vol. 35, no. 2, pp. 129-137, 2003.	Steel in among the highest consumers of embodied energy, and for such high energy demanding materials, the transportation embodied energy is negligible.
G. J. Treloar, "A comprehensive embodied energy analysis," Faculty of Science and Technology, Deakin University, 1998.	The group of materials formed by iron & steel, concrete, basic non-ferrous metals, plastic, glass, textiles, plasters and ceramics account for 90% of the total embodied energy in a building.
G. K. King, "The development of a multi-criteria approach for the measurment of sustainable performance for built projects and facilities," University of Technology, Sydney, 2004	A value of 7.83 GJ/m^2 has been obtained for an embodied energy analysis of a case study. List of different case studies of embodied energy calculation values [GJ/m^2]. The list can be found in Figure 9

3. Model construction methodology

The embodied energy calculation model is using as a starting point the Bath University Inventory of Carbon and Energy (ICE) version 2.0. This inventory provides a comprehensive list of materials and their associated embodied energy expressed in [MJ/kg].

The boundary of the ICE database is that it includes a cradle-to-gate calculation of the embodied energy, which means that the energy for the materials transportation to the construction site and the energy required for the construction process are not included. Because of this, the approximate distance from the manufacturer to the construction site has to be assumed for each material type and the embodied energy calculated based on a MJ/km/ton of material basis.

In the paper released by (United Nations 1991 [25]) a series of transport energy intensities for different types of material transportations for the UK and for India are presented (Table 2).

Table 2. Energy Intensities for different material transportation methods (Adapted from [25])

Transportation Mode		**Energy Intensity (UK) [MJ/ton/km]**	**Energy Intensity (India) [MJ/ton/km]**
Truck		2.5	2.85
Van		47.2	-
Rail		0.5	0.9
Water:			
	Sea	0.7	0.09
	Inland	-	0.9
Pipeline		0.18	-

Considering that the selected case study is from Portugal, with the assumption that all materials are transported to the construction site by either truck or sea, the values used as reference will be 2.5 [MJ/ton/km] for truck transportation and 0.7 [MJ/ton/km] for sea transportation.

Another important aspect that needs to be included in the embodied energy analysis is the construction process itself, with primary focus on the land preparations. During this stage the following construction processes have taken place (Table 3):

Table 3. Site preparation processes

Construction Process
Excavations of soils
Compaction of land
Transport to dump of products resulting from excavations
Excavation of foundation elements
Compaction of land
Transport to the dump of products resulting from excavation

The processes in Table 3 are structures as a timeline, being in the order that was provided in the project description of the case study. Further details will be provided in Chapter 5.

Each of these processes will be assessed based on the working area, quantity of materials and average consumption of construction machines and equipment.

It will be assumed that for the operations stated above the following machines were required: One hydraulic excavator; One soil compactor; One dump truck.

Considering the analysis found on (The Constructor website [26]), the daily work load that an excavator can process is approximately 250 m^3 of soil for an 8-hour working day. The same amount can be assumed for the compactor.

Regarding the dump truck, according to (Earth Haulers website [27]), a standard truck has a load capacity of approximately 10 m^3. This value will be used in the model calculations.

The assumed fuel consumption data is based on the paper of (Klanfar et al. [28]) and refers to the hydraulic tracked excavator Liebher R914B with a fuel consumption of 17.29 liters/hour and the dump truck Bell B40D with the fuel consumption of 18.67 liters/hour. There is no data present in the paper regarding soil compactors, but it can be assumed that the consumption is similar to the hydraulic excavator and the same value will be used.

The final embodied energy value will be the sum of the material’s embodied energy (cradle-to-gate), the embodied energy of the material’s transportation and the embodied energy of the construction process.

4. Case study analysis

The selected case study for the analysis of the embodied energy is the residential complex Belas Clube Campo – Lisbon Green Valley (Figure 10), located in the northern part of the Lisbon city in Portugal.

Figure 10. Lisbon Green Valley Location [29]

The complex is designed as a housing concept for upper-class citizens in which the architect has tried to combine modern standards of living with a natural, green aspect in the surroundings.

The location of the Belas Clube Campo is north-central ("Greater Lisbon Area") linked to the main highways and approximately 10-20 minutes away from all the major interest points around Lisbon.

The housing concepts put to offer are of two kinds: apartments and townhouses. The apartments are with 1,2 or 3 bedrooms with garage area and storage area. The townhouses are of two models: houses with 4 bedrooms and an office and houses with three suites and an office. All the townhouses come with a garage in the basement, swimming pool and garden.

According to Belas Clube de Campo [29] both housing concepts are equipped with smart house Domotics systems allowing control over air-conditioning, alarms and other equipment.

From the housing concepts offered in Lisbon Green Valley, the focus will be on the townhouse situated in Lot 307 (Figure 11). The house is currently in the operational phase and it has been evaluated by the LiderA certification system as being a class A+ building due to its high performances in energy management and good environmental and sustainable practices as stated in the LiderA report [30].

Figure 11. Lot 307 Townhouse [30]

The building on lot 307 is a semi-detached house with a T5 typology for single family use with three floors and a total area of 449.00 m^2. The three floors are distributed as follows:

- Floor -1 : A total area of 168.17 m^2. (Figure 21)
- Floor 0: A total area of 124.50 m^2. (Figure 22)
- Floor 1: A total area of 131.12 m^2. (Figure 23)

The floor plans can be found in Annex 4. Case study description, alongside with a more detailed description of each floor.

5. Results and discussions

5.1. Total embodied energy results

The model discussed in Chapter 3 has been applied on the Lisbon Green Valley townhouse on lot 307. A comprehensive list of materials has been analyzed and their respective embodied energy has been estimated.

With a total number of 117 identified materials, the list has been categorized in the different types of materials for an easier interpretation of the results. The categories can be seen in Annex 3. Materials list.

As previously described, the first part of estimating the embodied energy of the materials has used the Bath University database ICE. The cradle-to-gate values offered in the ICE database are expressed in [MJ/kg], while the materials in the above list were expressed in various units of measurement.

In order to easily estimate the energy embodied in each material, a series of calculations and assumptions were made as to match the lot 307 materials with the ICE database. The table below (Table 4) presents one example of the method used for one material:

Table 4. Cork Insulation Board EE estimation example

Material	**Mass [kg]**	**Origin**	**EE-Cradle to Gate [MJ]**	**Remarks/ Assumptions**	**EE-Transportation [MJ]**	**Total EE [MJ]**	**Reference**
Cork Insulation 6cm Effisus ECORK	940.92	Portugal	3763.68	Cork Insulation Board	117.62	3881.30	[31]

In order to determine the total mass of all the insulation boards, a series of calculations have been made. The dimensions of one board have been assumed from (Orcamentos 2018 [31]) as being 1 x 0.5 x 0.06 m. From this, the area of one board has been calculated as being 0.5 m^2.

From the material list provided by Casais, the total area covered by cork insulation is 78.41 m^2. Based on this number and the previously mentioned calculation, a total number of 157 necessary boards has been estimated.

Considering the volume of one board being 0.03 m^3 and the density of cork being 200 kg/m^3, the mass of one board is determined as being 6 kg. Knowing from before the total number of boards and the mass of one board, the total mass of all cork insulation boards has been calculated as being 940.92 kg.

For the embodied energy of transportation, the coefficient described in Chapter 0 of 2.5 [MJ/ton/km] is used together with the total mass of the material. For the distance, as the material is originating from Portugal and the construction site is in the proximity of the capital city, Lisbon, an average of 50 km distance is assumed.

The process is repeated for most of the materials and the full list with the respective quantities, embodied energy values, origins, assumptions and references can be found in Annex 1. List of materials embodied energy. The calculation process had been done in the software Microsoft Excel, and snapshots of the spreadsheet for all material calculations can be found in Annex 2. Materials mass calculation

The total value of embodied energy, incorporating both the cradle-to-gate value and the energy for transportation, has been calculated to be 3332.67 GJ. As previously described, to this value it must be added as well the embodied energy of the construction process.

The construction process details are presented in Table 5:

Table 5. Construction Process Amounts

Construction Process	Amount
Excavations of soils up to 0.30 m	670 m^3
Compaction of land	195 m^3
Transport to dump of products resulting from excavations	475 m^3
Excavation of foundation elements	52 m^3
Compaction of land	29 m^3
Transport to the dump of products resulting from excavation	28 m^3

Assuming an 8-hours work day, with the work capacity of the machines and their fuel consumption described in Chapter 3, the following total fuel consumption is obtained for the amount of soil that needs to be excavated and compacted (Table 6).

Table 6. Construction Process Calculation -Part 1

Amount	Unit	Machine Required	Days Required	Hours/day	Total hours	Total Fuel Consumption [L]
670	m3	Hydraulic Excavator	2.68	8	21.44	370.6976
195	m3	Soil Compactor	0.78	8	6.24	107.8896
52	m3	Hydraulic Excavator	0.208	8	1.664	28.77056
29	m3	Soil Compactor	0.116	8	0.928	16.04512

Assuming 10 transports of the resulting dump materials can be done in one day, and the capabilities and fuel consumption of the dump truck, described in Chapter 3, the following total fuel consumptions for the dump truck is obtained (Table 7).

