UNIVERSIDADE TÉCNICA DE LISBOA

INSTITUTO SUPERIOR TÉCNICO

LIFE CYCLE ASSESSMENT "FROM CRADLE TO CRADLE" OF BUILDING ASSEMBLIES - APPLICATION TO EXTERNAL WALLS

JOSÉ DINIS SILVESTRE

Supervisor: Doctor Jorge Manuel Caliço Lopes de Brito

Co-Supervisor: Doctor Manuel Guilherme Caras Altas Duarte Pinheiro

Thesis approved in public session to obtain the PhD Degree in Civil Engineering

Jury final classification: Pass with Distinction

Jury

Chairperson: Chairman of the IST Scientific Board

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Doctor Victor Miguel Carneiro de Sousa Ferreira
Doctor Ricardo Filipe Mesquita Silva Mateus
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Doctor Helena Maria dos Santos Gervásio

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ABSTRACT

The aim of this thesis is to improve the coherence and applicability of the environmental, economic and energy life cycle assessment "from cradle to cradle" of building materials and assemblies. To achieve this goal, Life Cycle Assessment (LCA) studies were completed, and two methodologies intended to be innovative at an international level are proposed.

LCA studies of 12 building materials based on production data of Portuguese companies are presented and include innovative products at an international level. A methodology for the selection of a coherent LCA data set to be used as generic for a national context (NativeLCA) was developed. NativeLCA provides data required by European standards, and can also be used to confirm the plausibility of LCA results. Its feasibility was proven in the application to 16 building materials, and potential improvements were identified.

A method (3E-C2C) for the assessment of the environmental, economic and energy performance of building assemblies "from cradle to cradle" using standardised criteria is proposed. 3E-C2C was applied in the design of an external wall for a building in Portugal through the quantification of each dimension of performance using the same unit. This case study tested, validated, and contributed to the improvement of 3E-C2C.

Key-words: building assemblies, building materials, construction materials, cradle to cradle, energy performance, environmental impact categories, external walls, life cycle assessment (LCA), LCA databases, whole-life cost (WLC).

AVALIAÇÃO DO CICLO DE VIDA "DO BERÇO AO BERÇO" DE SOLUÇÕES CONSTRUTIVAS EM EDIFÍCIOS - APLICAÇÃO A PAREDES EXTERIORES

RESUMO

O objetivo desta tese é melhorar a coerência e aplicabilidade da avaliação do ciclo de vida ambiental, económico e energético "do berço ao berço" de materiais e soluções construtivas em edifícios. Para atingir este objetivo, foram realizados estudos de Avaliação do Ciclo de vida (ACV) e são propostas duas metodologias que se pretendem inovadoras a nível internacional.

Apresentam-se estudos de ACV de 12 materiais de construção baseados em dados da produção de empresas Portuguesas, incluindo produtos inovadores a nível internacional. Foi desenvolvida uma metodologia para a seleção de conjuntos de dados de ACV coerentes para serem usados como genéricos num contexto nacional (NativeLCA). Esta metodologia fornece dados requeridos pelas normas Europeias e pode ser usada na confirmação da plausibilidade de resultados de ACV. A sua viabilidade foi provada através da aplicação a 16 materiais de construção, sendo identificadas potenciais melhorias.

Propõe-se um método (3E-C2C) para a avaliação do desempenho ambiental, económico e energético de soluções construtivas "do berço ao berço" usando critérios normalizados. Este método foi aplicado na conceção de uma parede exterior de um edifício em Portugal, sendo cada dimensão do desempenho quantificada na mesma unidade. Este caso de estudo testou, validou e contribui para a melhoria do método.

Palavras-chave: avaliação do ciclo de vida (ACV), bases de dados de ACV, categorias de impacte ambiental, custos no ciclo de vida global, desempenho energético, do berço ao berço, materiais de construção, materiais para edifícios, paredes exteriores, soluções construtivas em edifícios.

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LIST OF ACRONYMS

ADP - Abiotic Depletion Potential

AP - Acidification Potential

BEAS – Building Environmental Assessment System

C2C – Cradle to cradle

CFC - Chlorofluorocarbons

CHB - Hollow fired-clay bricks, horizontally perforated

CDW - Construction and demolition waste

DQI - Data Quality Indicator

ECS - External cladding systems

EIAM - Environmental Impact Assessment Method

EP - Eutrophication Potential

EPD - Environmental Product Declaration

EPS - Expanded Polystyrene

ETICS - External Thermal Insulation Composite System

GFRC - Glass Fibre Reinforced Concrete

GWP - Global Warming Potential

HCFC - Hydro-chlorofluorocarbons

ICB - Insulation cork board (or agglomerate of expanded cork)

ICS - Internal cladding systems

LCA - Life Cycle Assessment

LCB - Lightweight - with LECA - concrete blocks, vertically perforated

LCI - Life Cycle Inventory analysis

LCIA - Life Cycle Impact Assessment

LECA - Light Expanded Clay Aggregate

ODP - Ozone Depletion Potential

PCR - Product Category Rules

PE-Re - Consumption of primary energy, renewable (or renewable energy resources depletion)

PE-NRe - Consumption of primary energy, non-renewable (or non-renewable energy resources depletion)

POCP - Photochemical Ozone Creation Potential

PUR/PIR - Polyurethane/Polyisocyanurate

SLP - Service life prediction

SW - Stone Wool

VRF - Ventilated Rainscreen Façades

WLC - Whole-life cost

WPC - Wood-plastic composite

XPS - Extruded Polystyrene

1. INTRODUCTION

1.1. Relevance of the subject

“Sustainable construction” represents a paradigm to be accomplished by the different actors of public construction works and of private real estate projects. While building designers are increasingly concerned with finding sustainable building materials and assemblies to include in their projects, construction companies try to maximise the sustainability of this field of activity and private investors search for an additional way of promoting their investments, while simultaneously decreasing the impacts on the environment. However, to become “sustainable”, the construction sector needs scientific-based tools that allow the measurement of the “real” sustainability of each project. These tools also have to aid in the process of selection of building assemblies that maximise the environmental, economic (and also social) sustainability of a building, from the different alternatives available on the market.

The environmental impacts of building assemblies vary, as well as the economic and social ones, depending on:

- The origin of their components;
- The resources needed for their construction,
- Their maintenance needs;
- Their expected service life;
- The most probable destiny of the construction and demolition wastes when an element is replaced or the building is demolished.

Therefore, environmental concerns are no longer only centred in the construction stage and on the corresponding environmental impacts, the evaluation of these effects along the life cycle of the construction projects gaining importance. Thus, there is an increasing search for an integrated approach that takes into account the environmental (but also economic) impacts along the life cycle of each of the assemblies that make up the structures with the highest significance in the whole world: buildings. In this context, Life Cycle Assessment (LCA) appears as a relevant approach, despite the need for some scientific and technical adjustments to be adequately applied to this field of knowledge.

1.2. Thesis motivation

Some important questions still arise from the use of LCA methodology in the construction sector. The complexity of these questions even increases when an integrated assessment of the environmental and of the economic impacts has to be completed. Despite the fact that some of these questions are being answered by on-going standardisation initiatives, others need to be deeply examined and discussed, namely via thorough and systematic research studies. This thesis was therefore motivated by some unresolved issues in the framework of recent European Standards[1] concerning the LCA of building materials and the evaluation of the environmental (and also economic and energy) performance of building assemblies. Thus, the main research questions of this thesis are:

- Can a methodology for the selection of a coherent LCA data set of building products (based on available ones in the European context) to be used as generic for a national context be developed?
- Is it possible to simultaneously consider the environmental, economic and energy performance in the process of selection of each building product or assembly?

There are also secondary research questions, correlated with the main ones, for which this thesis will try to find an answer:

- Is it possible to improve the quantity of national LCA research studies on the production of building materials, using site-specific data, in order to provide important data for building designers?
- How to confirm the plausibility of available LCA results from research studies?
- Can LCA methodology contribute to "closing the loop" in the life cycle of building materials?

While all these research questions represent the motivation for this thesis, the next section includes the description of the methods that are proposed to be developed in the scope of this thesis to answer these questions.

1.3. Scope, aims and methodology for thesis development

The area of research of this thesis corresponds to the "assessment of the sustainability of buildings", and is within the broader field of "sustainable construction". The former is an on-going research stream at the DECivil of IST (Civil Engineering, Architecture and

[1] **Recent European standards** - developed by the Technical Committee (TC) 350 of the European Committee for Standardisation (CEN/TC 350).

Georressources Department at the *Instituto Superior Técnico*), namely via the research works completed or supervised by the two supervisors of this thesis (Professor Jorge de Brito, Full Professor and an expert in “Construction Technology” and on the performance of “Materials with recycled content”, and Professor Manuel Duarte Pinheiro, Assistant Professor and Environmental Engineer, who developed the first Portuguese Building Environmental Assessment System (BEAS) in his Ph.D. thesis).

In theory, the research proposed in this thesis could be applied to any building assembly. However, the scope was limited to the assessment (mainly environmental, but also economic and energy, as these three dimensions are linked and are within the priorities of the designer that intends to achieve the principles of sustainable construction) of the most common solutions of external walls of buildings in Portugal. Of the elements of the building envelope, external walls were chosen in order to define a narrower and more realistic scope of the thesis. The importance of external walls in the thermal performance of the building envelope also contributed to this choice, along with the fact that materials from different origins are included in their structure, cladding and insulation (e.g. mineral, polymeric, wood-based and metallic). External walls correspond to the area of the building envelope where a significant part of the thermal exchanges with the exterior occur, their better or worse thermal performance influencing the one of each flat, and of the building as a whole. As the opaque area of the vertical envelope of a building, external walls are also significant in terms of depletion of material resources in their execution and maintenance. This fact increases the importance of the environmental assessment of their construction materials. Moreover, and despite the recognised importance of these assemblies in the global performance of the building envelope, the available information linking their environmental and functional characteristics is still scarce.

Between the different types of external walls, the most common in Portugal were chosen to be studied in this thesis, namely the ones included in the publication used as reference in the national energy certification system of buildings ((Santos & Matias, 2006), from the National Laboratory of Civil Engineering (LNEC)). The external walls used in current buildings in Portugal are cavity walls built with two leaves of hollow fired-clay bricks with a thermal insulation in the cavity. However, single walls with insulation on the external or in the internal surface are gaining momentum.

The main aim of this thesis is to answer the research questions enunciated above taking into account the procedures included in recent European Standards, in order to improve the coherence and to ease the applicability of the environmental, economic and energy life-cycle assessment from cradle to cradle of building materials and assemblies. To achieve this goal, some intermediate objectives have to be accomplished:

- Completion of national LCA research studies on the production of building materials used in external walls, using site-specific data;
- Development of an innovative methodology for the selection of a coherent LCA data set of building products to be used as generic for a national context, which can also be used to confirm the plausibility of available LCA results from research studies;
- Development of a method for the simultaneous assessment of the environmental, economic and energy performance of external walls of buildings, which is intended to be innovative at an international level and that can aid in the minimisation of the depletion of many important resources;
- Setting up of a framework for the environmental assessment of construction and demolition wastes (CDW) to improve the contribution of LCA methodology to "close the loop" in the life cycle of building materials.

For the accomplishment of these aims it is necessary to establish the nature and the connection of the individual tasks of this thesis that, in conjunction and after being concluded, will allow the achievement of that desideratum:

1. The research work started with the identification of the Portuguese companies that are able to provide data for the LCA studies (of the production of building materials) intended to be completed in the scope of this thesis. After the conclusion of these studies, the corresponding results had to be organised and analysed in accordance with recent European standards;
2. A methodology to aid in the selection of a coherent LCA data set of building products (from available ones in the European context and that can be used as generic for a national context) was then developed. This methodology can also be used in the confirmation of the plausibility of the LCA results obtained at a national level in the last step;
3. Next, extending the scope of the assessment to the whole life cycle of building products, a framework for the environmental assessment of CDW was developed based on the provisions included in recent European Standards and in the experience from their application in national LCA studies of building products;
4. The LCA data sets of building products selected to be used as generic for a national context were then applied in the LCA study from cradle to cradle of several alternatives for external walls (from the extraction of raw materials to the production of their compo-

nents, including the transportation and on-site application of these elements, and their use and end-of-life stages);

5. Finally, an innovative method that provides the simultaneous assessment of the three dimensions of performance - environmental, economic and energy - of external walls of buildings from cradle to cradle, and follows recent European Standards, was proposed.

These tasks were preceded by a comprehensive state-of-art concerning the sustainability of the built environment, the LCA methodology, and the connection between the latter and the construction industry. The scope of the bibliographic research was narrowed to the LCA of building materials and assemblies, namely of external walls, in order to establish in an unequivocal manner the frontier between the research works already finished at a national and at an international level and the scope and the innovation of this thesis. This work resulted from an extensive search and revision of scientific studies in order to allow the collection of essential information for the definition of the thesis roadmap and adequately justify its relevance and the need for the research study proposed.

In this domain of engineering science, the most relevant scientific studies are published in conference proceedings and in international scientific journals. Those most related with the scope of this thesis are:

- Conference proceedings: SB series (World and regional Sustainable Building Conferences of 2000, 2002, 2005, 2007, 2008, 2010 and 2011, with the author presenting papers in the last two (Silvestre *et al.*, 2010a, 2011a));
- International scientific journals:
    - The International Journal of Life Cycle Assessment (Springer - Germany, included in the Environmental Engineering and Environmental Sciences categories of the ISI-Journal citation reports);
    - Building and Environment (Elsevier Science - United Kingdom, included in the Environmental Engineering, Civil Engineering and Construction & building technology categories of the ISI-Journal citation reports);
    - Journal of Environmental Engineering (American Society of Civil Engineers – USA, included in the Environmental Engineering, Civil Engineering and Environmental Sciences categories of the ISI-Journal citation reports);
    - Journal of Cleaner Production (Elsevier – United Kingdom, included in the Environmental Engineering and Environmental Sciences categories of the ISI-Journal citation reports);

   - Construction and Building Materials (Elsevier - United Kingdom, included in the Materials Science and Construction & building technology categories of the ISI-Journal citation reports).

During the development of this thesis, the author developed some additional activities, both at national and at international levels, which contributed to the accomplishment of the individual tasks referred to above:

- Co-authored four papers presented in International conferences (Silvestre *et al.*, 2010a, 2010b, 2011a, 2011b) and four papers presented in National conferences;
- Was invited to be a speaker at three national conferences;
- Collaborated in the development of five proposals for national research projects (de Brito - Coord., 2011, 2012; Ferreira - Coord., 2009a, 2009b; Pinheiro & Coord., 2009);
- Collaborated with a national company in the development of a winning application for the "Good Environmental and Energetic practices" award promoted by the "Portuguese Entrepreneurial Association" (*Associação Empresarial de Portugal* - AEP) in the scope of the "BenchMark A+E" project (AEP, 2012);
- Took part in five training courses related to the scope of this thesis (four in Portugal and one abroad);
- Became a member: of the technical commission of the national EPD program for the built environment (DAPHabitat); of the national mirror group of the CEN/TC 350 - "Sustainability of Construction Works" (and was responsible, along with other national experts, for the translation of an European standard and a Technical Report); and of the W115 "Construction Material Stewardship" Commission of the *Conseil International du Bâtiment* (CIB);
- Completed an internship in January-February 2012 in the Environment Division of the *Centre Scientifique et Technique du Bâtiment* (CSTB), in Grenoble, France.

1.4. Thesis structure

This thesis is composed of eight chapters and corresponding appendixes.

Chapter 1 is the introduction of the thesis, including some initial considerations related to the relevance of the subject proposed to be studied. The motivation of the thesis is presented next through its main and secondary research questions, followed by the enunciation of the scope and aims of the thesis. Then, the tasks that are proposed to be completed in this thesis to accomplish these aims are described.

Chapter 2 – Life Cycle Assessment (LCA) begins by discussing the unsustainability of the built environment, presenting afterwards the (completed and on-going) initiatives worldwide to improve the sustainability of construction materials, assemblies, and buildings. Then, the LCA methodology is summarily presented, besides its application to the construction industry at a national and at an international level. This chapter ends with a review of LCA results of international research studies on the environmental impact of a building’s external walls.

Chapter 3 – External walls of buildings presents a clear definition of the object of this thesis - the opaque areas of the external walls of buildings. Then, the division of this object into its primary components is presented (the elements of the wall structure, the insulation material, the internal and external claddings and the ancillary components), along with the description in detail of the latter. The most common external wall solutions in Portugal are characterised in detail in **Appendix 3.I**, and their characterisation is made based on the main Portuguese references in this field. The functional requirements that external walls of buildings have to achieve as a whole are presented next, followed by the description of the ones that should be accomplished by each part of its primary components.

Chapter 4 – Life Cycle Inventory analysis (LCI) is devoted to this specific phase of the LCA methodology, both in theoretical and practical terms. The corresponding procedures are described in detail, namely when LCA study is applied to building products. A summary of the stages of a building product’s life cycle, and of the corresponding environmental impacts, are presented next. Finally, the detailed LCI of the “Product stage” of the 12 building products studied in this thesis is presented, based on the actual production by a Portuguese company. **Appendix 4.I** includes an example of a form that was filled in during the LCI study of one of these products.

