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Assessing Initial Embodied Energy in Building Structures using LCA Methodology

Dissertation to obtain the Master Degree in Civil Engineering

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ABSTRACT

The considerable amount of energy consumed on Earth is a major cause for not achieving sustainable development. Buildings are responsible for the highest worldwide energy consumption, nearly 40%. Strong efforts have been made in what concerns the reduction of buildings operational energy (heating, hot water, ventilation, electricity), since operational energy is so far the highest energy component in a building life cycle. However, as operational energy is being reduced the embodied energy increases. One of the building elements responsible for higher embodied energy consumption is the building structural system. Therefore, the present work is going to study part of embodied energy (initial embodied energy) in building structures using a life cycle assessment methodology, in order to contribute for a greater understanding of embodied energy in buildings structural systems. Initial embodied energy is estimated for a building structure by varying the span and the structural material type. The results are analysed and compared for different stages, and some conclusions are drawn. At the end of this work it was possible to conclude that the building span does not have considerable influence in embodied energy consumption of building structures. However, the structural material type has influence in the overall energetic performance. In fact, with this research it was possible that building structure that requires more initial embodied energy is the steel structure; then the glued laminated timber structure; and finally the concrete structure.

Keywords: Initial embodied energy, LCA methodology, building structures.

RESUMO

A considerável quantidade de energia consumida na Terra é uma das maior causas para não se alcançar desenvolvimento sustentável. Os edifícios são responsáveis pelo maior consumo de energia a nível mundial, cerca de 40%. Grandes esforços têm sido feitos, no que diz respeito à redução da energia operacional dos edifícios (aquecimento, água quente, ventilação, eletricidade), devido ao facto de a energia operacional ser, até agora, a componente com maior consumo energético no ciclo de vida de um edifício. Contudo, à medida que a energia operacional vai sendo reduzida, a energia incorporada aumenta. Um dos elementos de um edifício responsável pelo maior consumo energético corresponde ao sistema estrutural. Por este motivo, o presente estudo vai estudar parte da energia incorporada (energia incorporada inicial) da estrutura de um edifício, através do uso da metodologia de avaliação de ciclo de vida, variando a distância entre pórticos e o tipo de material estrutural. A energia incorporada inicial é estimada para uma estrutura de edifício variando a distância entre os pórticos e o tipo de material estrutural. Os resultados são analisados e comparados para diferentes fases, e algumas conclusões são retiradas. No final deste trabalho foi possível concluir que a variação da distância entre pórticos estruturais não é significante no consumo de energia incorporada de estruturas de edifícios. Porém, o tipo de material estrutural tem influência no desempenho energético total. De facto, com esta pesquisa foi possível concluir que a estrutura de edifício que utiliza mais energia incorporada inicial é a de aço, seguida da de madeira, e, por fim, da de betão.

Palavras-chave: Energia incorporada inicial, metodologia ACV, estruturas de edifícios.

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Abbreviations

BEES – Building for environmental and economic sustainability
BESLCI – Building energy system life cycle inventory
BOS – Basic oxygen steelmaking
$CaCO_3$ – Calcium carbonate
CaO – Calcium oxide
CO_2 – Carbon dioxide
DE – Demolition energy
EE – Embodied energy
EIO-LCA – Economic Input-Output Life Cycle Assessment
GHG – Green house gases
HVAC – Heating, ventilation and air conditioning
ICE – Inventory of Carbon & Energy
I-O – Input –Output
ISO – International standards organization
LCA – Life cycle assessment
LCE – Life cycle energy
LCEA – Life cycle energy analysis
LCI – Life cycle inventory
OE – Operational energy
OPC – Ordinary Portland cement
SETAC – Society of environmental toxicology and chemistry
UNEP – United Nations environment program

Symbols

Roman Letters

C_i^k- Capacity for work per hour of equipment *k*

D_i^k - Duration of equipment *k* usage

E_C – Energy required for building construction

EC_i^j – Energy consumption per kilometer of vehicle *j* for a ton or cubic meter of material *i*

EC_i^k - Energy consumption per hour of equipment *k*

E_{C_E} – Energy required to construction equipment

E_{C_T} – Energy required to transport building materials from the plant to the construction site

E_D – Energy for destruction of the building

E_M – Energy required for material manufacturing

E_{OA} – annual operating energy

E_T – Energy for transportation of waste material

EE_i – Initial embodied energy

EE_r – Recurring embodied energy of the building

f_{ck} – Concrete strength class

f_{yk} – Steel strength class

g_k – Permanent dead load

L_b – Life span of the building

L_{mi} – Life span of the building material

m_i – Quantity of building material required to produce a building

M_i – Energy content of material per unit quantity

q_k – Daily use load

Q_i –Quantity of material *i*

TD_i^j– Transportation distance of the building material *i* from the plant to the construction site using vehicle *j*

Greek Letters

Σ - Sigma

1. Introduction

This chapter presents the background and motivation that support this study. The objectives of the study are presented, and it is explained the research process and methodology used. Finally, it is presented an overview of the thesis structure.

1.1 Background

The depletion and mismanagement of resources combined with the pollution is accentuating the global warming effects. Therefore, the sea level is rising and the world is facing alarming numbers of greenhouse-gases (GHG) and energy consumption.

Over the last decades the term sustainable development has been one of the most discussed topics in our society. In one hand, there is a demanding concern with environmental issues in order to preserving the Earth for the present generation, but also for the next ones. On the other hand, the population growth is expected to increase rapidly in the near future. Between 2011 and 2050 it is estimated an increase of 2,3 billion people (UnitedNations, 2014). In consequence, the social and economic activities will become more competitive. Associated with the population growth is associated a larger consumption of water, food, energy, and materials and higher values of waste production and CO_2 emissions.

Currently, more than half of world's population is living in cities and more and more people are expected to migrate from the rural areas to the urban areas, as it is possible to observe per figure 1.1.1.

This means that the population growth for the next decades will take place in cities. Consequently, it will be necessary to create more industries, transport systems and buildings to meet the increasing number of population in urban centres, which will raise the energy consumption. In fact, this situation is expected to complicate in the following years if no action is taken.

Buildings use 40% of global energy, 25% of global water, 40% of global resources, and emits into the atmosphere 1/3 of GHG world's emission (UNEP, 2015). Only the construction activities consume a considerable part of natural resources per year: 40% of global stone, sand and gravel; 25% of wood; and 16% of global water (Dixit M. K., Fernández-Solís, Lavy, & Culp, 2010), (Komurlu, Arditi, & Gurgun, 2015). During buildings operational phase about 60% of the world's electricity is consumed (UNEP, 2015).

Buildings are essential for the major socio-economic development of any nation, however they have serious negative environmental impacts in our planet. It is indeed necessary to promote the life quality of the populations without compromising the life quality on Earth. This goal can be achieved by implementing sustainable construction.

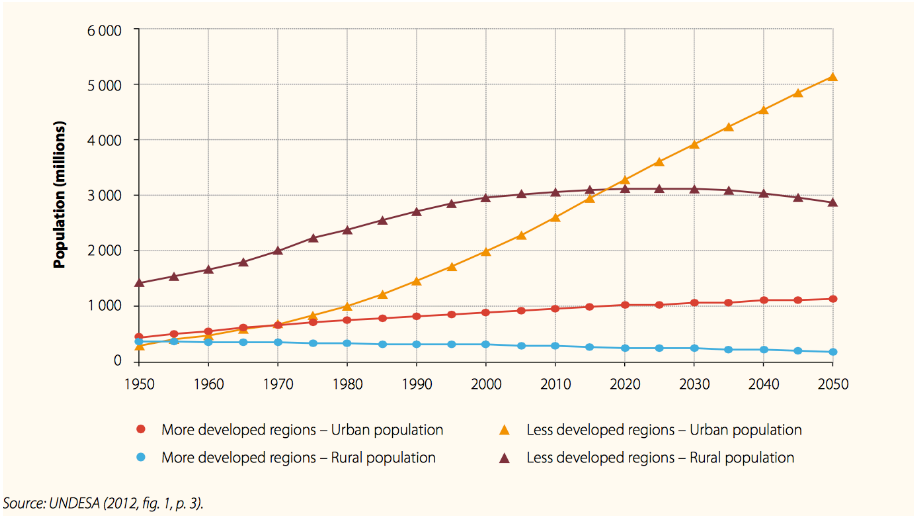

Figure 1.1.1 – Urban population growth in urban and rural areas, 1950-2050 (adapted from Water and Energy-Volume 1, 2014)

With sustainable construction it is intended to achieve sustainable development within building industry. To reach this goal, policies that promote sustainability are being implemented all over the world. In fact, recently new standards and methodologies that use a life cycle approach to evaluate buildings environmental impact have emerged. According to the United Nations Environment Programme (UNEP), the use of these methodologies can reduce the energy consumption in buildings from 80 to 30%.

1.2 Motivation

The main reason to carry out this research drives from the environmental problems that the building industry is currently facing. So far, there have been some considerable improvements to achieve sustainable construction in the building industry; further investigation is needed in order to solve the new challenges and to reach the goals established by political organizations.

It was decided to focus the research on buildings' energy consumption for two main reasons:

- The most significant environmental impact in the building industry is due to the higher energy consumption;

- It was found an opportunity to reduce energy consumption in buildings through the investigation of an energy component that received less attention from researchers over the last years, embodied energy. This component has a considerable importance in the total buildings' energy consumption, as it will be explained in Chapter 2.

Plus, there has always been my personal interest in the thematic of sustainability and energy efficiency in buildings, which pursue to carry out the investigation inside that thematic.

1.3 Objectives

The general objective of this thesis is assessing embodied energy in specific buildings structures using the principles of LCA methodology, whereas the main objective is to compare initial embodied energy in a structural system with constant dimensions, by varying the building span and the building material type. Initial embodied energy will be estimated in a simple structural system made of concrete, another one made of steel, and finally other made of timber.

With this, it is pretended to determine if different building materials types and different building spans have a significant impact on initial embodied energy consumption.

1.4 Research Process and Methodology

The research process during the development of the thesis was not static.

In figure 1.4.1 it is presented an analogy to the research process.

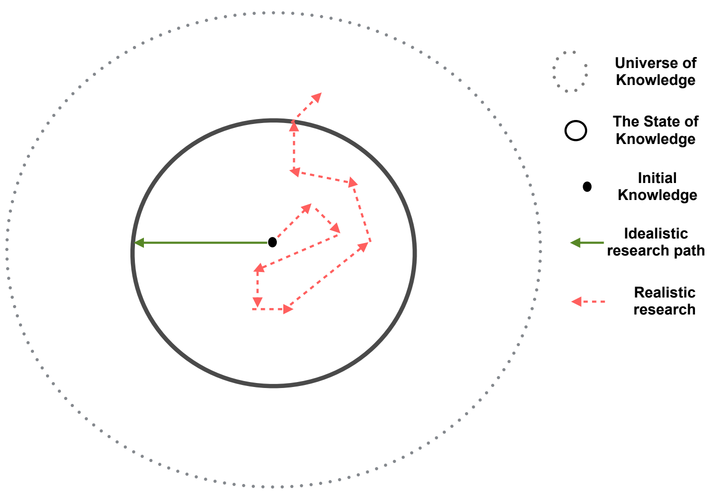

Figure 1.4.1 – Analogy to the research process

At the starting point of the research (small circle in the figure) the knowledge about the research topic, embodied energy, was very limited. Therefore, it was required an intensive literature review to achieve the actual state of knowledge (medium circle). During all the investigation process the cognitive progress was not straight (green arrow). In fact, it was combination of breakthroughs and setbacks, especially in the beginning of the research process (red arrows). When a comprehension of the theoretical concepts was achieved the cognitive progress become faster, which lead to a great comprehension within the topic of embodied energy. The main aim of the research process is “to break” at the end the circle line of the actual state of knowledge, in order to provide a new scientific contribution.

The methodology adopted during the research process consists on 3 steps and is presented in figure 1.4.2.

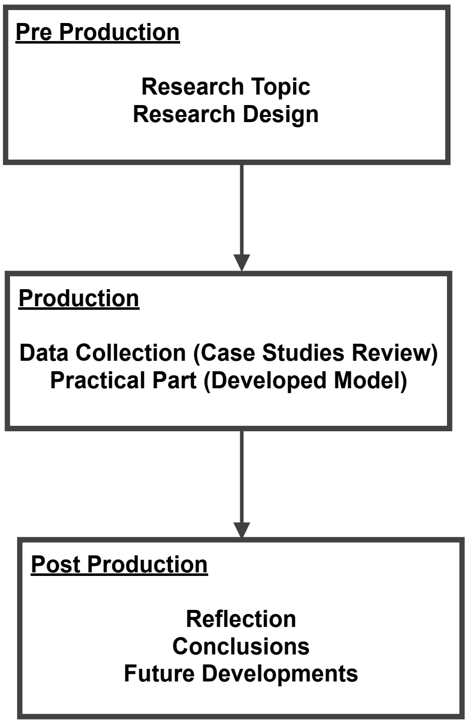

Figure 1.4.2 – Adopted Methodology

Pre Production

The research topic was established: assessing embodied energy in structural systems. Then, the research design was conducted through a systematic reading of literature review: scientific articles, dissertation papers and projects.

Production

It was collected data from case studies that assessed embodied energy in structural systems. Consequently, it was possible to identify some problems in LCA methodology, which allowed the development of the practical part of the thesis: a model that uses LCA methodology principles to assess initial embodied energy in a structural system.

Post-Production

The results were discussed, the general conclusions were drawn, the research contribution was identified and some recommendations were made for future research.

1.5 Thesis Organization

The thesis structure is presented in figure 1.5.1. As it is possible to observe it is organized through chapters. The purpose of the presented structure is to provide the reader an overview of the thesis, in order to facilitate the reading.

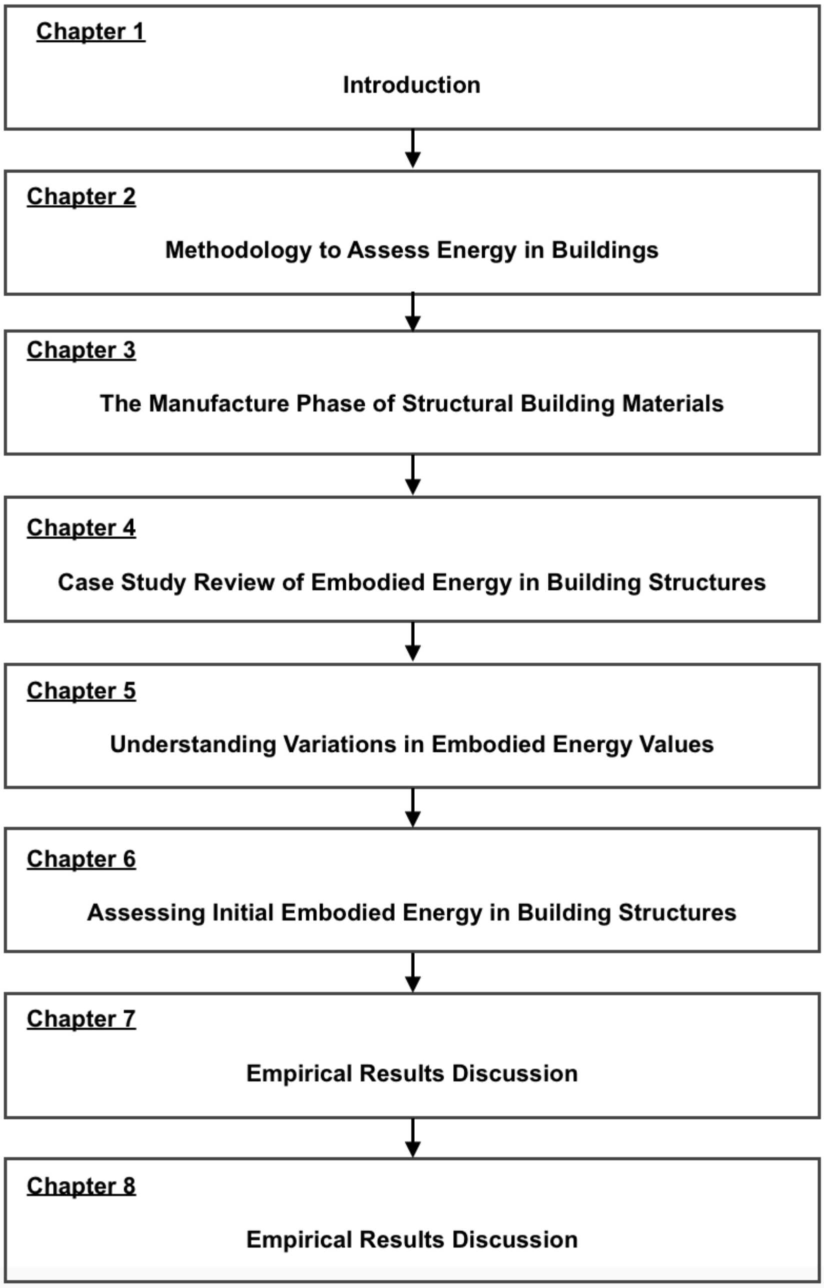

Figure 1.5.1 – Thesis Structure

Chapter 1 corresponds to the present section, where it is presented the background, motivations, scope and developed methodology of this study.

Chapter 2 presents the theoretical foundation of Life Cycle Energy in buildings and it is identified the problem statement that supports the research.

Chapter 3 is a complement of theoretical foundations to chapter 2, but focuses on the main research topic: embodied energy in structural systems.

Chapter 4 presents some relevant case studies necessary to get a better comprehension of embodied energy in structural systems.

Chapter 5 identifies the causes for discrepancies in embodied energy values for the structural systems presented in chapter 4.

Chapter 6 corresponds to the empirical part of the thesis. Initial embodied energy is assessed in a developed building structural frame. The results obtained are shown in this chapter.

Chapter 7 discusses the estimated initial embodied energy results presented in chapter 6. There is also a comparison with the embodied energy values from case studies in chapter 4. Furthermore, there is a reflection about the methodological limitations of this study.

Chapter 8 presents the scientific contribution of the thesis and presents also the main conclusions of the research. Moreover, some topics and advices for future research are suggested.

2. Methodology to Assess Energy in Buildings

This chapter introduces the broad theoretical foundations about LCA methodology, with focus on the building industry. Thanks to the great quantity of literature review read in the development of this chapter it was possible to define the problem statement of this study, that is also presented in this section.

2.1 Introduction

The assessment of sustainable construction is a key step towards achieving sustainable development in the building industry. Indeed, it is required approaches that focus on the environmental impacts and assess the sustainability of construction activities through a life cycle perspective. There are several methodologies to gather data and report information about the most significant environmental impacts on buildings, however the most used is the life cycle assessment (LCA).

2.2 Life Cycle Assessment (LCA)

The Life Cycle Assessment (LCA) is a methodology that assesses the environmental impact of a product or process, through all stages of life cycle.

The LCA methodology dates back the year of 1960, when the shortage of raw materials and larger energy consumption led to environmental concerns. However, it required more than thirty-seven years to formalize the LCA in the International Standards Organization (ISO 14000) series. In fact, the formalization process held from 1997 to 2002, due to the crescent need of a guide that evaluates the life cycle stages of the chemical, automobile, electronic and construction industries. It was a combined effort of the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC).

Over the last 30 years LCA has been used in organizations and companies to assess the

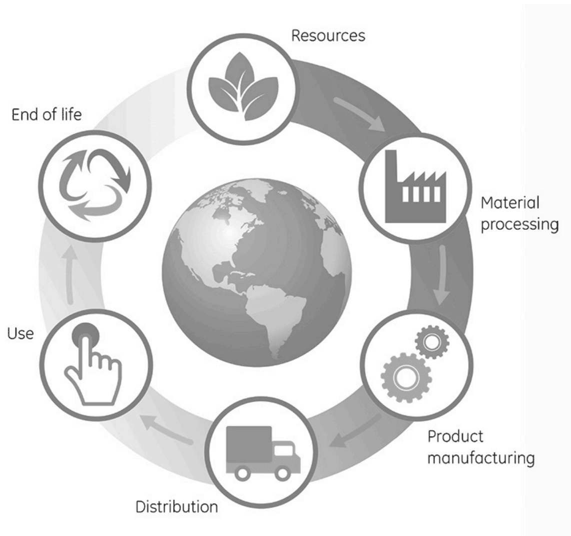

Figure 2.2.1 – Life Cycle Assessment (adapted from Ambiente, 2015)

environmental impact of products or processes both for internal and external uses.