Table 7 Construction Process Calculation -Part 2

Total volume to be moved	503	m3
Dump truck capabilities	10	m3/transport
Transports needed	50.3	transports
Assumed transports/day	10	transports
Number of days	5.03	days
Total hours	40.24	hours
Total Fuel Consumption	751.2808	liters

Assuming the energy content of diesel fuel to being 36 MJ/L, the embodied energy of the three machines could be determined and the total embodied energy of the construction process could be summed up (Table 8).

Table 8 Construction Process Calculation -Part 3

Energy Content diesel	36	MJ/L
EE - Excavator/Compactor	18842.50368	MJ
EE -Truck	27046.1088	
Total EE	45888.61248	MJ

Considering the values mentioned above, the total embodied energy for the construction process has been calculated to be 45.88 GJ.

Considering this, the total embodied energy for the Townhouse on lot 307 is 3378.55 GJ. From the description of the case study in chapter 0, the total area of the building is 449 m^2. Knowing this, the obtained value for the embodied energy is 7.52 GJ/m^2. Referring to the paper from (King [24]), in which the value proposed was 7.83 GJ/m^2, the present thesis analysis is on par with the case studies from the literature.

5.2. Embodied energy by materials results

As mentioned several times in the literature review, different categories of materials have different weights in the context of the embodied energy of the building. All the materials have been categorized in different types and the total embodied energy of the different categories is presented in Figure 12:

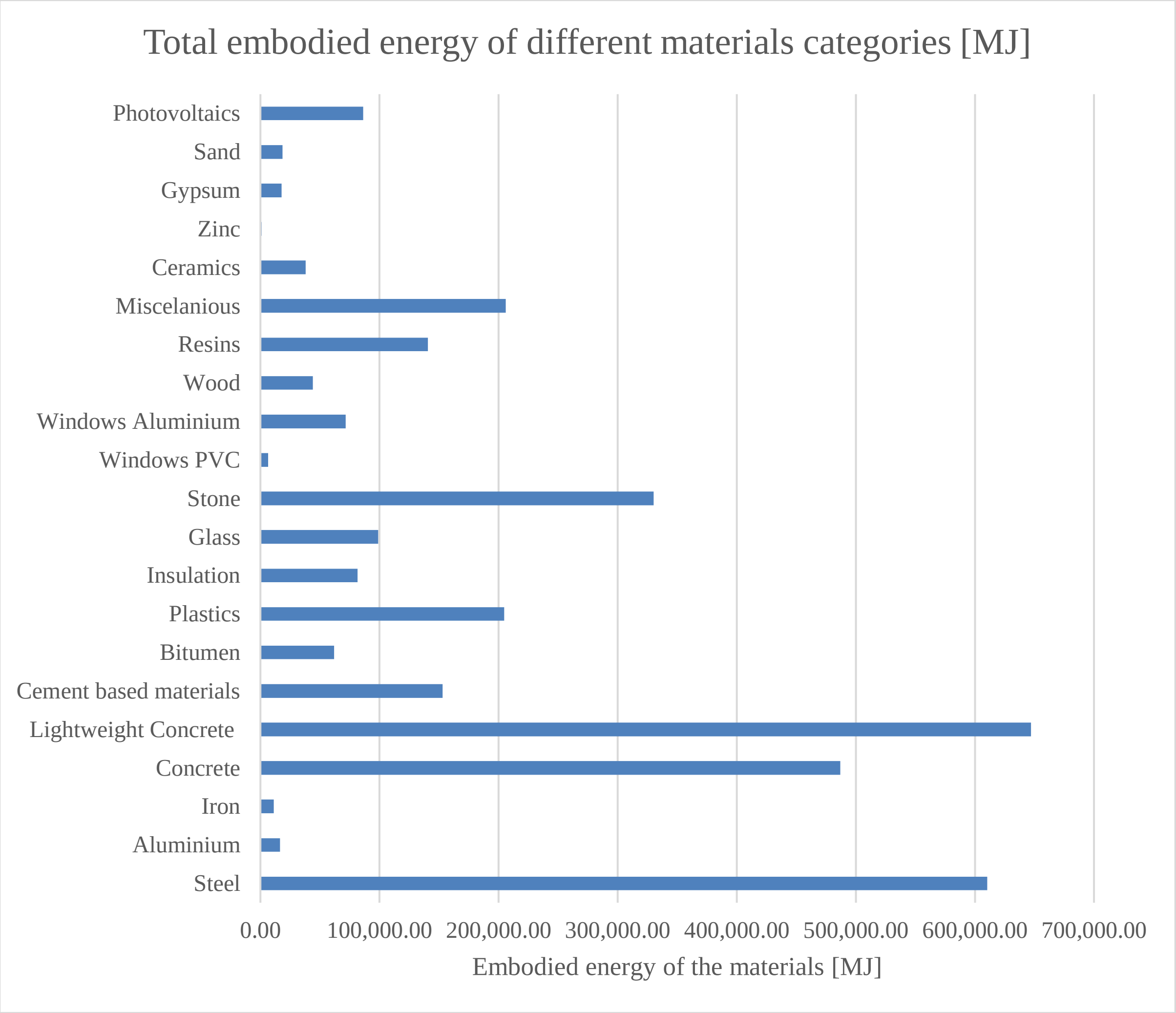

Figure 12. Embodied energy of the different material categories in Lot 307 Townhouse

As it can be seen, steel and concrete are the dominant categories in terms of embodied energy. Steel materials account for 18.31 % of the total embodied energy, while the concrete and lightweight concrete blocks account for 14.61 % and 19.42 % respectively. This is exemplified better in the chart in Figure 13:

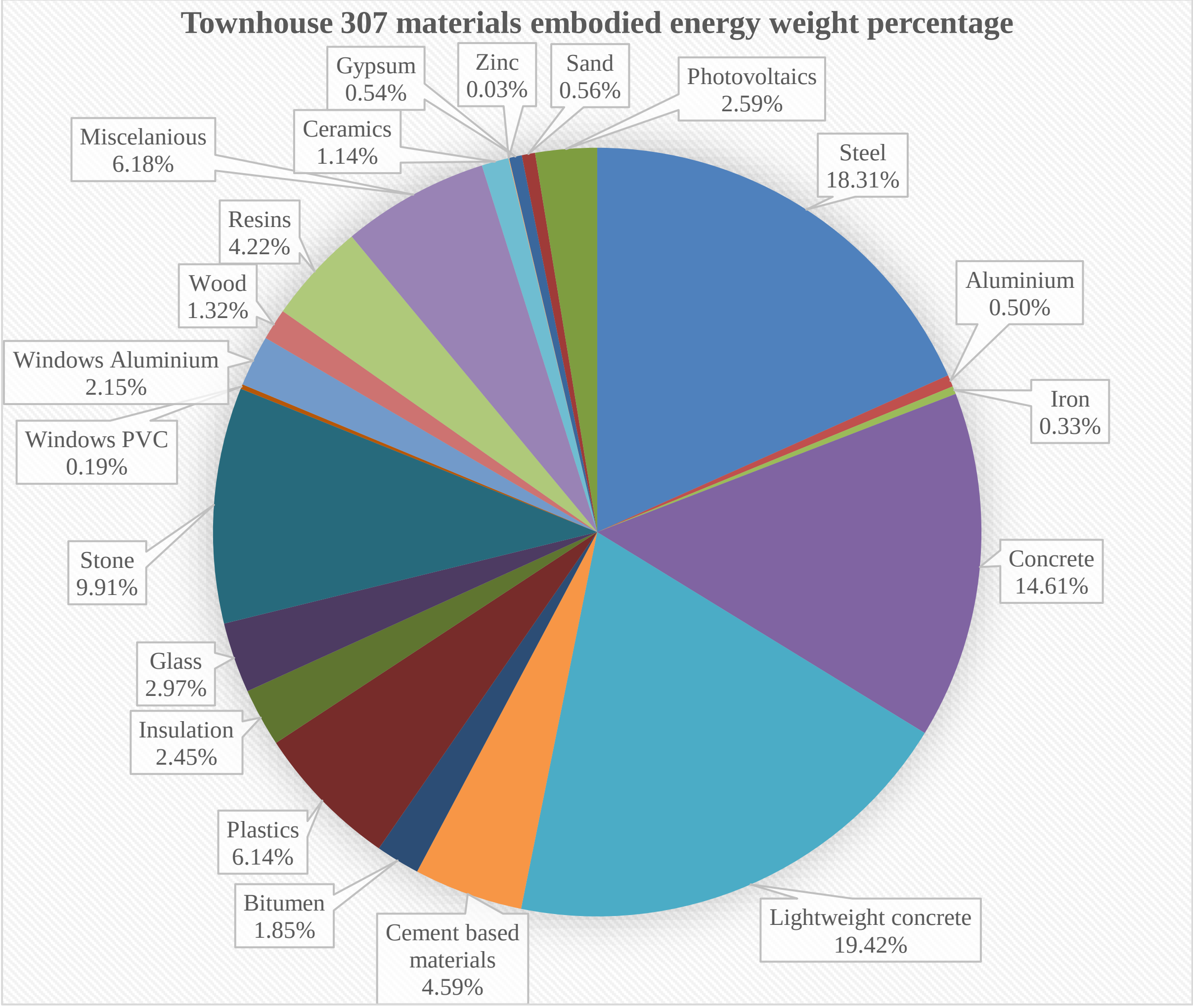

Figure 13 Townhouse 407 materials embodied energy weight percentage

The three categories, steel, concrete and lightweight concrete, account together for more than half of the total embodied energy with a percentage of 52.34%. Considering the literature review that was done, (Zabalza et al. [17]), (Norman et al. [18]), (Iddon and Firth [19]), (Chen et al. [20]), (Reddy and Jagadish [21]), (Asif et al. [22]) and (Treloar [23]), all account steel and concrete to be among the biggest contributors to the total embodied energy of a building. This credits the analysis that was done as being on par with the literature case studies in this domain.