The **Life Cycle Impact Assessment (LCIA)** phase of the LCA methodology is presented in detail in **Chapter 5**, along with its application to the building products studied in this thesis. This chapter also includes a thorough review of LCA tools available in the market, in conjunction with the corresponding databases. The LCIA of the building products studied in this thesis is preceded by the enunciation of the assumptions that were considered at this stage of a LCA study, and the justification of the choice of the Environmental Impact Assessment Method (EIAM) and of the environmental categories. Then, the LCA results of the studies completed in the scope of this thesis are presented in detail per life cycle stage and environmental category.

Chapter 6 - LCA data sets of construction materials and products: selection and benchmarking presents the development of an innovative methodology - NativeLCA - for the selection of a coherent LCA data set of construction materials and products to be used as generic data for a national context. The first part of this chapter is therefore devoted to the presentation of the aim, scope, and procedures of this methodology. Then, the application of this methodology to 12 case studies is presented, four in its full form and eight in its “simplified” form. In the first case, the application of NativeLCA allows the selection of coherent LCA data sets for building products not yet studied in the Portuguese context (or resulting from Portuguese LCA studies of other authors, but not all third-party verified). For the second group of materials, the aim is the verification of the plausibility of the LCA studies completed in the scope of this thesis. The results of these studies can therefore be used in LCA of building assemblies or buildings while externally verified LCA databases (e.g. based on EPD) are not available at a national level. The appendixes of this chapter summarise the main characteristics of the databases chosen to be included in this study (**Appendix 6.I**), and the information available in generic data sets, EPD, and National and European average LCA data sets for the construction materials and products selected for this study (**Appendix 6.II**), while **Appendix 6.III** presents the flowchart of NativeLCA implementation and the decision-making table of this methodology.

Chapter 7 is devoted to the **Environmental, energy and economic assessment of external walls of buildings from cradle to cradle** and starts by proposing a method **(3E-C2C)** with this aim that can be applied in the selection of construction materials or assemblies closely related to a building’s thermal performance. This method is supplemented by the 3E *cost*-C2C approach, which establishes weights for each dimension of performance. After the presentation of the LCA results from cradle to cradle of the external wall alternatives chosen to be studied in this thesis, the 3E-C2C method is applied to make their comparison and to select the one with the best performance in each aspect (environmental, economic, and energy), and in the integrated assessment of these three dimensions. This chapter ends with a discussion about the influence of the use rate of the heating and cooling equipment in the choice of the best alternative for external wall and with a sensitivity analysis of the influence of the location of the corresponding building in the same selection. **Appendixes 7.I** and **7.II** correspond to papers developed in the scope of this thesis and already submitted for publication in journals included in ISI-Journal of Citation Reports, while **Appendix 7.III** presents the composition, dimensions, thermal performance, and maintenance, repair and replacement operations of the external wall solutions evaluated in this chapter.

The final remarks of this research work are presented in **Chapter 8**, along with a summary of the main conclusions taken during its development. Finally, and in order to provide the continuation of the studies initiated with this thesis, the most promising, and ready to be developed, research streams are proposed.

1.5. References - Chapter 1

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2. LIFE CYCLE ASSESSMENT (LCA)

2.1. The unsustainable built environment

The environmental, economic and social impacts of the built environment are undeniable and, perhaps, unavoidable. Building and construction industries have the largest share in the use of natural resources, land, and in materials extraction. Energy use, liquid and solid waste generation, transport (of construction materials) and consumption of hazardous materials are also negative environmental impacts of this sector (UNEP, 2007). Despite this, information and data about the global impact of the built environment is not systematically collected and analysed. This assessment should comprise a myriad of components and facilities, including private and public construction, and every input and output of the life cycle stages of the built environment (Horvath, 2004). If it is possible to quantify its negative impacts, it should be possible to diminish them.

Worldwide, the “International Energy Agency” estimates that 30 to 40% of all primary energy is used in buildings. In OECD (Organisation for Economic Cooperation and Development) countries, buildings are responsible for about 30% of primary energy consumption and for approximately 30% of the greenhouse gas emissions. The residential sector is the most wasteful, followed by non-residential buildings (offices and public buildings) and hospitals (UNEP, 2007). Buildings are also estimated to be responsible for 40% of the materials and energy flows, 18% of the freshwater withdrawals and 25% of the wood harvest all over the world (Augenbroe *et al.*, 1998) cited by (Horvath, 2004)).

In the United States, the construction industry represents about 8% of the gross domestic product (Kibert, 2008). In this country, construction and operation of buildings account, directly or indirectly, for: 39% of total energy use (72% of electricity consumption), 38% of greenhouse gas emissions, 40% of raw materials used, 30% of waste output (136 million tons/year) and 14% of potable water consumption (USGBC, 2010).

Construction is the largest single industrial sector in the European Union, with around 30 million employees (CIB, 1999). Housing makes up 20 to 35% of the total environmental impact of products and the construction materials used in residential buildings are responsible for 3 to 4% (EC, 2006). Residential and commercial buildings represent an important part (about 40%) of the total final energy consumption and CO_2 emissions, about half of the emissions not covered by the “Emission Trading Scheme” and approximately 40% of all man-made waste in this community of countries. Activities related to buildings are also important to the European Union economy (9% of the “Gross Domestic Product” - GDP - and almost 8% of the employment). All possible reductions in the impact of a building lead to significant economic, social and environmental benefits and the reduction potential of this kind of construction is high (namely in CO_2 emissions) and has negative or low abatement costs (CIB, 1999; EC, 2008; UNEP, 2007).

In Portugal, in the 2006-2007 period, construction activities represented about 12% of the gross added value of the economy and buildings represented more than 60% of all construction activities (INE, 2010; Santander-Totta, 2008). The Energetic Balance of 2006 of the “Directorate-General for Energy and Geology” (DGEG) concluded that buildings in Portugal consume 29% of final energy (a similar value was revealed in 2007 (DGEG, 2010)) and consume 62% of electric energy (ADENE, 2009). In Lisbon, the consumption of primary energy in buildings is still greater, with 46%, followed by transports (42%) and industry (10%). Service buildings (offices, health, education and commercial) are responsible for 65% of this consumption and residential buildings for the remaining part (35%) ((Sá *et al.*, 2005) cited by (Pinheiro, 2008)).

The enumeration of the global impacts of the construction industry, and, chiefly, of the impact of the construction, use and rehabilitation of buildings, proves the urgency of proactive interventions in the built environment at a national, European or global level. The severity of this condition has already been recognised at an international level. Thus, global actions, principles of action and Directives have been developed and put into practice to support and guide the implementation of increasingly sustainable design and construction practices.

2.2. The sustainability of construction

In the 1990s, the increasing awareness of the importance and environmental responsibility of the construction sector led to the emergence of the “Sustainable Construction” concept. This view originated from an international movement which defended Sustainable Development and was initially proposed by Professor Charles Kibert in the Powell Centre for Construction and Environment (University of Florida, USA) in 1992. The first “International Conference on Sustainable Construction”, organised by the Powell Centre and Task Group 16 (TG 16 - Sustainable Construction) of CIB (*Conseil International du Bâtiment* or “International Council for Research and Innovation in Building and Construction”) was held in November 1994 in Tampa, Florida, USA. Sustainable Construction was defined by CIB - TG 16 as “(…) the creation and operation of a healthy built environment based on resource efficiency and ecological principles." The revelation of this concept was followed by the development of directions for its practical implementation and for the evaluation and recognition of the environmental attributes of construction, particularly of the buildings in urban areas (Cepinha, 2007; Kibert, 2003). The CIB - TG 16 defined seven principles of Sustainable Construction to inform decision-making during all stages of design, construction and use of the buildings and to be applied when evaluating components and other resources needed (which were materialised in a framework - see Figure 2.1) (Kibert, 2008):

1. **Reduce** resource consumption;
2. **Reuse** resources;
3. Use recyclable resources (**recycle**);
4. Protect **nature**;
5. Eliminate **toxic components**;
6. Apply whole-life costing (**economics**);
7. Focus on **quality**.

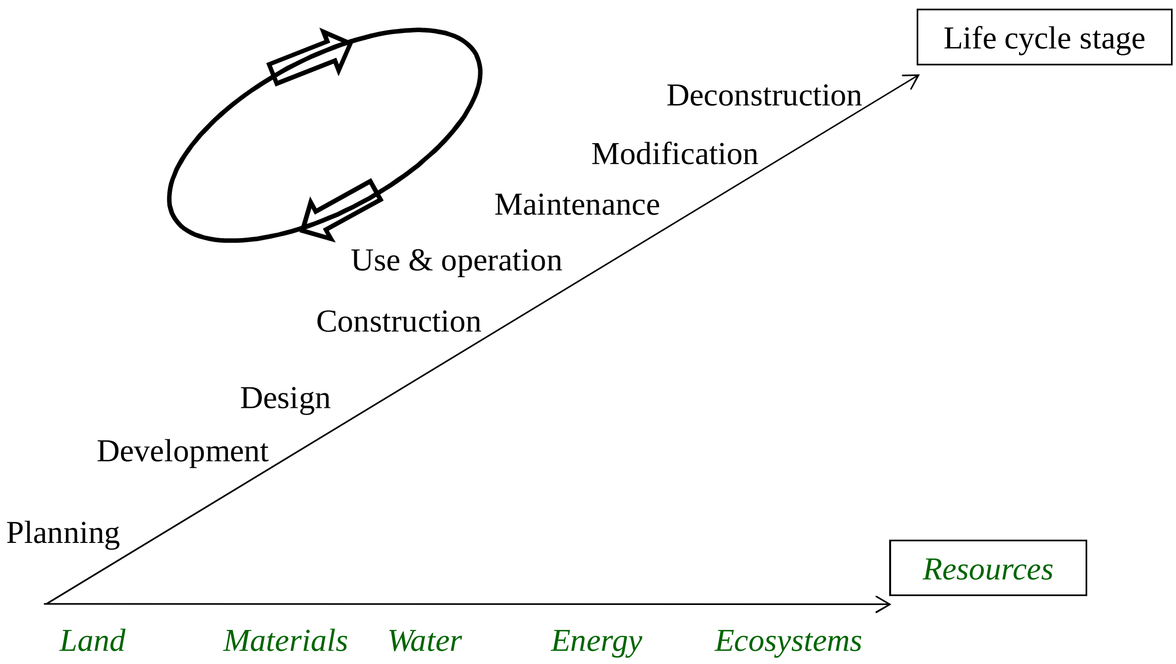

Figure 2.1 - Framework for sustainable construction (adapted from (Kibert, 2008))

After more than fifteen years, it is consensual that Sustainable Construction is not a static concept and still has to answer two major challenges: the minimisation of the negative impact of construction on the environment and the creation and preservation of healthy conditions for building users and neighbours. The response to these challenges shall also take into account the entire life cycle of a project that will last for a long time (Cepinha, 2007). The importance and vigour of this research area are exposed in many yearly conferences, innumerable books and journals published, academic degrees, research centres in different countries and in the products that are continuously launched on the market and that identify themselves with Sustainable Construction principles (Kibert, 2003). This movement has recently been described by Professor David Orr as "(…) a revolution in building design (…) that is manifest in buildings that function as ecologies existing in larger ecologies" (Kibert, 2008).

CIB has been one of the most important organisations in international research and cooperation in the building and construction sectors since the 1950s. This organisation had a primordial role in Sustainable Construction research early in 1995. In 1998, at its World Congress (Gavle, Sweden), CIB impelled the creation of "Agenda 21 for Sustainable Construction". This document would build a bridge between International Agendas, National and local actions related to the built environment and the construction sector. "Agenda 21 for Sustainable Construction" was published by CIB in 1999 (with the collaboration of other international organisations) and has the following primary goals:

- To create a global Framework and terminology that will add value to all national or regional, and sector-based Agendas;
- To create an Agenda for CIB activities in this field, and for co-coordinating CIB with its specialised partner organisations;
- To provide a source document for defining R&D (research and development) activities.

The achievement of these goals wishes to answer the greatest challenges that the construction industry had (and continues to have) to overcome (CIB, 1999; Gaspar, 2004; Pinheiro, 2006):

- The promotion of energetic efficiency;
- The reduction of the use and consumption of potable water;
- The selection of materials based on their environmental performance;
- The contribution to a sustainable urban development.

CIB still has various workgroups linked to the Sustainable Construction theme (namely in the areas of "Energy and Climate Change and the Built Environment", "Construction Materials Stewardship" and "Smart and Sustainable Built Environments"). This proves that this research area is not exhaustive and that there are yet different topics to be developed and challenges to be overcome (Figure 2.2).

"Agenda 21 for Sustainable Construction" only took into account the reality of developed countries. Therefore, years later, an interest arose to develop a similar Agenda, but committed to describe definite actions in developing countries in the short, medium and long-term. The "Agenda 21 for Sustainable Construction in developing countries" was launched in 2002 by "CSIR - Building and Construction Technology" (a South-African research agency) with financial support from various national and international organisations (Bakens, 2003).

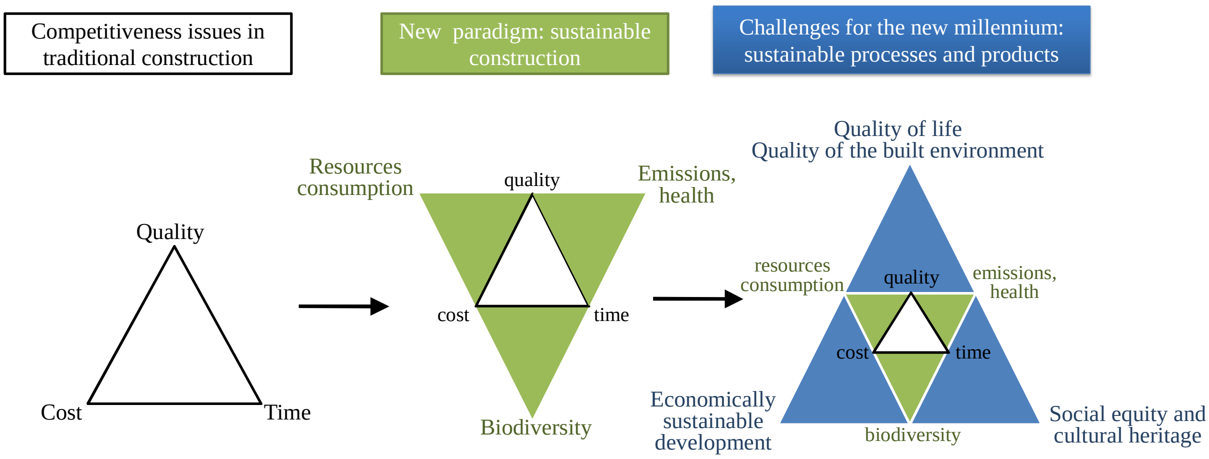

Figure 2.2 - Evolution of the concerns in the construction sector (adapted from (Pinheiro, 2006))

"Agenda 21 for Sustainable Construction" resulted from Agenda 21, which delineated strategies of Sustainable Development for this century. Agenda 21 was signed by over 178 countries at the Rio Earth Summit, organised by the United Nations in Rio de Janeiro (Brazil), in 1992 (Gaspar, 2004).

The United Nations Environment Programme established the "Sustainable Buildings and Climate Initiative" in 2006 (UNEP-SCBI) that joined key stakeholders in this sector (industry, business, governments, local authorities, research institutions, academia, experts and NGOs) all over the world to promote sustainable building practices worldwide (UNEP-SCBI, 2010).

In 2007, at the European level, the European Commission identified "Sustainable Construction" as one of the six markets with the potential of becoming a leading market. This means that the activity linked to Sustainable Construction can rapidly bring about visible advantage for Europe's economy and consumers ((EC, 2007) cited by (Pires, 2008)).

The "European Construction Technology Platform" (ECTP) is an open organisation that aims to improve the performance and competitiveness of this sector with the support of construction companies, research centres, universities and trade associations. There are already 15 National Construction Technology Platforms all over Europe that belong to this network, including the Portuguese and Spanish ones (both with an extensive plan of activities already in progress). ECTP has a "Vision" for the design and construction sector that proposes two interlinked key goals to be achieved by 2030: meet client/user requirements and become sustainable. To accomplish the second aim, the following recommendations have to be followed: reduce resource consumption (energy, water and materials); reduce environmental and man-made impacts; sustainable management of transport and utility networks; develop a living cultural heritage for an attractive Europe, and improve safety and security (ECTP, 2005).

"The vision of a Sustainable Smart-Eco building (SSE) in 2030", that is described in the final report of the EU-Funded Project "Smart-ECO", includes two important components out of ten. The first one is that the building will be "designed or refurbished from a life cycle perspective (…) cover(ing) planning, design, construction, operation and maintenance, renovation, and end of life (phases)". The second component is that the building will "have its environmental impact lessened over the estimated or remaining service life (…) taking into consideration regional and global requirements, resource consumption (energy, material and water) and waste and emissions reduction (to air, water and soil).". The ultimate vision requirement would be a SSE building which has the combination of: zero energy, zero net resource use and zero impact (CIB, 2010).

In France, research progresses to make all buildings "*Bâtiments à énergie positive*" by 2020. This means that, by that year, they will produce more energy than the quantity they consume in their operation (CSTB, 2010).

In 1999, the book "A Green Vitruvius - Principles and practice of sustainable architectural design" was published within the THERMIE programme of the European Commission by the "Architects' Council of Europe" (ACE) and other organisations (Lewis, 1999). A Portuguese edition was released by the "Portuguese Architects Association" (*Ordem dos Arquitectos*) two years after (Lewis, 2001) and is a reference "for the Architect that, serving the client, wants to design (…) a sustainable architecture". To support this, it points out paths to design and construction processes, includes concerns about the comfort of the inhabitants, presents strategies in the choice of construction assemblies, and describes some methods to evaluate the environmental performance of buildings (Lewis, 1999).