The principles and methods of LCA are based on the ISO Environmental Management and Systems:

- ISO 14040 (ISO, 2006a): promote LCA as a technique in order to better understand and address the possible environmental impacts related with products and also services;
- ISO 14040: defines the principles and framework of life cycle assessment;
- ISO 14040 (ISO 2006b): provides a more detailed LCA requirements and guidelines.

(Lehtinen, Saarentaus, Rouhiainen, Pitts, & Azapagic, 2011)

To perform a life cycle assessment it is essential to follow four steps:

1. Goal and Scope Definition;
2. Inventory Analysis;
3. Impact Assessment;
4. Results Interpretation.

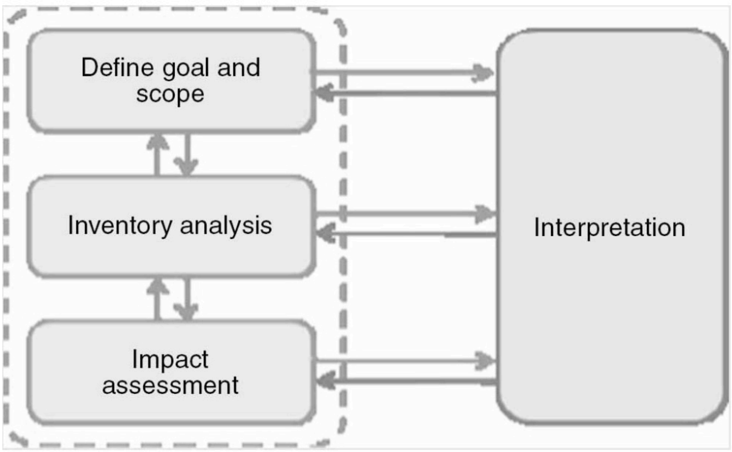

Figure 2.2.2 – Life cycle assessment framework (adapted from ISO,2006a)

Step 1: Goal and Scope Definition

In the first step it is defined the main goal of the project and the products or services to be assessed. It is also necessary to define the system boundary of the analysis to understand which materials and processes need to be considered. In this step the required level of detail is determined in order to get a better understanding of final results, and a functional unit is chosen. The definition of a functional unit is an important step, since it improves the precision of the analysis and enables a comparison between products or services.

Step 2: Inventory Analysis

The inventory analysis included the data collection and the description of all the energy inputs and outputs of a system. A Life Cycle Inventory (LCI) is a process that quantifies the raw materials, the emissions released into the atmosphere, water and solid waste originated during the life cycle of a product or process. Through the LCI it is possible to compare and evaluate products/processes.

In this step, software tools and databases are essential, since it is not possible to analyze individual materials and processes every time that a LCA analysis is performed. Thus, the software tools are connected to products and processes databases, which are crucial to perform a LCA. The software can be based on spreadsheets or more sophisticated software tools. The LCI databases account for energy use and emissions released into the atmosphere for the most common products and processes. Normally the data present in LCI databases covers the raw material extraction, transportation, manufacture process and distribution.

Step 3: Impact Assessment

In this step it is estimated the environmental impacts of the product or process. Basically, it is determined the possible contribution of the product or process to the environmental impact categories. In other words, the data collected form the LCI (step 2) is imputed to the appropriated impact category defined in the scope (step 1). The results can be obtained for different impact categories or for a single value that is be obtained by applying weights.

Step 4: Results Interpretation

The last step of an inventory analysis consists in drawing conclusions and elaborating hypothesis about the uncertainty of the results. It is important to have in mind that the results obtained are only indicative to support and recommend decisions in what concerns the materials or processes.

2.2.1 Life Cycle Assessment (LCA) Methods

There are several methods used in the Life Cycle Inventory (LCI) phase of Life Cycle

Assessment (LCA) to assess life cycle energy. Within these methods there are three that stand out:

- Process-based analysis;
- Input-Output (I-O) analysis;
- Hybrid analysis.

Process-based analysis

The process-based analysis is a methodology that documents all the processes related to the life cycle of a product, accounting for all the inputs and outputs of each process.

It is no more than the sum of all the environmental impacts of products and processes required to create a building (Moncaster & Song, 2012).

According to the system boundary established in the first step it is possible to perform different types of process-based analysis:

- **Cradle-to-Gate**: assesses the product life cycles from the extraction to the factory gate (transportation). This analysis comprises all the production processes;

- **Cradle-to-Grave**: assesses the entire life cycle of a product or process (extraction, use and disposal);

- **Cradle-to-Cradle**: consist in a specific cradle-to-cradle assessment. The disposal of the product consists in a recycling process.

- **Gate-to-Gate**: consists on a partial LCA analysis and looks only to one value process in the entire manufacture process.

Input-Output (I-O) analysis

The I-O analysis estimates the materials, energy use and the emissions related to the economic sector. This methodology considers all the inputs and outputs from the economic sector (all the industrial sectors), which allows this model to calculate impact of products or processes that would be omitted by other LCA processes.

From a building industry perspective, it can be seen as the percentage of impacts of the different economic sectors necessary to make of the building.

Hybrid analysis

The hybrid method was developed in order to overcome some problems present in the first two methodologies. The hybrid methodology combines a process-based analysis with I-O analysis. The elements of I-O analysis are replaced by more precise data than that of the process-based analysis.

From the three methods mentioned above the most used to assess the environmental impacts in the building industry is the process-based analysis.

2.2.2 Life Cycle Assessment (LCA) Tools

A life cycle assessment (LCA) tool is software that performs a life cycle inventory (LCI). Depending on the component of the building to assess, different life cycle assessment (LCA) tools or types software may be used. There are different tools to conduct a LCA and some of them have been developed for particular industries. The most popular and common LCA tools used are Gabi and SimaPro. In what concerns the tools used to perform LCA in buildings, there are three that stand out:

- Building product tools: BEEES (Building for Environmental and Economic Sustainability) software;
- Building assembly tools: Athena EcoCalculator;
- Whole Building LCA tools: Athena Impact Estimator.

2.2.3 Sophistication Level of Life Cycle Assessment (LCA)

There are three types of sophistication levels when performing a LCA:

- Detailed;
- Simplified;
- Conceptual.

Detailed LCA

The detailed LCA is the most complex and accurate type of LCA and consists on the full performance of LCA. It requires significant and extensive data collection. Despite being the most precise type of LCA it can be extremely time consuming and expensive. In extreme cases a detailed LCA may take years and have considerable expenses.

Simplified LCA

The performance of a simplified LCA consists on the application of the LCA method for a screening assessment. It is possible to evaluate a specific part of the life cycle or assess the whole life cycle. In other words, simplified LCA is a simplification of detailed LCA, yet with a significant reduction on the time used and costs. However, the accuracy of results is normally affected.

Conceptual LCA

The conceptual LCA is the simplest level of a LCA analysis. It is used to make an assessment of the environmental aspects based on a limited and usually qualitative inventory, which allows identifying products or processes that have less environmental impact. By using this type of LCA it is also possible to reduce the number of assessed parameters. For example, it is possible to evaluate only the energy consumption in the life cycle without assessing the associated green house emissions. The results obtained by performing this LCA cannot be used for public information.

The conceptual LCA is more a "life cycle thinking".

2.3 Life Cycle Energy Analysis (LCEA) in the Building Industry

To achieve sustainable construction in the building industry and minimize the energy consumption it is used a methodology known as Life Cycle Energy Analysis (LCEA). This methodology is practically the same as performing a simplified LCA. The difference is that the only parameter assessed in a LCEA is energy.

According to Dixit *et al* (2012) "buildings, building materials and components consume nearly 40 percent of global energy annually in their life cycle stages, such as production and procurement of building materials, construction, use and demolition." Hence, to achieve a better understanding of energy in buildings it is important to distinguish and quantify the energy requirements in each phase of the life cycle.

The system boundaries of a LCEA analysis include the energy use on the following phases:

1. Manufacture;
2. Use;
3. Demolition.

Manufacture Phase

The first phase of buildings energy life cycle, the manufacture phase, accounts for the energy consumption required for the following unit processes:

- Raw material extraction and assembly;
- Raw materials transportation until the factory;
- Building materials production;
- Buildings materials transportation from the factory until the construction site.

In addition, the manufacture phase also accounts for the energy consumption associated with buildings construction process, as well the activities required for buildings maintenance/renovation.

The manufacture phase corresponds to all the energy consumed for buildings production and maintenance.

Use Phase

The second phase of buildings energy life cycle is the use phase. The energy consumption for this phase includes the activities necessary to keep the indoor environment such as, heating, ventilation and hair conditioning (HVAC), and electrical appliances.

The use phase corresponds to all the energy required to maintain buildings operating.

Demolition Phase

The last phase of a building energy life cycle is the demolition phase. The unit processes associated to this phase are:

- Building demolition;
- Transportation of construction waste to landfill sites.

More and more, the demolition phase includes the recycling of construction waste.

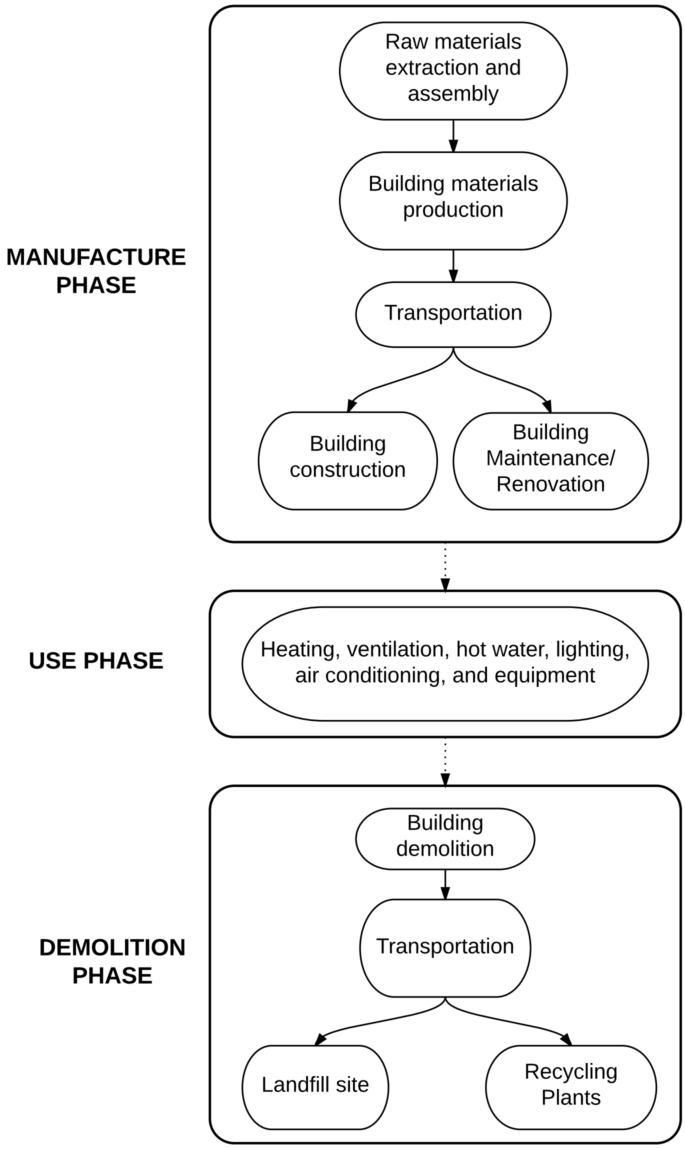

Figure 2.3.1 - Life cycle energy analysis and respective system boundaries (adapted from Ramesh *et al*, 2010)

2.3.1 Identifying Life Cycle Energy (LCE) Requirements

Embodied Energy (EE)

Embodied energy is defined as the energy required for building's material production, across the supply chain, and for building construction. In other words, it is the energy present in the building materials as well as the energy required to construct and to maintain buildings.

Embodied energy can be divided in two parcels:

1. Initial embodied energy;
2. Recurring embodied energy.

Initial embodied energy

The first parcel, initial embodied energy, corresponds to the energy required for extraction, manufacturing and transportation of building materials, and it is also the energy necessary for the entire construction process. It can be expressed as (Ramesh, Prakash, & Shukla, 2010):

$$EE_i = E_M + E_C \tag{2.1}$$

Where,

EE_i – Initial embodied energy of the building;
EE_M –Energy for building material manufacturing:
E_c – Energy used for building construction.

The **energy component for the product stage** can be calculated by the following expression (Ramesh, Prakash, & Shukla, 2010):

$$E_M = \sum m_i M_i \tag{2.2}$$

Where,

E_M – Energy required for material manufacturing;
m_i – Quantity of building material required to produce a building;
M_i – Energy content of material per unit quantity.

The **energy for building construction stage** is the sum of the energy required to transport building materials to the building yard and the energy consumption of the equipment during the construction works. It can be expressed by (Hong, Ji, Jang, & Park, 2014):

$$E_C = E_{C\_T} + E_{C\_E} \tag{2.3}$$

Where,

E_C – Energy required for building construction;
E_{C_T} – Energy required to transport building materials from the plant to the construction site;
E_{C_E} – Energy required to construction equipment.

The **energy component for the transportation** is defined as (Hong, Ji, Jang, & Park, 2014):

$$E_{C\_T} = 2 \cdot \sum_{j=1}^{m} \sum_{i=1}^{n} TD_i^j \cdot Q_i \cdot EC_i^j \tag{2.4}$$

Where,

E_{C_T} – Energy consumption from material transportation;

TD_i^j – Transportation distance of the building material *i* from the plant to the construction site using vehicle *j*;

Q_i – quantity of material *i*;

EC_i^j – Energy consumption per kilometer of vehicle *j* for a ton or cubic meter of material *i*.

The energy component for the on-site construction equipment is defined as (Hong, Ji, Jang, & Park, 2014):

$$E_{C\_E} = \sum_{k=1}^{l} \sum_{i=1}^{n} D_i^k \cdot EC_i^k \tag{2.5}$$

Where,

E_{C_E} – Energy consumption from on-site construction equipment;

D_i^k - Duration of equipment *k* usage;

EC_i^k - Energy consumption per hour of equipment *k*.

The duration of equipment usage, D_i^k, is calculated by the following formula (Hong, Ji, Jang, & Park, 2014):

$$D_i^k = Q_i / C_i^k \tag{2.6}$$

Where,

D_i^k - Duration of equipment *k* usage;

Q_i –Quantity of material *i*;

C_i^k- Capacity for work per hour of equipment *k*.

Recurring embodied energy

The second parcel, recurring embodied energy, is the energy used for maintenance and renovation activities that are related to replacement of building materials after buildings' construction. This energy can be expressed as (Ramesh, Prakash, & Shukla, 2010):

$$EE_r = \sum m_i M_i \left[\left(L_b / L_{m_i} \right) - 1 \right] \tag{2.7}$$

Where,

EE_r – Recurring embodied energy of the building;
m_i – Quantity of building material required to produce a building;
M_i – Energy content of material per unit quantity;
L_b – Life span of the building;
L_{mi} – Life span of the building material.

The **total embodied energy consumption** is the sum of initial and recurring embodied energy, and may be expressed as (Ramesh, Prakash, & Shukla, 2010):

$$EE = EE_i + EE_r \tag{2.8}$$

Where,

EE – Embodied energy of the building;
EE_i – Initial embodied energy of the building;
EE_r – Recurring embodied energy of the building.

Operational Energy (OE)

Operational energy is the energy used to maintain the comfort conditions inside buildings through processes such as heating, cooling, ventilation, lightning, hot water and appliances and equipment operation. Operational energy may be expressed as (Ramesh, Prakash, & Shukla, 2010):

$$OE = E_{OA} L_b \tag{2.9}$$

Where,

OE – Operating energy of the building;
E_{OA} – annual operating energy;
L_b – Life span of the building.

Demolition Energy (DE)

Demolition energy is defined as the energy required to demolishing and transporting the waste materials to landfill sites or recycling plants. This energy is associated to the end of the building life cycle. It can be expressed as (Ramesh, Prakash, & Shukla, 2010):

$$DE = E_D + E_T \tag{2.10}$$

Where,

DE – Demolition energy of the building;
E_D – Energy for destruction of the building;
E_T – Energy for transportation of waste material.

Life Cycle Energy (LCE)

The total energy in buildings' life cycle can be defined as the sum of the three parcels mentioned above. It is expressed as (Ramesh, Prakash, & Shukla, 2010):

$$LCE = EE + OE + DE \tag{2.11}$$

Where,

LCE – Life cycle energy of the building;
EE – Embodied energy of the building;
OE – Operating energy of the building;
DE – Demolition energy of the building.

Relating the building life cycle energy with LCEA phases it is intuitive to comprehend that embodied energy is the energy required for the manufacture phase, operating energy is the energy consumed in the use phase, and demolition energy is the energy necessary for the demolition phase.

2.3.2 Embodied Energy (EE) vs Operational Energy (OE)

Previous studies and investigation make possible to assert that operational energy is by far the largest contributor to the total energy consumption in buildings' life cycle. It can account approximately 80% of the total energy consumption in a buildings life cycle (Ramesh, Prakash, & Shukla, 2010). For that reason, during the last decades, studies have been focusing on reducing operational energy, while embodied energy and demolition energy received less attention. In fact, demolition energy can be despised, since it only represents 1% of the building's total life cycle energy (Aye, Ngo, Crawford, Gammampila, & Mendis, 2012). However embodied energy may no longer continue to be ignored. Recent research has indicated that embodied energy could reach approximately 40% of the total energy used during the lifetime of the building (Huberman & Pearlmutter, 2008).

According to many authors, there is a cause-effect relationship between operating and embodied energy, which means that a decrease in operational energy efficiency is going to lead to an increase in embodied energy. For example, a reduction in operating energy can be considerably decreased by improving the insulation of the building envelope or technical solutions. However, the embodied energy will increase, due to energy intensive materials used in the energy saving measures (Thormark, 2002) (Ramesh, Prakash, & Shukla, 2010). Sartori and Hestnes found out a lineal relation between operating and total energy, as it possible to observe in the figure 2.3.2.1.

Once significant efforts were made so far to reduce operational energy, embodied energy becomes more important to minimize in buildings overall consumption.

Although operational energy is by far the major contributor in the life cycle energy (LCE), embodied energy is increasingly prominent and cannot be overlooked.

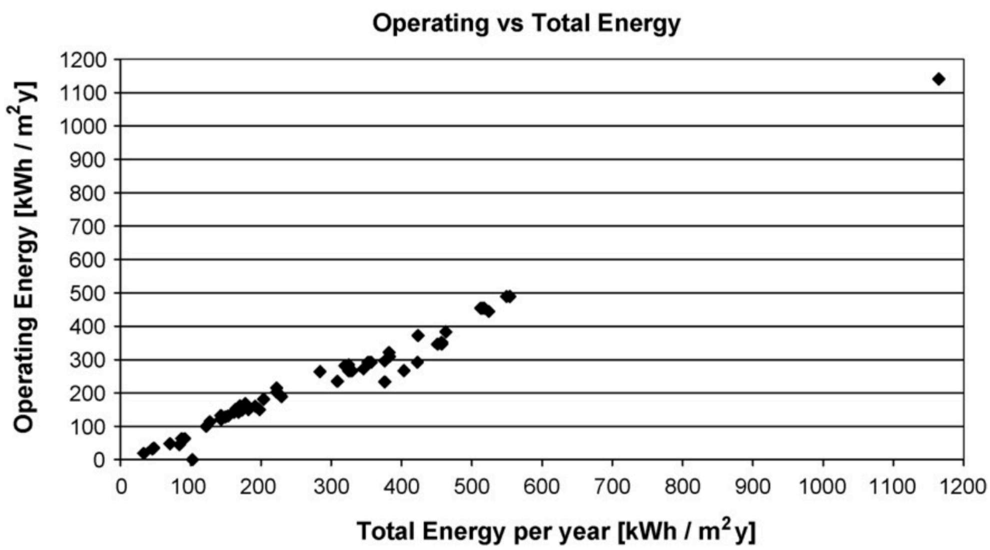

Figure 2.3.2.1 – Relation between operating and total energy (Sartori *et al,* 2007)

2.3.3 Problem Statement

The construction sector has a large potential to increase energy conservation. Applicable efforts were made in order to reduce operational energy, through use of passive and active technologies, high-performance design, construction and equipment. However, much more emphasis was placed into research of the operating energy domain, which leads to a lack of knowledge in what concerns the embodied energy topic. The reasons for that could be due to the following facts:

- Operational energy is still the largest energy consumer in LCE;
- It is easier to define operational energy, since the determination of embodied energy is complex and requires more time;
- In comparison to other goods, assess energy in a building is harder, since buildings are part of a complex and dynamic process, due to the variety of materials used in the construction that provides unique feature for each building (Scheur, Keoleian, & Peter, 2003)

As mentioned above, a crescent improvement in operational energy leads to a considerable increase in embodied energy. Therefore, the target in future search should focus on the problematic of embodied energy, in order to achieve sustainable construction.