The next category of material with the highest embodied energy percentage, after the above mentioned three, is stone. Stone was used in big quantities especially as crushed stone in different construction processes, but as well in form of tiles for different pavements and finishes.

The biggest impact for the stone category has been the “tout-venant”, which is crushed stone that is used for paving or filling the land in order to prepare the site for the construction (Figure 14). With a massive quantity of 125 tones, this stone type accounts for 173 GJ of embodied energy.

Figure 14 Tout-venant [32]

It is important to notice that insulation accounts for a smaller percentage of the total value, and this is due to the good thermal properties of the lightweight concrete blocks that were used, which lowered the need for too much insulation.

From the category of steel, the biggest embodied energy percentage is accounted by the steel rods (Figure 15) in different dimensions, with a value of 83.98%. These products are used as a metal base for the concrete pillars used for the construction of the building.

Figure 15 Steel Rods [33]

The cement based materials, plastics, glass, windows, resins and other types of materials make up for the total value but with a much lower percentage. From these, the resins account for 4.22 % and cement based materials for 4.59%. These types of materials are usually binders or insulators and are heavily used in construction. One example is the Weber Fix Premium for ceramics and stone (Figure 16) which is used for sealing ceramics or stone on interior walls. As it is made from synthetic resins and used in big quantities, the material outputs 137 GJ of embodied energy.

Figure 16 Weber Fix Premium for ceramics and stone [34]

For the lightweight concrete, the material category with the highest embodied energy, the lightweight concrete blocks (Figure 17) account for approximately 78 tons of material and are the primary construction element of the building. They have very good thermal and acoustical properties and utilize the expanded clay LECA in their composition for the light concrete aggregate state. Because of this, their embodied energy per kilogram is slightly higher than for a normal concrete block and in total they account for 505 GJ of embodied energy.

Figure 17. Lightweight concrete block LECA [35]

5.3. Possible improvement solutions

As described in chapter 1.2, the objective of the present thesis is to determine the embodied energy of the selected case study and as well to propose certain possible solution for the reduction of this value.

Two different possible solutions will be analyzed and the reduction potential of each of them will be determined.

5.3.1. Scenario 1 – 100% local materials

The first scenario will analyze the impact of having materials that originate only from Portugal with zero imported materials. It is important to mention that it may be impossible to find the exact same materials in Portugal as the ones that are imported, so it is assumed that equivalent ones will be suitable.

This scenario will affect the transportation embodied energy and the saving percentage will be determined.

Table 9 is presenting the materials which do not originate from Portugal:

Table 9 Imported materials townhouse 307

Material	**Origin**
Steel Rod (including all dimensions)	Turkey
Waterproofing agent for concrete	Italy
Caleira Aco Drain Multiline V200, C125	Spain
Weber Products (Classic, Premium Ceramic, Anti-Fungal)	Germany
Roofmate SL 60mm	Spain
Wooden floor Sucupira	Brazil
Wooden stairs Sucupira	Brazil

By assuming that the above mentioned materials are manufactured in Portugal, the embodied energy for transportation lowers from 462.32 GJ to 134.89 GJ, achieving a 70 % reduction.

In the context of the total embodied energy, the value lowers from 3378.55 GJ to 3051.11 GJ, achieving a 9.82% reduction of the value. It is important to mention that the value is relatively low because of the small amount of imported materials. For a different case study, which may have more materials from outside of national territory, the impact might be much higher.

5.3.2. Scenario 2 – Possible replacements for energy demanding materials

The second scenario will analyze the potential of substituting certain energy demanding materials with less energy demanding ones.

The following table (Table 10) presents possible replacements for three energy-demanding materials used in the townhouse 307:

Table 10. Possible replacements for materials - Townhouse 307

Current Material	Possible replacement	Reference
Polyethylene Film 500mcr	Cellulose Acetate Film	[36]
Steel Rods	Continuous Basalt Fiber (CBF)	[37]
Concrete (C12/15; C16/20; C25/30)	Concrete with 30% furnace slag	[38]
EPS boards	Cork Insulation	[31]
Ceramic tiles	Quarry tiles	[17]

In the provided materials lists, it is mentioned the use of 685 m^2 of polyethylene film, which gives a very high value of embodied energy of 165 GJ. The replacement with the more environmentally friendly cellulose acetate film (Figure 18) would reduce this value down to 0.77 GJ.

Figure 18. Cellulose roll [39]

As previously presented, steel is among the most energy demanding materials for the building, especially in the form of steel rods. One possible replacement is the basalt fiber (Figure 19), which presents itself with similar characteristics as steel. By replacing all steel rods with basalt fiber rods the embodied energy of the rods goes down from 325 GJ to 205 GJ.

Figure 19 Basalt fiber rod [40]

In case of the concrete, by using the more environmentally friendly concrete which replaces cement with furnace slag, the embodied energy lowers from 404 GJ to 42 GJ, reducing it by almost 10 times.

In the case of the EPS boards, by completely replacing them with cork insulation boards, the embodied energy can be lowered from 18 GJ to 10 GJ.

By replacing the ceramic deck with quarry tiles (Figure 20), the embodied energy can be reduced from 26.16 GJ to 14.17 GJ. Aside from the lower energy demand, quarry tiles are also much more durable than ceramics lowering the possibilities of cracks like in the left picture of Figure 20.

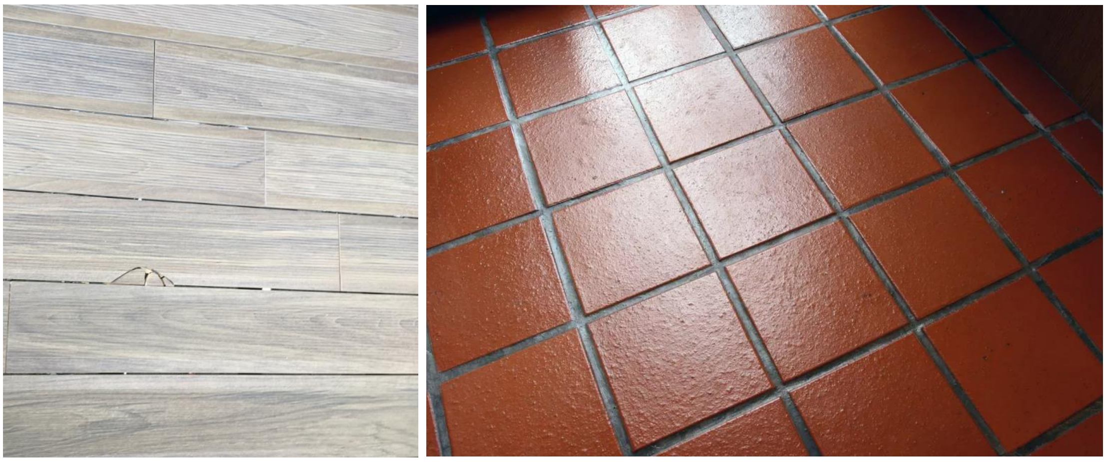

Figure 20 . Ceramic deck at townhouse 307 (left) and possible quarry tiles replacement (right) [41]

By implementing all the above mentioned replacements, a total embodied energy reduction of up to 25% is possible.

It is important to mention that replacement with more environmentally friendly alternatives for the rest of the materials is possible, but for this study only the most impactful were calculated.

If both of the scenarios described above are implemented together, the reduction potential goes as high as 35%.

5.4. Discussions

The hypothesis set in chapter 1.2 mentioned that embodied energy is a crucial part of the life cycle energy of a building and the objective was to determine if this is the case for the selected case study and if there are potential solutions for lowering it.

In order to confirm or infirm this hypothesis, the operational energy of the lot 307 had to be assessed. The estimated primary energy need for the operational energy, mainly for heating, is estimated to be 11.3 kWh/m^2/year [30].

Considering the total area of 449 m^2, the total energy demand can be estimated to be 5073.7 kWh/year.

In order to make a comparison, two building lifetimes can be assumed: 50 years and 70 years.

- For the period of 50 years, the total operational energy accumulates to 253,685 kWh (0.253 GWh).
- For the period of 70 years, the total operational energy accumulates to 355,159 kWh (0.355 GWh).

The total calculated embodied energy value is 3378.55 GJ. Considering the 1 GJ is equal to 0.00028 GWh, the total embodied energy accounts for 0.945 GWh.

By comparing the embodied energy value with the two operational energy values calculated above, it can be seen that the embodied energy is almost three times higher than even the operational energy for 70 years, accounting for 72% of the life cycle energy.