In Portugal, the "National Strategy for Sustainable Development" of 2002 (developed by the Environment Institute - *Instituto do Ambiente*) proposes the "development of a policy of sustainable housing in order to revalue outskirt areas and degraded residential areas and promote the rehabilitation of the built environment", laid out in four principles (Pinheiro, 2006):

1. Durability, namely of construction materials;
2. Flexibility (adaptation to different uses along the building life cycle);

3. Social cohesion, guaranteeing the accessibility to dwellings for the families with less resources and independence, guaranteeing the sense of community and improving social solidarity;
4. Ecologic efficiency, including the rationalisation of land use and of the consumption of construction materials, energy and water.

The “National Strategy for Sustainable Development” was reviewed in 2007, in order to meet the guiding principles of the European strategy. The main purpose of this document is the development of a sustainable development model for Portugal that turns it in one of the most competitive and attractive countries of the European Union by 2015, namely by accomplishing high economic, environmental and social standards ((CM, 2007) cited by (Gervásio, 2010)).

In 2006, the European Directive 2002/91/CE of 16 of December was transposed to national law, in order to comply with European legislation and promote the reduction of consumption of electric energy in buildings via the improvement of their energetic efficiency. The three corresponding law decrees (78, 79 e 80/2006) allowed the creation of the “National system of energy certification and indoor air quality in buildings” (*Sistema Nacional de Certificação Energética e da Qualidade do Ar Interior nos Edifícios* - SCE) (RCCTE, 2006; RSECE, 2006; SNCEQAIE, 2006). This certification system makes it compulsory for the construction, sale or rental of a building or house to be accompanied by the corresponding certification of its energetic performance.

In 2007, Lívia Tirone (Architect) published the book “Sustainable Construction” (in Portuguese), which includes the design principles followed in her work developed over the last two decades (Tirone & Nunes, 2007). The book was followed by the launch of the “Sustainable Construction Initiative” that has coordinated a set of communication actions (conferences, workshops, seminars and road shows) in Continental Portugal, Madeira and Azores since 2008.

The “Platform for Sustainable Construction - *Plataforma para a Construção Sustentável*” was founded in 2007 and has its head office in the central region of Portugal. The activity of this platform comprises the organisation of conferences and congresses (such as the congresses CINCOS - Innovation in Sustainable Construction, in 2008, 2010 and 2012) which potentiates the interrelation and the creation of networks between its members (researchers, private companies and the construction industry) that promote sustainable construction and innovation. Within the call for the “National strategic reference framework“ (NSRF; *Quadro de Referência Estratégico Nacional* - QREN) for the recognition of poles and clusters of competitiveness (Strategies of Collective Efficiency - *Estratégias de Eficiên-*

cia Colectiva (EEC)), the cluster “Sustainable Habitat - *Habitat Sustentável*” was recognised in July 2009. The headquarters of the cluster is in Aveiro University and its driving forces are the “Platform for Sustainable Construction” (that manages the cluster), the “Technological centre for ceramic and glass” (*Centro Tecnológico da Cerâmica e Vidro* - CTCV) and the “Institute for research and technologic development in construction sciences - ITeCons” (these last two in Coimbra). The public (research centres and governmental institutes) and private (as the producers of construction materials) entities that belong to the cluster have prior and enlarged access to European Union financial support (PCS, 2010).

Despite all the finished and ongoing initiatives at national and international levels, the determination of the effects of building materials and products in the environment is still a central unresolved problem in sustainable construction (Kibert, 2008). The following sections of this Thesis (2.2.1, 2.2.2, 2.3 and 2.4) describe the certification systems, databases and methodologies of evaluation that ease the work of the designer that wishes to choose ecological materials and products for a building.

2.2.1. Environmental certification of construction materials and assemblies

The pursuit of a more suitable way to communicate the environmental impacts of construction materials to everyone involved in the production chain continues to be a problem not totally solved. The number of players in the construction industry is huge and the spatial distribution of the trading of construction materials and of the operation of construction companies is global. Therefore, the dissemination of environmental information related to the construction industry that “touches” everyone involved is a herculean work but is the only way of inducing them to demand construction materials with better environmental performance (Horvath, 2004).

The “Integrated product policy” (IPP) strategy proposed by the European Commission in 2003 intends to reinforce and focus on the environmental policy of products in order to develop a market for “greener” products. Construction is one out of ten priority sectors of this strategy (Almeida *et al.*, 2010). To achieve this goal, the strategy aims for:

- A reduction of the environmental impacts;
- An extension of the responsibility of the producer to the complete life cycle of the product from cradle to grave by the use of suitable criteria and evaluation systems;
- The availability of information about the environmental performance of the products for the consumers.

To realise these goals, *ecodesign* (ecologic design) of products and the creation of information and stimulus of the efficient use of more ecologic products should be motivated (EC, 2003). The implementation of this strategy at a European level is giving rise to the birth of criteria for ecologic purchases (green procurement). The use of this type of criteria in public purchases, in particular, can lead to a positive differentiation of the products that comply with the requirements demanded, and to the implementation of environmental improvements in the production processes of the products with the worst performance.

These principles must be adopted by the construction industry as soon as possible, despite the fact that the European standardisation that supports the assessment of construction sustainability is still in progress. However, some countries in Europe and outside already have voluntary systems for environmental certification of construction products. There are also multinational producers of construction materials that have developed "Environmental product declarations" based on the standards suitable for all kinds of industries. Taking this panorama into account, the following section of this Thesis presents the environmental certification systems of construction materials and assemblies existing all over the world. The information already available in Portugal concerning the environmental performance of these elements is highlighted, namely the foreign environmental certificates assigned to construction materials produced in Portugal and the construction products that already have "Type III environmental declarations" (produced by multinational companies that develop these declarations based on standards suitable for all kinds of industries).

The main goals of "Environmental product declarations" are to (Rocha, 2010):

- Provide information about the environmental performance of the product;
- Stimulate the supply and demand of products with less environmental impacts throughout their life cycle;
- Create potential factors of positive differentiation in public and private purchases;
- Induce an improvement in the environmental profile of the products of other suppliers, leading to a reduction of the environmental pressure of that category of product.

The environmental certification of construction materials is still at a preliminary stage and in a voluntary regimen in most countries, namely in Portugal. The European Directive in development related to "Sustainability in Construction" foresees the generalisation of the use of "Environmental product declarations" in all construction products by 2016 (Dias, 2010). This irreversible process is already in progress, namely in France, where regulations are being prepared to obligate all companies to disclose the carbon footprint (or even a broader group of environmental impacts) of their products. The standard "EN ISO

14020:2001 - Environmental labels and declarations - General principles" (IPQ, 2005) supports the processes of environmental certification of different products, including the environmental declarations of Types I, II and III.

2.2.1.1. Type I environmental declarations - environmental labelling

Type I environmental declarations can be awarded within a voluntary programme developed by a private or public organisation. It awards a license to the producer to use environmental labelling on its products. Each label points out that a product is preferable in terms of some environmental requisites that consider its life cycle, with or without a "Life Cycle Assessment" (LCA, a methodology described in detail in section 2.3) study (IPQ, 2006).

The "European Union Eco-label" (EU *Ecolabel*) is a voluntary system of certification of the environmental performance of different groups of materials. Created in 1982 (and revised in 2000 and 2010), this system defines different demands for different groups of products. The requisites are periodically revised (usually every 3 years) to take into account the permanent scientific and technological evolution, and to allow the introduction of improvements in the environmental performance of the products. This labelling is assigned with the support of tools of environmental evaluation such as LCA studies, and the organisation responsible for this labelling in Portugal is the "Directorate General for Economic Activities" (*Direcção Geral das Actividades Económicas* - DGAE) (Almeida & Machado, 2009).

The construction materials that can apply for a EU *Ecolabel* are only paints and varnishes (for interior or exterior use) and hard floor coverings (initially only natural stones, concrete paving units, terrazzo tiles, ceramic tiles and clay tiles) (Figure 2.3). The revision of the EU *Ecolabel*, completed in 2010, allowed for the group of floor coverings to include wooden and textile coatings, and ceramic tiles for walls. The webpage of EU *Ecolabel* (UE, 2010) contains a database of the products that already have this labelling. Within this database, it is possible to confirm that there are products (that belong to paint, varnish and floor covering groups) that are available in the Portuguese market. However, in the hard floor covering group (mainly ceramic, 141 from Italy, 8 from France and 27 from Spain) and in the group of exterior paints and varnishes (only two products from Denmark) none of the products is produced in Portugal. The causes of this lacuna may be related to the production technology in use in Portugal and with the high level of exigency of the requirements applied to the environmental performance of the products (Almeida & Machado, 2009). In the group of inner paints and varnishes, about a quarter of the products are produced in Portugal (18 out of 68, the remaining being from France - 31, Spain - 13, Germany - 5 and Sweden - 1).

The last revision of the EU *Ecolabel* included measures to encourage the harmonisation of various environmental labelling systems that coexist in Europe (or at least the level of exigency of and the compatibility between the systems) (UE, 2010). The most well known systems in Europe are the German "Blue Angel" (*Blaue Engel* in German) and "White Swan" (*Nordic Ecolabel*, in use in Norway, Finland, Iceland, Denmark and Sweden), but not all of them comprise a complete LCA approach. The following is a description of the existing environmental labelling systems all over the world, which do not contain any material on sale in Portugal (within the research made).

The German "Blue Angel" is an environmental labelling system, created in 1978 and coordinated by the "Federal Ministry for Environment", which comprises about 90 product categories. The characteristics evaluated include the saving of resources and the reutilisation of residues. The system also makes a global evaluation of the environmental quality of the product in comparison with other products of the same category (Bento, 2007). Among the construction materials (mainly from Germany) that already have this label, there are: insulation products that use recycled glass (glass foam) or paper, wooden floor coverings, and suspended ceiling solutions (FME, 2010).

The "White Swan" of the Scandinavian countries (*Nordic Ecolabel*) is a programme, started in 1989 and comprising 65 categories of products, which applies an environmental evaluation using a life cycle approach (Figure 2.4). The categories related to buildings are: construction materials; heating; dwellings; kitchens and bathrooms; paints and varnishes. This last group, for example, only contains materials produced in Scandinavian countries and there are no construction materials in this programme from Portugal, Spain or France (ES, 2010; Jonsson, 2000).

In Spain, the "Association of Normalisation and Certification" (AENOR) created *AENOR - MEDIO AMBIENTE*, an environmental labelling for the built environment that considers the entire life cycle of the product. Paints and varnishes are materials that can receive this label and have a dedicated standard: UNE 48300:1994 - *Pinturas y barnices. Criterios ecológicos* (Paints and varnishes - ecologic requirements) (Cabello, 2007). In *Cataluña,* the Autonomic Government created a label of environmental quality of products in 2004, the "Distintiu de Garantia de Qualitat Ambiental" (which has also comprised services since 1998). Despite having an approach that comprises the whole life cycle, the focus of the assessment is on resource consumption and waste minimisation. This system considers nine groups of construction materials which contain 79 certified products of 12 companies (UNEP, 2008).

Figure 2.3 - EU *Ecolabel* official symbol (UE, 2010)

Figure 2.4 - *Nordic Ecolabel* official symbol (ES, 2010)

In France, the "Association of Normalisation and Certification" (*Association Française de Normalisation* - AFNOR) has also had an official system of ecological certification - the *NF Environnement* - since 1991, which is based on requirements of aptitude of use. In this system, paints and varnishes are also the only construction materials that can obtain a certification (AFNOR, 2010).

The *Ecologo* (or *Environmental Choice* - Figure 2.5) *Programme* was implemented in Canada in 1988 and evaluates the environmental quality of a product (namely saving resources and reuse of waste) along its life cycle and compares it with other products from the same group. This programme already has more than five thousand certifications including, in the construction materials group, floor coverings, partition walls, concrete release agents, thermal insulation materials, paints, steel and ceramic tiles for walls (Bento, 2007; EcoLogo, 2010).

There are also other environmental labelling programmes all over the world, such as the following ones:

- "Good Environmental Choice" in Australia (GECA; http://www.geca.org.au/) which has a database with the environmental label (denominated EPD) of different construction materials, which are produced following the GECA standards suitable to each group of products (Ecospecifier, 2010; Johnson & Paufler, 2008);
- The *"Falcão Bauer Ecologic Seal"*, managed by the "Falcão Bauer Institute of Quality", has existed in Brazil since 2007 and is applied to sustainable products and technologies in three categories, according with the decreasing environmental impact in the life cycle and the increasing content of recycled or recyclable components (IFBQ, 2010);

- The "Green Seal" in the USA (http://www.greenseal.org/ - managed by *Green Seal Inc.* with the close collaboration of producer associations, traders, consumers and governmental agencies) has requirements for more than 30 groups of products, including paints and wall coatings (UNEP, 2008);
- The "Green Building Material" (GBM) was launched in Taiwan (Formosa Island) in 2004 by the "Architecture and Building Research Institute" to evaluate and certify the environmental performance of construction materials in Health, Ecology, Recycling and High-Performance categories (1032 by June 2008); since 2006, the use of, at least, 5% of materials certified under this system is mandatory in new buildings (Ming-Chin *et al.*, 2008).

Since 2007, the "Ecolabel Index" *(*http://www.ecolabelindex.com - maintained by "Big Room Inc." in Canada) aims at being a database of environmental labelling and improving the transparency related to the processes and qualities of these kinds of systems. This webpage contains information about 327 programmes of 207 countries, comprising 40 industrial sectors. This work helps the producers, suppliers, buyers, consumers and public entities to use environmental labels in a more efficient and effective way (EI, 2010).

The environmental labelling programmes or research projects to which construction materials produced or exported to Portugal are associated are analysed next. The list of materials of these two groups that have an environmental label is presented in Table 2.1

Table 2.1 - Construction materials produced in or imported to Portugal with an environmental label

Country	**Environmental labelling system**	**Construction materials with label**	
		Produced in Portugal	**Imported to Portugal**
Germany	***R***	Agglomerate of expanded cork	Hemp fibre mats or rolls for thermal insulation
International	**FSC**	Medium density fibreboard (MDF), agglomerate of expanded cork, cork granule, floor coverings and pine wood for kitchen furniture	Flexible, rigid and granulated materials for thermal insulation, partition or ceiling boards and timber structures
	Natureplus	Agglomerate of expanded cork and a complete system for the structure and envelope of wood houses	Flexible, rigid and granulated materials for thermal insulation, partition or ceiling boards, timber structures and paints and varnishes
	PEFC	-	Wood-based decks
Italy	**ICEA**	Agglomerate of expanded cork	Different construction materials
Japan	***Ecomark***	Floor coverings	-
USA	***C2C***	Thermal insulation materials	Thermal insulation materials
	GREENGUARD	Floor coverings	-

"Green-It: Green Initiative for energy efficient eco-products in the construction industry" was a European research project carried out between 2006 and 2008 with the participation of the "National Institute for Engineering, Technology and Innovation" (*Instituto*

Nacional de Engenharia, Tecnologia e Inovação - INETI). The main goals of the projects were the improvement and development of systems of energetic and environmental labelling of construction materials and buildings, and to give incentive to the production and use of more energetically efficient products at competitive costs. The tasks completed were:

- The study of the most common construction solutions in different countries of the European Union;
- A survey of the most relevant indicators of energetic performance;
- Evaluation of the different systems of energetic and environmental labelling and comparison with the requirements of the European Directives.

One of the outputs of this Project was an energetic and environmental labelling system for construction products, complementary to the existing ones, which can lead to a high competitiveness of the market in view of a higher energetic and environmental performance of the buildings. The construction material studied in Portugal was ceramic brick. The LCA of the production of this material was completed according to data collected from different Portuguese plants. The construction materials evaluated in all the countries that participated in this European research project are identified in the database *e2pilot* (http://www.bre.co.uk/e2pilot/) by their dimensions and thermal performance. These characteristics have been certified by the participating organisations (Green-It, 2010).

The Italian ecologic certification of the "*Istituto per la Certificazione Etica e Ambientale*" (ICEA - Figure 2.6) covers different kinds of products, including construction materials. This system considers the raw materials, the production process, the environment and the product itself. The "Italian association of bio-ecologic architecture" (*Associazione Nazionale Architettura Bioecologica* - ANAB) develops relevant standards for ecologic construction materials and ICEA awards the certificate (ICEA, 2010).

Figure 2.5 - Symbol of the Canadian *Ecologo* / *Environmental Choice* system (EcoLogo, 2010)

Figure 2.6 - Italian ecologic certification of the "*Istituto per la Certificazione Etica e Ambientale*" (ICEA, 2010)

The German “R” system of ecologic certification of materials allows the recognition of the proportional composition of the product depending on the colour of the “R” letter: red for fossil resources; yellow for mineral resources; green for renewable resources (as the example in Figure 2.7) (R, 2010).

For wood, the certification system “Forest Stewardship Council” (FSC) is the programme with the greatest acceptance worldwide. The “FSC national initiative” was introduced in Portugal in 2006 by the “World Wildlife Fund” (WWF) (FSC, 2010). This programme certifies sustainable management of the forest (responsible management at economic, social and environmental levels) and the chain of responsibility (or chain of custody), of which the latter is suitable for organisations that process, transform, produce or trade wooden products.