Many studies have been placing effort on building materials energy performance, since inside this topic there is a great opportunity to reduce embodied energy. However, there is less research in what respects embodied energy in an entire building. It is difficult to transpose the embodied energy of each construction material to a real building project, since in reality buildings are much more than individual materials; they are a combination of different materials, which in turn also have different energy performance and consumption. Besides, building materials have different strengths according to the loads they are subject. According to Tommark (2002) “structural system should be a primary target for reducing the embodied energy of a building”.

Thereby, instead of studying individually the embodied energy in materials used for structural systems, it would be interesting to study the embodied energy in entire structural systems. In consequence, it was possible to define and specify the general research topic of this study: initial embodied energy in building structures. It was considered interesting to compare initial embodied energy in the same building structure, by varying the span and the material type. The building materials chosen for the building structure are concrete, steel and timber.

Figure 2.4.3.1 – Concrete structural frame (Shay Murtagh, 2015)

Figure 2.3.3.2 – Timber structural frame (Vision Development, 2015)

Figure 2.5.3.3 – Steel structural frame (Ecplaza, 2015)

3. The Manufacture Phase of Structural Building Materials

In the previous chapter was defined the research area of this study. The theoretical foundations presented so far are not enough to provide an overall comprehension of initial embodied energy in building structures. Therefore, this chapter describes (from a LCEA perspective) the manufacture phase of the three building materials used in the empirical part of this research: concrete, steel and timber. It was considered fundamental to study the energy processes involved during the fabrication, transportation, and construction of structural materials to understand embodied energy consumption in building structures.

3.1 Introduction

In life cycle assessments industrial-environmental systems are presented as a connection of processes with inputs and outputs, in a larger environment system (Srinivasan, Ingwersen, Trucco, Ries, & Campbell, 2014). In the building sector, the interaction between different materials and energy to gather and assemble building materials and the construction works constitute the building manufacture phase.

In figure 3.1.1 it is illustrated the general process and material inflows involved in the manufacture phase of a building.

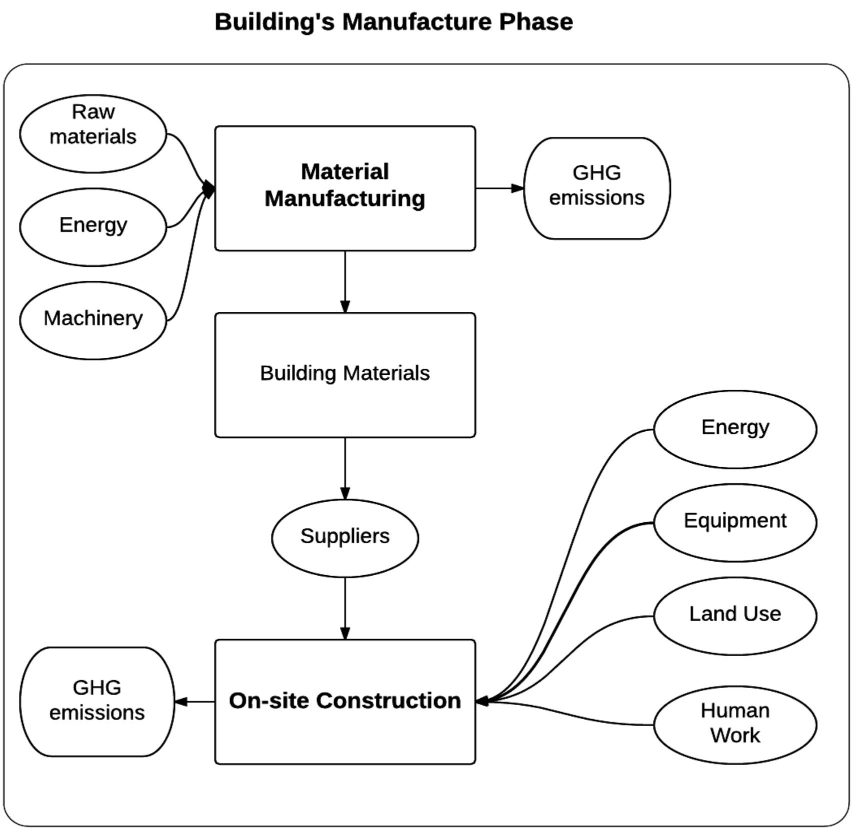

Figure 3.1.1 – The energy system diagram of building manufacture phase (adapted from Pulselli *et al*, 2007)

The manufacture phase of building starts with extraction and assembly of raw materials. After raw materials are assembled, they are transported to the respective factories, where the different raw materials are combined to produce building materials. Then, the suppliers transport the building materials to the building yard. At the construction site, besides building materials, is also required other inputs such as equipment, human work, land use, and energy, in order to produce the final building.

During buildings' manufacture phase, embodied energy is released through three different stages:

1. Product stage;
2. Construction stage;
3. Maintenance stage.

Manufacture Phase - Embodied Energy

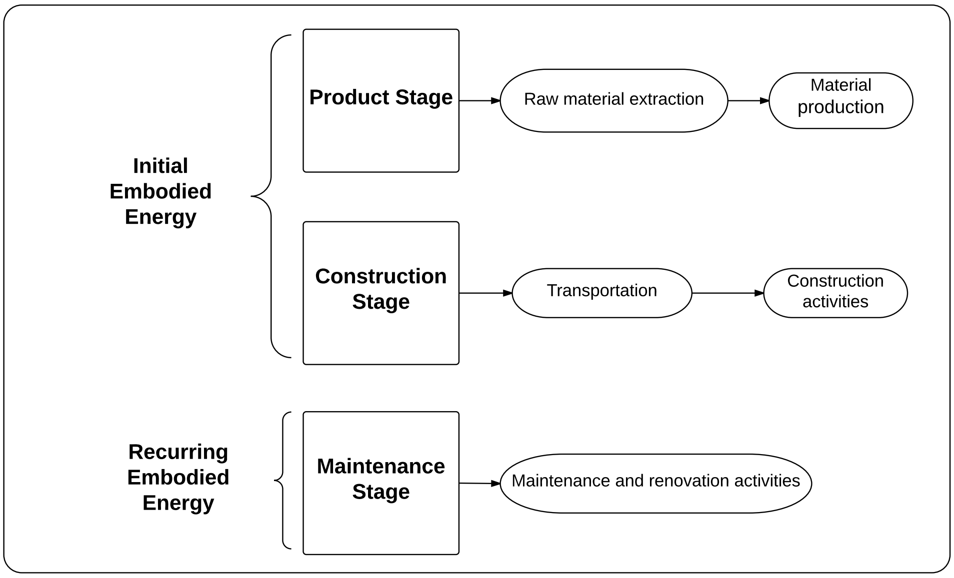

Figure 3.1.1.2 – Life cycle energy manufacture phase stages

The first two stages, product and construction stage, correspond to initial embodied energy parcel, whereas the third stage, maintenance stage, corresponds to recurring embodied energy parcel.

Embodied energy consumption in buildings is difficult to assess and quantify because it is influenced by materials type, energy sources needed for the manufacture process, and construction practices (Ramesh, Prakash, & Shukla, 2010). Although, it is known that the largest embodied energy consumption is driven by the material production and its respective transportation (Cole R. , 1999).

The importance of the manufacture phase is expected to increase in the near future, since there are already several improvements to reduce operational energy, as explained in the previous chapter. Construction materials may have the promising potential to reduce the energy consumption in buildings' life cycle, especially the structural ones. According to numerous authors, structural materials are responsible for the major consumption of embedded energy. For example, Cole *et al* (1996) research compared different building components (envelope, structure and services) and concluded that "the biggest part of the building's initial (non-renewable) embodied energy is taken from the main structure of the building and it takes up to 74% of the total initial embodied energy" (Cole & Kernana, 1996).

In order to comprehend embodied energy in structural systems it is fundamental to study the manufacture and construction processes. In this research the focus will be placed only in initial embodied energy and recurring embodied energy will not be considered in this research.

In the next sub-chapters a shortly description about concrete, steel and timber production stages and the construction stage is going to be carried out.

3.2 The Product Stage

Manufacturing is imperative for world's economy. It provides goods necessary for industries in the entire world and is also responsible for a significant part of the employment. Manufacturing activities consume a large amount of renewable and non-renewable materials and energy. In fact, the manufacture sector is the main responsible for industrial energy consumption. Every product requires energy to be produced. In consequence, more energy is consumed and more CO_2 emissions are released into atmosphere. And the building industry is no exception to this. According to Ding *et al* (2004) "the production of building components off-site accounts for 75 % of the total energy embedded in buildings". This highlights the importance to achieve sustainable manufacturing and improving energy efficiency of products and processes. And as it was mentioned above, the major embodied energy consumption is present in the product stage, namely in the material production, that accounts for the majority of total embodied energy (Scheur, Keoleian, & Peter, 2003).

Therefore, to understand why material production has the highest consumption of embodied energy it is important to look into structural materials production, in order to achieve a better comprehension of structural systems' embodied energy.

3.2.1 Concrete raw material extraction and production

This sub-chapter is mainly based on the following literature review: (PCA, 2015) and (CIMPOR, 2015).

Concrete is an artificial building material created by the combination of aggregates with binder, water, and some chemical additives in different proportions. The high compressive strength and durability, versatility, good thermal mass, long durability and low maintenance make concrete the most used world's building material (Habert, d'Espinose de Lacaillerie, & Roussel, 2011).

In order to study embodied energy in concrete it is necessary to have a comprehensive knowledge of the processes involved in its manufacture.

Aggregates

Aggregates constitute approximately 80% of a unit of concrete and provide strength to overall composite. The most common aggregates used are sand, gravel and stone. The aggregates used to produce concrete arrive into cement factories by lorries and are stored in appropriate locations, according to their typology and grain size. From the storage locations the aggregates are forwarded to the weighing system. After that, they are discharged into a batching plant, where the mixture with the other components will be performed.

Binders

Ordinary Portland Cement (OPC) is the most common binder used to produce concrete and consume approximately 50% of the embodied energy (Goggins, Keane, & Kelly, 2010), which makes the OPC manufacturing the most energy and emission intensive process in concrete production. In fact, 5% of the world's CO_2 emissions are due to the cement industry (Huntzinger & Eatmon, 2009). According to Huntzinger *et al* (2009) "the calcination process (driving off CO_2 from $CaCO_3$ to form CaO) accounts for roughly half of the CO_2 emitted, while the remaining carbon results from energy usage during the production process". For this reason, more emphasis is going to be placed into the description of cement manufacture.

Traditional Portland cement is composed essentially of calcium silicate minerals. The manufacture process begins with the extraction of limestone and the other raw materials necessary to produce cement (clay, sandstone shale that contain alumina or silica minerals). The materials extracted are transported to crushing plants, where they are crushed and mined into a fine powder, until they have acceptable size to use in cement production (0-30/0 mm). Limestone, marl, other raw materials and corrective materials are mixed and fed to a cement kiln. The ingredients are displayed into a large cement kiln at high temperature

(2000^{o}C) and all the ingredients are heated. The finely ground raw material is fed into the higher end. At the lower end is a roaring blast of flame, produced by precisely controlled burning of powdered coal, oil, alternative fuels, or gas under forced draft. As the material moves through the kiln, certain elements are driven off in the form of gases. The remaining elements unite to form a new substance called clinker (1400^{o}C). Clinker comes out of the kiln as grey balls, about the size of marbles. Then clinker is discharged red-hot from the lower end of the kiln and generally is brought down to handling temperature in various types of coolers. The heated air from the coolers is returned to the kilns. After the clinker is cooled, cement plants grind and mix it with small amounts of gypsum to regulate the setting time. The end product is very fine-grained mixture. The cement is stored in silos and is ready to be transported and used to make concrete.

In figure 3.2.1.1 it is presented a flow diagram of general cement manufacturing process, with the different inputs and emissions during the production process.

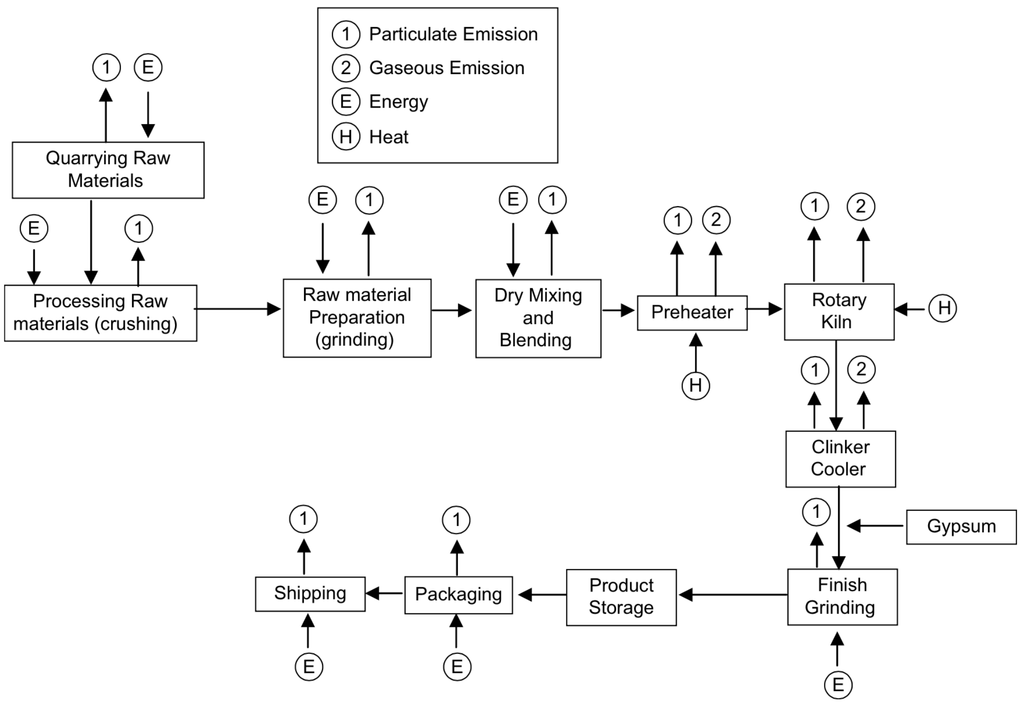

Figure 3.2.1.1 – Process flow diagram for the cement manufacturing (Huntzinger *et al*, 2009)

To manufacture concrete, the production of cement alone involves a huge consumption of raw material, energy and heat and releases an important amount of solid waste materials and gaseous emissions. The manufacturing process is complex, as it was explained above, and requires a considerable number of different materials, techniques and the use of fuel resources, such as coal, oil, natural gas and petroleum coke (Huntzinger & Eatmon, 2009).

Water

The quality of water used in concrete production is essential. The use of impure water during the setting can affect the strength of concrete and cause corrosion in case of reinforcement.

During the hydration process, the combination of water with cement forms a binder. Through this process chemical reactions occur and, as the reactions proceed, there is a bonding with sand and gravel particles, which forms a solid mass.

The impact of water is low in what concerns CO_2 emissions during concrete manufacturing (Goggins, Keane, & Kelly, 2010).

Admixtures

Admixtures are chemicals added to concrete to provide it certain characteristics. Successful use of admixtures depends on the use of appropriate methods of batching and concreting. Certain admixtures, such as pigments, expansive agents, and pumping aids are used in very small amounts during mixing.

The effectiveness of an admixture depends on several factors including: type and amount of cement, water content, mixing time, slump, and temperatures of the concrete and air.

The energy consumption of admixtures is difficult to quantify, because of the nature of their production. Since they account for such a small part of a unit of concrete their contribution can be despised.

3.2.2 Steel raw material extraction and production

This sub-chapter is mainly based on the following literature review: (TATA, 2015)

Steel is the most important metal in modern society, with an annual global production of over 700 million tonnes. The low price and high strength make steel a material used in structures of buildings. The iron and steel industries are very energy-intensive; the production of steel releases a significant amount of greenhouse gas (GHG) emissions and consumes large quantities of raw materials (Burchart-Korol, 2013) (Spengler, Geldermann, Hahre, Sieverdinbeck, & Rentz, 1998).

Steel is composed by iron and carbon and other alloying elements may also be present in varying proportions. The properties of steel are dependent on the proportion of alloying elements and they also depend on the heat treatment of the metal.

Since hot rolled steel is much more used in construction than cold rolled steel, only the manufacturing of hot rolled steel is going to be described.

Iron making

The raw materials necessary to produce iron, sinter, iron ore and coke are extracted and placed into the blast furnace, where they are fled into the top of the furnace with limestone. The temperature inside the furnace rises around 2200ºC to reduce and melt the iron ore and the sinter. Then, is formed a pool of molten iron designated for cast iron. Although, some carbon and some impurities remain so they must be reduced by refinement, before the material becomes steel. The amount of carbon content of steel is crucial to provide strength to steel.

Refining iron into steel

Basic oxygen steelmaking (BOS) is the main bulk production process to transform iron to steel. The BOS process starts with the deposit of the hot metal (that has been previously pre-treated to remove undesirable elements) into the vessel. After that, a water-cooled lance is lowered into the vessel and oxygen is blown through the surface of the hot metal. At this stage the steel obtained is designated by crude steel.

Continuing with the refining process, the crude steel is teemed through a gas tight refractory tube into the tundish. Tundish it is a reservoir that allows the steel to flow at a controlled rate through further gas tight refractory tubes and into a series of water-cooled copper moulds. With only the outer shell solidified, the steel is drawn from the bottom of the mold through a curved arrangement of support rolls and water sprays.

Shaping steel

To shape steel is used hot rolling technique. Steel is squeezed between rolls until the final thickness and shape are achieved. The rolls exert forces of more than ten millions of newtons. The rolled steel is then cooled and prepared for further processing or is then ready to be dispatched.

The hot rolled steel life cycle is represented in figure 3.2.2.1.

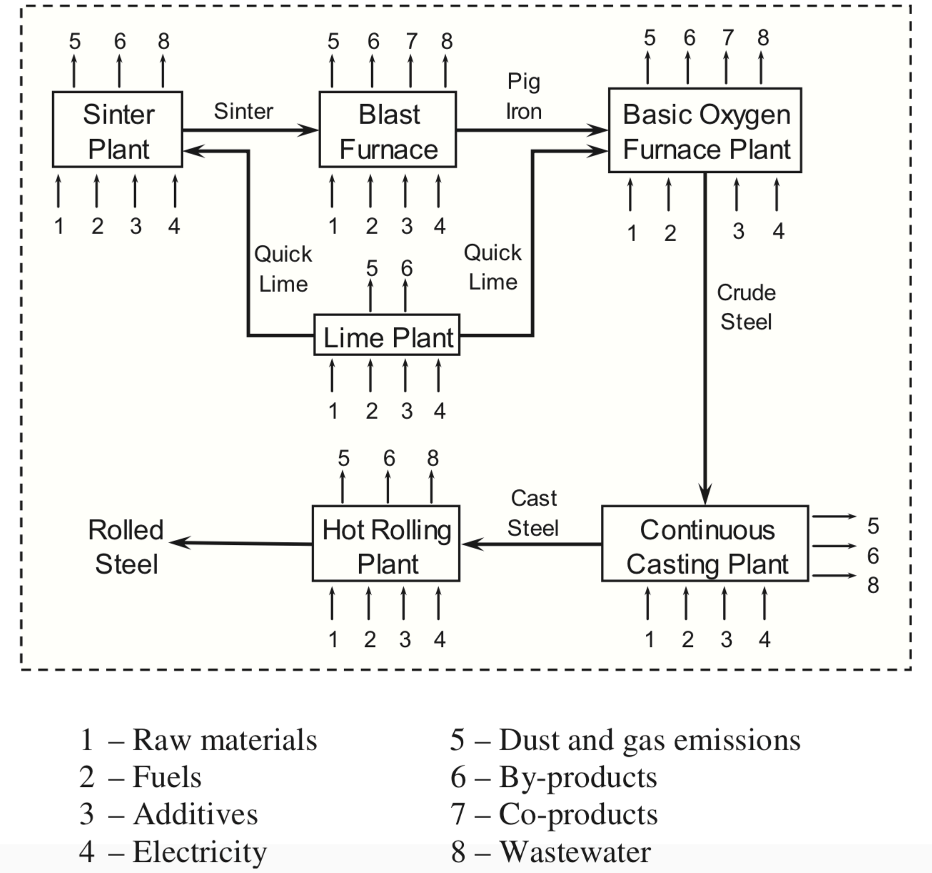

Figure 3.2.2.1 – Process flow diagram for the steel manufacturing (Burchart-Korol, 2013)

The manufacture phase of steel that consumes more energy is the blast furnace. About 69% of energy is consumed due to the chemical reactions between coke and iron oxide (Michaelis, Jackson, & Clift, 1997).