This proportion is higher than values found in the literature such as (Zabalza et al. [17]) or (Iddon and Firth [19]), but the value is, as mentioned previously, similar to the literature values found in the paper of (King [24]).

The very big disproportion between the operational and embodied energy is caused by the design thinking towards a very efficient building. The townhouse 307 is a low energy building which can even achieve self-sustainment, and as mentioned in most of the literature analyzed, this increases the material use and automatically the embodied energy.

It is important to mention that the recurrent embodied energy and the final disposal embodied energy have not been analyzed, and these two would have increased the value even more.

Considering the above mentioned results, the hypothesis that the embodied energy is a crucial part of the total life cycle energy is confirmed for the present case study.

Regarding the solutions described in chapter 5.3, they prove that the embodied energy can be reduced by selecting more environmentally friendly materials or by choosing locally produced ones. The calculations done are estimative and because no economic feasibility study was undertaken, the results have to be considered as rough order of magnitude.

Considering the embodied carbon, an estimation has been done utilizing the ICE database values for different material types. Due to some missing data not all the materials from the list could be analyzed. Therefore, a value between 150-200 tons CO_2-equivalent can be estimated as being the embodied carbon of the whole townhouse 307. As expected, the biggest amounts remained the same as for the embodied energy for the steel, concrete and lightweight concrete.

The main limitation of the analysis was the accuracy of the source data. The material list analyzed was comprehensive but not 100% complete and certain assumptions regarding the quantity and type of materials had to be made. Also, as mentioned before, no economic analysis has been done mainly due to the degree of complexity that it would have added and that would have been out of the scope of the project.

The final outcome of the thesis, after all the values and calculations have been explained, is the fact that embodied energy is a vital part of life cycle energy and should be carefully analyzed prior to any construction project.

6. Conclusions and future work

The main conclusions of the work have been discussed in chapter 5.4 and can be summarized as follows:

- The total calculated embodied energy for the townhouse 307 is 3378.55 GJ
- The embodied energy represents approximately 72 % of the total life cycle energy of the building
- The possible reduction solutions discussed can achieve a reduction of up to 25 % of the embodied energy
- The embodied carbon of the building has been estimated to be between 150-200 tonCO_2-eq
- The high values are a direct consequence of the low operational energy design of the building

The approach and scope of the work was to obtain an estimation of the impact that the embodied energy of the materials has on the total life cycle energy of the building. This has been achieved and the results have been summarized in the previous paragraph.

Considering the limitations mentioned in chapter 5.4 and the fact that the recurring and final disposal embodied energy have been neglected from the study, the future work recommendation is a more comprehensive analysis of the townhouse 307.

In order to achieve more accurate results, a complete list of materials with proper descriptions and quantities should be available, a different embodied energy analysis should be done in parallel with the ICE coefficients, and the recurring and final disposal energy should be included. As well, an economic feasibility study for any possible improvements that can be suggested should be also included.

The above-mentioned suggested future work can use the present thesis hypothesis, methodology, literature review, data and results as a base to start and work upon.

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Annexes

Annex 1. List of materials embodied energy

Table 11. List of materials -Part1

Material	Mass	Origin	EE - Cradle to Gate	Remarks / Assumptions	EE - Transportation	Total EE	References
	[kg]		[MJ]		[MJ]	[MJ]	
steel rod A 400 NR diameter = 6 mm	187.77	Turkey	3,267.20	Assumed as Steel Rod	1,877.70	5,144.90	
steel rod A 400 NR diameter = 8 mm	1,094.48	Turkey	19,043.95	Assumed as Steel Rod	10,944.80	29,988.75	
steel rod at 400 nr diameter = 10 mm	2,262.23	Turkey	39,362.80	Assumed as Steel Rod	22,622.30	61,985.10	
steel rod A 400 NR diameter = 12 mm	7,146.12	Turkey	124,342.40	Assumed as Steel Rod	71,461.15	195,803.55	
steel rod A 400 NR dia = 16 mm	4,456.69	Turkey	77,546.45	Assumed as Steel Rod	44,566.93	122,113.37	
steel rod A 400 NR diameter = 20 mm	1,690.24	Turkey	29,410.09	Assumed as Steel Rod	16,902.35	46,312.44	
steel rod A 400 NR diameter = 25 mm	579.13	Turkey	10,076.91	Assumed as Steel Rod	5,791.33	15,868.23	
steel bar A 400 NR diameter = 32 mm	80.32	Turkey	1,397.61	Assumed as Steel Rod	803.23	2,200.84	
Steel rod A 500 NR diameter = 6 mm	8.64	Turkey	150.38	Assumed as Steel Rod	86.43	236.80	
Steel rod A 500 NR diameter = 8 mm	79.75	Turkey	1,387.69	Assumed as Steel Rod	797.53	2,185.22	
Steel rod A 500 NR diameter = 10 mm	190.25	Turkey	3,310.26	Assumed as Steel Rod	1,902.45	5,212.71	
Steel rod A 500 NR diameter = 12 mm	360.65	Turkey	6,275.27	Assumed as Steel Rod	3,606.48	9,881.74	
Steel rod A 500 NR diameter = 16 mm	304.04	Turkey	5,290.30	Assumed as Steel Rod	3,040.40	8,330.70	
Steel rod A 500 NR diameter = 20 mm	160.88	Turkey	2,799.23	Assumed as Steel Rod	1,608.75	4,407.98	
Steel rod A 500 NR diameter = 25 mm	99.53	Turkey	1,731.82	Assumed as Steel Rod	995.30	2,727.12	
Steel rod A 500 NR diameter = 32 mm	7.92	Turkey	137.85	Assumed as Steel Rod	79.23	217.08	

Table 12. List of materials -Part 2

Material	Mass	Origin	EE - Cradle to Gate	Remarks / Assumptions	EE - Transportation	Total EE	References
	[kg]		[MJ]		[MJ]	[MJ]	
Burned annealed wire	177.52	Turkey	6,390.54	Assumed as Steel Wire	1,775.15	8,165.69	
Welded mesh 'malhassol' CQ 30	290.09	Turkey	10,443.41	Produced from steel wire. Assumed as steel wire	2,900.95	13,344.36	
Welded mesh 'malhassol' CQ 38	466.50	Turkey	16,794.14	Produced from steel wire. Assumed as steel wire	4,665.04	21,459.17	
Welded mesh 'malhassol' AQ 38	693.88	Turkey	24,979.51	Produced from steel wire. Assumed as steel wire	6,938.75	31,918.27	
Cement type II - 32.5 N	18,010.77	PT	72,043.08	Assumed as 36-65% GGBS (CEM III/A)	2,251.35	74,294.43	
Medium-thick sand	90,360.81	PT	7,319.23	The density of dry sand has been assumed	11,295.10	18,614.33	
Crushed concrete stone (Rachao)	1,109.50	PT	832.13	Assumed as general concrete	138.69	970.81	[42]
Brita 15/25	7,328.48	PT	9,233.88	Assumed as general stone	916.06	10,149.94	[42]
Brita 25/40	49,138.48	PT	61,914.48	Assumed as general stone	6,142.31	68,056.79	[42]
Tout venant 2ª	125,090.78	PT	157,614.38	Assumed as general stone	15,636.35	173,250.72	[43]
Cobblestone (Godo)	37,170.00	PT	46,834.20	Assumed as general stone	4,646.25	51,480.45	
White Marble Pebbles	4,927.00	PT	9,854.00	Assumed as marble	615.88	10,469.88	
Concrete C12 / 15 X0 Cl 1.00 Dmax 25 S2	25,622.00	PT	17,935.40	Assumed as 16/20 Mpa concrete	3,202.75	21,138.15	[44]
concrete C16 / 20 .XS1 (P). Cl0.20 Dmax.20 S3	85,100.00	PT	59,570.00	Assumed as 16/20 Mpa concrete	10,637.50	70,207.50	[44]
Concrete C25 / 30 XC2. D20. S3	37,812.00	PT	29,493.36	Assumed as 25/30 Mpa concrete	4,726.50	34,219.86	[44]
concrete C25 / 30. S3. D25 _XC1	381,225.00	PT	297,355.50	Assumed as 25/30 Mpa concrete	47,653.13	345,008.63	[44]