The Portuguese “Programme for the endorsement of forest certification” (PEFC) is another system that awards a certification of sustainable management of forests (PEFC, 2010).

The *natureplus* seal is an environmental labelling managed by the “International Association for Sustainable Building and Living e.V.” (Figure 2.8) (with its headquarters in Germany and 100 members in Europe). This association joined, under one label, different prior European systems. The webpage of this system contains a database with a list of all the products already certified (http://www.natureplus.org/) (natureplus, 2010).

The *natureplus* seal guarantees that a product:

- Results from sustainable raw materials and production processes;
- Is made from almost 85% of renewable raw materials or from almost unlimited mineral resources;
- Complies with other environmental, functional or health requirements.

Figure 2.7 - German “R” system - the proportional composition of the product is represented by the different colours of the symbol: red for fossil resources; yellow for mineral resources; green for renewable resources (R, 2010)

Figure 2.8 - The European *natureplus* environmental seal (natureplus, 2010)

The “GREENGUARD Environmental Institute” (GEI) is a non-governmental and non-profit organisation in the USA that certifies products or buildings that guarantee the quality of indoor air (GEI, 2010).

Also in the USA, the “Cradle to Cradle (C2C) Certification” confers Basic, Silver, Gold and Platinum seals to products, and their production processes, weighing five criteria (material health, material reutilisation, renewable energy use, water stewardship and social responsibility) representing the product’s safety to humans and the environment, and design for future life cycles (MBDC, 2010).

The *Ecomark,* launched by the “Japan Environment Association” (www.ecomark.jp/english), certifies different types of construction materials (Bento, 2007).

2.2.1.2. Type II environmental declarations - self-declared environmental claims

Type II environmental declarations are known as “self-declared environmental claims” because they are developed by the producers, importer or suppliers to communicate information on the environmental characteristics of their products or services, without being exposed to external verification (Cabello, 2007; ISO, 1999). An example of a Type II environmental declaration is the recycled content, which can be represented by a *Möbius* strip formed by three curved arrows, one following the other to build a triangle, and a number (representing the percentage of recycled content in the product) in the middle (Figure 2.9).

Directive 2004/42/CE of the European Parliament (transposed to national law as law decree 181, 6 of September 2006) limits the emission of “Volatile Organic Compounds” (VOC) that result from the use of some paints and varnishes. Despite not considering the whole life cycle of these products, this requirement has a huge importance when these products are applied indoors. Some of the products available in the Portuguese market have an indication of compliance with this European Directive, namely paints and varnishes

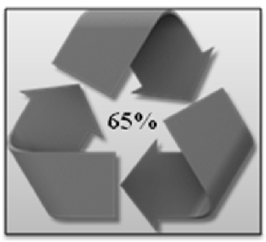

Figure 2.9 - Example of a Type II environmental declaration: percentage of recycled content of a product, represented by a *Möbius* strip with the corresponding figure in the middle

In the Portuguese market, there are cement-based products available with low emission of dust (up to 90% of reduction) in the mix, preparation and application phases, and these characteristics are voluntarily declared by the manufacturer. As well, a national producer of ceramic tiles has created a seal that guarantees that its factory follows sustainable production practices.

2.2.1.3. Type III environmental declarations - LCA based

Type III environmental declarations are defined in detail in the international standard "ISO 14025:2006 - Environmental labels and declarations - Type III environmental declarations - Principles and procedures" (ISO, 2006b) and are normally known as "Environmental product declarations" (EPD). This document is voluntarily developed and presents quantified environmental information on the life cycle of a product, thus allowing comparisons between functionally equivalent products. Type III environmental declarations are based on:

- Data related to the "Life Cycle Assessment" (LCA, methodology thoroughly described in section 2.3) of a product, which is independently verified - internally or externally;
- Modules of information, in accordance with international standards related to LCA: ISO 14040:2006 and ISO 14044:2006 (ISO, 2006c, 2006d);
- Results of the analysis of the "Life Cycle inventory" (LCI) (also described in section 2.3);
- Additional environmental information, when adequate.

These declarations, developed in accordance with predetermined parameters (resulting from impact categories, results of the inventory of elementary flows, and data that does not represent elementary flows), can be developed within an EPD programme (Figure 2.10). This kind of programme has a coordinator (a company, a group of companies, industrial sector or trading association, public agency or independent scientific body) which manages its development and the certification process. EPD represent a complete, robust and scientifically validated source of information of the environmental impacts of a product along the phases of its life cycle included in the study. The development of EPD within this kind of programme also makes the comparison of the results between products easier (Rocha, 2010).

One of the differences between EPD and "Type I environmental declarations" is that every product can have an EPD whereas only the products whose performance is in accordance with the minimum predefined requirements can have an environmental label (Osset *et al.*, 2005).

The LCA approach was highlighted by the European Commission as an important tool to support IPP, and EPD were defined as a mode of presenting quantitative information related to the life cycle of a product in a standard way (EC, 2003). The production of an EPD also allows for the analysis of a whole productive process and the verification of the compliance with all the environmental legislative requirements (Rocha, 2010). The development of LCA studies for EPD can result in the implementation of business-related environmental strategies, which can comprise all the production stages, namely reduction of raw material consumption, minimisation of waste generation, and energetic savings. But most LCA studies are private and strictly confidential, and the 5% that are made public have protectionist intentions (Cabello, 2007). It is also important to highlight that the development of EPD permits surpassing some of the inherent problems of LCA studies such as the standardisation of the input and output data and the improvement of the reliability and clearness of the inventory stage (Silva, L. S. d. *et al.*, 2007).

The Construction Products Directive (CPD) (EC, 1988) defines a range of basic requirements related with construction works, and not with individual construction products, such as: mechanical resistance and stability; fire safety; hygiene, health and environment; safety and accessibility; protection against noise; energy saving and thermal insulation (for a more detailed description see section 3.2). The Construction Products Regulation (CPR) (EP, 2011), that revokes and will replace definitively the CPD as of 1 July of 2013, also includes a seventh group of basic requirements related with the “sustainable use of natural resources” (Cunha, 2011). This innovative requirement (Santos, 2011):

- Should take into account the recyclability of construction works, their materials and parts after demolition, their durability and the use of environmentally compatible raw and secondary materials in construction works;
- EPD can be used, when available, for the assessment of the sustainable use of resources and of the impact of construction works on the environment.

The production of “Product Category Rules” (PCR) for EPD design allows for harmonisation of the information collected and the LCA methodology used. PCR also allow the comparison of results between products with similar functions or applications and achieving verifiable and consistent results (Silva, L. S. d. *et al.*, 2007). PCR can be a set of rules, requirements or guidelines to develop Type III environmental declarations for one or more product categories, defined in accordance with the interested parties (Figure 2.10). It must be possible to apply the same “functional equivalent” to the products of the same category in order to achieve a quantified performance by functional unit. PCR harmonisation among EPD programmes is stimulated at an international level to satisfy the comparability principle (Almeida, 2010; I.EPDS., 2010).

The producer is responsible for the content of the environmental declarations of construction products. These declarations are a tool for the dissemination of the characteristics of the product and can function as a marketing and promotional instrument, but do not necessarily mean that the product is environmentally superior. They can also contain relevant additional information (such as the content of hazardous substances, instructions of use, management of product at end-of-life, among others) (Duarte, B. M. A., 2009; Rocha, 2010). The information that is mandatory in an EPD includes:

- The recycled content and the recyclability rate;
- The predicted service life of the product (according to the ISO 15686-8:2008 standard (ISO, 2006a));
- Transport operations (of the raw materials to the plant, and of the product from the factory to the reseller, from the reseller to the builder and/or site and from the building to the end-of-life site);
- Construction, use and operation, maintenance and replacement during the life cycle;
- The definition of end-of-life;
- The energetic content that can be recovered (Silva, L. S. d. *et al.*, 2007).

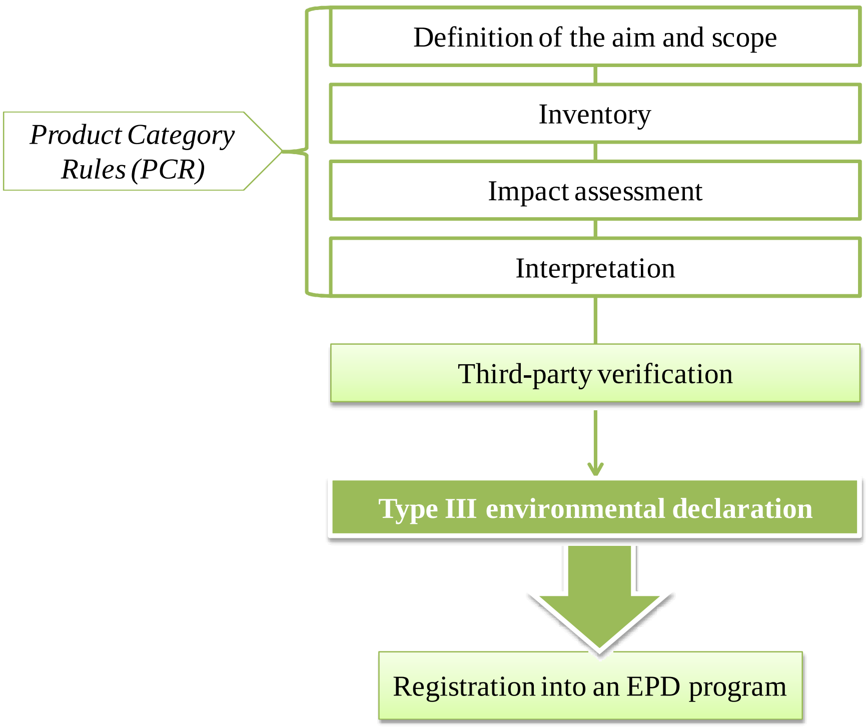

Figure 2.10 - Different stages of development of an EPD before registration in an official programme (adapted from (Rocha, 2010))

The principles and requirements included in "ISO 21930:2007 - Sustainability in building construction - Environmental declaration of building products" (ISO, 2007) work as guidelines in the development and implementation of Type III environmental declarations of construction materials and products, even if this standard does not include recommendations for EPD programmes (Krigsvoll *et al.*, 2007). The Technical Committee (TC) 350 of the European Committee for Standardisation (CEN/TC 350) is devoted to “Sustainable construction” and is developing, within its Workgroups (WG), the following standards related to EPD (Ekvall, 2005; Krigsvoll *et al.*, 2007):

- WG1 - Environmental Performance of Buildings
    - WI 003:2009 “Sustainability of construction works - Assessment of environmental performance of buildings - use of Information from Environmental Product Declarations (EPD)”;
- WG3 - Product Level
    - EN 15804:2012 “Sustainability of construction works - Environmental Product Declarations - Core rules for the product category of construction products”;
    - FprEN 15942:2011 “Sustainability of construction works - Environmental Product Declarations (EPD) - Communication format - Business to Business”;
    - CEN/TR 15941:2010 “Sustainability of construction works - Environmental Product Declarations (EPD) - Methodology for selection and use of generic data”.

When the work of this CEN commission finishes by the end of 2012, it will be possible to elaborate Type III environmental declarations of construction materials and building assemblies based on Rules for each Category of construction Products (PCR). The standards for the environmental product declaration of construction products will also be important in improving the environmentally conscious choice of construction products and systems (Ekvall, 2005; Krigsvoll *et al.*, 2007).

The “International EPD System” (I.EPDS., 2010) is a non-profit international organisation which supports the development and dissemination of Type III environmental declarations of any company and helps national or sector-based EPD programmes (Figure 2.11). On the webpage of this organisation, maintained by the “Swedish Environmental Management Council” (which created this programme in 1999), it is possible to have access to updated information about PCR (concluded or under development) of different kinds of products and to EPD already recorded and certified within this system (I.EPDS., 2010). In July of 2010, it was possible to find the following PCRs related to the construction industry: wood floor coverings (in Swedish); wood particleboards, cement, concrete, concrete roof tiles, ceramic products, windows, marble or other calcareous stone, granite, sandstone and other monumental or building stone (in English). These PCRs allowed the development and publication of the following EPD of construction materials for buildings: wood particleboards, in Italy and Japan; cement, concrete, concrete and ceramic roof tiles, clay bricks for masonry, windows and thermal insulation boards in “Extruded polystyrene foam” (XPS - EPD in pre-registration, as there is not yet a valid PCR for this product), in Italy.

Figure 2.11 - Identification badge included in all the documents developed within the “International EPD System” (I.EPDS., 2010)

There are national EPD programmes already ongoing, namely the following ones:

- The “*Umwelt-Deklarationen*” (EPD), developed by the “Institute of Construction and Environment” (*Institut Bauen und Umwelt* - IBU) of Germany, develops EPD based on German PCRs and divulges them (Figure 2.12); this system only comprises materials and products for building construction divided in ten groups, including floor and roof coverings, masonry units, and wood and insulation products, and some of them being sold in Portugal (IBU, 2010; UNEP, 2008);
- The “*Declaración Ambiental de Producto*” (DAPc or EPD - http://es.csostenible.net/dapc/el-sistema-dapc/), is managed in Spain by the “*Collegi d’Aparelladors, Arquitectes Tècnics i Enginyers d'Edificació*” of Barcelona and by the “*Generalitat de Catalunya*”, and has a database of construction materials on its webpage that can be searched by type of environmental labelling (such as the “*Distintiu de Garantia de Qualitat Ambiental*”, already described, the DAPc, from which there is no EPD yet, or the FSC certification); this database is essential in helping to fulfil the “eco-efficiency decree” of the “*Generalitat de Catalunya*” which stipulates that:”(…) at least one family of products (set of products with the same use) included in a building should have a Type I or Type III environmental declaration” (DAPc, 2010);
- The “Green Standard” in the USA has made the methodology of EPD development known since 2000 with the collaboration of governmental institutions and, since 2008, has developed EPD of construction materials (and has already finished five with two different companies: four of carpets and one of inner coatings of recycled glass in a resin binder) (GSEPDS, 2010);

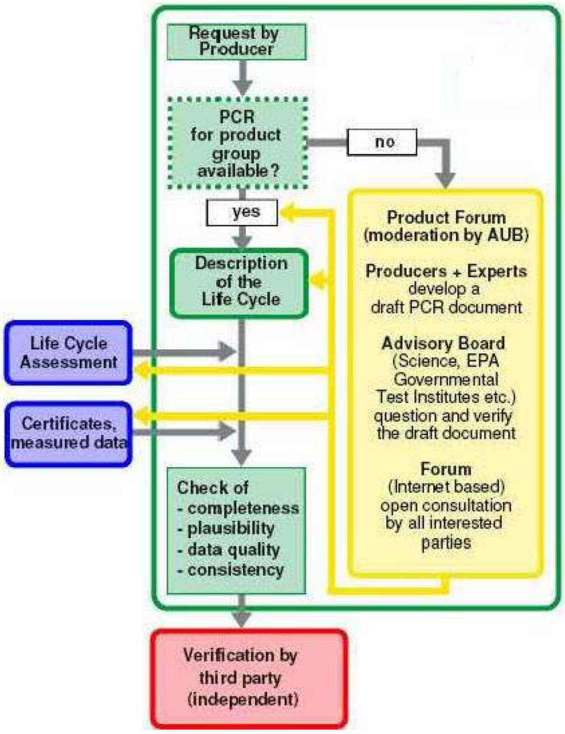

Figure 2.12 - *Institut Bauen und Umwelt* (IBU) procedure for developing EPD (IBU, 2010)

- Since 2004, the Finnish “RT - Environmental declaration” (http://www.rts.fi/ymparistoseloste/index_RTED.htm) has developed environmental declarations of construction materials, based on national and international standards, with the support of organisations linked to the construction industry and scientific research; this organisation has already published 35 documents of 20 products (UNEP, 2008);
- In the Netherlands, the “Federation of the Suppliers of the Construction Industry (NVTB) started the programme for “Relevant Environmental Information of Products” in 1995 (*Milieurelevante Productinformatie* - MRPI), which has been maintained by the MRPI Foundation since 1999; this programme is based on a Dutch standard and on a manual that works as a global PCR, and already has prepared EPD of 30 groups of construction materials of 200 companies (UNEP, 2008) which are used in the *Eco-Quantum* LCA tool;
- The *EcoLeaf* (*http://www.jemai.or.jp/english/ecoleaf/)*, launched in Japan by the “Japan Environmental Management Association For Industry” (JEMAI) in 2002, has already published hundreds of EPD of more than 50 companies (UNEP, 2008);
- The “Building Research Establishment (BRE) Environmental Profiles Certification” in the United Kingdom contains the LCA results of more than 250 construction assemblies; this database, available as a book and on the internet, was developed with the collaboration of the construction industry and is used in the “Building Research Establishment En-

vironmental Assessment Method” (BREEAM) system (BRE, 2010; Cabello, 2007).

There is a considerable delay of the USA in the development of a national EPD programme. This is already a present environmental, but also economic, concern (Schenck, 2009).

In France, the “*Programme de Déclaration Environnementale et Sanitaire pour les produits de construction*” develops EPD of products or group of products (called “*Fiches de Déclaration Environnementale et Sanitaire*“ (FDES)) in accordance with a French standard, a general PCR and the international standardisation related to LCA. These EPD are available in a free, public database (http://www.inies.fr), managed by the “*Centre Scientifique et Technique du Bâtiment*” (CSTB), which already contains more than 450 documents.