3.2.3 Timber raw material extraction and production

Timber it is produce by natural processes in the forest ecosystems and it is one of the most sustainable resources available. It is an organic material, a natural composite of cellulose fibres, and has specific physical and mechanical properties in the longitudinal, radial and tangential directions, according to the type of tree. It has been used for years as a primary source of material and energy in human society and it is the oldest material used in the construction sector. Due to a high strength ratio, timber can transfer tension and compression forces. Is used for a range of structural forms such as beams, columns, trusses and girders. It is also used in building systems as deck members and in formwork of concrete. Timber structures are resistant, and the proof of that are the historical buildings spread all over the world (Porteous & Kermani, 2007).

Wood materials have the great potential to reduce GHG, since they can storage carbon from atmosphere, and create a major role in the sustainable development of the building industry (Sathre, 2014).

In general, the life cycle of timber building materials begins with the growth of trees, followed by the harvest and processing of woody biomass, the manufacture and assembly of wood based products, the utilization and maintenance of buildings, ending with the disassembly and management (Sathre, 2014).

However, depending on the product purpose the manufacture process differs. Since it is intended to assess the structural materials, the focus of this research is going to be on the manufacture process of glued-laminated timber, also known as glulam. Glued-laminated timber is one of the oldest engineered wood products. It is a structural material prepared from selected pieces of wood, and can have a straight or curve form. It may be used as beams and columns in residential and commercial dwellings, such as church arches, warehouse roof beams and as purlin. It is produced from small sections of timber boards, designated by laminates, which are glued together with the grain of all layers parallel to the longitudinal axis. The lumber used in the glued-laminated timber production is produced from the softwood process, and it is a special lumber used in the construction of laminated timber and it is known as lamstock (Puettmann, Oneil, & Johnson, 2013).

The manufacture of glulam starts with extraction of wood in the forest, through forestry operations, that include site preparation, planting, fertilization and final harvest. During this process, different levels of energy are used to extract wood. After the extraction the logs are carried to lumber mills by lories.

The manufacturing process of glued laminated timber can be divided in four parts:

1. Drying and grading lumber;
2. End jointing the lumber into longer laminations;
3. Face bonding the lamination;
4. Finishing and fabrication.

When the lumber (lamstock) arrives to the glulam facilities it is kiln-dried until it raises maximum moisture content of 16 %. Then, it is finger jointed with longer laminations in order to obtain glulam beams beyond the commonly available for lumber. The following step consists of bonding the laminations with resin. The laminations are assembled into required layup and curing. Finally the beams are removed from the presses and the wide faces are planed to remove adhesive and should also be sanded. According to the final use, final cutes are made, holes are drilled, connectors are added and a finish is applied. (Puettmann, Oneil, & Johnson, 2013).

In the figure 3.2.3.1 it is possible to observe the different inputs and outputs necessary to produce the glued-laminated timber.

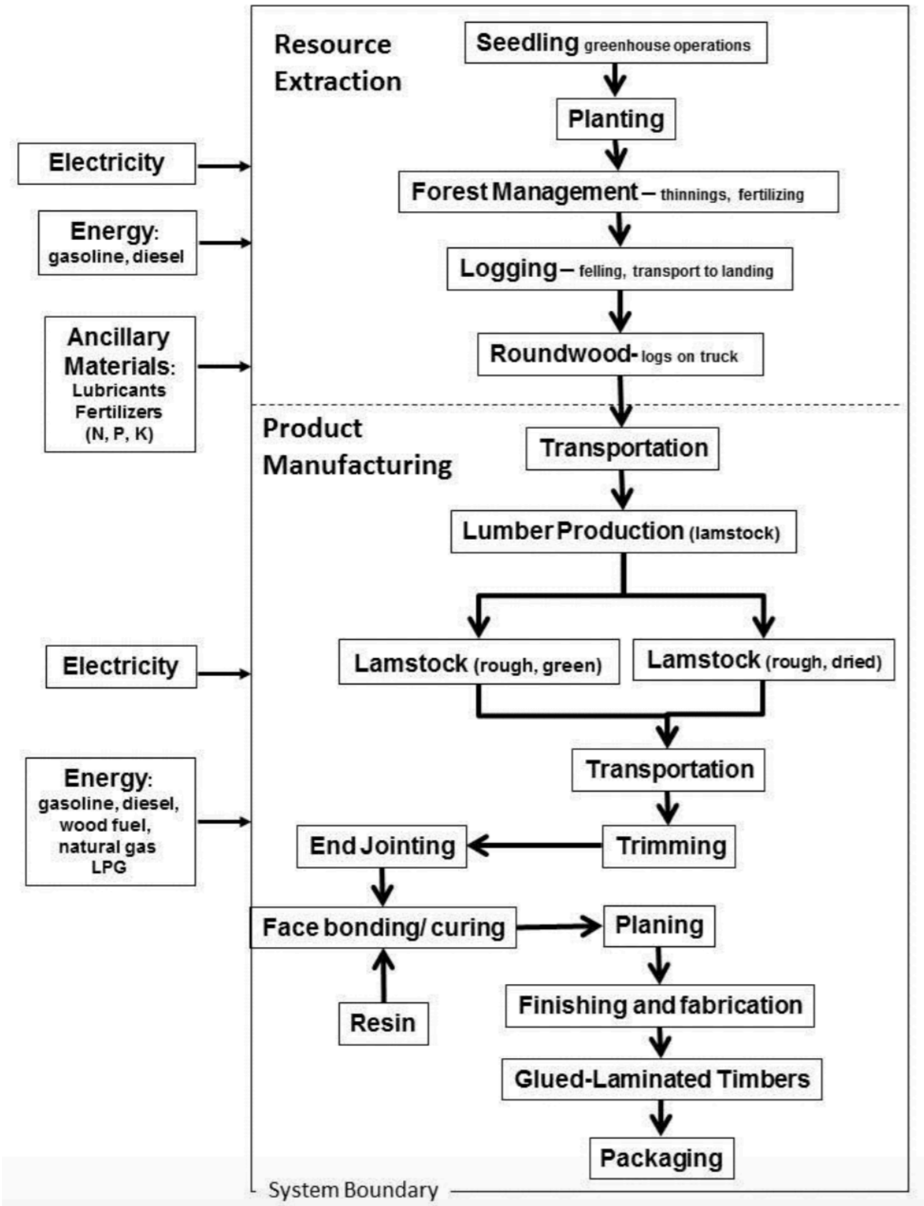

Figure 3.2.3.1 – Process flow diagram for the glued laminated timber manufacture process (Puettman *et al*, 2013)

During the manufacturing phase of glulam, the quantity of GHG emissions released into the atmosphere is very low.

3.3 The Construction Stage

On-site construction activities are responsible for significant environmental impacts, such as greenhouse emissions, land use and solid and liquid waste, and also for energy consumption.

It is estimated that in Europe and in the United States energy consumption in the construction stage can reach between 7 a 10% of the total embodied energy (Cole R. , 1999). In fact, embodied energy related with construction only account for a minor part of the total life cycle energy demand (Gustavsson, Joelsson, & Sathre, 2010), and few studies have quantified the energy consumption in the construction stage (Hong, Ji, Jang, & Park, 2014). However, to make a correct initial embodied energy analysis, it is fundamental to quantify embodied energy consumption for construction activities.

The construction process and efficiency of the equipment's adopted can have significant impacts in the construction costs and construction delays (Cole R. , 2000). So it is fundamental to choose good construction practices in the design phase of buildings, which can also be achieved by assessing the embodied energy in the construction stage.

The construction process for structural assemblies cover the activities related with the erection of the building structural system. The construction process can be different from structural system to structural system, but in general the main processes and on-site activities are common to the three structural materials used in this research: concrete, steel and timber.

The energy consumption in the construction stage is directly related to:

1. Transportation of building materials;
2. On-site construction equipment.

3.3.1 Transportation

The energy consumption during building materials transportation is related to:

- The distance travelled from the distribution centres to the building yard;
- Fuel type and efficiency;
- Vehicle type and size;
- Weight of vehicle and building material to transport.

On the one hand, the type and size of vehicle depend on the type and quantity of building materials to transport. On the other hand, according to the vehicle type different will be used, so the energy consumption will vary from case to case (Moussavi & Akbarnezhad, 2015). For these reasons it is difficult to estimate the energy consumption for transportation. Nevertheless, according with the type of material to transport to the construction site, it is possible to predict the type of vehicle to use and the distance to travel.

Concrete transportation normally requires diesel powered mixer lorries, in order to maintain the concrete fluid until the arrival to the construction site. It seems quite obvious that the transportation distances cannot be too long, since concrete should be removed from the mixer lorry after two hours of leaving the central (Cole R. , 1999).

In most cases, steel assemblies are shipped from the factories to the construction site. The transportation is usually made by flat deck semi-trailer lorries or by flat-bed lorries (Cole R. , 1999).

Large quantities of timber are transported from the suppliers to the construction site by diesel flat-bed lorries or by semi-trailer lorries with flat deck trailers (Cole R. , 1999).

Figure 3.4.1.1 – Concrete mixer lorry (InvestConsult, 2015)

Figure 3.3.1.2 – Flat deck semi-trailer lorry (Alibaba.com, 2015)

3.3.2 On-site construction equipment

The construction works are not static. As construction works progress, different construction processes and equipment are required. The energy consumption varies from equipment to equipment, and also depends on the construction method to use and physical and geotechnical site conditions (Hong, Ji, Jang, & Park, 2014).

The construction stage involves the use of different equipment. To construct buildings structural assemblies it is normally required powerful equipment such as saws, compressors, drills, and welders (Cole R. , 1999). The type and duration of equipment in the construction site depends on the project. During the construction phase of building structures also depends on the structural material to use and the complexity of the building structure. For these reasons, it is also difficult to assess embodied energy of the construction works.

4. Case Study Review of Embodied Energy in Building Structures

In order to understand what has been done so far inside the thematic of embodied energy in structural systems it was considered necessary to find in literature review case studies that the research topic was also the same as the main research topic of the presented research: embodied energy in structural systems. The case studies review was a really helpful and important step for this research, since with that it was possible to identify problems and weaknesses in embodied energy data and improving a different approach to assess embodied energy in structural systems.

4.1 Introduction

More and more it is fundamental to achieve sustainable construction and energy efficiency in the building industry. An essential requirement for new engineering projects is to make buildings with the maximum lifespan and the minimum resources consumption as possible, taking into account the economical and social demands (Griffin, Reed, & Hsu, 2010). To achieve the sustainability goal, engineers must define structural elements from a sustainable perspective, reducing the amount of energy and natural resources consumption. And as mentioned in the previous chapters, one important step to reduce embodied energy can be reached in the design phase of a structural system, since the buildings structure can be one of the major contributors for embodied energy consumption. Suzuki *et al* (1998) analysed life cycle energy consumption and they conclude that the structural system can consume an average of 4,1 GJ/m^2 of embodied energy (6% of the total energy consumed in the entire life cycle) and emit to the atmosphere an average of 0,38 ton/m^2 of CO_2 emissions.

In general, embodied energy is a good indicator of the overall environmental impact of building materials, assemblies or systems. Building materials may have the potential to increase sustainable properties of structural systems, although this does not mean that a structural system itself will reach the most sustainable configuration (Danatzko, 2010). For this reason it is crucial to quantify embodied energy in structural systems, and not only in building materials.

It is important to identify the consumption on each embodied energy component in order to really comprehend the whole embodied energy consumption. In fact, understanding individual components will provide a better knowledge and will allow to act more efficiently to reduce the consumption on each parcel.

The purpose of this chapter is to analyse embodied energy in building structures through existing literature and identify and compare the consumption on each component. As a matter of fact, comparing energy consumption in different buildings is quite popular. Authors like Buchanan *et al* (1993), Ramesh *et al* (2010) and Dixit *et al* (2010) used this approach to investigate the amount of energy in buildings life cycle to develop a consistent and comparable embedded energy database.

In the following sub-chapter it is going to be presented some previous research of embodied energy in building structures, namely in concrete, steel and timber.

All the data was treated in order that the results were presented in the same unit: m^2.

4.2 Case Studies

Case Study 1

In this case study is presented a resume of the research by Cole *et al* (1996) for embodied energy in an office building located in the United Kingdom with three-storey with an area of 4620 m^2 for different building structural systems: wood, steel and concrete. The authors assessed the embodied energy for the product stage using the Life cycle assessment tool Athena software.

The results obtained are presented in table 4.2.1.

Table 4.2.1 – Case study 1 embodied energy values (adapted from Cole *et a*l, 1996)

Case Study 1	Product Stage EE (GJ/m^2)		
Office building	**Steel**	**Concrete**	**Wood**
Structure	1,22	0,93	0,67
Total	4,86	4,52	4,26

As it is possible to observe from the table, the structure that consumes more initial embodied energy is the one made of steel, 1,22 GJ/m^2, followed by concrete, 0,93 GJ/m^2, and then wood, 0,67 GJ/m^2. The energy consumed by the steel structure corresponds to 25,2% of the total embodied energy needed to produce the office building. For the concrete structure the energy consumption is slightly lower, 20,6% of the total embodied energy, and the wood structure is the one with the smallest consumption, 15,7% of the total embodied energy.

Case Study 2

In this case study is presented the research of Xing *et al* (2007). The authors studied the life cycle energy consumption in two typical office buildings in Shanghai, China. One of the building structures is made of steel and the other one is made of concrete. The first building has an area of 46,240 m^2, while the second one has a smaller area, 34,620 m^2. In this research the authors investigate buildings life cycle embodied energy and operating energy, but since the goal of this thesis is to assess embodied energy in structural systems only the embodied energy data will be taken in consideration.

In this case study embodied energy was estimated for building materials manufacture. It is not one hundred per cent clear if the embodied energy for remaining parcels of the product stage (raw materials extraction and transportation to the industry) was assessed. It was used Building Energy System Life Cycle Inventory (BESLCI) to estimate embodied energy.

The values obtained are presented in table 4.2.2.

Table 4.2.2 – Case study 2 embodied energy values (adapted from Xing *et al*, 2007)

Case Study 2	EE for building materials manufacture
Office Building	(GJ/m^2)
Steel	2,9
Concrete	3,9

It is observed that concrete structure consumes more 1,0 GJ/m^2 of embodied energy during the material manufacture than the steel structure.

Case Study 3

In case study 3 is presented two cases studies, case study 3.1 and 3.2, of Buchanan *et al* (1993) research, conducted at University of Canterbury, in New Zealand.

The first case, 3.1, consists in the comparison of embodied energy consumption in a five-storey reinforced concrete office building with alternative designs of structural steel and glued laminated timber. The building area is not mentioned.

The results obtained show that the total embodied energy consumption is superior in the steel structure, followed by the concrete structure, and then by the wood structure: 4,4 GJ/m^2, 3,4 GJ/m^2, and 1,5 GJ/m^2, respectively.

Table 4.2.3 – Case study 3.1 embodied energy values (adapted from Buchanan *et al*, 1993)

Case Study 3.1 Office Building	Product Stage EE (GJ/m^2)
Steel	
Structure	4,4
Total	6,6
Concrete	
Structure	3,4
Total	5,6
Wood	
Structure	1,5
Total	3,7

In the second case, 3.2, the authors compared the embodied energy consumption in a typical industrial building with two different structural designs: steel and glued laminated timber. Also in this case study the construction area is not mentioned. The results showed, once again, that the embodied energy consumption is larger in the steel structure. In fact, the embodied energy for steel is 1,6 GJ/m^2 while the wood only consume 0,2 GJ/m^2.

Table 4.2.4 – Case study 3.2 embodied energy values (adapted from Buchanan *et al*, 1993)

Case Study 3.2 Industrial Building	Product Stage EE (GJ/m^2)
Steel	
Structural	1,6
Total	3,2
Wood	
Structural	0,2
Total	1,8

In these two case studies is not detailed clearly what stages and respective stages are being assessed. Although, it is believed from case study interpretation that embodied energy for the product stage was assessed, but it is not possible to conclude if also embodied energy for the construction stage was estimated. In both case studies it was used energy coefficients from Baird and Chan database to estimate the energy requirements for building materials.

Case Study 4

This case study was conduct by Griffin *et a*l (2013) in Portland, United States. The authors analyzed embodied energy in three parking garages: one using precast concrete spans, the other using cellular steel spans, and other one using post tensioned concrete spans.

The parameters for each parking garage used in this research are presented in table 4.2.5.

Table 4.2.5 – Case study 4 parameters (adapted from Griffin *et al*, 2013)

Parking Garage (Primary Span)	Storey	Area (m^2)	Span (m)
Precast Concrete	3	12,3	17,1
Cellular Steel	4	13,3	17,8
Post-Tension Concrete	4	29,1	18,5

The embodied energy for the product stage of each parking garage was calculated according to concrete's strength and type of steel. The database used to obtain the embodied energy coefficients was the Inventory of Carbon & Energy (ICE).

The values for embodied energy consumption are presented in table 4.2.6. Comparing them it is possible to observe that the steel structure consumes almost twice the embodied energy of the concrete structures.

Table 4.2.6 - Case study 4 embodied energy values (adapted from Griffin *et al*, 2013)

Case Study 4 Parking Garage	Product Stage EE (GJ/m^2)
Precast Concrete	1,3
Cellular Steel	2,3
Post-Tension Concrete	1,5

Case Study 5

In case study 5 is presented the research lead by Kofoworola *et al* (2009). It was analyzed the life cycle of a typical office building with 60,000 m^2 in Thailand, through the use of LCEA methodology. Embodied energy consumption for the product stage was study. It was used an Economic Input-Output Life Cycle Assessment (EIO-LCA) spreadsheet model developed by the authors to estimate embodied energy.

As per table 4.2.7, results show that the embodied energy consumed for all material production is 6,8 GJ/m^2. Regarding the structural materials, which are the main focus of this study it is possible to conclude that steel is the system that consumes more embodied energy in the material production, 2,88 GJ/m^2, followed by concrete, 2,41 GJ/m^2, and finally wood, 0,03 GJ/m^2. It is interesting to notice that steel consumption in the manufacturing phase is almost 50% of the total of material production for the office building.

Table 4.2.7 – Case study 5 embodied energy values (Kofoworola *et al*, 2009)

Case Study 5 Office building	Product Stage EE (GJ/m^2)
Steel	2,88
Concrete	2,41
Wood	0,03
Total	6,80

Case Study 6

In this case study is presented Aye *et al* (2012) research, which main goal was to assess and compare the life cycle energy performance between different constructions in Australia: pre fabricated modular steel and timber structures and a conventional concrete structure. The building model is an eight-storey multi-residential building with an area of 3943m^2 and a total of 63 apartments, 58 single-storey and 5 double-storey apartments. Once more, only the data concerning embodied energy will be considered. Embodied energy was evaluated for each building element. It was used an I-O based hybrid analysis and the data required for the inventory analysis was taken from the Australia National Accounts.

The results obtained for columns and beams are presented in table 4.2.8.

Table 4.2.8 – Case study 6 embodied energy values (Aye *et al*, 2012)

Case Study 6 Multi-Residential Building	Product Stage EE (GJ/m^2)
Structural Steel	
Columns and beams	3,4
Total	14,4
Concrete	
Columns and beams	0,5
Total	9,6
Timber (softwood)	
Columns and beams	3,5
Total	10,5

The authors calculated embodied energy for the product stage, but again it is not one hundred per cent clear if it was also assessed the embodied energy for the maintenance stage.