Table 13. List of materials -Part 3

Material	**Mass**	**Origin**	**EE - Cradle to Gate**	**Remarks / Assumptions**	**EE - Transportation**	**Total EE**	**References**
	[kg]		**[MJ]**		**[MJ]**	**[MJ]**	
SIKA Super sikalite	48.35	PT	3,384.50	Assumed as similar resins with EE value of 70 MJ/kg	6.04	3,390.54	[45]
Surface hardener MASTERTOP 100	902.49	PT	4,070.23	Cement based. Assumed general cement.	112.81	4,183.04	[46]
Waterproofing agent for concrete	20,790.00	ITALY	17,713.08	Based on sillica, quartz. Assumed as quartz powder	103,950.00	121,663.08	[47]
PVC diameter Ø 200	114.33	PT	7,717.50	PVC pipe	14.29	7,731.79	
Sanitation ring 125x50cm	14.10	PT	82.48	Made from concrete. Assumed as general concrete	1.76	84.24	
Caleira Aco Drain Multiline V200, C125	575.40	SPAIN	4,459.35	New material! Can be assumed as fibre-reinfroced concrete	719.25	5,178.60	[48]
Grampos alvenaria (Clamps Masoniry)	11.17	PT	194.36	Steel Masoniry Clamps	1.40	195.76	[49]
Concrete block 50 * 20 * 15	34.50	PT	1,109.52	Concrete Block 10 Mpa	4.31	1,113.83	
Concrete block 50 * 20 * 20	46.00	PT	1,747.49	Concrete Block 10 Mpa	5.75	1,753.24	
Lightweight concrete block BLE / BLEFV 7 50x20x7	123.48	PT	801.44		15.44	816.87	[35]
Lightweight concrete block BLE / BLEFV 10 50x20x10	6,330.10	PT	41,085.13		791.26	41,876.40	[50]
Lightweight concrete block BLE / BLEFV 15 50x20x15	15,114.75	PT	98,101.38		1,889.34	99,990.72	[51]
Lightweight concrete block BLE / BLEFV 20 50x20x20	26,245.10	PT	170,342.25		3,280.64	173,622.88	
Lightweight concrete block BLE / BLEFV 25 50x20x25	4,159.75	PT	26,998.61		519.97	27,518.58	
Light concrete block BTE PROETICS20 50X20X20	20,831.30	PT	135,204.30		2,603.91	137,808.22	[52]

Table 14. List of materials -Part 4

Material	Mass	Origin	EE - Cradle to Gate	Remarks / Assumptions	EE - Transportation	Total EE	References
	[kg]		[MJ]		[MJ]	[MJ]	
Lightweight concrete block BTE PROETICS25 50X20X25	5,034.75	PT	32,677.74		629.34	33,307.09	
Reboc RHP exterior fina cinzento CS-IV	4,952.19	PT	22,334.37	Made from cement	619.02	22,953.39	[53]
Arg pront ext traç 1: 2 (cement + sand)	86.25	PT	114.71	Assume Mortar Cement:sand 1:3	10.78	125.49	[54]
Arg pron ext trace 1: 4 (cement + sand)	30,052.50	PT	33,358.28	Assume Mortar Cement Sand 1:4	3,756.56	37,114.84	[54]
Stucco plaster mass - Seral	2,447.45	PT	4,405.40	Gypsum Plaster	305.93	4,711.33	
Seral finishing compound "Mecafino"	489.49	PT	881.08	Assumed as well as gypsum plaster for finishing	61.19	942.27	
Barmat Mármocer 60X60X1,2 White	2,617.52	PT	8,716.35	Assumed as Marble Tile	327.19	9,043.55	[55]
Marble "Extremoz Tigrado" 3cm	1,424.12	PT	4,742.32	Assumed as Marble Tile	178.02	4,920.34	[56]
Cape Moleans Marble 4cm	847.60	PT	2,822.51	Assumed as Marble tile	105.95	2,928.46	
Grelhas de enrelvamento (Green Pavements)	8,296.87	PT	6,222.65	Assume as concrete	1,037.11	7,259.76	[57]
Cement white glue (Weber.col classic)	957.87	Germany	5,268.26	Assume as average cement	5,986.66	11,254.91	[58]
Weber.fix premium Ceramic and Stone	957.70	Germany	131,204.22	Assumed close to epoxy resin	5,985.59	137,189.81	[34]
Weber.color premium Anti-fungal joints	148.19	Germany	815.05	Assume as average cement	926.19	1,741.23	[59]
Ceramic Deck	2,180.49	PT	26,165.85	Assumed as ceramic tiles	272.56	26,438.41	[60]
Mosaico Vitrico Evinél Azul	7,773.57	PT	89,396.06	Assumed as secondary (recycled) glass tiles	971.70	90,367.75	[61]
Cinca Adamastor gray 50x50cm	712.53	PT	8,550.39	Assumed as ceramic tiles	89.07	8,639.46	[62]
Cinca Adamastor gray 30x50cm Phoenix	72.51	PT	870.09	Assumed as ceramic tiles	9.06	879.15	[62]
Cinca Adamastor gray 30x50cm Phoenix	62.32	PT	747.80	Assumed as ceramic tiles	7.79	755.59	[62]

Table 15. List of materials - Part 5

Material	**Mass**	**Origin**	**EE - Cradle to Gate**	**Remarks / Assumptions**	**EE - Transportation**	**Total EE**	**References**
	[kg]		**[MJ]**		**[MJ]**	**[MJ]**	
Cinca Adamastor gray 33x50cm Cobertor	70.68	PT	848.14	Assumed as ceramic tiles	8.83	856.97	[62]
Expanded polystyrene boards 20mm	40.83	PT	3,617.80	EPS board	5.10	3,622.91	[63]
Roofmate SL 60mm	663.70	Spain	58,803.47	XPS BOARD (Assumed the same EE as EPS)	829.62	59,633.09	[64]
Cork insulation 6cm Effisus ECORK	940.92	PT	3,763.68	Cork Insulation Board	117.62	3,881.30	[31]
Plastic film 0.5cm IMPACTODAN	5.01	PT	0.45	Polyethiline foam membrane (RECYCLED)	0.63	1.08	[65]
Film Polyethylene 500m	1,851.94	PT	165,377.95	Low Density Polyethiline Film	231.49	165,609.44	[66]
Geotextile blanket 150 gr / m2 (Impersep)	24.87	PT	2,467.40	Assumed as Popropilyne fibers	3.11	2,470.51	[67]
Geotextile blanket 300 gr / m2	140.04	PT	13,891.67	Assumed as Polipropilyne fibers	17.50	13,909.18	[67]
NODULAR HDPE DAN	1,011.23	PT	91.01	RECYCLED High density polyethilane	126.40	217.41	[68]
Tampa B125 30x30cm	25.20	PT	630.00	Assumed as general iron	1.05	631.05	[69]
Iron Steps	13.00	PT	325.00	Assumed as general iron	0.13	325.13	[69]
Tampa D400 - 60x60cm	103.80	PT	2,595.00		6.49	2,601.49	[69]
Flintkote	427.35	PT	21,794.85	Based on bitumen	53.42	21,848.27	[70]
EPS boards	163.13	PT	14,452.88	Assume 10 cm thick	20.39	14,473.27	[63]
Revestimento plástico espesso – RPE	163.13	PT	13,131.56	Based of acrylic resins (plastic). Assumed as general plastic	20.39	13,151.95	[71]
Armadure- Fibra de vidro	827.59	PT	82,758.75	Assumed 5 mm thick	103.45	82,862.20	

Table 16. List of materials -Part 6

Material	Mass	Origin	EE - Cradle to Gate	Remarks / Assumptions	EE - Transportation	Total EE	References
	[kg]		[MJ]		[MJ]	[MJ]	
Floor with Microcement	27.55	PT	1,257.04	Assumed as cement + epoxy resins	3.44	1,260.48	[72]
Wooden Floor	2,656.00	Brazil/ Portugal	27,622.40	SUCUPIRA HARDWOOD	10,411.52	38,033.92	[73]
STAIRS with solid wood sucupira	168.32	Brazil/ Portugal	1,750.53	SUCUPIRA HARDWOOD	659.81	2,410.34	[73]
Finishing mineral fine smooth Viero	4.50	PT	24.75	Cementious material (Assume avg cement)	0.56	25.31	[74]
Lightweight concrete layer	17,372.25	PT	130,125.80	Assumed the same as lightweight concrete blocks	2,171.53	132,297.33	
Two coats of bituminous emulsion	87.81	PT	4,478.31	Assumed as general bitumen	10.98	4,489.29	[75]
Imper imperkote	514.83	PT	26,256.08	Assumed as general bitumen	64.35	26,320.43	[75]
PolyPlas 30	72.41	PT	3,692.66	General Bitumen	9.05	3,701.71	[76]
Polyxis R50C	46.43	PT	2,367.68	General Bitumen	5.80	2,373.48	[77]
Polyester 40T	59.40	PT	3,029.40	General Bitumen	7.43	3,036.83	[78]
Waterproof membrane. Effisus Ecoroof	10.11	PT	775.38	Assumed as HDPE resin	1.26	776.65	
Funilarias	40.00	PT	904.00	Assumed as galvanized steel	5.00	909.00	[79]
Pre-patinated zinc sheet coating	18.13	PT	962.60	Assumed 1 mm plate	2.27	964.86	
Wood Doors	240.00	PT	2,400.00	Assumed as 20 kg door (general timber)	30.00	2,430.00	[80]
Kitchens Ceramic tiles	32.00	PT	384.00	Ceramic tiles. Assumed around 4 kg for 0.4 m2	4.00	388.00	[81]
Wood Cabinets	100.00	PT	1,100.00	Made of MDF. Assumed 20 kg for one	12.50	1,112.50	[82]
Aluminum profiles	28.32	PT	4,388.83	Assumed as general Aluminum	3.54	4,392.36	