GEDnet (http://www.gednet.org/) is the international network of organisations and professionals linked to EPD (from Asia, Oceania and Europe) that was founded in 1999. This network has the following goals: pursue the cooperation and encourage the exchange of information among the members and other professionals that develop EPD programems or Type III Environmental Declarations; creation of a database of EPD of different countries; be an international vehicle of PCR harmonisation. The “Japan Environmental Management Association For Industry” (JEMAI, Japanese member of *GEDnet*) has developed a PCR library that can be searched by product or country (http://www.cfp-japan.jp/english/gpl/index.html) and includes PCRs for insulation materials and glass (GEDnet, 2010).

In Portugal, the activity on EPD is still small, but some already finished projects are highlighted next. Moreover, a national programme of environmental certification of building products and services for the built environment based on type III environmental declarations is already in its starting point (DAPHabitat (DAPHabitat, 2012)). The author and the co-supervisor of this thesis are members of the technical commission of this program, which is being developed with the collaboration of IBU (responsible for the similar German programme – see section 2.2.1.3).

The European Project “STEPWISE EPD” aimed at building a method that allows for the sequential production of environmental product declarations and is suitable for small and medium companies (more data on this project is available at http://extra.ivf.se/stepwiseEPD2). This project only included an initial LCA of the product, and the final verification of this assessment. The final goal of “STEPWISE EPD” was to ease the adhesion of these groups of companies to this instrument of communication and marketing of the environmental profile of their products via a first step that could thereafter turn into a national or international EPD programme. The main conclusion of this project was that the major profit for the companies that invest in EPD arises from internal learning and identification of opportunities of product improvement. Nevertheless, there is still a low acknowledgement of EPD by the market (with the exception of some business sectors) and there is a need to supply additional information to make these documents intelligible to everyone (Rocha, 2010).

As a result of the “STEPWISE EPD” project, the “Centre for Sustainable Business-related Development (*Centro para o Desenvolvimento Empresarial Sustentável* - CENDES) of the “*Instituto Nacional de Engenharia, Tecnologia e Inovação*” (INETI) (now integrated in the *Laboratório Nacional de Energia e Geologi*a - LNEG) developed an EPD in 2005 of the ready-mixed concrete produced by the company “*Concretope - Fábrica de Betão-Pronto S.A.*” located in *Sobreda da Caparica*, in Portugal (Concretope & INETI/CENDES, 2005). This EPD comprises the LCA from cradle to gate (including end-of-life) of 1 m^3 of *C25/30 D25/S3 Ec2* ready-mixed concrete, which includes: the list of materials and chemical components needed for its production; brief information about the different phases of the life cycle of the product; the resources and energy consumption, the environmental impacts and the waste generation in each phase of the life cycle (Figure 2.13).

This EPD can be compared with another EPD of ready-mixed concrete of the Italian company *Buzzi Unicem* (http://www.buzziunicem.it). The latter includes information related to five classes of this material and a virtual class with average characteristics: description of the company and product; life cycle phases included and boundaries of the assessment; resources with and without energetic content used in the production; LCA, including the potential of environmental impacts and the generation of wastes by life cycle phase and the atmospheric emissions in the production (Figure 2.14) (I.EPDS., 2010).

The “Technological Centre for Ceramic and Glass”, in collaboration with the “Portuguese Association of the Ceramic Industry” (*Associação Portuguesa da Indústria da Cerâmica* - APICER), developed an EPD programme in the ceramic industrial sector. This project started with the definition of forms for EPD and PCRs for each subsector of this industry: masonry units with vertical hollows, roof tiles, wall and floor tiles, and sanitary ware. The following phase included the LCA from cradle to gate of the products based on data collected from 11 sites (data from 2008 validated with data from 2006 and 2007) and on international databases. Each EPD contains a brief description of the company and product, including a summary of the technical characteristics of the latter, the LCA results and information about the use and end-of-life phases (Almeida, 2010; Almeida *et al.*, 2010).


stepwise Environmental Product Declaration

Product	Ready-mixed concrete
Company	Concretope – Fabrica de Betão-Pronto S.A.

This EPD provides a quantitative and verified description of 1 m^3 of C25/30 D25/S3 EC2 ready-mixed concrete, viewed from a life cycle perspective.

The company

CONCRETOPE – Fabrica de Betão Pronto S.A.
EN 10/11 – Quinta dos Porfírios, Sobreda da Caparica
Portugal
Contact person: Dra. Maria João Carvalho
geral@concretope.pt
T. +351-21-2557330
F. + 351-21-2542471

CONCRETOPE is a ready-mixed concrete production company which started its activity in Portugal in 1970. The company encompasses four concrete plants (Sobreda da Caparica, Odiáxere, São Brás de Alportel and Albufeira) and has its own fleet (truck mixers and pumps). The company belongs in equal parts to LONDIMO, SGPS, S.A, a Portuguese group based in Montijo and to Cimentos Nacionais e Estrangeiros.

Concretope
Fábrica de Betão Pronto, S.A.

The product

The declared product, 1 cubic meter of C25/30 D25/S3 Ec2 ready mixed concrete, has the following technical characteristics:

Class of strength	C25/30	Maximum aggregate size	D25
Slump Class (consistency)	S30	Exposure class related to environmental conditions	Ec2

Concrete is a structural element to support loads by compression. The studied product has a technical life time of 50 years, after which maintenance is required. C25/30 D25/S3 EC2 ready-mixed concrete is manufactured in Sobreda da Caparica, Portugal and from there distributed to construction sites in the peninsula of Setubal (municipalities of Almada, Seixal, Barreiro and

Figure 2.13 - Part of an EPD of ready-mixed concrete developed within the "STEPWISE EPD" project (Concretope & INETI/CENDES, 2005)

2.2.2. From the environmental certification of construction materials and assemblies to the environmental assessment of buildings

In Portugal, the "National system of energy certification and indoor air quality in buildings" (already described in section 2.2) has already had positive consequences but not only in terms of the thermal performance of the buildings. Hence, it is already possible to establish a direct relationship between the energetic class and the quality of construction. With the minimisation of carbon emissions resulting from the exploitation of buildings, the measures to control and reduce the environmental impacts of the entire production chain of construction becomes a priority. For this reason, it is time to begin "accounting" the "carbon invoice" of the production of construction materials and construction of buildings (Machado, 2009). As soon as this calculation has credible and statistically significant data, the theoretical "carbon invoice" can become a real environmental tax to be applied to new constructions (and may be an incentive for rehabilitation works). Even though the Portuguese building industry has energetic efficiency and certification as its most recent priority, in a desirable future it will be possible to evaluate a building, and make its energetic certification via a balance of the environmental impacts of its materials in its whole life cycle (Figure 2.15).

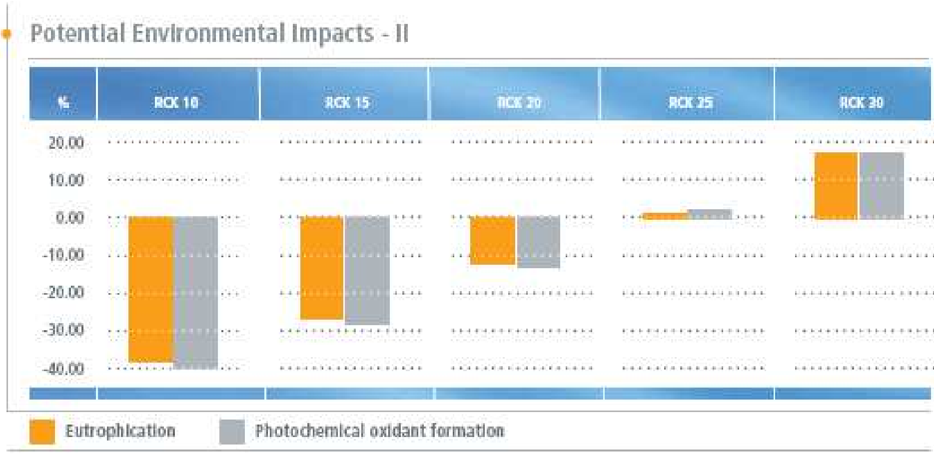

Figure 2.14 - Part of an EPD of ready-mixed concrete of the Italian company Buzzi Unicem (I.EPDS., 2010)

In Spain, for example, a simplified LCA methodology to be included in the process of energetic certification of buildings has already been proposed. This method uses the EPD of construction materials that are already available (Bribián *et al.*, 2009). In Italy, the need to integrate life cycle assessment quantitative indicators in the process of energy certification has also been identified (Campioli & Lavagna, 2007).

As stated before, the European Directive under development related to the “Sustainability in Construction” foresees the generalisation of the use of “Environmental product declarations” in all construction products by 2016 (Dias, 2010). Each EPD can be devoted to a material, component or construction assembly of a building (ISO, 2007). Thus, it is possible to build EPD of complete construction assemblies from the EPD of the corresponding individual construction materials. It is also possible to make the environmental assessment of a building via a set of EPD of all its components. Nevertheless, this result has to be integrated with data of the life cycle stages of the building (e.g. construction, use, energy consumption, maintenance – see Figure 2.16) as the sum of EPD of building products only gives some synthetic indicators on impacts in the production, construction and end-of-life phases (Campioli & Lavagna, 2007).

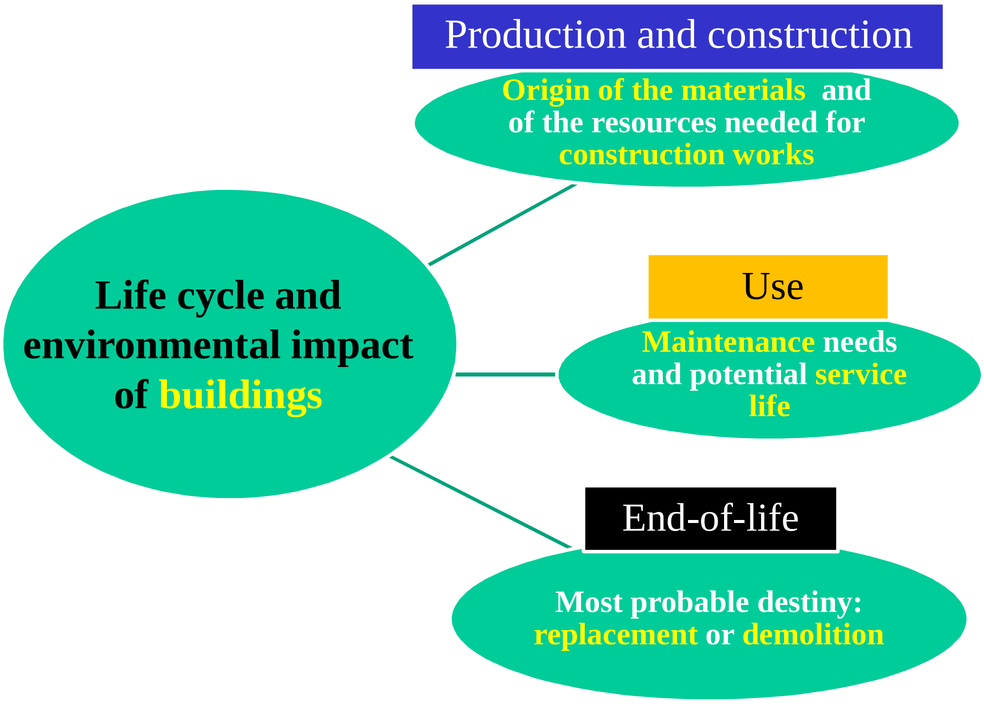

Figure 2.15 - Stages of the life cycle of a building and factors that influence its environmental impacts due to construction materials (adapted from (Duarte, A. P., 2009))

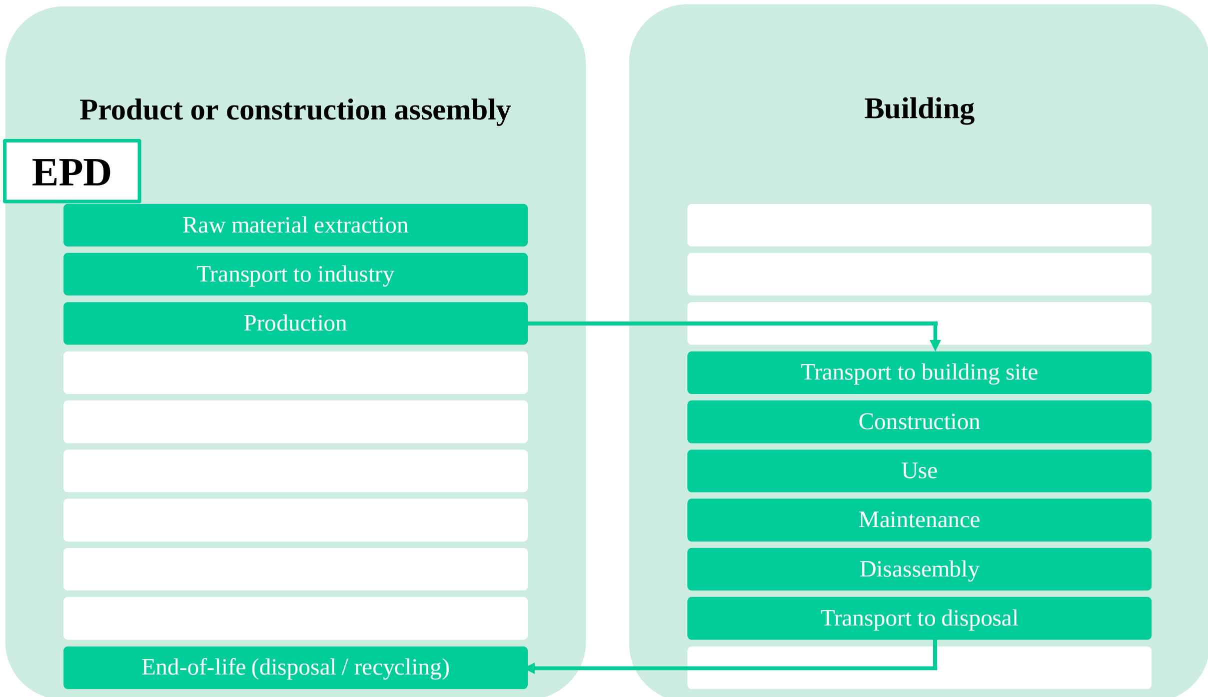

Figure 2.16 - Data included in an EPD of a construction product or assembly and life cycle stages of this component within a building (adapted from (Campioli & Lavagna, 2007))

To allow the environmental assessment of a building based on detailed information of the environmental impacts of its materials in their whole life cycle, it is necessary to develop new tools or link tools already in use. Some projects underway with this aim are analysed in the following sections of this chapter (2.2.2.1, 2.2.2.2 and 2.2.2.3).

2.2.2.1. Databases of environmental information of construction products

Despite the countless efforts underway to build EPD databases and make them free and available to the public, there is still an insurmountable barrier: EPD are made for "business to business" (B2B) communication and most people have difficulty reading and correctly interpreting them (Figure 2.17). A tool to support the selection of construction materials was developed in Norway (in Norwegian) to surpass this problem (corresponding to a PhD Thesis completed in the *SINTEF Byggforsk*). This tool, called *ECOproduct*, is based on the data of EPD and marks each product with a colour - green (good), white (acceptable) or red (not acceptable) - in accordance with four environmental criteria (Folvik & Wærp, 2009).

A Master Thesis recently completed in Portugal proposes a methodology to use EPD in the design and call for construction tender phase of a building and to also use it to verify the characteristics of materials in the execution phase. This work is based on the hypothesis that most of the construction materials for buildings have their EPD available, which is not a reality yet. It also includes the analysis of the advantages of this paradigm in the choice of environmentally preferable materials in the design phase and their use on-site (Duarte, B. M. A., 2009).

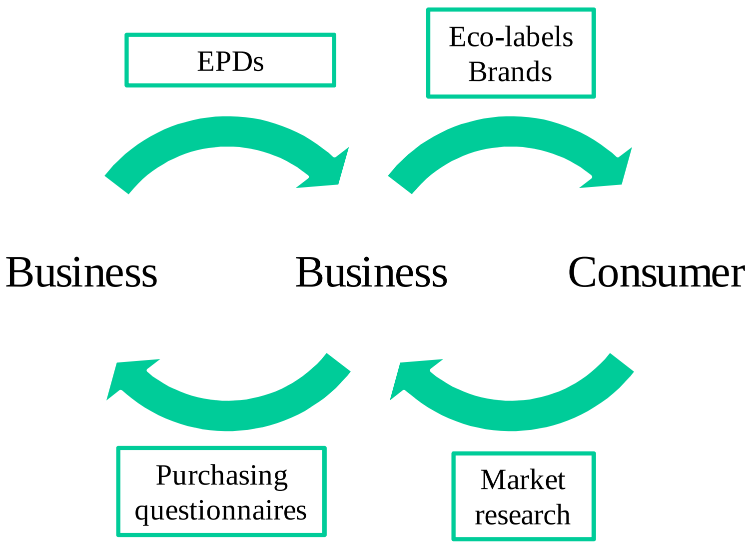

Figure 2.17 - Flows in environmental market communication and corresponding placement of EPD and Eco-labels ((Nebel & Warnes, 2007) adapted from (Baumann & Tillman, 2003))

There are many decision-making support tools for building design that do not allow the introduction of data specific to each project and that only provide, online or in printed form, mainly qualitative assessments of the environmental claims of products and their possible benefits. Examples of this kind of tools are the *checklists* or the "green product guides" to choose construction materials with high environmental performance. The classification or profile presented for each material may have resulted from LCA methods but the designer can only decide to either accept the results (environmental impacts of the different construction materials or construction assemblies) or not (CfD, 2001; IEA, 1997). From these tools some are highlighted: *One-Stop Timbershop* (devoted to certified timber) in Australia; *GreenSpec Directory* (which contains more than 2000 products in 250 categories) in the USA; and "Green Guide to Specification" in the United Kingdom (which comprises the information acquired within the programme "Building Research Establishment (BRE) Environmental Profiles Certification" already described in section 2.2.1.3) (Anderson *et al.*, 2002; CfD, 2001; Erlandsson & Borg, 2003). In Australia, the database *Ecospecifier* offers paid access to a set of construction materials and assemblies that are environmentally preferable. This web service is maintained by a team with significant experience in sustainable construction, which selects products (based on information of producers and/or third-party verified): that have one or more ecologic or health characteristics, among the ones predefined by *Ecospecifier*, superior to other products of the same category; or which belong to a category that is itself preferable in environmental or health terms; or that do not have a "significant" content with hazardous effect on the environment or on health. Access to the database is available in five different plans of increased cost which also correspond to the quantity and quality of the information related to the environmental performance of the products (namely LCA studies, EPD or environmental labelling) (Ecospecifier, 2010; Pinheiro, 2006). Also in Australia, the "Australian Institute of Architects" contains a field concerning the sustainability attributes of the products in its construction product database *Selector* (http://selector.com) (Graham, 2003).