Comparing the results obtained it is possible to observe that the structural elements with major energy consumption are the ones made of steel, followed by wood and then concrete. It is important to highlight the energy consumption in concrete columns and beams: the energy consumption is lower, only 0,5 GJ/m^2.

Case Study 7

In case study 7 is presented Cole (1999) research, conducted in Canada. The author investigated embodied energy associated with on-site construction of three structural systems: concrete, steel, and glued laminated timber. The embodied energy account for the on-site construction works and included the energy consumption of the equipment and the transportation of workers, materials and equipment to the construction site. In order to calculate embodied energy for the construction stage transportation distances, fuel type, vehicles and equipment have to be assumed.

The results obtained are presented in table 4.2.9.

Table 4.2.9 – Case study 7 embodied energy values (adapted from Cole *et al*, 1999)

Case Study 7 On-site construction	Construction Stage EE (GJ/m^2)
Steel	0,005
Concrete	0,075
Glued laminated timber	0,012

As per table above, the results show that the construction activities for the concrete structural assembly are the ones that consume more embodied energy, 0,075 GJ/m^2, followed by glued laminated timer, with a consumption of 0,012 GJ/m^2, and then steel assemblies, which construction works consume only 0,005 GJ/m^2 of embodied energy.

4.3 Case studies discussion

The presented case studies have the purpose to understand the relation between embodied energy and structural systems. Structural systems of different building types were evaluated. They had in common three structural materials: steel, concrete and timber.

In table 4.3.1 it is summarized the type of embodied energy assessed, as well the building type, the country where the research took place, and LCA tool used.

Table 4.3.1 – Case studies inclusion or exclusion of manufacture phase life cycle stages

Case Study	Building Type	Country	LCA Tool/ Database	Initial EE					Recurring EE
				Product Stage			Construction Stage		Maintenance Stage
				Raw Materials Extraction	Transport to Production Centre	Building Materials Manufacture	Transport to Construction Site	Building Construction	Renovation/ Maintenance
1	Office	UK	Athena software	Yes	Yes	Yes	No	No	Yes
2	Office	China	BESLCI software	Yes	Yes	Yes	No	No	Not specified
3.1	Office	New Zealand	Baird and Chan database	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified
3.2	Industrial			Not specified	Not specified	Not specified	Not specified	Not specified	Not specified
4	Parking Garage	USA	ICE database	Yes	Yes	Yes	No	No	No
5	Office	Thailand	EIO-LCA software	Yes	Yes	Yes	No	No	No
6	Multi-Residential	Australia	I-O analysis/ Australian National Account database	Yes	Yes	Yes	No	No	Not specified
7	Construction works	Canada	–	No	No	No	Yes	Yes	No

As it is possible to observe per table 4.3.1, all case studies used different software tools and database to assess the embodied energy consumption in the building structures.

Also the major part of literature review assessed the embodied energy for the product stage, while only one case study (case study 7) assessed construction stage embodied energy. There are also some cases studies where is not possible to understand clearly which were the components assessed, due to shortage information detail found on literature review.

Therefore, in order to drawn some conclusions from the presented case studies only data concerning the ones with the specification of assessed components were considered. The values from case study 3 (case study 3.1 and 3.2) were not take into consideration, since the stages considered are not clearly specified.

First, it will be presented the results concerning the product stage, followed by the results from construction stage. Then it will be carrying out a discussion of possible reasons for the values obtained in case studies.

The values of embedded energy obtained for the product stage are presented in the graphic 4.3.1.

From the bar chart bellow it is possible to drawn some evident conclusions:

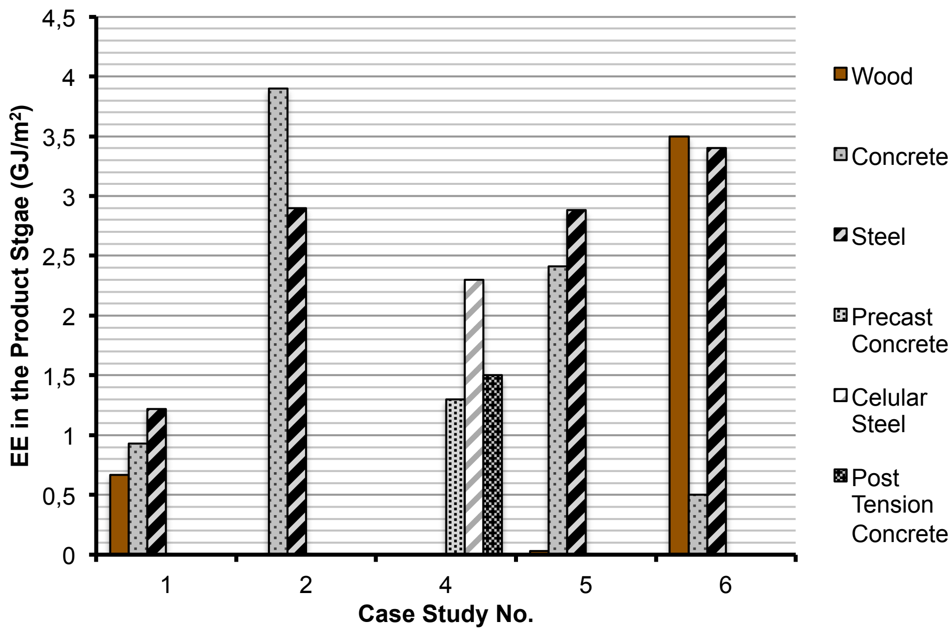

Figure 4.3.1 – Case studies product stage embodied energy consumption

- The biggest consumption of embedded energy correspond to the concrete structure frame, 3,9 GJ/m^2, in case study 2;
- The smaller consumption correspond to the wood structure, 0,03 GJ/m^2, from case study 5;
- In the majority of the case studies the building structural frame with more energy consumption correspond to steel;
- The minimum and maximum range of values for embodied energy consumption in the steel structure vary from 1,22 to 3,3 GJ/m^2;
- The minimum and maximum range of values for embodied energy consumption in the concrete structure vary from 0,5 to 3,9 GJ/m^2;
- The minimum and maximum range of values for embodied energy consumption in the wood structure vary from 0,03 to 3,5 GJ/m^2;
- Only in case study 2 was found that concrete's embodied energy consumption is bigger than steel's;
- Only in case study 6 the consumption in the timber structure was higher than the other two structures.

In what concerns the embodied energy consumption for the construction stage only one case study that assessed energy consumption for the structural systems construction was found in literature review. Nevertheless, it is still important to take a closer look at the values obtained, even without other case studies to compare results.

In graphic 4.3.2 it is present the values of embodied energy consumption from case study 7. From there it is possible to understand that:

- The concrete structure is the one with the major value of embodied energy, followed by the timber structure and then the steel structure;
- The embodied energy consumption values for the construction stage are much more smaller in comparison with the embodied energy values for the product stage presented above.

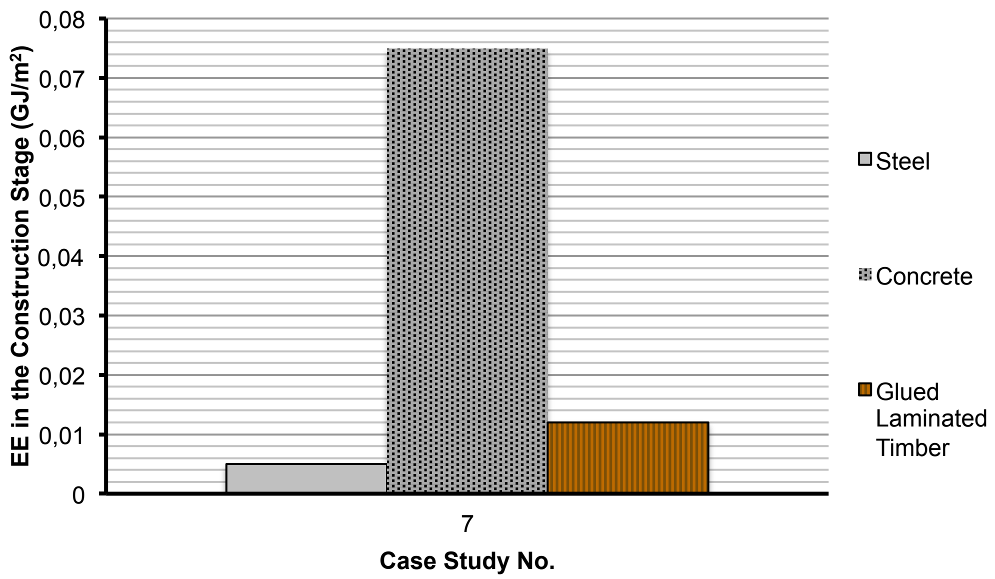

Figure 4.3.2 – Case study construction stage embodied energy consumption

From the two bar charts elaborated it is easy to understand that the component of LCEA manufacture phase responsible for the major part of embodied energy consumption corresponds to the product stage. And accord to what was described and explained in the previous chapter it makes sense. During the manufacture process of some building materials, the energy consumption intensity and the high temperatures (especially in the cement manufacture) lead to an increasing of embodied energy values. Besides that, the considerable mass of some materials like steel, cement and sand can contribute to increase embodied energy in steel and concrete structural systems (Cabeza, Rincón, Vilariño, Pérez, & Castell, 2014). In what concerns timber structures, it is expected the consumption to be lower, because wood is an organic material and during the manufacture process the carbon withheld is larger than the carbon released. So, probably in timber structures is required less embodied energy in the entire process of building materials manufacture. However, exactly the opposite of this statement happen in case study 6. In fact, the timber structure was the one with more energy consumption during the product stage.

Although only one case study assessed the embodied energy in construction stage, due to the insufficient data source, the values obtained are really small in comparison with the values of energy consumed in the product stage. So, with this it is possible to assert that the energy consumption in the construction stage has almost a negligible impact in the manufacture phase. In fact, other author research claims that the portion of embodied energy for the transportation and construction accounts only about 6% of the total embodied energy of buildings (Scheur, Keoleian, & Peter, 2003).

Finally, from data interpretation, another interesting conclusion can be drawn: it is very likely that the total amount of embodied energy is straightly related with the specific structure and the structural dimensions, once the values obtained differ considerably between each other.

Even though there is a big chance that these hypotheses are true, they cannot be proved by only comparing the results of the presented case studies. The analysis of different literature does not provide a realistic approach for the following reasons:

- Only seven cases studies were compared, which is a very small sample to take viable conclusions;
- From the seven case studies it was only possible to compare the data of five, since two of them did not indicate clearly which parcels of embodied energy were being assessed;
- It is difficult to compare and generalize embodied energy in structural systems, especially when buildings have different areas and quantity of building materials;
- Different spans and column sizes can make difference on the performance of embodied energy consumption;
- The energy efficiency of manufacture processes vary from country to country, and even from factory to factory, so the database used can lead to different result;
- Also the software tool used to perform a LCA can conduct to different results;
- The life cycle energy of different building types is distinctive. The life cycle energy of an office building is different of the energy life cycle of residential building;
- The construction processes adopted and the energy efficiency of equipment used to construct the framed building skeleton differs from construction site to construction site.

Another problem found in the previous research was the fact that almost cases studies calculated the embodied energy for product stage and only one assessed the energy for the constructions stage. Only a case study (case study 1) assessed the recurring embodied energy; in some of the remaining case studies authors do not specify if this energy parcel was assessed. A unique case study that assessed the total embodied energy necessary to construct a building structural system was not found, which means literature review does not perform a complete life cycle analysis for embodied energy. It is concluded that the documentation provided in the journal articles assessed is not sufficient. Calculation methods and life cycle stages considered are not clearly defined, which makes difficult to compare the embodied energy results in the presented case studies.

Consequently, this leads to a big uncertainty in the data analyzed and it is not possible to draw certain conclusions. To solve this problem it was considered necessary to make a little big dipper research about the possible causes of unconformity of data assessed and understand why it happens in order to identify the problems and develop new solutions that may provide a more realistic and trustable approach of embodied energy in structural systems.

5. Understanding Variations in Embodied Energy Values

In Chapter 4 was possible to identify differences in the embodied energy values in the presented case studies, even when it was being compared similar building assemblies. Although, it was not possible to draw objective conclusions about the considerable differences found on EE values. Thus, arose a need to comprehend the reasons for that, through a more detailed reading of literature review.

5.1 Introduction

LCA is a really helpful methodology to measure the environmental impact of a building. With the results obtained by performing a LCA analysis it is possible to achieve a more sustainable construction. In fact, the biggest advantage of LCA methodology is to help engineers to take decisions in the design phase of a building. Although, it does not provide accurate results about the environmental impact, it just makes decisions easier to take. In other words, LCA methodology allows engineers to predict the energy consumption and CO_2 emissions released during a building life cycle, and with that information it is possible to make a choice about the materials and process that may have smaller environmental impact.

From the previous chapter it was concluded that there are some factors that may influence the embodied energy results. It was also possible to understand that the documentation provided in some case studies is not enough or sufficiently precise to make comparisons and conclusions about embodied energy in structural systems. For that reasons it was considered important to understand the possible causes for the variation of embodied energy values.

Thus, it was possible to conclude that there are to main factors that can affect embodied energy values: direct and indirect drivers.

The direct drivers correspond to all the variations introduced in embodied energy results, due to some subjectivity inherent to the LCA methodology

The indirect drivers correspond to misinterpretations of embodied energy values in literature by other readers due to insufficient documentation posted by the authors, who conducted the embodied energy analysis.

5.2 Direct Drivers

5.2.1 Embodied Energy Data

The embodied energy term is not that simple, as it seems. Despite of being easy to understand and assimilate the concept, there is no standard terminology for buildings embodied energy (Chang, Ries, & Lei, 2012). This might lead to certain personal interpretation on each author's definition for embodied energy. Even the embodied energy definition presented in Chapter 2 was based in what was considered the more correct and accurate definition and complemented with other authors' definitions. So, a starting point for the variations in embodied energy values can be due the fact of non-existing embodied energy standard definition.

Regardless of more or less correct embodied energy definitions, it is a fact that there are some factors that will always affect the embodied energy values. During the product stage the energy consumption is strictly related with the efficiency of the manufacture process, proximity and availability of raw materials. In turn, the transportation type, material weight and the travelled distance from the production centre to the construction site, energy consumed by the equipment and labour work during the on-site operations influence the embodied energy consumption during the construction stage (Cabeza, Barreneche, Miró, & Morera, 2014).

The values of energy required for the product stage of building materials are going to origin the databases necessary for the LCI. As it is possible to understand the values used in the databases will be different from each other, mainly due to the following reasons:

- Geographic location of the manufacture process;
- Technology used in the manufacture process;
- Feedstock energy consideration;
- Energy efficiency of the manufacture process.

(Cabeza, Barreneche, Miró, & Morera, 2014)

For this reason, depending on the source and quality of database chosen for the LCA analysis, some embodied energy values in the product stage can be more precise and accurate than others. Plus, even the completeness and age of database will have impact in the final values.

In what concerns embodied energies data for the construction stage, there are few databases available and there is a lot of inaccurate data for the transportation and construction processes used in LCA tools (University of Cambridge, 2015).

5.2.2 Subjectivity in LCA Methodology

There are several LCA methods to assess embodied energy, but none of them are considered consistent or accurate (Cabeza, Barreneche, Miró, & Morera, 2014). In fact, LCA is a complex methodology that varies according to the goal and scope of the LCA analysis defined by each LCA practitioner and leans on the excellence of data. Every time that a LCA study is perform, is always some subjectivity inherent to the analysis (Optis & Wild, 2010). The subjectivity present in the LCA methodology, is reflected on the liberty and lack of options that the LCA practitioner has to choose, namely:

- The LCA method (process-based, I-O, or hybrid analysis);
- The LCI database;
- The LCA software used to perform the analysis.

Another thing that may lead to uncertainty of embodied energy values can be the complexity or non-complexity of the building or building component that wants to be assessed. For example, if the analysis is quite complex a LCA computer program will be required for sure and consequently the definition of the system boundaries will be complex and it will require time. If it is simple building or a simple part of the building that wants to be evaluated the definition of the system boundaries may compromise the correct performance of the LCA software, because there are not sufficient inputs to define the system boundaries in the software.

5.3 Indirect Drivers

5.3.1 Insufficient Documentation in Literature Review

The omission or lack of detailed information in literature review can have significant impacts on embodied energy values interpretation and difficult the comparison of embodied energy results between LCA studies.

There are three essential components in a LCA analysis that have to be well documented in literature review, in order to avoid wrong interpretations:

1. System boundary definition;
2. Choice of data sources;
3. Choice of calculation procedures.

(Optis & Wild, 2010)

System Boundary Definition

The system boundaries of a LCA analysis define the unit processes of embodied energy components that will be evaluated.

When a system boundary is defined all the life cycle phases included in the analysis should be listed. Plus, also a list of the unit processes of each life cycle stage should be mention.

One of the problems found in the cases studies presented in Chapter 4 was the fact that some of them did not indicate clearly what stages or what unit processes were being assessed. According to Optis *et. al* (2010) "such omissions are commonplace for LCA studies on buildings given the larger number of life cycle stages, unit processes and unit processes, and flows". In consequence, the data becomes useless once it is not detailed enough to be compared with other embodied energy data.

Choice of Data Sources

The database used in a LCA analysis should be mentioned and justified to avoid misinterpretation or wrong assumptions of embodied energies values by other readers.

It is also recommended to use a trustable database, preferably from the country where the analysis is being performed. If there is no developed database in the country where the building is being assessed is advised to use a recognized data source, to have more precise and credible results.

Choice of Calculation Procedures

The chosen LCA method as well as all the assumptions necessary to proceed with the calculations must be provided, when a LCA analysis is performed. Plus, the software program used or the mathematical equations behind the calculations should be clearly identified. The software tools may use different calculation methodologies when performing LCA. According to Optis (2008), the embodied energy results obtained by a process-based analysis or I-O analysis can differ by 4% and 20,5%, respectively.

6. Assessing Initial Embodied Energy in Building Structures

After understanding the discrepancies in reported EE values in the previous chapter, it was possible to develop an approach that estimates initial EE in building structures. This approach avoids committing some of the most common LCA errors, which leads to more accurate values. Through this chapter it is going to be presented the initial embodied energy results obtained for the building structure, by varying the span and the material type.

6.1 Introduction

It is fundamental to increase different approaches that may provide a trustable and realistic comparison of embedded energy in different building structures. So far, the research developed does not provide a detailed analysis of embodied energy consumption for each stage of the manufacture phase, and does not allow engineers to use that information in the design phase. And it is important for engineers to have trustable information in what concerns the energy consumption, in order to make fast decisions about the structural assembly to project. In fact, it is not viable in the design phase of a building to calculate the embodied energy consumption for numerous configurations of building structures, due to the time required to perform that task.

In order to address these problems, initial embodied energy is going to be assessed and quantified for each manufacture stage in a simple structure. The structural frame dimension is constant during the LCA performance. Only the building span and the material type of the structure will be varied.

It is expected that the information obtained will help in the development of embodied energy data.

6.2 Developed Methodology

In the previous chapters were identified some problems of previous research, when assessing embodied energy in building assemblies. Some case studies did not specify the energy consumption for all manufacture phase stages. In fact, some of them only calculate part of embodied energy. Moreover, the subjectivity inherent to each LCA case study leads to different interpretation of embedded energy values. In order to solve those difficulties it was considered necessary the use a different approach. With this, it is pretended to avoid the introduction of more errors due to direct drivers (LCA software and LCI database) and indirect drivers (lack of clarification of procedures and assumptions made).

The methodology adopted in the empirical study of this research evaluates initial embodied energy through the use of LCA methodology, considering the four steps necessary to perform a LCA assessment.

6.2.1 Structural Analysis

In order to evaluate initial embodied it was necessary to define a building structure. Thus, a simple structural building frame that may correspond to an industrial or office building was used to perform initial embodied energy calculations. It is intended to study the influence of building span and structural materials on initial embodied energy consumption, per square meter. Therefore, the span is going to be varied from 0,60 to 0,60 meters and it is going to be used three different materials: concrete, steel and timber.