Table 17. List of materials - Part 7

Material	Mass	Origin	EE - Cradle to Gate	Remarks / Assumptions	EE - Transportation	Total EE	References
	[kg]		[MJ]		[MJ]	[MJ]	
Skylights	57.00	PT	6,450.00	Assumed as PVC framed windows. Assumed weight 19 kg	7.13	6,457.13	[83]
Fornt yard doors	250.00	PT	6,250.00	Assumed as iron. Assumed to have 50 kg / 200 kg	31.25	6,281.25	
Garage Door	80.00	PT	4,536.00	Assumed as stainless steel. 80 kg	10.00	4,546.00	
Guardas (Metalic Railings)	600.00	PT	12,060.00	Assumed as 30 kg for 1 m. Steel	75.00	12,135.00	[84]
Guardas vidro (Glass Railings)	480.00	PT	7,200.00	Assumed to be 80 kg/unit	60.00	7,260.00	[85]
Cover cast iron class D400 60x60	155.70	PT	3,892.50		6.49	3,898.99	[69]
ALUMINUM Grille type Renson	38.34	PT	5,942.70	Assumed as general Aluminium	4.79	5,947.49	[86]
Mosquito net	14.01	PT	1,401.38	Assumed from fiberglass	1.75	1,403.13	[87]
Tubular profile 60x40x2	44.25	PT	876.09	Assumed as Steel Pipe	5.53	881.62	[88]
Tubular profile 40x45x2	79.09	PT	1,565.90	Assumed as Steel Pipe	9.89	1,575.79	[88]
False ceilings	1,777.78	PT	12,000.00	Plasterboard ceiling. Assumed 32 kg for 3.6 m2	222.22	12,222.22	[89]
Exterior wall painting	5.00	PT	39.38	Assumed as Single coat	0.38	39.75	
Metal Railings painting	15.00	PT	118.78	Assumed as Single coat	1.25	120.03	
Blinds	40.00	PT	6,200.00	Aluminium blinds. Assumed 10 kg /unit	5.00	6,205.00	[90]
Resguardos (Shower Glass)	47.42	PT	711.36	Assumed as normal glass	1.48	712.84	[91]
Mirrors	34.68	PT	520.20	Assumed as normal glass	4.34	524.54	[92]

Table 18. List of materials -Part 8

Material	**Mass**	**Origin**	**EE - Cradle to Gate**	**Remarks / Assumptions**	**EE - Transportation**	**Total EE**	**References**
	[kg]		**[MJ]**		**[MJ]**	**[MJ]**	
200mm rigid PVC pipe	10.50	PT	708.75		1.75	710.50	
Solar Photovoltaics	240.50	PT	86,243.30	Polycrystaline PV	30.06	86,273.36	
Sliding Windows x 11 -Aluminium	3,900.00	PT	71,110.00	Assumed as all the same	487.50	71,597.50	[93]

Annex 2. Materials mass calculation

Table 19. Materials Mass Calculation [kg] - Part 1

	Area [m2]	Mass [kg]
Welded mesh 'malhassol' CQ 30	392.02	290.0948
Welded mesh 'malhassol' CQ 38	392.02	466.5038
Welded mesh 'malhassol' AQ 38	392.02	693.8754
Density sand	1602	kg/m3
Amount of half-sand in construction (volume)	56.405	m3
Mass of sand	90360.81	kg
Density Rachao (crushed concrete stone)	1585	kg/m3
Amount of Rachao (volume)	0.7	m3
Mass of rachao	1109.5	Kg
Density Brita 15/22	1410	kg/m3
Amount of Brita 15/22 (volume)	5.1975	m3
Mass of Brita 15/22	7328.475	kg
Density Brita 25/40	1556	kg/m3
Amount of Brita 25/40 (volume)	31.58	m3
Mass of Brita 25/40	49138.48	kg
Density Tout venant 2ª	2610	kg/m3
Amount of Tout venant 2a (volume)	47.9275	m3
Mass of Tout venant 2a	125090.775	kg

Table 20. Materials Mass Calculation [kg] - Part 2

Density Cobblestone	1500	kg/m3
Amount of Cobblestone (volume)	24.78	m3
Mass of Cobblestone	37170	kg
Density White Marble	2600	kg/m3
Amount of White Marble (Volume)	1.895	m3
Mass of White Marble	4927	kg
Density concrete C16 / 20 .XS1 (P). Cl0.20 Dmax.20 S3	2300	kg/m3
Amount of concrete C16 / 20 .XS1 (P). Cl0.20 Dmax.20 S3 (Volume)	37	m3
Mass of concrete C16 / 20 .XS1 (P). Cl0.20 Dmax.20 S3	85100	kg
Density concrete C25 / 30 XC2. D20. S3	2300	kg/m3
Amount of concrete C25 / 30 XC2. D20. S3 (Volume)	16.44	m3
Mass of concrete C25 / 30 XC2. D20. S3	37812	kg
Density concrete C25 / 30. S3. D25 _XC1	2300	kg/m3
Amount of concrete C25 / 30. S3. D25 _XC1 (Volume)	165.75	m3
Mass of concrete C25 / 30. S3. D25 _XC1	381225	kg
Density concrete C12 / 15 X0 Cl 1.00 Dmax 25 S2	2300	kg/m3
Amount of concrete C12 / 15 X0 Cl 1.00 Dmax 25 S2 (Volume)	11.14	m3
Mass of concrete C12 / 15 X0 Cl 1.00 Dmax 25 S2	25622	kg

Table 21. Materials Mass Calculation [kg] - Part 3

Total Length PVC pipe	49	m
Mass of 6 m PVC pipe	14	kg
Mass of PVC pipe	114.3333333	kg
Density of sanitation ring	2300	kg/m3
Volume sanitation ring 125x50 cm	0.00613	m3
Mass of sanitation ring	14.099	kg
1 meter of Caleira Aco Drain Multiline V200, C125	41.1	kg
14 meter of Caleira Aco Drain Multiline V200, C125	575.4	kg
Density concrete	2300	kg/m3
Volume Concrete block 50 * 20 * 15	0.015	m3
Volume Concrete block 50 * 20 * 20	0.02	m3
Mass Concrete block 50*20*15	34.5	kg
Mass Concrete block 50*20*20	46	kg

Table 22. Materials Mass Calculation[kg] -Part 4

Mix Lightweight Concrete			
	Cement	Fine agregate (Sand)	LECA
	1	1.24	0.63
EE [MJ/kg]	4.5	0.081	3
EE of 1kg of Lightweight Concrete	6.49044	MJ/kg	

Table 23. Materials Mass Calculation [kg] - Part 5

Density Lightweight Concrete	700	kg/m3
Volume Lightweight concrete block BLE / BLEFV 7 50x20x7	0.007	m3
Volume Lightweight concrete block BLE / BLEFV 10 50x20x10	0.01	m3
Volume Lightweight concrete block BLE / BLEFV 15 50x20x15	0.015	m3
Volume Lightweight concrete block BLE / BLEFV 20 50x20x20	0.02	m3
Volume Lightweight concrete block BLE / BLEFV 25 50x20x25	0.025	m3
Volume Light concrete block BTE PROETICS20 50X20X20	0.02	m3
Volume Lightweight concrete block BTE PROETICS25 50X20X25	0.025	m3
Mass Lightweight concrete block BLE / BLEFV 7 50x20x7	4.9	kg
Mass Lightweight concrete block BLE / BLEFV 10 50x20x10	7	kg
Mass Lightweight concrete block BLE / BLEFV 15 50x20x15	10.5	kg
Mass Lightweight concrete block BLE / BLEFV 20 50x20x20	14	kg
Mass Lightweight concrete block BLE / BLEFV 25 50x20x25	17.5	kg
Mass Light concrete block BTE PROETICS20 50X20X20	14	kg
Mass Lightweight concrete block BTE PROETICS25 50X20X25	17.5	kg
Density mortar (cement:sand 1:2)	1500	kg/m3
Volume mortar cement:sand 1:2	0.0575	m3
Mass of Mortar	86.25	kg
Volume mortar cement:sand 1:4	20.035	m3
Mass of Mortar	30052.5	kg

Table 24. Materials Mass Calculation [kg] - Part 6

Area of 1 Barmat refªMármocer 60X60X1,2 White Car	0.36	m2
Total Area of Barmat refªMármocer 60X60X1,2 White Car	83.895	m2
Number of Barmat refªMármocer 60X60X1,2 White Car	233.0416667	pieces
Volume of Barmat refªMármocer 60X60X1,2 White Car	0.00432	m3
Total volume Barmat refªMármocer 60X60X1,2 White Car	1.00674	m3
Density White Marble	2600	kg/m3
Total mass of Barmat refªMármocer 60X60X1,2 White Car	2617.524	kg
Density of 1 Mármore "Extremoz Tigrado" 3cm	2713	kg/m3
Area of 1 Mármore "Extremoz Tigrado" 3cm	0.36	m2
Number of Mármore "Extremoz Tigrado" 3cm	48.60416667	pieces
Volume of 1 Mármore "Extremoz Tigrado" 3cm	0.0108	m3
Total Volume of 1 Mármore "Extremoz Tigrado" 3cm	0.524925	m3
Mass of Mármore "Extremoz Tigrado" 3cm	1424.121525	kg
Volume Capeamento Mármore moleanos c/4cm	0.326	m3
Density White Marble	2600	kg/m3
Mass of Capeamento Mármore moleanos c/4cm	847.6	kg
Weight Grelhas de enrelvamento	32.2	kg /unit
Area of 1 Grelhas de enrelvamento	0.24	m2
Total Area Grelhas de enrelvamento	61.84	m2
Number of Grelhas de enrelvamento	257.6666667	pieces
Total mass of Grelhas de enrelvamento	8296.866667	kg