The "Department of Human Settlements Science and Technology" (DINSE) of the "Politecnico di Torino", in Italy, has built a database of environmental indicators of construction materials called "COM.PRO: ecoCOMpatibility of PROducts". This database contains technical and environmental information concerning 90 of the most common construction materials, and has been partially completed with the collaboration of producers and construction companies (Giordano & Torresan, 2007a, 2007b).

In Spain, the "College of Architects of Valencia" (*Colegio Territorial de Arquitectos de Valencia* - CTAV) has a directory of construction materials on its webpage (http://www.ctav.es/ctav/icaro/materiales/). Each material is classed from 1 to 10 in a broad set of ecological (such as the recycled content and the embodied energy) and economic (such as the material, and corresponding installation costs) criteria with weights also defined by CTAV (CAV, 2010). In the same country, the "*Instituto de Tecnología de la Construcción de Cataluña*" (ITEC) has developed a database of economic and technical information of construction materials called BEDEC (ITEC, 2010). BEDEC contains the price of more than 350,000 construction elements and construction works, 5,000 documents of technical information of materials, and environmental data of 100 raw materials or basic materials used in construction. This environmental data comprises: generated waste in weight and volume; packaging in weight and volume; and embodied energy cost and CO_2 emissions of each material. Only part of this data came from LCA studies.

In Portugal, some research studies have been developed for specific industries or products, such as ceramic materials (Almeida *et al.*, 2010), ready-mixed concrete (Concretope & INETI/CENDES, 2005), or concrete with recycled aggregates (Evangelista & de Brito, 2010). A Portuguese Architect and researcher developed a tool to support building rehabilitation projects in the Netherlands. This tool contains a database of construction materials which considers the classifications achieved in the system "Building Research Establishment (BRE) Environmental Profiles Certification" (Roders, 2007).

2.2.2.2. Building environmental assessment systems (BEAS)

The practical and methodological need of making the environmental and performance assessment of the built environment is increasing. This need is vital at a national, but also at an international level (Pinheiro, 2006). The tools that are used in the environmental assessment of buildings and their components should ensure a scientific, global and integrated vision, by considering the life cycle of the construction assemblies selected during the design process. The methods and tools already available to accomplish this goal are described in detail in Chapter 5.

Within the tools available to allow for the environmental assessment of the buildings and their components, the "Building Environmental Assessment Systems" (BEAS) are undoubtedly the most important. BEAS aims at evaluating and communicating the environmental performance of buildings, usually after their construction. This evaluation comprises the use of resources, generation of environmental loads and indoor environmental quality, among other aspects. The global environmental performance is materialised in a seal or performance level. The evaluation may also include: verification by an external entity before the attribution of a ranking; reference to, or explicit use of LCA tools; support of the use of BEAS by architects via educational programs (Cole, 2005; Pinheiro *et al.*, 2007). BEAS are normally made up of three main components (Cole, 2003):

- The structure, which comprises environmental performance criteria organised in a logical fashion;
- The scoring system, comprising the assignment of a number of possible points or credits for each criterion in order to meet a given level of performance;
- The output, which is a means of showing the overall score of the environmental performance of the building.

Table 2.2 contains the description of the most important BEAS all over the world. Most of the BEAS are tailored to be used in the country where they are developed as they consider the customs and conditions of each particular region. However, some national BEAS were developed based on systems from other countries, in an attempt to introduce sustainability values in the construction sector. The differences in the environmental state of the countries, and in the priorities defined in each country, make this practice "dangerous". The greatest risk is that these assessment systems could become homogeneous and lose sensibility (Pinheiro, 2006).

At an international level, ISO 21931:2010 is the reference concerning BEAS standardisation (ISO, 2010). This standard was developed under ISO TC 59 (Sub-Committee 17) devoted to "Sustainability in Building Construction", which was also responsible for ISO 15392:2008, ISO/TS 21929-1:2006 and ISO 21930:2007 (ISO, 2006e, 2007, 2008b).

At a European level, it is expected that a standard methodology to evaluate the sustainable performance of buildings and construction works will be developed. This methodology can include the life cycle cost and must be sufficiently flexible to be adapted to the present reality of each country. It should be based on the current processes of evaluation of the energetic performance of buildings, or on other related on-going initiatives, and has to be developed in collaboration with all interested parties. This methodology ought to be appropriate for new and old buildings and significant rehabilitation works, in order to motivate the adoption of sustainable techniques in the design phase. Results of the environmental evaluation may lead to regional or national financial incentives for buildings with better environmental and economic performance. As the benefits of sustainable construction are noted only in the long-term, there is a need for actions that highlight these benefits in the short-term to encourage buyers, banks and loan institutions to favour buildings with better environmental classification (Pinheiro, 2006). A standardised methodology may also allow *benchmarking* between buildings evaluated in different countries.

Table 2.2 - Description of the most important BEAS all over the world

Country	BEAS	Organisation (description)
Australia	**NABERS (National Australian Buildings Environmental Rating System)**	NSW - Department of Environment, Climate Change and Water (suitable for residential and commercial buildings - http://www.nabers.com.au/)
Canada	**Green Globes**	Canadian Standards Association (CSA) (system based on BREEAM and adopted to be used in Canada and USA - http://www.greenglobes.com))
	***SBTool* (former GBTool)**	International Initiative for a Sustainable Built Environment (iiSBE) (developed within the “Green Building Challenge”, this system works like a global research forum with the participation of 60 countries, with the aim of making the environmental *benchmarking* of buildings; allows changes in the evaluation parameters depending on the building’s use and on the stage of development of the design, among other criteria; this system is suitable for multiuse buildings - http://www.iisbe.org/sbmethod) (Pinheiro, 2006; Pinheiro *et al.*, 2007)
France	**Habitat & Environnement**	CERQUAL - QUALITEL (suitable for residential buildings and retirement buildings - http://www.cerqual.fr/cerqual/habitat_environnement/ (Pinheiro, 2006))
	HQE (*Haute Qualité dès Bâtiments*)	AFNOR (suitable for residential buildings but also for office, commercial, industrial and educational buildings - http://www.assohqe.org (Pinheiro, 2006; Pinheiro *et al.*, 2007))
Japan	**CASBEE (Comprehensive Assessment System for Building Environmental Efficiency)**	Japan Green Build Council (JaGBC) / Japan Sustainable Building Consortium (JSBC) (http://www.ibec.or.jp/CASBEE/english/)
Portugal	**LiderA (Leading on behalf of the environment)**	Prof. Manuel Duarte Pinheiro at “Instituto Superior Técnico” (applies an environmental management approach along the life cycle to different building uses - www.lidera.info/ (Pinheiro, 2008))
United Kingdom	**BREEAM (Building Research Establishment Environmental Assessment Method)**	Building Research Establishment (BRE) (developed with the participation of private companies and in partnership with industry, in 1998, there are already different versions suitable for different uses such as residential and offices buildings, which could be new or in use- http://www.breeam.org/ (Pinheiro *et al.*, 2007))
USA	**LEED (Leadership in Energy & Environmental Design)**	United States Green Building Council (suitable for new residential and commercial buildings, significant refurbishments and existing buildings (http://www.usgbc.org/LEED))

The European Commission foresaw, in 1999 (Pinheiro, 2006), that the future “Thematic Strategy about Sustainable Construction” would define that a standard methodology to evaluate the general sustainability of buildings and the built environment (including indicators of life cycle costs) should be developed in the European Union (EU). For that purpose, the following main activities have to be scheduled:

- Countries from the EU must be incited to: adapt and adopt this methodology and use it in the support of best practices; develop and implement a national programme of sustainable construction; define high performance requirements, using harmonised European standards and Eurocodes; introduce sustainability requirements in the procedures of the construction work contracts; develop financial incentives for the most sustainable buildings;

- The European Commission must explore opportunities for training, orientation, experience interchange and other research works about sustainable construction, develop environmental labelling of construction materials (environmental product declarations and/or EU *Ecolabels*), and propose a EU *Ecolabel* and/or standard environmental product declarations for buildings and/or its equipment and services.

Presently, only some of the measures foreseen in this European Strategy are already ongoing.

Nevertheless, Technical Committee (TC) 350 of the "European Committee for Standardisation" (CEN/TC 350 - "Sustainability of Construction Works") is developing a set of European standards for the sustainability assessment of buildings and construction products that have been structured into three horizontal levels (framework, building and product) and three vertical columns (environmental, social and economic) while always taking into account technical and functional performance characteristics. These standards only deal with the analytical part of the building assessment system and do not provide "subjective" issues such as valuation methods nor set levels, classes or benchmarks for any measure of performance. The establishment of assessment and weighting factors will be handled as part of national assessment systems (Ilomäki *et al.*, 2008a, 2008b). Only quantifiable environmental indicators are to be considered both in building and construction material evaluations. These indicators are common to both levels and to standard "ISO 21930:2007 - Sustainability in building construction - Environmental declaration of building products"(Ilomäki *et al.*, 2008b; ISO, 2007).

CEN/TC350 has four active workgroups, which are developing the following standards (and the ones related to EPD already cited in section 2.2.1.3):

- TG - Framework
    - EN 15643-1:2010 "Sustainability of construction works - Sustainability assessment of buildings - Part 1: General framework";
    - FprEN 15643-2:2010 "Sustainability of construction works - Assessment of buildings - Part 2: Framework for the assessment of environmental performance";
- WG1 - Environmental Performance of Buildings
    - FprEN 15978:2011 "Sustainability of construction works - Assessment of environmental performance of buildings - Calculation methods";
- WG4 - Economic Performance Assessment of Buildings

  - FprEN 15643-4:2011 “Sustainability of construction works - Assessment of buildings - Part 4: Framework for the assessment of economic performance”;
- WG5 - Social Performance Assessment of Buildings
  - FprEN 15643-3:2011 “Sustainability of construction works - Assessment of buildings - Part 3: Framework for the assessment of social performance”.

These standards will be in their final version by the end of 2012. This harmonised European system will allow for the assessment of the environmental, social and economic performance of buildings based on a life cycle approach. It will also allow the comparison between LCA studies of functionally equivalent buildings (or construction products), which means that they have similar technical and functional performance. The assessment of environmental performance is based on the “Life Cycle Assessment” methodology (LCA, to be described in section 2.3), thus allowing LCA results from different studies to be compared and to be used to make meaningful choices (Ekvall, 2005; Krigsvoll *et al.*, 2007). The assessment of economic performance is based on the “Whole-Life Cost” (WLC) (ISO, 2008a) and the rules for the service life issues are based on the guidance of the “Service Life Planning” standard series (ISO, 2000). To fulfil the ISO 15392 general principle “holistic approach” (ISO, 2008b), the sustainability assessment of a building constitutes a part of an assessment of integrated building performance (Ilomäki *et al.*, 2008a, 2008b). This standard also has other principles to be assumed by the construction industry to respond to the sustainable development agenda: continuous improvement, equity, global thinking and local action, involvement of interested parties, long term consideration, precaution and risk, responsibility and transparency (CIB, 2010).

Portugal has a mirror group of CEN/TC 350: the CT171 of IPQ (Portuguese Quality Institute) which has representatives from Universities, Research Centres, industry, consultants and NGOs. This Technical Committee has two workgroups: “Sustainability assessment of buildings” and “Products”. The supervisor and the co-supervisor of this thesis, and also the author, are involved in the activities of CT171.

2.2.2.3. Link between systems of environmental certification of materials and BEAS

After the detailed description of the different systems available for the environmental certification of construction materials and the presentation of the most important “Building environmental assessment systems”, it is necessary to acknowledge the relationship between these systems and tools in different countries all over the world. The links described in this part of the thesis are like individual steps that will allow, in the near future, the environmental assessment of buildings using the information available in the EPD of its components.

“Building for Environmental and Economic Sustainability” (BEES) is a tool developed in the USA by the National Institute of Standards and Technology (NIST) based on LCA studies made according to international standards. This tool allows the choice of cost-efficient and environmentally preferable construction materials to be used in a building. These components can be selected among the 230 available in the database - which is distinguished because it is free, and because the data can be used in BEAS (Erlandsson & Borg, 2003).

In the United Kingdom, the environmental profiles included in the “Building Research Establishment (BRE) Environmental Profiles Certification” are used in the BREEAM system to support the architect in the selection of construction materials for buildings. These environmental profiles are also used in the LCA and LCC tool *envest 2*, also developed by BRE (BRE, 2010; Cabello, 2007), and in the scope of the “Code for Sustainable Homes” (both described in detail in Chapter 5).

In Taiwan (*Formosa* island), the use of a minimum of 5% of materials certified by the “Green Building Material” (GBM) in building construction has been mandatory since 2006 (Ming-Chin *et al.*, 2008).

In the Netherlands, EPD developed in the scope of the “Relevant Environmental Information of Products” (*Milieurelevante Productinformatie* - MRPI) are used in the LCA tool *Eco-Quantum* (described in Chapter 5). At Stuttgart University, in Germany, a LCA tool for buildings is being developed from the data available in a German public database and in EPD. This tool will allow the LCA development to certify the environmental performance of the buildings as demanded by the “German Association for Sustainable Building” (DGNB-certificate) (Wittstock *et al.*, 2010).

In France, EPD (*Fiches de Déclaration Environnementale et Sanitaire* (FDES)) available in the public database INIES are used in the HQE system to evaluate the environmental impacts of the construction materials (UNEP, 2008).

Not only in France, but also in Australia, New Zealand and other countries, it is possible to observe an increasingly stronger relationship between the “Green Building Councils” (or entities responsible for the BEAS) and the organisations that make the ecologic characterisation and/or certification of construction materials. This collaboration generates synergies and increases efficiency via the introduction of environmentally certified materials in new buildings and the introduction of a LCA methodology in the appreciation of all their components. Environmentally certified materials are normally numerous as their certification systems normally precede BEAS (Johnson & Paufler, 2008).

In Portugal, this kind of work has just started to allow the expedite classification of the environmental performance of construction materials in the scope of a BEAS (such as LiderA or SBTool^{PT}). The BEAS *LiderA* (acronym of "leading on behalf of the environment" - *LIDERar pelo Ambiente*) has a classification system of construction products within the environmental dimension (4Rs, 2012). The author aided in the definition of the requirements of environmental performance that have to be complied by insulation materials to achieve a better classification in this system (Silvestre *et al.*, 2011). The environmental classification of the construction products in classes will allow for a better classification of the building in the BEAS area corresponding to the materials. In the beginning, this classification is based on environmental information made available by the producers (that could correspond to Type I, II or III environmental declarations). Then, *LiderA* system will started doing LCA studies to obtain a better environmental characterisation of the classed materials (Pinheiro, 2010). The Portuguese version of the BEAS *SBTool* (*SBTool^{PT}*) contains a LCA database of the most common construction materials and assemblies of buildings. This database was built based only on generic international LCA data sets (Mateus, 2009).

In Portugal, adhesives for floor tile bedding are available that fulfil the four criteria of environmental performance demanded by the American BEAS LEED. The use of these products allows a building to achieve points in the "Materials and Resources" categories of this system. The criteria are: recycled content (up to 30%); use of local materials; adhesives and sealants with low emission of substances harmful to the health of the inhabitants and to the environment; and indoor air quality before use. Also timber with FSC certification is taken into account in the LEED system (USGBC, 2010).

2.3. Life Cycle Assessment (LCA) methodology

The "Life Cycle Assessment" (LCA) methodology was originally defined in 1991 by SETAC (Society for Environmental Toxicology and Chemistry) as a process to (Pinheiro, 2006):

- Evaluate the environmental impacts of a product, process or activity by identifying and quantifying the environmental emissions and consumption of energy and materials;
- Evaluate the environmental impact of emissions and consumption of energy and materials;
- Identify and evaluate the opportunities of making environmental improvements.