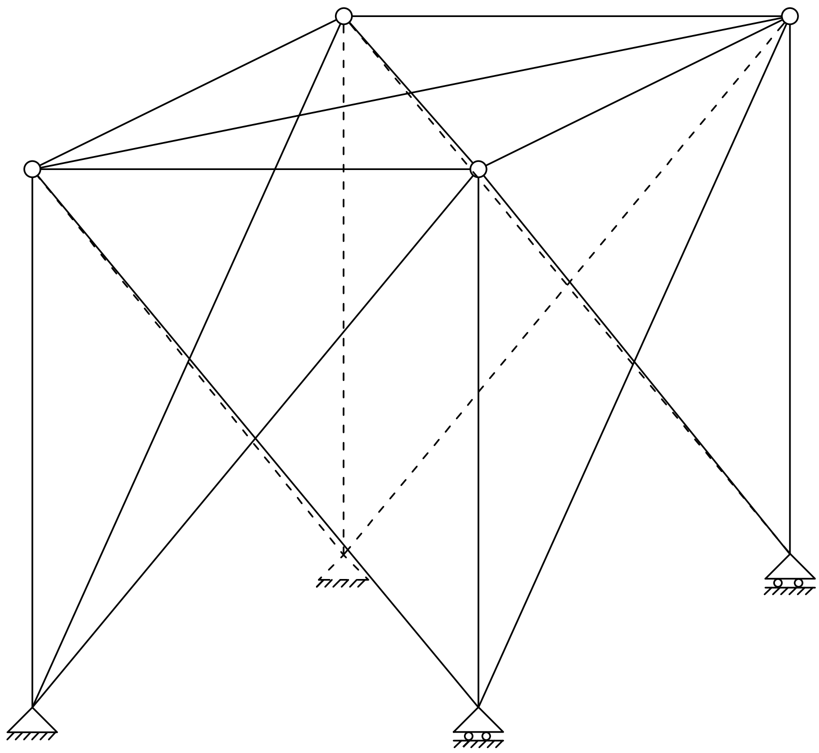

Figure 6.2.1.1 – Building structural frame defined to perform initial embodied energy calculations

In figure 6.2.1.1 it is represented the generic configuration of the building structure defined to perform initial embodied energy calculations.

The basis of the building consists in beams and columns connected to each other in joints with moment releases. The structural analysis performed was based in the Eurocode and took into consideration both ultimate and serviceability state of use. The load on the beams consists in a permanent dead load (g_k) of 16,67 KN/m and daily use load (q_k) of 12,60 KN/m.

A structural analysis for small and large building was performed with the purpose to have a larger sample of embodied energy results.

The maximum dimensions defined for beams spans and columns heights are presented in table 6.2.1.1.

Table 6.2.1.1 – Maximum dimensions for beams spans and columns heights defined for the building structure

Building	Maximum Beam Span (m)	Maximum Column Height (m)
Small	9	6,5
Large	13	7

The span for small building structures vary from 3,0 meters to 9,0 meters, and the spans dimensions were established based on the span dimensions used to project small office buildings. For the large building, the beam span cannot exceed more than 13 meters, once the timber assemblies do not have a good structural performance for bigger spans, as result of the fluency effect.

The lateral span dimension is always constant, 4,2 meters, for both small and large buildings calculations.

The characteristics and dimensions of beams and columns for each material were defined in the structural analysis, and they are presented in the following table.

Table 6.2.1.2 – Characteristics of structural materials defined for the building structure

Structural element	Concrete		Steel		Timber	
	Small Building	Large Building	Small Building	Large Building	Small Building	Large Building
Beams	240 x 480	300 x 600	IPE 400	IPE 550	185 x 800	185 x 1167
Columns	240 x 240	300 x 300	HE 140B	HE 160 B	185 x 333	185 x 500

The building materials used in the building structural assembly have the following characteristics:

- The concrete is standard concrete created with CEM I Portland cement and has a strength class (f_{ck}) of 40 MPa;

- The steel used for the reinforcement of the concrete structure has a strength class (f_{yk}) of 550 MPa;
- The steel used for the steel structure is virgin steel and has a strength class (f_{yk}) of 355 MPa;
- The timber structure is made of homogeneous glued laminated timber.

6.2.2 Performed LCA

This study estimates initial embodied energy using LCA methodology. As it was explained in chapter 2, to perform any type of LCA it is fundamental to follow four steps.

In order to avoid misleading of results, the four steps considered to fulfil a LCA methodology are going to be clearly identified in this sub-chapter.

Step 1: Goal and Scope Definition

1. The goal and scope of this research is to assess initial embodied energy in building structures.
2. The functional unit defined to present the results is GJ/m^2.
3. The system boundary of this analysis accounts only for the life cycle manufacture phase. The unit processes of embodied energy components and the unit size evaluated are listed in the table below.

Table 6.2.2.1 – Manufacture phase unit processes considered for the performed LCA

Unit Process	Unit size
Raw material extraction and assembly	(MJ/kg)
Material production	(MJ/kg)
Transportation	(MJ/unit size.km)
On-site Construction Equipment	(MJ/h)

Step 2: Inventory Analysis

1. The database used to perform the LCI is presented per table bellow.

Table 6.2.2.2 – LCI database sources

	Unit Process	LCI Data Source
Product Stage	Raw material extraction and assembly	ICE (2011)
	Material production	
Construction Stage	Transportation	Hong *et al*. (2012)
	On-site Construction Equipment	Hong *et al*. (2012) Haney (2011)

2. The initial embodied energy calculations were performed with a spread sheet, using the equations (2.1), (2.2), (2.3), (2.4), (2.5) and (2.6) presented in chapter 2.

Step 3: Impact Assessment

The estimated environmental impacts results, initial embodied energy consumption in building structures, are presented in **sub-chapter 6.3**.

Step 4: Results Interpretation

The results obtained by performing LCA methodology are discussed in **sub-chapter 7.2**.

6.3 Initial Embodied Energy Calculations

It is going to be presented the calculations performed as well the respective assumptions made.

The initial embodied energy calculations will proceed with the following steps:

1. Calculate the energy for the product stage;
2. Calculate the energy for the construction stage (transportation and construction equipment);
3. Sum up the values obtained from the step 1 and 2, in order to obtain the total energy consumption.

6.3.1 Product Stage Calculations

Raw Material Extraction and Material Production

The product stage corresponds to the energy required for the extraction and manufacturing of building materials, as explained in the previous chapters.

In order to calculate the embodied energy for this stage it is fundamental to know the building materials quantities as well the energy content of the materials. The energy content is no more than an embodied energy coefficient, which is a factor that represents the embodied energy for construction materials. The value of the embodied energy coefficient differs from LCI database from LCI database. Each LCA computer program uses it own database and there are several publications where embodied energy coefficients are complied in databases. Since this study does not use LCA software to calculate embodied energy, the embodied energy coefficients used for the calculations were extracted from a database developed by Bath University in the United Kingdom called "Inventory of Carbon and Energy" (ICE). It was used is the latest version (Version 2.0), that was released in 2011. The LCI method used to develop this database was the process-based and the system boundary defined corresponds to a cradle-to-gate analysis. The reason for using this database and not another one is due to the fact that ICE is considered the most known and trustable database (RICS, 2012).

In the table 6.3.1.1 it is presented the values for embodied energy coefficients used in this study.

Table 6.3.1.1 – Embodied Energy Coefficients (adapted from ICE, 2011)

EE Coefficients (MJ/kg)	
Concrete (40 MPa)	1,04
Virgin Steel	20,1
Glued Laminated Timber	12

The materials quantities for each structure were calculated based on the material weight defined on the structural analysis performed.

Table 6.3.1.2 – Materials weight (kg/m)

Structural element	Concrete		Steel		Timber	
	Small Building	Large Building	Small Building	Large Building	Small Building	Large Building
Beams	276	432	66,3	106	75,5	110
Columns	138	216	33,7	42,6	31,4	47,2

The embodied energy for the product stage was calculated by multiplying the material quantities for the respective embodied energy coefficient. The mathematical formula used corresponds to equation (2.2), defined in chapter 2.

The embodied energy values obtained for each building span and material type are presented on the following tables.

Table 6.3.1.3 – Embodied energy calculations for concrete structure product stage

Concrete						
Building Type	Span (m)	Area (m^2)	Quantity (kg)	EE (MJ)	EE (GJ)	**EE (GJ/m^2)**
Small	3	12,6	7562,4	7864,9	7,86	**0,62**
	3,6	15,12	7893,6	8209,3	8,21	**0,54**
	4,2	17,64	8224,8	8553,8	8,55	**0,48**
	4,8	20,16	8556	8898,2	8,90	**0,44**
	5,4	22,68	8887,2	9242,7	9,24	**0,41**
	6	25,2	9218,4	9587,1	9,59	**0,38**
	6,6	27,72	9549,6	9931,6	9,93	**0,36**
	7,2	30,24	9880,8	10276,0	10,28	**0,34**
	7,8	32,76	10212	10620,5	10,62	**0,32**
	8,4	35,28	10543,2	10964,9	10,96	**0,31**
	9	37,8	10874,4	11309,4	11,31	**0,30**
Large	9,6	40,32	17971,2	18690,0	18,69	**0,46**
	10,2	42,84	18489,6	19229,2	19,23	**0,45**
	10,8	45,36	19008	19768,3	19,77	**0,44**
	11,4	47,88	19526,4	20307,5	20,31	**0,42**
	12	50,4	20044,8	20846,6	20,85	**0,41**
	12,6	52,92	20563,2	21385,7	21,39	**0,40**

Table 6.3.1.4 – Embodied energy calculations for steel structure product stage

			Steel			
Building Type	Span (m)	Area (m^2)	Quantity (kg)	EE (MJ)	EE (GJ)	**EE (GJ/m^2)**
Small	3	12,6	1830,92	36801,5	36,80	**2,92**
	3,6	15,12	1910,48	38400,6	38,40	**2,54**
	4,2	17,64	1990,04	39999,8	40,00	**2,27**
	4,8	20,16	2069,6	41599,0	41,60	**2,06**
	5,4	22,68	2149,16	43198,1	43,20	**1,90**
	6	25,2	2228,72	44797,3	44,80	**1,78**
	6,6	27,72	2308,28	46396,4	46,40	**1,67**
	7,2	30,24	2387,84	47995,6	48,00	**1,59**
	7,8	32,76	2467,4	49594,7	49,59	**1,51**
	8,4	35,28	2546,96	51193,9	51,19	**1,45**
	9	37,8	2626,52	52793,1	52,79	**1,40**
Large	9,6	40,32	4118,4	82779,8	82,78	**2,05**
	10,2	42,84	4245,6	85336,6	85,34	**1,99**
	10,8	45,36	4372,8	87893,3	87,89	**1,94**
	11,4	47,88	4500	90450,0	90,45	**1,89**
	12	50,4	4627,2	93006,7	93,01	**1,85**
	12,6	52,92	4754,4	95563,4	95,56	**1,81**

Table 6.3.1.5 – Embodied energy calculations for timber structure product stage

			Timber			
Building Type	Span (m)	Area (m^2)	Quantity (kg)	EE (MJ)	EE (GJ)	**EE (GJ/m^2)**
Small	3	12,6	1903,6	22843,2	22,84	**1,81**
	3,6	15,12	1994,2	23930,4	23,93	**1,58**
	4,2	17,64	2084,8	25017,6	25,02	**1,42**
	4,8	20,16	2175,4	26104,8	26,10	**1,29**
	5,4	22,68	2266	27192,0	27,19	**1,20**
	6	25,2	2356,6	28279,2	28,28	**1,12**
	6,6	27,72	2447,2	29366,4	29,37	**1,06**
	7,2	30,24	2537,8	30453,6	30,45	**1,01**
	7,8	32,76	2628,4	31540,8	31,54	**0,96**
	8,4	35,28	2719	32628,0	32,63	**0,92**
	9	37,8	2809,6	33715,2	33,72	**0,89**
Large	9,6	40,32	4357,6	52291,2	52,29	**1,30**
	10,2	42,84	4489,6	53875,2	53,88	**1,26**
	10,8	45,36	4621,6	55459,2	55,46	**1,22**
	11,4	47,88	4753,6	57043,2	57,04	**1,19**
	12	50,4	4885,6	58627,2	58,63	**1,16**
	12,6	52,92	5017,6	60211,2	60,21	**1,14**

6.3.2 Construction Stage Calculations

In the construction stage calculations, the energy inputs considered correspond to vehicles and equipment. The energy associated to human work and land use is not in the scope of this study.

Transportation

Transportation is one part of embodied energy that comprises the construction stage. The transportation component is the energy consumption associated with the transport of building materials from the factories to the construction sites.

The energy consumption associated with the transportation of building materials was calculated by:

- Defining an appropriate vehicle to each material, having in mind the general vehicles used to transport concrete, steel and timber;
- Establishing the transportation distance between the factories and the construction site;
- Using the materials quantities to estimate the number of travels required;
- Multiplying the total weight transported by each vehicle with the correspondent energy consumption associated to each vehicle.

The distance assumed for all the three building materials was the same. Therefore, the energy consumption in the different structural systems will not be influence by the travelled distance.

The transportation distance assumed was 40 kilometers.

The vehicles assigned to each building material are the following:

- For concrete transportation it is used a mixer lorry, with a 6 cubic meters size;
- For virgin steel and glued laminated timber transportation it is used a flatbed lorry of 8 tonnes.

For the concrete structure it was necessary two travels in order to deliver the required quantity of concrete, for building spans longer than 9 meters. The maximum capacity of the mixer lorry (6 cubic meters) was exceed by the total volume of concrete necessary to transport to the construction site.

The energy consumption for each vehicle data was taken from Hong *et al* (2014) and it is presented in the following table.

Table 6.3.2.1 – Vehicle energy consumption (adapted from Hong *et al*, 2014)

Vehicle	Size	Energy consumption (MJ/unit size.km)
Mixer lorry	6 m^3	2,06
Flatbed lorry	8 t	1,44

In order to calculate the embodied energy for transportation it was use equation (2.4).

The results obtained for the different structures and ranges of spans are presented in the tables below.

Table 6.3.2.2 – Embodied energy calculations for concrete structure transportation

Concrete						
Building Type	Span (m)	Quantity (m^3)	Area (m^2)	EE (MJ)	EE (GJ)	**EE (GJ/m^2)**
Small	3	3,2	12,6	520,2	0,52	**0,041**
	3,6	3,3	15,12	543,0	0,54	**0,036**
	4,2	3,4	17,64	565,8	0,57	**0,032**
	4,8	3,6	20,16	588,5	0,59	**0,029**
	5,4	3,7	22,68	611,3	0,61	**0,027**
	6	3,8	25,2	634,1	0,63	**0,025**
	6,6	4,0	27,72	656,9	0,66	**0,024**
	7,2	4,1	30,24	679,7	0,68	**0,022**
	7,8	4,3	32,76	702,4	0,70	**0,021**
	8,4	4,4	35,28	725,2	0,73	**0,021**
	9	4,5	37,8	748,0	0,75	**0,020**
Large	9,6	7,5	40,32	2468,0	2,47	**0,061**
	10,2	7,7	42,84	2539,2	2,54	**0,059**
	10,8	7,9	45,36	2610,4	2,61	**0,058**
	11,4	8,1	47,88	2681,6	2,68	**0,056**
	12	8,4	50,4	2752,8	2,75	**0,055**
	12,6	8,6	52,92	2824,0	2,82	**0,053**

Table 6.3.2.3 – Embodied energy calculations for steel structure transportation

Steel							
Building Type	Span (m)	Quantity (kg)	Quantity (t)	Area (m^2)	EE (MJ)	EE (GJ)	**EE (GJ/m^2)**
Small	3	1830,92	1,8	12,6	210,9	0,21	**0,017**
	3,6	1910,48	1,9	15,12	220,1	0,22	**0,015**
	4,2	1990,04	2,0	17,64	229,3	0,23	**0,013**
	4,8	2069,6	2,1	20,16	238,4	0,24	**0,012**
	5,4	2149,16	2,1	22,68	247,6	0,25	**0,011**
	6	2228,72	2,2	25,2	256,7	0,26	**0,010**
	6,6	2308,28	2,3	27,72	265,9	0,27	**0,010**
	7,2	2387,84	2,4	30,24	275,1	0,28	**0,009**
	7,8	2467,4	2,5	32,76	284,2	0,28	**0,009**
	8,4	2546,96	2,5	35,28	293,4	0,29	**0,008**
	9	2626,52	2,6	37,8	302,6	0,30	**0,008**
Large	9,6	4118,4	4,1	40,32	474,4	0,47	**0,012**
	10,2	4245,6	4,2	42,84	489,1	0,49	**0,011**
	10,8	4372,8	4,4	45,36	503,7	0,50	**0,011**
	11,4	4500	4,5	47,88	518,4	0,52	**0,011**
	12	4627,2	4,6	50,4	533,1	0,53	**0,011**
	12,6	4754,4	4,8	52,92	547,7	0,55	**0,010**

Table 6.3.2.4 – Embodied energy calculations for timber structure transportation

Timber							
Building Type	Span (m)	Quantity (kg)	Quantity (t)	Area (m^2)	EE (MJ)	EE (GJ)	**EE (GJ/m^2)**
Small	3	1903,6	1,9	12,6	219,3	0,22	**0,017**
	3,6	1994,2	2,0	15,12	229,7	0,23	**0,015**
	4,2	2084,8	2,1	17,64	240,2	0,24	**0,014**
	4,8	2175,4	2,2	20,16	250,6	0,25	**0,012**
	5,4	2266	2,3	22,68	261,0	0,26	**0,012**
	6	2356,6	2,4	25,2	271,5	0,27	**0,011**
	6,6	2447,2	2,4	27,72	281,9	0,28	**0,010**
	7,2	2537,8	2,5	30,24	292,4	0,29	**0,010**
	7,8	2628,4	2,6	32,76	302,8	0,30	**0,009**
	8,4	2719	2,7	35,28	313,2	0,31	**0,009**
	9	2809,6	2,8	37,8	323,7	0,32	**0,009**
Large	9,6	4357,6	4,4	40,32	502,0	0,50	**0,012**
	10,2	4489,6	4,5	42,84	517,2	0,52	**0,012**
	10,8	4621,6	4,6	45,36	532,4	0,53	**0,012**
	11,4	4753,6	4,8	47,88	547,6	0,55	**0,011**
	12	4885,6	4,9	50,4	562,8	0,56	**0,011**
	12,6	5017,6	5,0	52,92	578,0	0,58	**0,011**

On-site Construction Equipment

The on-site construction equipment is the other parcel of construction stage embodied energy.

The energy consumption associated with the use of construction equipment was calculated as follows:

- Defining the equipment required to the construction works of a building superstructure;
- Estimating the number of working hours of equipment (duration of equipment usage), by dividing the quantity of material processed by the equipment capacity (daily output of the equipment);
- Calculating the energy consumption multiplying the number of working hours by the energy consumption factor.

The equipment for the concrete structural assembly construction works calculations, as well the respective work capacity and energy consumption it is presented in the table below.

Table 6.3.2.5 – Work capacity and energy consumed by equipment for concrete structural works (adapted from Hong *et al*, 2014)

Equipment	Work Capacity (m^3/h)	Energy consumption (MJ/h)
Concrete pump car	22,1	1094,3
Plate compactor	9,696	35,3
Air compressor	425	968,8
Concrete vibrator	2,5	34,9

The equipment defined for the steel structural system construction works, as well the work capacity and energy consumption is presented in the table below.

Table 6.3.2.6 – Work capacity and energy consumed by equipment for steel structural works (adapted from Haney, 2011)

Equipment	Work capacity (min/piece)	Energy consumption (MJ/h)
Diesel Welder	11,8	198
Forklift	5,1	792

For the timber structural works it was necessary to consider a forklift to help the transportation of glued laminated timber columns and beams. The forklift used for the embodied energy calculations is the same as the one defined for the steel works, in the table 6.3.2.6.

The calculations were performed using equations (2.5) and (2.6), defined in chapter 2.

The results obtained for the structure by varying the span and the material types are presented in the following tables.