Table 25. Materials Mass Calculation [kg] -Part 7

Deck ceramico dimensions	60x15x0.95	cm
Area 1 deck ceramico	0.09	m2
Total Area Deck ceramico	114.7625	m2
Number of deck ceramico	1275.138889	pieces
Volume deck ceramico	0.000855	m3
Density ceramics (ASSUMED)	2000	kg/m3
Total volume of deck ceramico	1.09024375	m3
Mass of deck ceramico	2180.4875	kg
Mosaico Vitrico Evinél Azul mesclado Dimensions	4x4x4	cm
Area 1 Vitrico Evinél Azul mesclado Dimensions	0.0016	m2
Total Area Vitrico Evinél Azul mesclado Dimensions	71.9775	m2
Number of Vitrico Evinél Azul mesclado Dimensions	44985.9375	pieces
Volume Vitrico Evinél Azul mesclado Dimensions	0.000064	m3
Density Glass	2700	kg/m3
Mass of 1 Vitrico Evinél Azul mesclado Dimensions	0.1728	kg
Total Mass of Vitrico Evinél Azul mesclado Dimensions	7773.57	kg

Table 26. Materials Mass Calculation [kg] - Part 8

Cinca Adamastor grey 50x50cm Dimensions	500*500*9.7	mm	300x500x9.7	mm	80*500*9.7	mm	330*500*9.7	mm
Area 1 Cinca Adamastor grey 50x50cm	0.25	m2	0.15	m2	0.04	m2	0.165	m2
Total Area Cinca Adamastor grey 50x50cm	36.7285	m2	3.7375	m2	3.2122	m2	3.6432	m2
Number of Cinca Adamastor grey 50x50cm	146.914	pieces	24.91666667	pieces	80.305	pieces	22.08	pieces
Volume of Cinca Adamastor grey 50x50cm	0.002425	m3	0.001455	m3	0.000388	m3	0.0016005	m3
Density Ceramics	2000	kg/m3	2000	kg/m3	2000	kg/m3	2000	kg/m3
Mass of 1 Cinca Adamastor grey 50x50cm	4.85	kg	2.91	kg	0.776	kg	3.201	kg
Total Mass Cinca Adamastor grey 50x50cm	712.5329	kg	72.5075	kg	62.31668	kg	70.67808	kg

Table 27. Materials Mass Calculation [kg] - Part 9

Total Area Placa poliestireno expandido 1x1-e=20mm	136.11	m2
Surface covered by 1 Placa poliestireno expandido 1x1-e=20mm	0.5	m2
Nb of Placa poliestireno expandido 1x1-e=20mm	272.22	boards
Volume of one board	0.01	m3
Density Placa poliestireno expandido 1x1-e=20mm	15	kg/m3
Mass of 1 Placa poliestireno expandido 1x1-e=20mm	0.15	kg
Total Mass Placa poliestireno expandido 1x1-e=20mm	40.833	kg
Roofmate sl 60mm Dimenssions	1.25*0.6*0.06	m
Area of 1 Roofmate sl 60mm	0.75	m2
Total Area Roofmate sl 60mm	335.2	m2
Number of Roofmate sl 60mm	446.9333333	boards
Volume of 1 Roofmate sl 60mm	0.045	m3
Density Roofmate sl 60mm	33	kg/m3
Mass of 1 Roofmate sl 60mm	1.485	kg
Total Mass Roofmate sl 60mm	663.696	kg
Isolamento cortiça 6cm esp.Effisus ECORK Dimensions	1 x 0.5 x 0.06	m
Area of 1 Isolamento cortiça 6cm esp.Effisus ECORK	0.5	m2
Tolta Area of Isolamento cortiça 6cm esp.Effisus ECORK	78.41	m2
Number of Isolamento cortiça 6cm esp.Effisus ECORK	156.82	boards
Volume of 1 Isolamento cortiça 6cm esp.Effisus ECORK	0.03	m3
Density of cork	200	kg/m3
Mass of 1 Isolamento cortiça 6cm esp.Effisus ECORK	6	kg
Total mass of Isolamento cortiça 6cm esp.Effisus ECORK	940.92	kg

Table 28. Materials Mass Calculation [kg] - Part 10

1 Role of tela/película plástica 0,5cm _IMPACTODAN	50*2*0.005	m
Area of tela/película plástica 0,5cm _IMPACTODAN	34.53	m2
Area of 1 role tela/película plástica 0,5cm _IMPACTODAN	100	m2
% of role used	0.3453	%
Volume of 1 role	0.5	m3
Density of role	29	kg/m3
Mass of 1 full role	14.5	kg
Mass of role actually used	5.00685	kg
Film separator d polyethylene 500mcr Role Dimensions	1.2*130*0.003	m
Area of 1 role	156	m2
Total Area Film separator d polyethylene 500mcr	685.9025	m2
Number of Film separator d polyethylene 500mcr	4.396810897	pieces
Volume of 1 role	0.468	m3
Density Film separator d polyethylene 500mcr	900	kg/m3
Mass of 1 role	421.2	kg
Total MASS Low Density Polyethylene	1851.93675	kg
Weight Manta Geotextixl 150	150	g/m2
Weight Manta Geotextixl 300	300	g/m2
Total Area Geotextil 150	165.82	m2
Total Area Geotextil 300	466.79	m2
MASS Geo 150	24.873	kg
MASS Geo 300	140.037	kg

Table 29. Materials Mass Calculation [kg] - Part 11

Dimenssions Lâmina drenante NODULAR HDPE DAN	2.1*30*0.0075	m
Area of 1 role Lâmina drenante NODULAR HDPE DAN	63	m2
Total Area	139	m2
Number of roles Lâmina drenante NODULAR HDPE DAN	2.206349206	roles
Volume of 1 role Lâmina drenante NODULAR HDPE DAN	0.4725	m3
Density high density polyethylene (HDPE)	970	kg/m3
Mass of 1 role high density polyethylene (HDPE	458.325	kg
TOTAL MASS high density polyethylene (HDPE	1011.225	kg
Weight Tampa ff. B125 30x30cm reb._mod.FUCOLI	8.4	kg
Weight Degraus ferro em câmaras visita	1	kg
Weight Tampa ff. D400 - 60x60cm modelo ESTAQUE	51.9	kg
Dimensions Revest.de ESCADAS c/madeira maciça Sucup	0.02	cm thick
Total volume	0.2104	m3
Density solid wood (SUCUPIRA)	800	kg/m3
Total MASS	168.32	kg
Acabamento mineral fino liso mate Viero	1.2	kg/m2
Total Area Covered	3.75	m2
MASS of Acabamento mineral fino liso mate Viero	4.5	kg

Table 30. Materials Mass Calculation [kg] - Part 12

Density Lightweight Concrete	700	kg/m3
Volume Lightweight Concrete	24.8175	m3
Mass of Lightweight Concrete	17372.25	kg
Two coats. bituminous emulsion	Assumed 2kg/m2	
Total area covered	43.905	m2
Mass of bituminous emulsion	87.81	kg
Dimensions Effisus Ecoroof	0.00114 x 221.695 m2	
Volume Effisus Ecoroof	0.2527323	m3
Density Effisus Ecoroof	40	kg/m3
Mass Efisus Ecoroof	10.109292	kg
Volume Revestime em chapa de zinco pré-patinado	0.0025425	m3
Density Zinc	7130	kg/m3
Mass of Revestime em chapa de zinco pré-patinado	18.128025	kg
Dim Grelha ALUMINIO tipo Renson ref.ªLouvre	0.15x0.15x 0.004	m
Area of 1 Grelha ALUMINIO tipo Renson ref.ªLouvre	0.0225	m2
Total Area of Grelha ALUMINIO tipo Renson ref.ªLouvre	3.55	m2
Number of Grelha ALUMINIO tipo Renson ref.ªLouvre	157.7777778	pieces
Volume of Grelha ALUMINIO tipo Renson ref.ªLouvre	0.0142	m3
Density of Aluminium	2700	kg/m3
Mass of Grelha ALUMINIO tipo Renson ref.ªLouvre	38.34	kg

Table 31. Materials Mass Calculation [kg] - Part 13

Volume Rede mosquiteira	0.0092075	m3
Density of fiberglass	1522	kg/m3
Mass of Rede mosquiteira	14.013815	kg
Mass of 4.6 m pvc pipe	10.5	kg
Mass of 6 m PVC pipe	14	kg
Hidrofugo para betão Density	0.7	g/cm3
Density	700	kg/m3
Total Volume	29.7	m3
Total Mass	20790	kg
Imperkote F Density	1	g/cm3
	1000	kg/m3
Use of imperkote	2	kg/m2
Total Area used	257.4125	m2
Total Mass of Imperkote	514.825	kg
Use of PolyPlas 30	3	kg/m2
Total Area used	24.135	m2
Total Mass of Poly 30	72.405	kg
Use of PolyPlas R-50C	5	kg/m2
Total Area used	9.285	m2
Total Mass of R-50C	46.425	kg