In 1993, the “Code of practice for LCA” was also launched by SETAC. This document began the process of standardisation of this methodology (Gervásio & Silva, 2007b), which is now already finished. Detailed LCA allows for the evaluation of the environmental impacts of processes or products during their complete life cycle without geographic or temporal limitations and is based on ISO 14040:2006 and ISO 14044:2006 international standards (ISO, 2006c, 2006d). These standards reflect a higher level of consensus on general LCA methods (Blok *et al.*, 2007) and resulted from the extensive work of one of the Technical Committees of the “International Organization for Standardization” (ISO): TC 207. This ISO TC has been responsible for the development of international standards for sustainable management since 1992. These standards are used by an organisation to:

- Create and improve an “Environmental Management System” (EMS);
- Evaluate specific aspects of the environmental system;
- Assess environmental characteristics of the products.

TC 207 was divided into six subcommittees, which were responsible for the development of the standards of series ISO 14000 (Pinheiro, 2008). Subcommittee 5 was responsible for the two ISO standards related to LCA already cited (ISO 14040:2006 - “Principles and framework” and ISO 14044:2006 - “Requirements and Guidelines”).

LCA methodology comprises four analytical phases interlinked by iterative cycles (Blok *et al.*, 2007; Bragança & Mateus, 2008; Duarte, B. M. A., 2009; Ferrão, 2009; ISO, 2006c, 2006d; Ortiz *et al.*, 2009):

1. Definition of the goal and scope of the assessment;
2. Life Cycle Inventory analysis (LCI);
3. Life Cycle Impact Assessment (LCIA);
4. Life Cycle Impact interpretation.

The definition of the goal and scope of the assessment comprises the description of the product to be assessed, the boundary of the associated system (including the definition of the cut-off criterion) and the functional unit. It also comprises the selection of the environmental interventions and of the method (or methods) of environmental impact assessment, the definition of the goal of the study, its intended audience, strategy for data collection’ and assumptions and limitations of the study.

The “Life Cycle Inventory” analysis (LCI) phase comprises the inventory, and compilation, and quantification of the inputs and outputs of the system for the processes included along the life cycle of the product. This comprises the collection and treatment of the data related to these flows (of mass - quantification of materials, energy, and emissions to the air, water or soil). The LCI of the product is presented in inventory tables that show the material and energetic balance of the system. LCI studies finish with the analysis of the inventory obtained. This phase of the LCA is described in more detail in section 4.2 of this thesis.

The "Life Cycle Impact Assessment" (LCIA) phase comprises the estimation and evaluation of the magnitude and significance of the potential environmental impacts of a product throughout its life cycle. This evaluation is based on the environmental interventions obtained in the LCI (e.g. Chlorofluorocarbons - CFC, CO, CO_2, Halon, and Methane - CH_4) and in the impact categories chosen (between 10 and 20) via a process of classification and characterisation. This process makes use of an "Environmental Impact Assessment Method" (EIAM), which converts the LCI results obtained in midpoint (e.g. potential of ozone layer depletion or greenhouse effect) or endpoint impacts (e.g. damage to human health or to the ecosystems) assuming a cause-effect relationship with different characterisation factors for each pair intervention-environmental impact. The LCIA phase can also include optional elements, as shown in Figure 2.18:

- Normalisation - calculation of the magnitude of each category indicator in relation to reference information;
- Grouping - comprising the sorting and possible ranking of the impact categories;
- Weighting - conversion, and possibly aggregation across impact categories, of the results of the indicators using numerical factors based on value-choices.

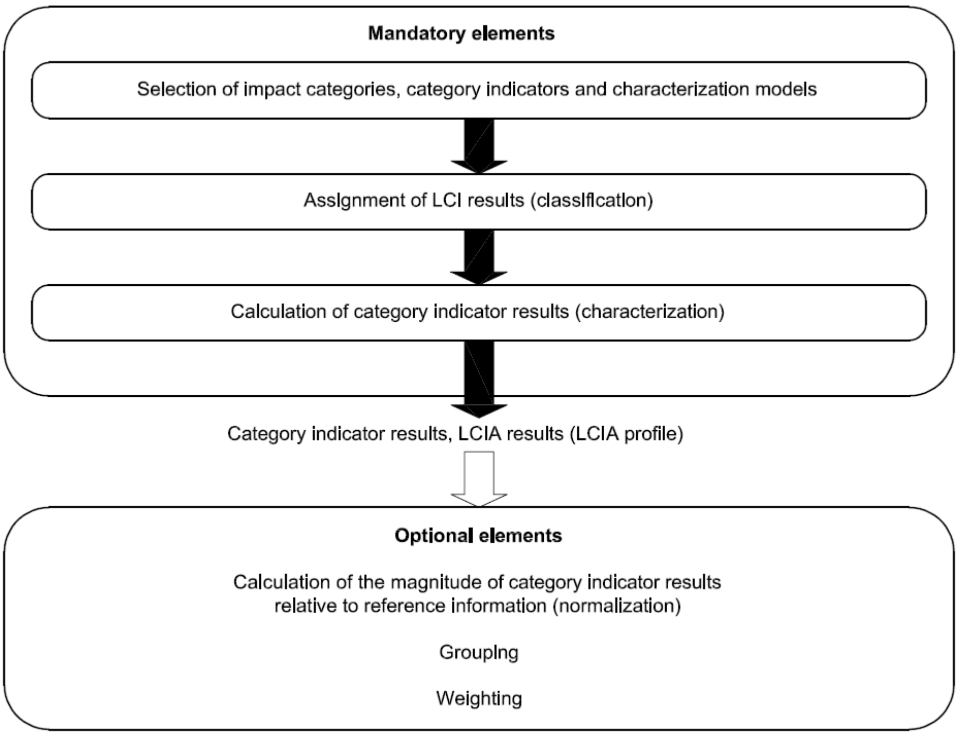

Figure 2.18 - Elements of the LCIA phase (ISO, 2006c)

The “Life Cycle Impact interpretation” phase comprises the identification, interpretation and evaluation of the most important results obtained in LCI and LCIA phases, in accordance with the goal and scope defined for the study, in order to confirm whether they are supported by the initial data and the model chosen (Figure 2.19). The final report contains the main conclusions of the study and the necessary recommendations for the production and use of the product. It may also contain data on the product that is relevant for the analysis but has not been included in LCI or LCIA, such as the environmental impacts during use phase, the durability of the product or the sensitivity analysis of some of the results obtained.

LCA involves modelling and cannot be seen as a complete reflection of the real world. Therefore, all the decisions related to the modelling, such as data reliability and uncertainties, the effects to be included, the boundaries to be set, cut-off rules or the interpretation, must be well documented (Blok *et al.*, 2007). The LCA study can also be subjected to a critical review made in accordance with ISO 14040:2006 and ISO 14044:2006 international standards. The critical review is made to ensure the consistency of the study with the principles and requirements of these standards. The qualifications of the reviewer should be defined in the part related to the scope of the study (ISO, 2006c).

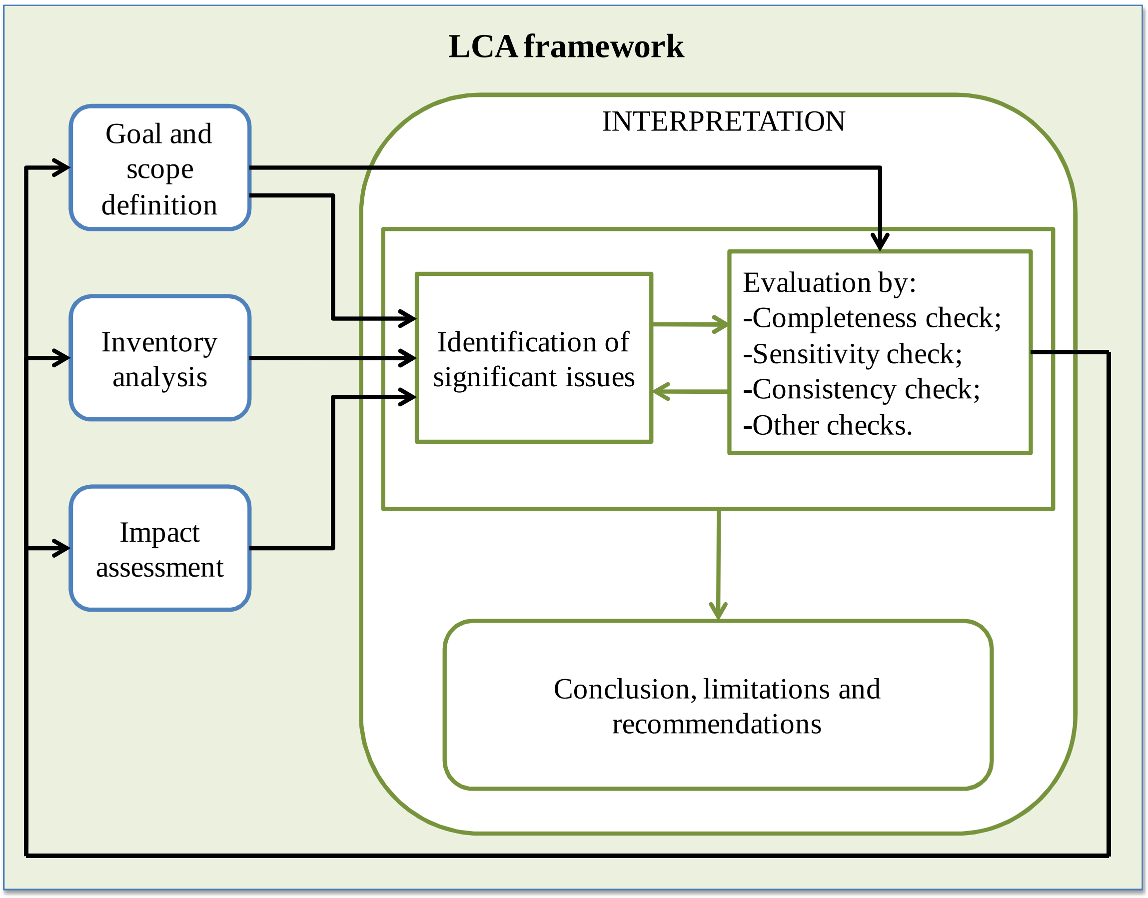

Figure 2.19 - Relationships between elements within the interpretation phase with the other phases of LCA (ISO, 2006d)

The boundaries of the system subject to a LCA define whether it is applied from cradle to gate (including the extraction and processing of raw materials and the production), from cradle to grave (including also the transport, distribution and assembly, the use, maintenance and final disposal), or from cradle to cradle" (also including the reuse, recovering and/or recycling potentials) (see Figure 2.20) (Ferrão, 2009; Ortiz *et al.*, 2009).

The application of the cradle to cradle perspective in a LCA study implies the appraisal of the product in terms of its eco-effectiveness. To follow the eco-effective principles, the design of the products (or the industries) must allow the creation of cyclic metabolisms from cradle to cradle based on upcycling processes. These metabolisms can be of two types: biological or technical. The latter correspond to the "nutrients" processed by the human being and not assimilated by nature. These principles are opposite to the traditional eco-efficiency strategy, in which the aim is only to reduce the flows of materials from cradle to grave (Braungart & McDonough, 2009; Farrall, 2010).

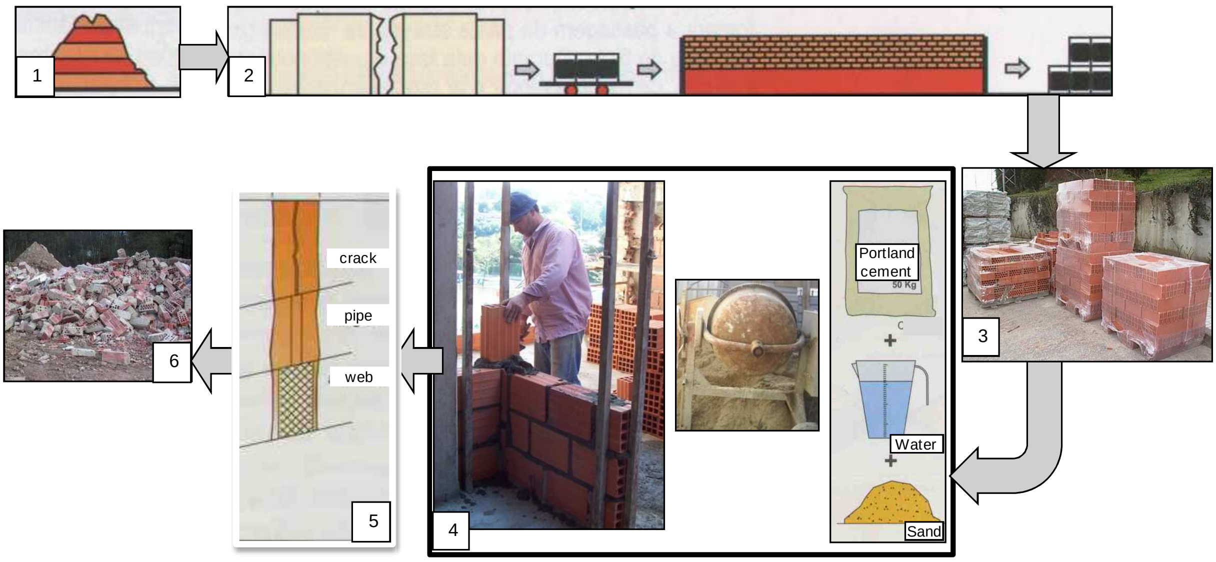

Figure 2.20 - Life cycle of hollow fired-clay bricks: 1 - clay extraction and deposit in layers; 2 - final stage of block production - drying, transport to the kiln and palletisation (3); 4 - application on site, including mixing of the masonry mortar; 5 - crack repair; 6 – demolition and waste management (partially adapted from (APICER, 2000))

There are different LCA approaches, from which two of the most divergent are: process-based LCA and the LCA via economic *inputs-outputs* ("Economic Input-Output" LCA - EIO-LCA). The former approach uses the flow analysis to model the activities and life cycle phases, including in the processes the most important *inputs* and *outputs* of materials and energy. The impacts of the environmental emissions are estimated for each process, as already described. This approach is very demanding in terms of time and cost due to the enormous quantity of data required. Therefore, process-based LCA needs the definition of a boundary of the analysis in order to be implemented.

The EIO-LCA approach uses the data of the economic *input-output* and the *input* of resources and the environmental *output* data of different industrial sectors available in the country of the study. This way it is possible to complete the study via the characterisation of the supply chain and the quantification of the direct effects (Gervásio & Silva, 2007b; Horvath, 2004). The level of detail of this approach is low, preventing the achievement of different results for products of the same economic area and the detailed characterisation of their use and end-of-life phases (Gervásio & Silva, 2007b; Rebitzer *et al.*, 2004).

Despite the fact that they were largely used independently, the joint use of process-based LCA and EIO-LCA allows for the reduction of the consumption of time and money in data collection and allows for the capitalisation of the advantages of each approach. This hybrid LCA approach (or hybrid EIO-LCA) also allows a more complete definition of the systems being studied and a better comprehension of the environmental impacts along the whole life cycle of the product, simultaneously conserving the specificity of the processes with reduced need of additional information or inventory data (Horvath, 2004; Rebitzer *et al.*, 2004; Sharrard, 2007) (Figure 2.21). A tool to support hybrid LCA adapted to the economic characteristics of North America is available (Suh & Huppes, 2002) and extensive research concerning the application of this approach to the calculation of the environmental impacts of the building construction phase has already been finished (Sharrard, 2007). If the processes with the most significant environmental impacts are correctly identified, this hybrid approach can also be applied on the study of the construction materials and assemblies.

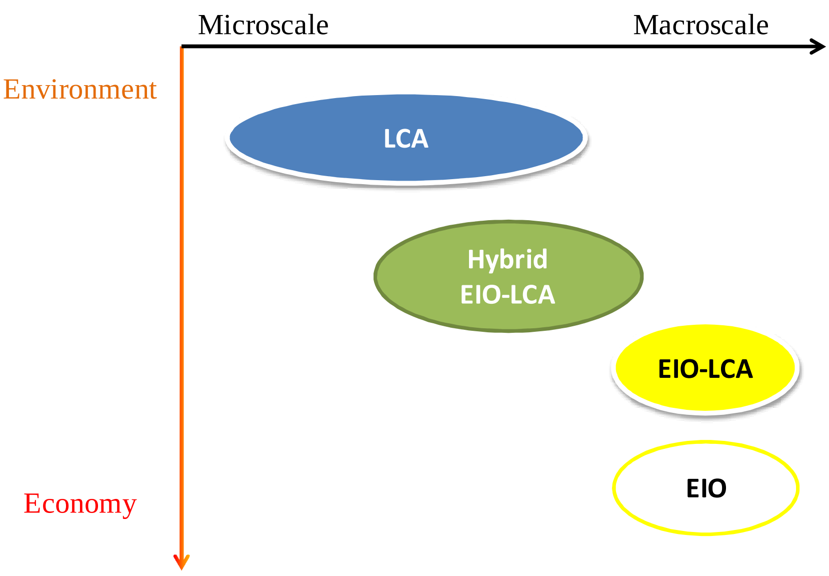

Figure 2.21 - LCA approaches dependent on their relationship with the environment and the economy in local and global terms (adapted from (Ferrão, 2009))

LCA can be used in companies, in a private manner, in product development, in a comparative and iterative process, which consists of a simplified LCA called "*screening* LCA". This methodology can also be used for *eco-labelling*, as described in section 2.2.1, in order to rank a product in environmental terms among its competitors. The quantity and quality of the data, as well as the precision of calculus, are much greater in this second type of LCA study, which can be a development of a "*screening* LCA" (Ozik, 2006). LCA studies of both types have difficulties, the most important of which is the subjectivity of the analysis of the data and of the interpretation of results, and the manipulation and treatment of confidential information.