Table 6.3.2.7 – Embodied energy calculations for on-site construction equipment for concrete structure

Concrete						
Building Type	Span (m)	Quantity (m^3)	Area (m^2)	EE Equipment (MJ)	EE Equipment (GJ)	**EE Equipment (GJ/m^2)**
Small	3	3,2	12,6	219	0,22	**0,017**
	3,6	3,3	15,12	229	0,23	**0,015**
	4,2	3,4	17,64	238	0,24	**0,014**
	4,8	3,6	20,16	248	0,25	**0,012**
	5,4	3,7	22,68	257	0,26	**0,011**
	6	3,8	25,2	267	0,27	**0,011**
	6,6	4,0	27,72	277	0,28	**0,010**
	7,2	4,1	30,24	286	0,29	**0,009**
	7,8	4,3	32,76	296	0,30	**0,009**
	8,4	4,4	35,28	305	0,31	**0,009**
	9	4,5	37,8	315	0,31	**0,008**
Large	9,6	7,5	40,32	520	0,52	**0,013**
	10,2	7,7	42,84	535	0,53	**0,012**
	10,8	7,9	45,36	550	0,55	**0,012**
	11,4	8,1	47,88	565	0,56	**0,012**
	12	8,4	50,4	580	0,58	**0,011**
	12,6	8,6	52,92	595	0,59	**0,011**

Table 6.3.2.8 – Embodied energy calculation for on-site construction equipment for steel structure

Building Type	Span (m)	Quantity (m^3)	Area (m^2)	EE Equipment (MJ)	EE Equipment (GJ)	**EE Equipment (GJ/m^2)**
			Steel			
Small	3	0,2	12,6	425	0,43	**0,034**
	3,6	0,2	15,12	425	0,43	**0,028**
	4,2	0,3	17,64	425	0,43	**0,024**
	4,8	0,3	20,16	425	0,43	**0,021**
	5,4	0,3	22,68	425	0,43	**0,019**
	6	0,3	25,2	425	0,43	**0,017**
	6,6	0,3	27,72	425	0,43	**0,015**
	7,2	0,3	30,24	425	0,43	**0,014**
	7,8	0,3	32,76	425	0,43	**0,013**
	8,4	0,3	35,28	425	0,43	**0,012**
	9	0,3	37,8	425	0,43	**0,011**
Large	9,6	0,5	40,32	425	0,43	**0,011**
	10,2	0,5	42,84	425	0,43	**0,010**
	10,8	0,6	45,36	425	0,43	**0,009**
	11,4	0,6	47,88	425	0,43	**0,009**
	12	0,6	50,4	425	0,43	**0,008**
	12,6	0,6	52,92	425	0,43	**0,008**

Table 6.3.2.9 – Embodied energy calculations for on-site construction equipment for timber structure

Building Type	Span (m)	Quantity (m^3)	Area (m^2)	EE Equipment (MJ)	EE Equipment (GJ)	**EE Equipment (GJ/m^2)**
			Timber			
Small	3	3,7	12,6	269	0,27	**0,021**
	3,6	3,9	15,12	269	0,27	**0,018**
	4,2	4,1	17,64	269	0,27	**0,015**
	4,8	4,3	20,16	269	0,27	**0,013**
	5,4	4,4	22,68	269	0,27	**0,012**
	6	4,6	25,2	269	0,27	**0,011**
	6,6	4,8	27,72	269	0,27	**0,010**
	7,2	5,0	30,24	269	0,27	**0,009**
	7,8	5,2	32,76	269	0,27	**0,008**
	8,4	5,3	35,28	269	0,27	**0,008**
	9	5,5	37,8	269	0,27	**0,007**
Large	9,6	8,5	40,32	269	0,27	**0,007**
	10,2	8,8	42,84	269	0,27	**0,006**
	10,8	9,1	45,36	269	0,27	**0,006**
	11,4	9,3	47,88	269	0,27	**0,006**
	12	9,6	50,4	269	0,27	**0,005**
	12,6	9,8	52,92	269	0,27	**0,005**

7. Empirical Results Discussion

This chapter is a reflection of the past three chapters. The initial embodied energy results obtained in the empirical part of the research, as well the values from the case studies, and the methodological limitations are discussing in this section.

7.1 Introduction

The estimated initial embodied energy values are going to be discussed through this chapter. First, it is going to be discussed the embodied energy results for product stage and then for the construction stage, comparing the structural frame for the different building materials and spans. Afterwards, the initial embodied energy consumption for each one of the three structures is discussed. Lastly, the initial embodied energy consumption is going to be compared for the different spans and material types and it is concluded which is the building structure with better environmental impact.

Furthermore, the percentage difference between the initial embodied energy associated to each structural frame is presented.

7.2 Initial Embodied Energy Results Discussion

7.2.1 Product Stage Energy Consumption Discussion

In graph 7.2.1.1 it is presented the embodied energy values obtained for each building structure in function of the building span.

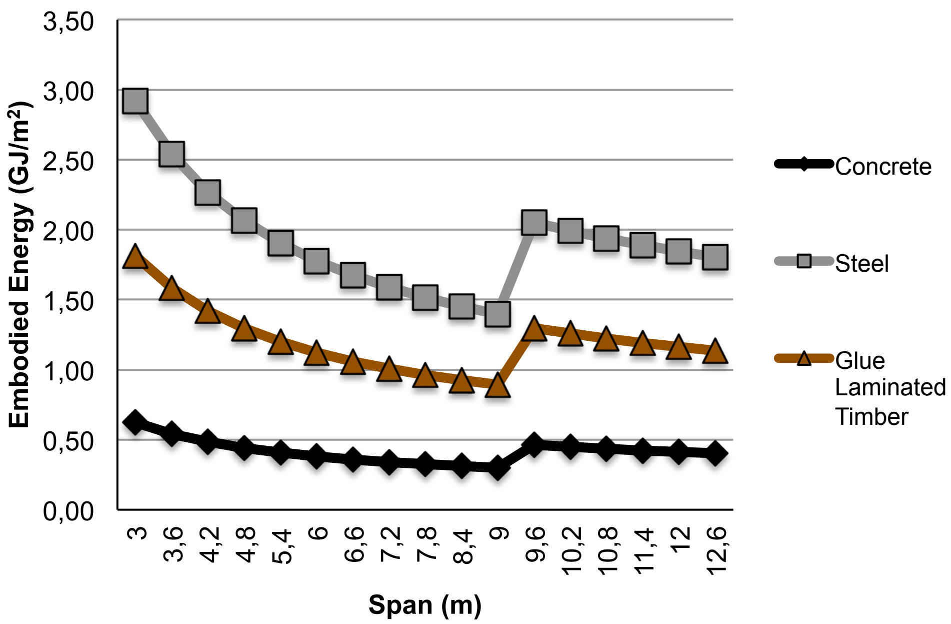

Figure 7.2.1.1 – Embodied energy variation in the building structure during the product stage, in function of span and material type

As it is possible to observe from the graph, during the product stage energy consumption is larger for the steel structure, followed by the glued laminated timber structure, and finally concrete structure.

In fact, the results obtained for the steel structure were expected; in the majority of presented case studies in chapter 4, the embodied energy for the product stage is in general higher for the steel framed-structures. This result is related with the great energy consumption present in the extraction and manufacture of steel.

However, the same is not verified for concrete and timber structure. At the outset of this research these results were not anticipated. In fact, the presented case studies in chapter 4 demonstrated (with the exception of case study 6) that the timber structural systems have lower energy consumption than concrete structural systems. Moreover, the high-energy intensity and high temperatures during cement manufacture lead to expectation of better energy performance in the timber structure. Instead, the acquired results revealed astonishing. The energy consumed in the production of the timber materials exceed the energy consumed in the manufacture of concrete, between a range of 0,59-1,9 GJ/m^2 for small buildings, and 0,74-0,84 GJ/m^2 for large buildings.

At a first instance, the results obtained were not clear. Although, taking a closer look to glued-laminated timber manufacture process, described in chapter 3, it was possible to understand and interpret the higher consumption on the assessed timber structure. It is important to notice with special attention the face bonding lamination process. During this process the laminations are bonded with resins derived from fossil fuels. So, the use of these resins may introduce higher energy consumption in the glued-laminated timber structural frames.

As a matter of fact, when assessing embodied energy in laminated timber structures it is important to make a clear distinction between process energy and feedstock energy. On one hand, the process energy corresponds to the energy released during the production of industrial processes through the combustion of fuels. On the other hand, feedstock energy is the potential energy withhold in fuel resources extracted from Earth, such as natural gas that contain potential energy within the molecular structure of the fossil fuel based wood adhesives (Robertson, Lam, & Cole, 2012). Thereby, it is very likely that the amount of feedstock energy consumed in the glued laminated timber manufacture is higher than the feedstock energy consumed during concrete manufacture.

It is also important to mention a fundamental difference between light-frame timber and heavy timber. The main difference consists in the volume of wood required. Heavy timber construction requires much larger volumes of wood, which in turn, results in higher energy process (Robertson, Lam, & Cole, 2012).

Thus, the timber structures described in chapter 4 might have lower energy consumption, since they are made of light-frame timber and they do need resins during their production.

Furthermore, it is important to highlight that all case studies in chapter 4 used different databases to perform the calculations. Case study 4 utilized the same database used in this study for product stage calculations, ICE database. It is interesting to notice that the embodied energy values are not that far from the ones estimated. Therefore, LCI database source might have significant influence on product stage results.

After discussing the influence of the material type on embodied energy is going to be discussed the variation of building span.

From the graph 7.2.1.1, it is possible to observe that, in general, the embodied energy in the three structural frames decreases slightly with the variation of the span. There is a sharp increase in the values, when the building span ranges from the 9 meters to 9,6 meters, due the size difference in the structural dimensions defined for the small building to the large building. It is also possible to assert that the concrete structure is the one where embodied energy consumption is less affected by the variation of the span, since the decreasing of values is not as pronounced as in the other two structures.

7.2.2 Construction Stage Energy Consumption Discussion

Transportation

In graph 7.2.2.1 it is presented the embodied energy values in GJ/m^2 obtained for the building structure in function of the material type and building span.

Observing the graph above, one evident conclusion that can be drawn is that the increasing of span does not have a significant influence on the embodied energy consumption per square meter during the transportation, since the embodied energy values do not have an expressive variation range. There is a slight fluctuation of values for steel and glued laminated timber structure, when the building span varies from 9 meters to 9,6 meters (transition from small to large building), but it is not significant in the overall consumption. A higher fluctuation is verified for the concrete structure when the building span varies from 9 meters to 9,6 meters. This occurs because the travelled distance doubles, which leads to a linear increase of embodied energy to the double.

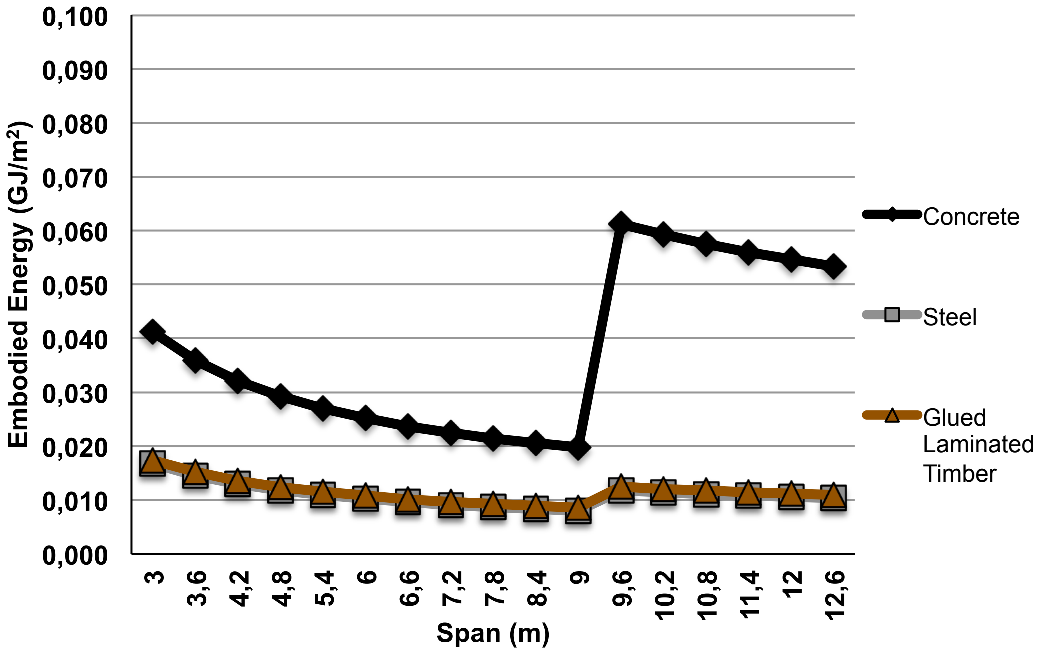

Figure 7.2.2.1 – Embodied energy variation for the building structure during transportation, in function of span and material type

It is also possible to observe from the graph that the structural system that consumes more energy per square meter during the transportation process it is concrete structural frame; glued laminated timber and steel structural frame utilized practically the same amount of energy. Since the transportation distance is the same for all the structural systems it is possible to conclude that the embodied energy consumption is strictly related with the quantity of building materials to transport.

On-site Construction Equipment

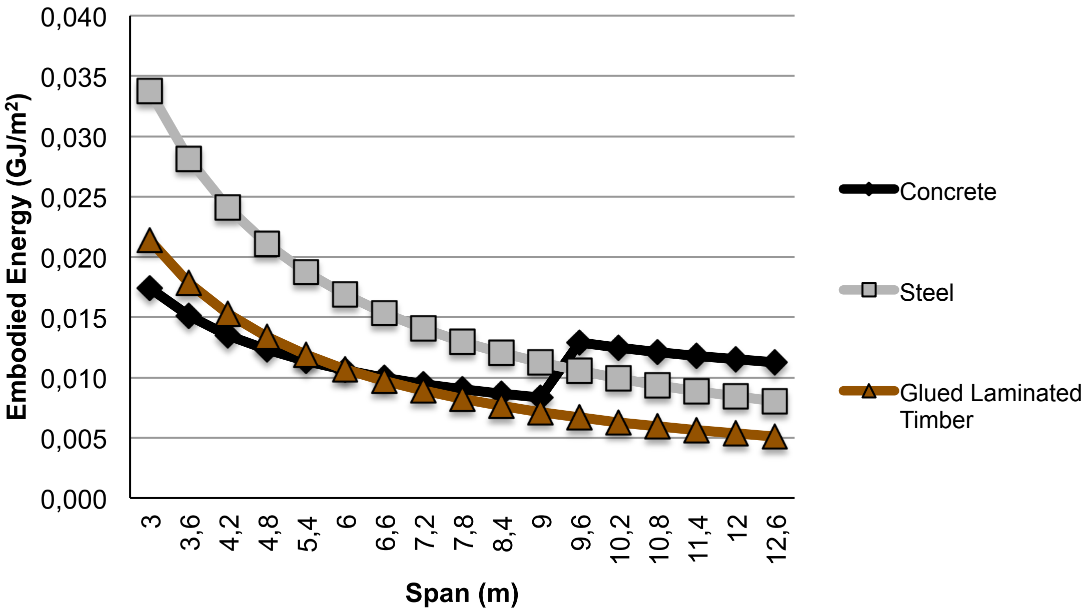

Figure 7.2.2.2 – Embodied energy variation in the building structure during on-site equipment, in function of span and material type

In the graph 7.2.2.2 above it is presented the embodied energy values in GJ/m^2 obtained for each structural system in function of the building span.

It is interesting to observe the energy consumption variation in the three structural systems. Embodied energy variation is very similar for steel and timber structure, whereas the variation for concrete structure is quite different. In the steel and timber structures embodied energy decreases with the increasing of span, while in the concrete structure there is a slight increasing of embodied energy in the transition of small to large buildings. This variation of embedded energy is related with the duration of equipment usage. In fact, for steel and timber structure the equipment defined for the construction works depends on the number of the pieces (beams and columns) to weld and to lift. In the case of the concrete structure, the equipment defined depends on the quantity of concrete (cubic meter) used for the beams and columns, which increases with the increasing of span. Therefore, having in mind the equation (2.6) presented in chapter 2, it is easy to understand that the duration of equipment usage is variable for the concrete structure, and constant for steel and timber structure (the number of beams and columns to weld and lift is always the same).

Yet, it was expected a larger energy consumption for the concrete structural system, since the concrete structural construction works are the ones that require more electrical equipment. However, there are few case studies that focus on the construction stage energy. It was difficult to find more data in order to have more case studies results to compare with the ones obtained in the empirical part of the research. Therefore, it is not clear if in general concrete structural systems consume more energy through equipment usage than the steel and timber structural systems. Although, it is important to remember that the data used for equipment energy come from different data sources, as mentioned in chapter 6. Thus, the results might be different if data from the same source was used. It important to mention that was not used the same data source for all the calculations, since there was no sufficient information for steel and timber equipment in Hong *et al* (2014) research, and vice versa.

Transportation and On-site Construction Equipment

In order to compare the values obtained for construction stage with the results from case study 7, a graph that accounts with the energy of transportation and equipment usage was elaborated.

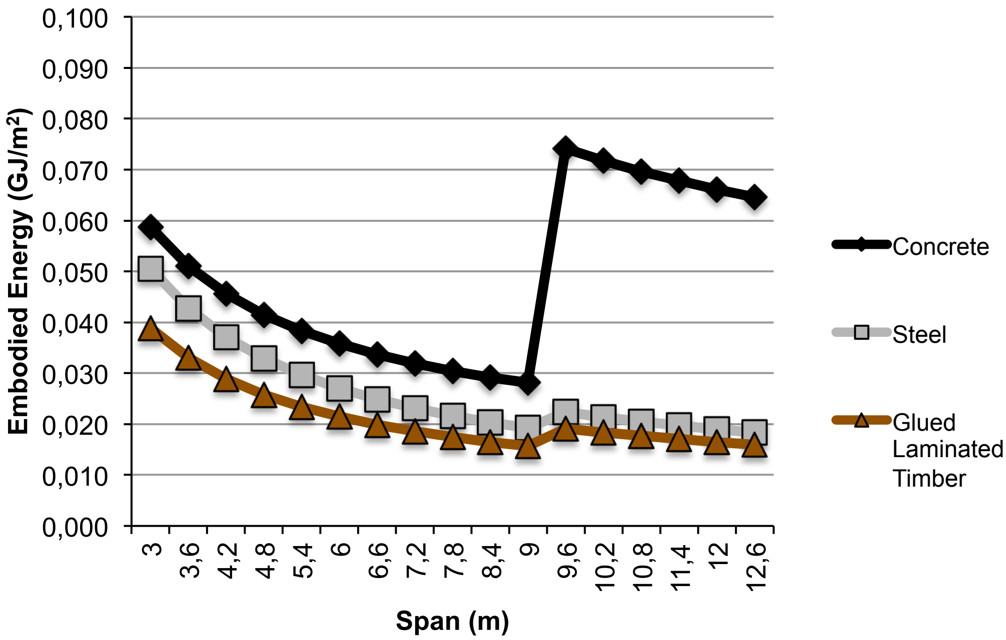

Figure 7.2.2.3 – Embodied energy variation in the building structure during the construction stage, in function of span and material type

As per graph above it is possible to observe that the embedded energy consumption in the construction stage is higher for the concrete structure, then for the steel structure, and, lastly, for the timber structure. Although, it may be asserted that in general the energy consumed during construction stage is more or less the same for the three structural systems.

It may be observed that the results, obtained for the construction stage, are not that distant from the ones in case study 7. In fact, concrete structural system was the one with the major embodied energy consumption, 0,056-0,095 GJ/m^2, the same as the concrete structural system from the case study, 0,075 GJ/m^2. The same is not verified for steel and timber structure. In reality, the energy consumption for the steel structural system was almost 6 times bigger than the energy consumption obtained in the case study. The range of results for the timber structure, 0,037-0,024 GJ/m^2, did not match with the one from the case study 7, 0,012 GJ/m^2. However, the energy consumption is more similar than the energy obtained for the steel structure.

With this comparison, it is possible to conclude that the energy consumed during the construction stage is strictly related with the chosen equipment and respective efficiency, as well the travelled distance, chosen vehicle (for concrete larger building transportation was necessary to two travels which duplicate the energy) and building materials weight. It is also very likely that between these three structural systems, the one that requires more energy during the construction stage is the concrete one. In fact, in the case study 7 presented in chapter 4 and in the empirical part of the research of this research the concrete structural system was the one with major energy consumption during the construction stage.

7.2.3 Total Initial Embodied Energy Consumption Discussion

In this sub-chapter the initial embodied energy results are going to be discussed first, individually, for each structural system; then it is going to be discussed the overall initial embodied energy in the three structural systems, and it is going to be reflected which is the structural system that, in long-term, as the most sustainable configuration.