Table 32. Materials Mass Calculation [kg] - Part 14

Use of PolyPlas 40T	4	kg/m2
Total Area used	14.85	m2
Total Mass of 40T	59.4	kg
Total Volume EPS Board	10.875	m3
Density EPS board	15	kg/m3
Total Mass EPS Board	163.125	kg
Total volume fibra de vidro	0.54375	m3
Density fibra de vidro	1522	kg/m3
Total mass	827.5875	kg
Dimenssion Floor (Solalho)	0.02	m thick
Total volume	3.32	m3
Density solid wood sucupira	800	kg/m3
Total mass wood sucupira	2656	kg
Dimensions Resguardos	1.3x0.76x0.005	m
Volume	0.00494	m3
Glass density	2400	kg/m3
Weight of 1 Resguardos	11.856	kg

Annex 3. Materials list

Table 33. Townhouse lot 307 material list

Category	**Materials**
Steel	• steel rod A 400 NR diameter = 6 mm • steel rod A 400 NR diameter = 8 mm • steel rod at 400 nr diameter = 10 mm • steel rod A 400 NR diameter = 12 mm • steel rod A 400 NR diameter = 16 mm • steel rod A 400 NR diameter = 20 mm • steel rod A 400 NR diameter = 25 mm • steel bar A 400 NR diameter = 32 mm • Steel rod A 500 NR diameter = 6 mm • Steel rod A 500 NR diameter = 8 mm • Steel rod A 500 NR diameter = 10 mm • Steel rod A 500 NR diameter = 12 mm • Steel rod A 500 NR diameter = 16 mm • Steel rod A 500 NR diameter = 20 mm • Steel rod A 500 NR diameter = 25 mm • Steel rod A 500 NR diameter = 32 mm • Burned annealed wire • Welded mesh 'malhassol' CQ 30 • Welded mesh 'malhassol' CQ 38 • Welded mesh 'malhassol' AQ 38 • Steel Masonry Clamps • Tampa D400 - 60x60cm • Funilarias

	• Garage Door • Metal Railings • Tubular profile 60x40x2 • Tubular profile 40x45x2
Aluminum	• Aluminum profiles • Aluminum ventilation grill • Aluminum blinds
Iron	• Tampa B125 30x30cm • Iron steps • Front yard doors • Cover cast iron class D400 60x60
Concrete	• Crushed concrete stone (Rachao) • Concrete C12 / 15 X0 Cl 1.00 Dmax 25 S2 • concrete C16 / 20 .XS1 (P). Cl0.20 Dmax.20 S3 • Concrete C25 / 30 XC2. D20. S3 • concrete C25 / 30. S3. D25 _XC1 • Sanitation ring 125x50cm • Caleira Aco Drain Multiline V200, C125 • Concrete block 50 * 20 * 15 • Concrete block 50 * 20 * 20 • Green pavements
Lightweight concrete	• Lightweight concrete block BLE / BLEFV 7 50x20x7 • Lightweight concrete block BLE / BLEFV 10 50x20x10 • Lightweight concrete block BLE / BLEFV 15 50x20x15 • Lightweight concrete block BLE / BLEFV 20 50x20x20 • Lightweight concrete block BLE / BLEFV 25 50x20x25 • Light concrete block BTE PROETICS20 50X20X20

	• Lightweight concrete block BTE PROETICS25 50X20X25 • Lightweight concrete layer
Cement based materials	• Cement type II - 32.5 N • Surface hardener MASTERTOP 100 • Reboc RHP exterior fina cinzento CS-IV • 1: 2 (cement + sand) • 1: 4 (cement + sand) • Cement white glue (Weber.col classic) • Floor with Microcement • Finishing mineral fine smooth Viero
Bitumen based materials	• Flintkote • Two coats of bituminous emulsion • Imper imperkote • PolyPlas 30 • Polyxis R50C / Polyester 40T
Plastics	• PVC diameter Ø 200 • Plastic film 0.5cm IMPACTODAN • Film Polyethylene 500m • Geotextile blanket 150 gr / m2 (Impersep) • Geotextile blanket 300 gr / m2 • NODULAR HDPE DAN • Revestimento plástico espesso – RPE • 200mm rigid PVC pipe • Waterproof membrane. Effisus Ecoroof
Insulation	• Expanded polystyrene boards 20mm • Roofmate SL 60mm • Cork insulation 6cm Effisus ECORK

	• EPS boards
Glass	• Mosaic Vitrico Evinél Azul • Glass railings • Shower glass • Mirrors
Stone	• Brita 15/25 • Brita 25/40 • Tout venant 2ª • Cobblestone (Godo) • White Marble Pebbles • Barmat Mármocer 60X60X1,2 White • Marble "Extremoz Tigrado" 3cm • Cape Moleans Marble 4cm
Ceramics	• Ceramic Deck • Cinca Adamastor gray 50x50cm • Cinca Adamastor gray 30x50cm Phoenix • Cinca Adamastor gray 30x50cm Phoenix • Cinca Adamastor gray 33x50cm Cobertor • Kitchens Ceramic tiles
Gypsum	• Stucco plaster mass - Seral • Seral finishing compound "Mecafino" • False ceilings
Wood	• Wooden Floor • STAIRS with solid wood Sucupira • Wood Doors / Cabinets

Resins	• SIKA Super sikalite • Weber.fix premium Ceramic and Stone
Sand	• Medium-thick sand
Zinc	• Pre-patinated zinc sheet coating
Windows PVC	• Skylights
Windows Aluminum	• Aluminum sliding windows
Power generation equipment	• Solar photovoltaic modules
Miscellaneous	• Waterproofing agent for concrete • Armadure- Fiberglass • Mosquito net • Exterior wall painting • Metal Railings painting

Annex 4. Case study description

Figure 21. Lot 307 Floor -1 [29]

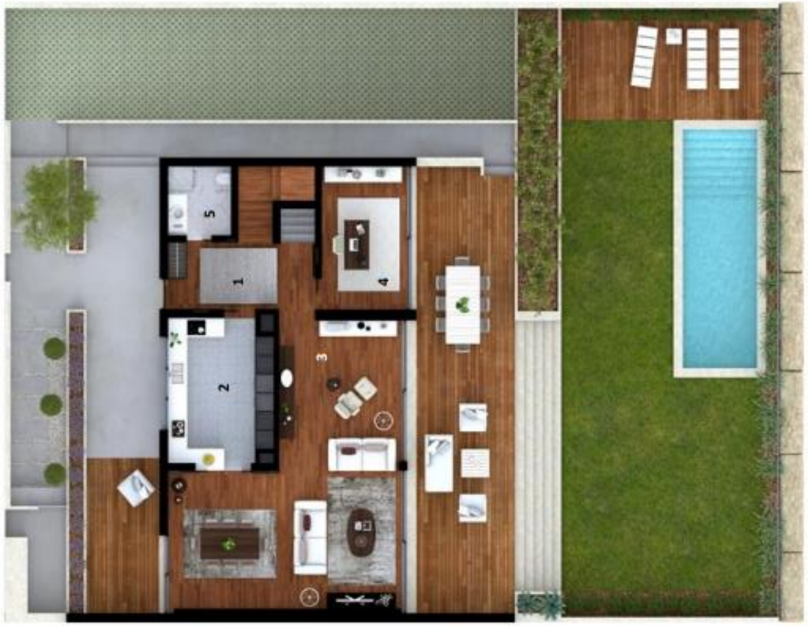

Figure 22 Lot 307 Floor 0 [29]

Figure 23 Lot 307 Floor 1 [29]

On the floor 0, the living room facing west with a big opening to the terrace and swimming pool (Figure 24). The orientation is selected for the solar gains and as well for the aesthetically pleasing view offered. [30]

Figure 24. Terrace area townhouse 307 (left), swimming pool townhouse 307 (middle) and overview (left)

The terrace is protected by the upper floors’ volumes. The entrance hall is shared between the kitchen, living room , toilet, office and stairs access to the first floor and the basement (Figure 25)

Figure 25. Townhouse 307 floor 0 living room (left), office (middle-left), bathroom (middle), kitchen (middle-right), stair (right)

On floor 1, two suites, two bedrooms and a toilet are present, while floor -1 incorporates a big parking garage, storage space and technical area (Figure 26 and Figure 27).

Figure 26 Townhouse 307 floor -1 parking space and technical area

Figure 27. Townhouse 307 floor 1 bedroom, suits and bathrooms examples

From a renewable generation point of view, the townhouse has installed 2 “Vulcano FKC 2W” solar panels for domestic hot water production. They are installed on the roof, occupy 4.5 m^2 of area and have a slope of 35 °. They work together with a 300 liter indoor water tank [30]. For electricity production, 13 solar photovoltaic panels “Genius 4BB 250W” are also installed on the roof and work together with a battery for energy storage with a 6 kW capacity. (Figure 28)

Figure 28 Townhouse 307 solar photovoltaic and solar panel (left) and battery storage (right)

Considering the construction process it has to be mentioned that is was not easy due to the hard rocky soil that needed to be excavated. As well, given the extremely rigorous efficiency measures implemented, extra care was taken when building the townhouse (Figure 29).

Figure 29 Townhouses construction process

In the global environmental performance, the townhouse on lot 307 was evaluated as exceptional A+ performance, obtaining 65.5 % improvements compared to common practices. [30]