Concrete Structure

In the graph 7.2.3.1 it is presented the initial embodied energy values per square meter obtained for concrete structural system.

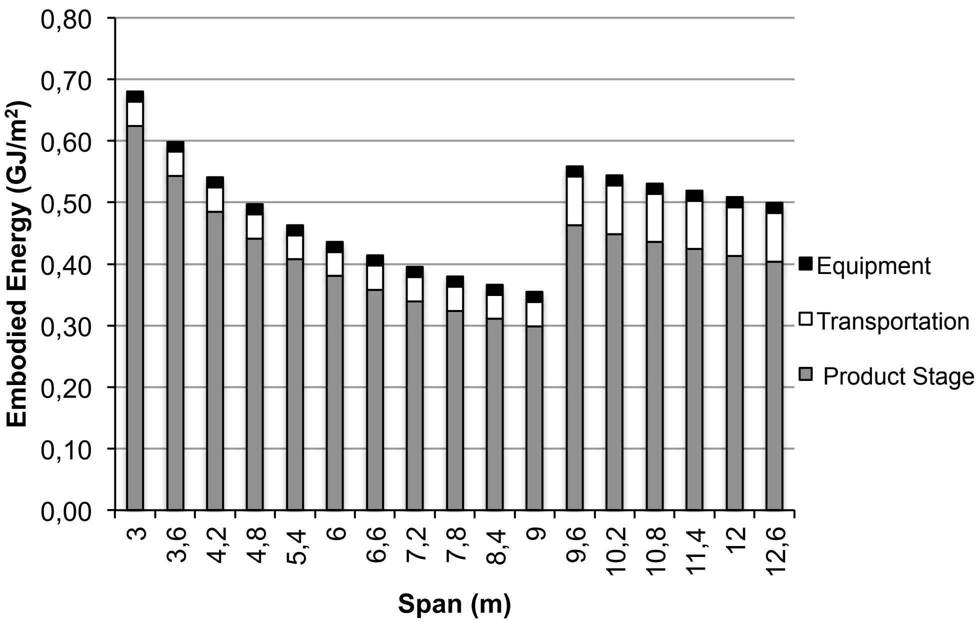

Figure 7.2.3.2 – Initial embodied energy consumed per span in the concrete structure

From the graph it is possible to understand that the product stage is the component with higher influence in the total initial embodied energy consumption. As a matter of fact, the product stage in concrete structural system can represent 86-91%, according to the span size, of the overall initial embodied energy consumption.

The transportation of concrete corresponds to the second component with higher influence in initial embodied energy consumption. Of course the percentage of energy consumed during the transportation is not as representative as the energy in the product stage. However, the estimated energy for concrete transportation was the highest within the three structural systems assessed, with an overall consumption that can reaches 6-11%, depending on the span size.

Lastly, the component with smaller impact in the overall structural system energy consumption corresponds to the equipment usage during construction works. The equipment represents only 2-3% of the energy required to produce an entire concrete structural frame.

Steel Structure

In the graph 7.2.3.2 it is represented the initial embodied energy consumption per square meter required to build the steel structural system.

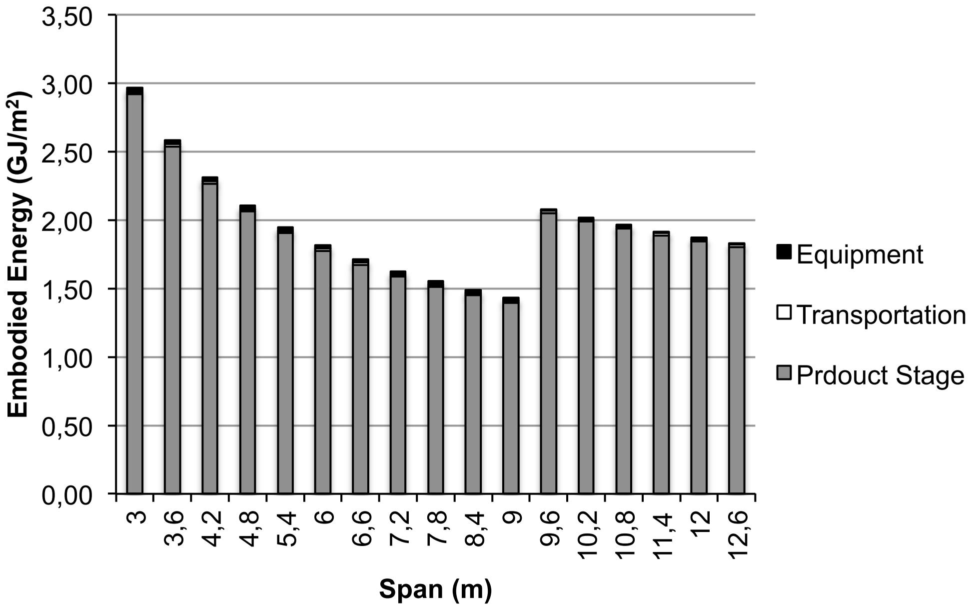

Figure 7.2.3.2 – Initial embodied energy consumed per span in the steel structure

First of all, it is possible to observe that the product stage is the component responsible for the major part of embedded energy consumption. In fact, according to the span size the product stage can account between 98-99% of consumption, which corresponds practically to the entire energy consumption in the steel structure.

Secondly, the transportation energy does not have influence in steel structural system energy consumption; it represents only 1% of overall energy. The steel structure has the lowest transportation environmental impact in comparison with the two other structures assessed.

Finally, the energy consumed by construction equipment can account between 0,4-1% of the total initial embodied energy consumption. It has a more significant than the transportation, however negligible.

Timber Structure

In the graph 7.2.3.3 it is represented the initial embodied energy consumption per square meter required to produce the glued laminated timber structural system.

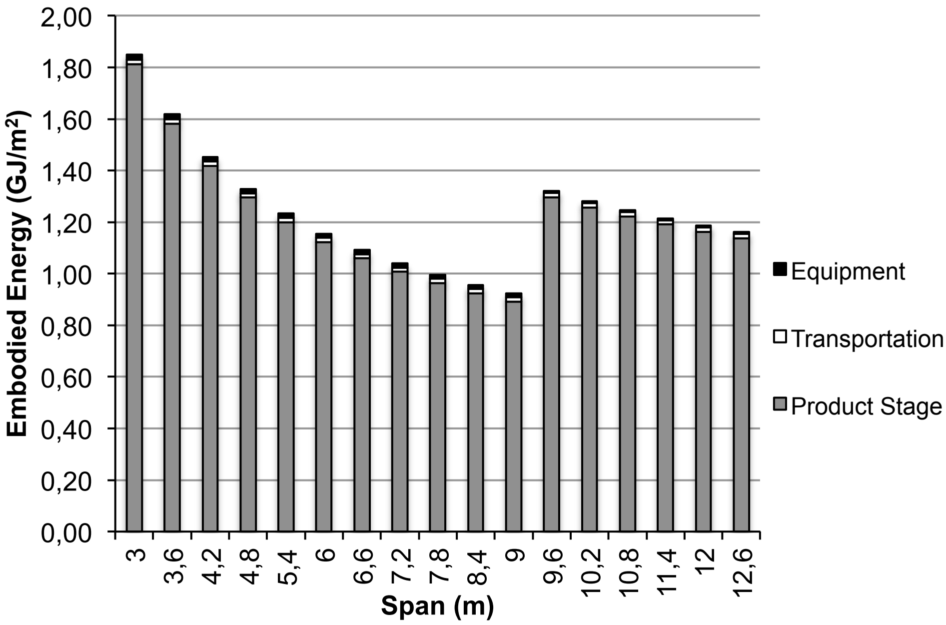

Figure 7.2.3.3 – Initial embodied energy consumed per span in the timber structure

It is possible to conclude that, as in the other two structural systems, the product stage is responsible for the highest initial embodied energy consumption, and can vary from 98-99% of overall energy in the timber structural system.

The energy associated with building materials transportation represents only 1% of total energy consumption.

Lastly, the energy consumed by equipment is slightly bigger than transportation energy, but it is also insignificant in the global consumption; it in general accounts 0,4-1%.

All Structures

After discussing the total initial energy consumption in the three structural systems individually, it is going to be discussed and compared the initial embodied energy results looking at the three structural systems at the same time.

The initial embodied energy consumption estimated for square meter of different buildings structural frames is compared in graph 7.2.3.4.

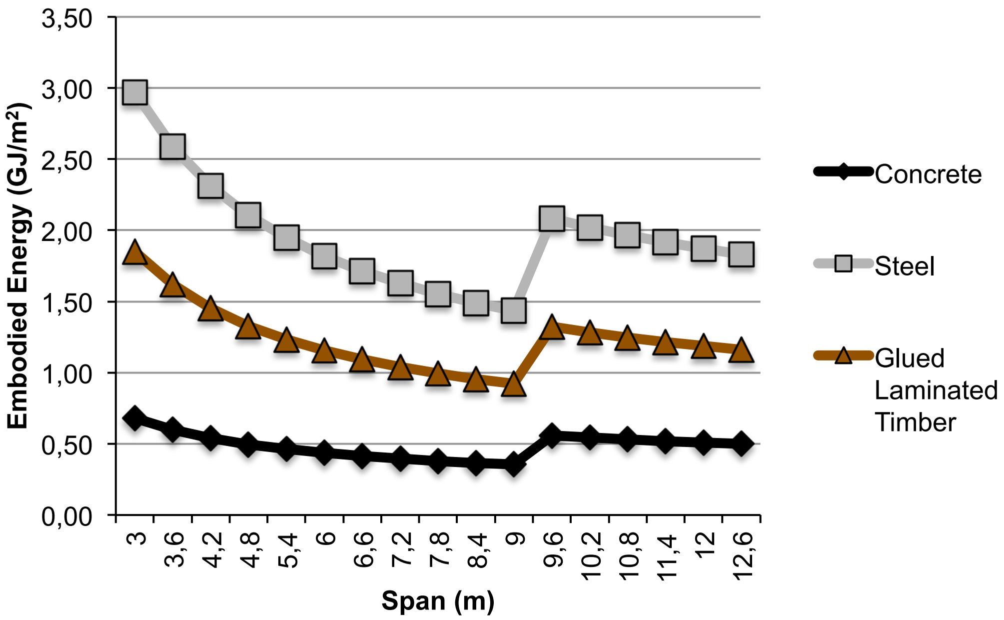

Figure 7.2.3.4 – Initial embodied energy variation in the building structure, in function of span and material type

As shown per graph above, the building frame with higher initial embodied energy consumption corresponds to the structure made of steel, followed by the timber structure, and then the concrete structure.

First of all, it is going to be discussed the impact of building span variation in initial embodied energy consumption per square metre of the different building-frame structures.

From the graph 7.2.3.4 it is possible to observe that the relation of initial embodied energy per square meter to building span is decreasing with longer spans. In the transition from small to large buildings (9-9,6 meters), there is a significant increase in initial embodied energy consumption. This is due to the change in the structural elements dimensions.
In general, it is possible to assert that the variation of span does not have relevant impact in the global initial embodied energy consumption.

Secondly, it is going to be compared the initial embodied energy per square meter of different structures according to the material type.

The results obtained indicate significant variations in initial embodied energy consumption. As a matter of fact, the building structural frame has the same dimensions and it is subject to the same load in the three cases; therefore it is interesting to observe that the material type has significant influence in the embodied energy consumed of a building structure. There is an average increase of 38% of initial embodied energy consumption from the concrete structure to the timber structure. Moreover, the initial embodied energy increases significantly from the concrete structure to the steel structure, by up 75% of the average value.

Thus, the results obtained may suggest that the building structure with less environmental impacts corresponds to the concrete structure, followed by the timber structure, and then by the steel structure.

It is strange to think that using timber to produce a structural-frame is less sustainable than using concrete. Nevertheless, this should only be interpreting from a short-term perspective. In fact, the results estimated reveal that is required more energy to produce a glued laminated timber structure than a concrete structure. As mentioned above, the product stage is responsible for the major energy consumption; and the manufacture process of glued laminated timber requires high feedstock energy, which raises significantly the embodied energy value during the product stage. Also the higher amount of energy consumed might be due to the wood treatment in order to transform the loggings into glued laminated timber, especially during the face bonding lamination and curing process. However, the results calculated are not indicative of lower environmentally performance of timber structure, and better environmentally performance of concrete structure. It is necessary to evaluate the entire life cycle energy of the structures assessed. Buildings are projected for 50 years of life span and it is important to have in mind another component of embodied energy related with buildings maintenance, which was not in the scope of this research: recurring embodied energy. Recurring embodied energy is influenced by the durability of building materials, systems, components and the building life span (Holtzhausen, 2007). As a matter of fact, Cole *et al* (1996) estimated and compared recurring embodied energy in three building structures: concrete, steel and timber, and they conclude that the structure that requires less energy was the timber structure. While concrete and steel require 8 GJ/m^2, the timber structure needs 6,3 GJ/m^2.

Also the higher amount of potential energy stored during the manufacture process of glued laminated timber is a good environmental indicator in the demolish phase of these structures. In fact, the timber products can be readily combusted after their useful lives. Thus, the energy consumed through the life cycle can be reused to generate new energy sources. The same is not verified for concrete, since the incineration is not common in this material, and it is more difficult to extract useful energy at the end of its life service (Robertson, Lam, & Cole, 2012). Moreover, it should be remembered that timber structures store CO_2 during their life cycle, unlike concrete and steel structures.

For the mentioned reasons, the timber structure may have a bigger initial energetic consumption. However investing in a timber structure will have return in the future, since the energy gains, as well as the reducing of CO_2, will be compensated.

Therefore, when projecting structures in buildings design phase it is important to interpret the estimated initial embodied energy values, not only from a cradle-to-gate perspective, but also from a cradle-to-cradle perspective.

7.3 Methodological Limitations

During the developing of this research there were some methodological issues that influence the final results.

First of all, the use of LCA methodology has its owns limitations, which are strongly linked to the nature of LCA itself. Thus, the variations in embodied energy from different studies, may lead to a degree of incomparability between embodied energy results.
Also the number of collected embodied energy case studies (presented in chapter 4) is small to make "universal conclusions" about embodied energy consumption. Perhaps, if the number of case studies collected were bigger, it would be possible to make further comparisons with estimated values of this research, which might lead to great certainty of the results obtained.

Secondly, the database used to perform LCI for the different manufacture stages (product stage and construction stage) come from different sources. This might introduce errors in the final results.

In this research it was intended not enter more errors in the final initial embodied energy results for using a specific LCA software tool. However, the results estimated would be easier to interpret if some software performed the LCA. The calculations performed through the spreadsheet show the total embodied energy consumption in the building structure for each stage, but do not provide important information, such as the energy sources (renewable or non-renewable), and the amount of embodied energy consumed through different processes (feedstock energy versus process energy). In fact, if that information was available the obtained results would have been simpler to interpret and the comparison of results between the different building structures would have been more accurate.

Plus, the sophistication level of LCA performed might influence the results precision. In fact, it was performed a simplified LCA, and it was only evaluated part of the manufacture phase. And, as it was explained in the discussion, it is fundamental to have in mind the entire product life cycle, in order to make more precise conclusions.

Despite of the methodological limitations, it is considered that the adopted methodology provided correct and fast results, in what concerns initial embodied calculations in the building structure and will be helpful as a supporting tool to make decisions in the design phase of buildings.

8. Conclusions and Future Developments

In this final chapter the main conclusions and findings are summarized. It is presented the scientific contribution and some suggestions to carry out future research are presented.

8.1 Conclusions

This study provides an examination of initial embodied energy in buildings structures and highlights the importance of considering embodied energy in the structural design to achieve sustainable construction. Thus, being the main objective of this work, the study of initial embodied energy in building structures, a comparison of the same building frame by varying the span and the material type was carried out in order to properly assess their influence in initial embodied energy consumption.

Through the performance of LCA methodology, it has been verified that the variation of building span does not have a significant impact in initial embodied energy consumption, per square meter, while the material type affects significantly initial embodied energy consumption, per square meter. Regarding the LCA analysis, it is has been found out that timber structures may consume more energy during the manufacture than concrete structures. In addition, it was shown that the selection of the best material for a building structure, based on energy consumption from a single life cycle phase, might be misleading and the building structure with less embodied energy will not necessary be the most favourable in terms of global life cycle energy. Thus, the selection of best building structure design should not be only based on the energy consumed in a life cycle stage, but in the overall energy effects through all the life cycle phases.

Moreover, the initial embodied energy consumption for the manufacture stages, product stage and construction stage, was estimated. On one hand, during the values estimated for the product stage of the concrete structure were 0,30-0,62 GJ/m^2 for small buildings and 0,40-0,46 GJ/m^2 for large buildings; for the steel structure it was estimated 1,40-2,92 GJ/m^2 for small buildings and 1,81-2,05 GJ/m^2 for large buildings; the timber structure the values calculated were 0,89-1,81 GJ/m^2 for small buildings and 1,14-1,30 GJ/m^2. On the other hand, during the construction stage the values estimated for the concrete structure were 0,028-0,058 GJ/m^2 and 0,064-0,074 GJ/m^2 for small and large buildings, respectively; for the steel structure the values estimated were 0,019-0,056 GJ/m^2 for small buildings and 0,018-0,023 GJ/m^2 for large buildings; finally the estimated values for the timber structure were 0,016-0,038 GJ/m^2 and 0,016-0,019 GJ/m^2 for small and large buildings, respectively. In fact, the results obtained are in line with literature review. In fact, this study demonstrate that the product stage is responsible for the highest embodied energy consumption; it can accounts with 86-99% of initial embodied energy, whereas the construction stage is responsible for a much smaller consumption, representing 9-16% of initial embodied energy. Also the embedded energy values for concrete and steel structure are in agreement with the majority of values presented in chapter 4. Even the embodied energy values obtained for the glued laminated timber structure are slightly close with the results from the case study that assessed a glued laminated timber structure (case study 6). Therefore, it is considered that scope of the research was achieved.

It is believed that the main contribution of this work is in the opportunity to use the estimated values to elaborate tables that provide information about the initial embodied energy consumption for a generic structure according to the material type and building span. This would allow engineers to consult those tables before projecting a structure in order to have an overall idea of the initial embodied energy consumption expected. The great advantage of this tables would be the fast decision making during the structural design, since it would not be necessary to perform a LCA in order to estimate the embodied energy values for a variety of possible structure configurations.

8.2 Future Developments

Even though contributions to the scientific knowledge have emerged through this research, it is still necessary a greater comprehension of embodied energy. In fact, there are some unanswered questions and possible opportunities still exist to reduce energy consumption in the building industry.

Therefore, it is suggested to carry out this research with the estimation of recurring embodied energy in the same building structure used in this study. It is considered essential the evaluation of recurring embodied energy in order to understand the overall embodied energy impact in building structures. It is also encouraged to establish different building structures to estimate embodied energy on them. Having more structures with the respective embodied energy consumption, will help in the development of embodied energy tables, which may help engineers during the decision making process of a building structure.

Furthermore, it must be encouraged the use of LCA methodology within the building industry, even if just the performance of the lowest LCA sophistication level (life cycle thinking), because it can make the difference to achieve more sustainable construction in the future.

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Appendix

Initial Embodied Energy

$$EE_i = E_M + E_C \tag{2.1}$$

$$E_M = \sum m_i M_i \tag{2.2}$$

$$E_C = E_{C\_T} + E_{C\_E} \tag{2.3}$$

$$E_{C\_T} = 2\,.\sum_{j=1}^{m}\sum_{i=1}^{n} TD_i^j.\,Q_i.\,EC_i^j \tag{2.4}$$

$$E_{C\_E} = \sum_{k=1}^{l}\sum_{i=1}^{n} D_i^k\,.\,EC_i^k \tag{2.5}$$

$$D_i^k = {}^{Q_i}\!\big/_{C_i^k} \tag{2.6}$$

Recurring Embodied Energy

$$EE_r = \sum m_i M_i \left[\left(L_b / L_{m_i}\right) - 1\right] \tag{2.7}$$

Embodied Energy

$$EE = EE_i + EE_r \tag{2.8}$$

Operational Energy

$$OE = E_{OA} L_b \tag{2.9}$$

Demolition Energy

$$DE = E_D + E_T \tag{2.10}$$

Life Cycle Energy

$$LCE = EE + OE + DE \qquad (2.11)$$