LCA is a tool with many advantages but with some disadvantages and limitations. LCA is considered the only tool that examines the environmental impacts of a product or service throughout its life cycle via an ISO standardised method. It also provides a comprehensive overview of a product or service, preventing the shifting of the source of the pollution from one life cycle stage to another. This method challenges preconceived notions by distinguishing between the information that is relevant for objective quantification and the issues that pertain to policies, priorities, and social choices. The limitation of this tool stems from the geographic dependency of the results, the assessment of potential and unreal impacts, and the influence on the results of the objectives, processes, quality of data, and impact assessment methods used (CIRAIG, 2010). Moreover, LCA cannot determine the temporal or spatial character of the analysed effects on the environment (Cabello, 2007). A survey of unresolved problems in all the phases of life cycle assessment is presented in two papers published in the *International Journal of Life Cycle Assessment* (Reap *et al.*, 2008a, 2008b). In order to address the problems of consistency of data and different methodologies of LCA studies, in 2005, the European Commission launched the project of the "European Platform on Life Cycle Assessment" (Gervásio & Silva, 2007b). This platform promotes guides, indicators, reference databases and pilot studies to increase the awareness and quality-assurance of the LCA method and "Life Cycle thinking" general approach (EC, 2010).

2.4. Interlink between LCA and construction industry: construction materials and buildings

LCA is one of the tools developed in the field of industrial ecology. Industrial ecology has investigated, since 1989, the application of the behaviour of natural ecologic systems to industrial activities. In 1999, Professor Charles Kibert organised a workshop at the University of Florida, USA, to evaluate the use of this approach by the building industry. A group of well-known architects, ecologists, industrial ecologists and material manufacturers were invited to the “Rinker eminent scholar workshop on construction ecology and metabolism”, whose results were published in a book called “Construction ecology”. This is already an important area of research that aims at using the concepts and methods of industrial ecology to help designers to acknowledge and quantify the effects on the natural world of decisions concerning sustainable design and construction (Kibert, 2002).

The evaluation of the environmental impacts of buildings should be made from a life cycle point of view. This implies the consideration, for each building assembly, of the source of the construction materials, the resources used in their manufacture, the maintenance operations, their expected service life, and the replacement or demolition operations. Therefore, environmental concerns should focus on the evaluation of the effects of these impacts during the life cycle of construction projects and in the upstream supply chain, and not only at the execution phase. Therefore, there is an increasing search for an integrated approach that considers the environmental impacts along the life cycle of each of the construction assemblies that are used in the most significant structures all over the world: buildings. The LCA integrated approach is one of the most used ways to achieve this goal and is the answer to the increasing need of extending the environmental responsibility of products from its production to the whole life cycle (Ferrão, 2009; Ortiz *et al.*, 2009; Pinheiro, 2006).

The construction of buildings distinguishes itself, in relation to other industrial processes, in being an activity that executes all the processes *in situ* (on the site where the construction is occurring). When the works finish, the materials stay incorporated in a permanent location, but not everlasting. Other industrial processes are characterised by static factories and by products with shorter and more intense life cycles. With these characteristics, these projects turn out to be more completely defined (Cabello, 2007). Therefore, the application of a detailed LCA approach to buildings or other construction works is a complex, onerous and extensive task (Figure 2.22). This also happens because of the quantity of products and processes included in this industry, the long life cycle of these products when finished, the different service life of the components of the building and the dynamic that differentiates buildings from other standard industrial products, namely during execution, use and end-of-life phases (Blok *et al.*, 2007; Chevalier & LeTeno, 1996; Kibert, 2002). The application of the LCA approach in its purer form to this industry is also difficult because of the quantity of data concerning its processes. This makes the definition of a functional unit (that is a service and not only a product), the boundary of the assessment and the databases to be used even more important, in order to lessen the sensitivity and errors of the results (Erlandsson & Borg, 2003; Ozik, 2006). With this purpose, software and databases of general application or construction specific to support LCA have been developed, which are thoroughly described in Chapter 5.

The question of a building's service lifespan is critical. Construction, disposal and deconstruction can be modelled in terms of processes that can be generally 'traced' and described such as to associate impacts, whereas the building's use, maintenance and management are characterised by utmost variability. In these phases, there are other variables totally unpredictable and hard to outline because they are dependent on decisions concerning building operation and maintenance scheduling. This limits the actual reliability of LCA studies, but this can be overcome through the participation of clients and users together with building designers at the planning and design stages. Also, building materials are normally examined on the basis of hypothetically correct use/maintenance/replacement conditions that have to be carefully observed anyway during on-site laying and service life (Lassandro *et al.*, 2007). Nevertheless, there already is an ISO standard that makes the interface between LCA and service life planning and describes how to consider service life of construction materials and buildings in LCA studies (ISO, 2004).

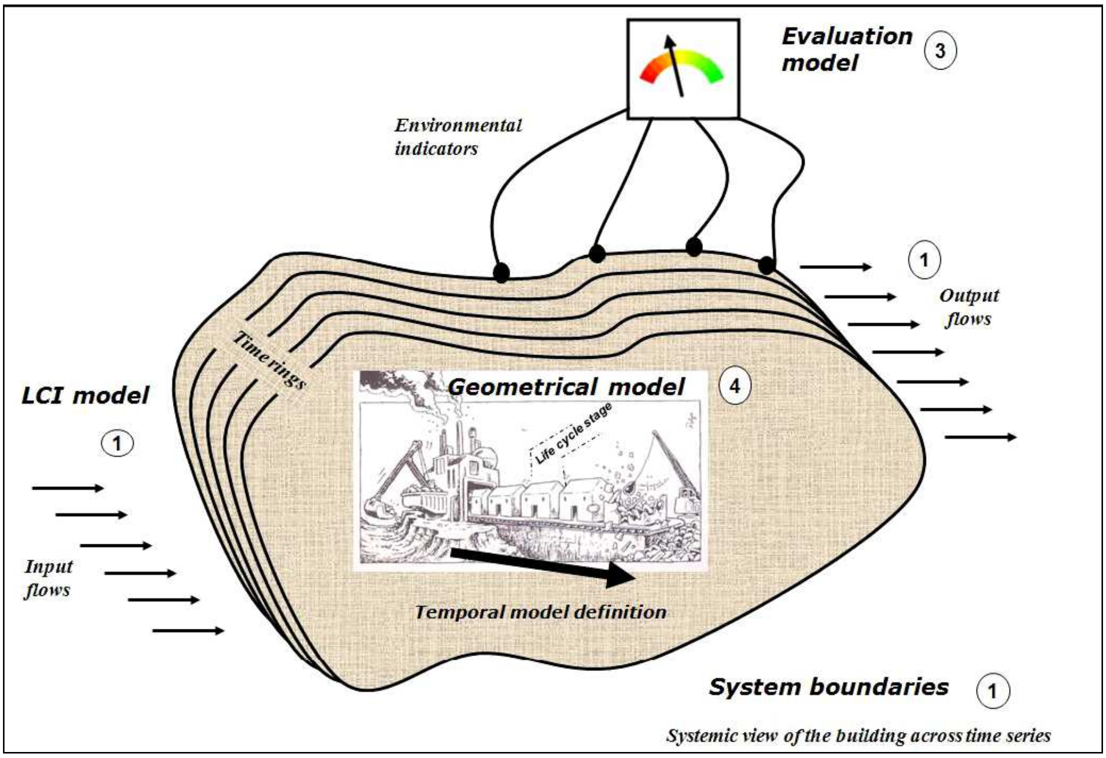

Figure 2.22 - Example of a LCA-based model for buildings, which tries to represent the complexity of this kind of approach ((Lasvaux *et al.*, 2010))

Due to all of these difficulties, LCA tools are not customarily used by everyone involved in the building design, construction, trading or use phases. These tools are only used by experts, mainly at an academic level (Bragança & Mateus, 2008; Pinheiro, 2006). A balance of the drivers behind and remaining barriers to the execution of LCA studies in construction has recently been presented (Table 2.3). Some of the drivers, such as the marketing benefit and the environmental loans and subsidies, can be important means to overcoming barriers such as the low demand and high cost of LCA.

The European project “ENSLIC - ENergy Saving through promotion of LIfe Cycle assessment in buildings” (http://circe.cps.unizar.es/enslic/texto/home.html) promoted the use of LCA techniques in refurbishment and design of new buildings, in order to achieve energy savings in the construction and operation of buildings (Malmqvist *et al.*, 2010). One of the outputs of this project was a list of the advantages of using LCA in the building industry. Within this list, the most important points are:

- Minimisation of costs (namely environmental costs), and of the use of energy, materials and water;
- Identification of opportunities to improve the environmental aspects associated with the construction sector over the complete life cycle of the building (which corresponds to a holistic approach that should also include the auxiliary activities, as shown in Figure 2.23);
- Environmental labelling of buildings, resulting in marketing benefits, easier access to loans and subsidies, and reduction of local taxes;
- Ease of comparison of the environmental impacts of buildings located in different geographical zones and with different uses;
- Evaluation of the influence that decisions at the design phase have over the environmental impact of the building, and evaluation of the potential for energy saving and reduction of emissions associated with the implementation of different low-impact construction and architectural solutions.

Table 2.3 - Drivers and barriers to the execution of LCA studies in construction (Bribián *et al.*, 2009)

Drivers	**Barriers**
Marketing benefit	Prejudices about LCA complexity, accuracy and arbitrary results
Simplified data acquisition	Poor knowledge on environmental impact (e.g. assumptions, calculation and consequences)
Environmental labelling of buildings	Low demand for LCA
	Excessively complicated calculations and high costs
Environmental targets for buildings, the building sector, nations and Europe	Lack of standardised interfaces in programmes used in the building sector (CAD, tendering, building physics)
	Poor cooperation between application manufacturers and potential customers
Loans and subsidies for environmental impact reduction	Too many applications displaying different results
	Difficulties in understanding and applying LCA results
	Lack of legal requirements and poor incentives
	Low link with the energy certification applications

In the North-West of Europe, the “Cycle Assessment Procedure for Eco-Materials” (CAP’EM) is another ongoing research project regarding the development of a simplified LCA methodology suitable for construction materials. This project has the participation of 11 partner organisations from the UK, the Netherlands, Belgium, Germany and France, and aims to evaluate 150 building materials with the methodology that was finished by the end of 2010. Then, these results were made available on the website of the project and in exhibition centres in these five countries, together with the classification of the building materials according to multiple criteria. The exhibition centres also demonstrated the use of eco-materials in new building and renovation contexts.

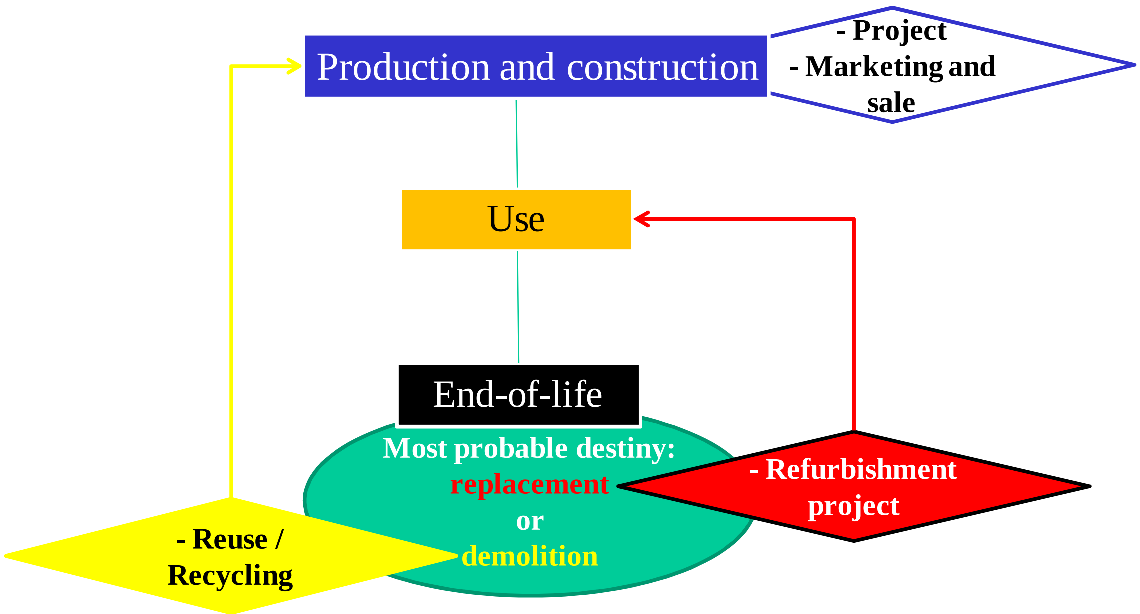

Figure 2.23 - Auxiliary activities during building life cycle (adapted from (Duarte, A. P., 2009))

LCA is also a tool that needs to be improved (Reap *et al.*, 2008a), be adjusted or have a referential system, in order to be applied in a satisfactory and broad manner to the construction industry. Nevertheless, the LCA approach is unquestionably a powerful tool with an extraordinary capacity of evaluating the environmental impacts throughout the life cycle of a construction material, building assembly or even a whole building. Among the restrictions to the use and application of LCA, it is possible to highlight the difficulty in dealing with variations on data from different geographies and environments. This problem can be solved by dynamic and spatially explicit modelling of the data collected (Reap *et al.*, 2008b). Other problems are the dependency of the LCA of a product on a production technique, the distance from the factory to the site, and the construction technique chosen (which can affect the durability and end-of-life options and, consequently, the LCA result) (Ozik, 2006). Another restriction corresponds to the lack of good quality and reliable data (Reap *et al.*, 2008b). To solve the problem of the effective and reliable collection of data, it is necessary to:

- Build a large and significant database and an information repository (a proper LCI) associated with the LCA, as has already been done in Europe (European Life Cycle Database - ELCD (Commission, 2009)) and North America (US LCI Database - http://www.lcacenter.org/ database.html); this data should be collected with the permanent support of the professionals of the construction material production industry, namely the data related to products, services and materials for construction, but most of the companies are not able to provide this data since it is confidential information (Ozik, 2006);
- The development of case studies of different types of common buildings in different regions to be used as references, after which the institution in charge of each BEAS has to define the mode of considering the results of each building in relation with a reference building of the corresponding system (Pinheiro *et al.*, 2007).

The need for developing case studies (of different types of common buildings in different regions) results from the great variation among the data from different sources. As an example, depending on the source, the embodied energy in 1 m^3 of concrete may differ by more than 217% and the embodied energy in 1 m^3 of plastic material may differ by more than 500% (Lewis, 1999).

The LCA of construction materials or assemblies, and buildings, provides quantitative data that is essential in ensuring that the architect chooses the most adequate options on his road to sustainable construction. The resulting information includes the environmental impacts resulting from the complete life cycle of construction assemblies. Thus, it allows the architect to compare similar alternatives in functional terms and achieve:

- The minimisation in the consumption of materials, energy and water;
- The elimination or reduction of the use of hazardous materials;
- The prevention or the minimisation of the emissions and waste.

This choice is wiser and results from a more detailed analysis than the application of singular criteria for material choice, such as (Duarte, A. P., 2009):

- More durability;
- Recycled and/or recyclable;
- Extracted in a rational manner (e.g. ornamental stones);
- Extracted from forests with sustainable management (wooden products);

- With reduced emissions of harmful compounds along the life cycle (e.g. paints, resin, carpets, among others);
- With no/low danger in terms of manipulation and maintenance;
- With low maintenance requirements;
- Use of local materials.

There is a remarkable discrepancy between the amount of time necessary for data collection and the rapid evolution capacity of specific “technology oriented” sectors, where data on the environmental performance of building components closely depends on the technologies used for their development (Lassandro *et al.*, 2007). Related areas for research in the application of LCA to building and construction include, among others, the relationship between durability and environmental effects (*dynamic modelling*), the clarification of the interrelation between LCA and “Environmental Impact Assessment” and the combination of LCA with WLC (Ekvall, 2005).

2.4.1. LCA and the construction industry: state-of-art around the world

Most of the applications of the LCA approach have been in the comparison of solutions (materials and construction assemblies) similar in functional terms but that can have very different environmental impacts. These studies can be a basis for environmental labelling (as described in section 2.2.1.3), for design of products “for the environment” (Design for environment - DFE - or *eco-design*), for projects of “cleaner production” (Ferrão, 1998) or may support the choice of alternatives related to the construction of a building (Ortiz *et al.*, 2009). Research related with LCA of construction products continues to gain momentum and already comprises: initial and simplified approaches (Bekker, 1982); detailed LCA of construction materials highlighting the significance of LCI representative of each country (e.g. LCA of cement (Filho, 2001)); *benchmarking* between different construction materials (Glover, 2001; López, 2001) or building assemblies. Detailed LCA of buildings is also being developed via simplified energy analysis (Blanchard & Reppe, 1998; Mithraratne & Vale, 2004) and studies at an international level (Junilla, 2004; Junilla & Horvath, 2003; Ortiz *et al.*, 2009; Trusty & Horst, 2002). A detailed analysis of LCA studies published between 2000 and 2007 devoted to construction materials, assemblies, and buildings was published in a recent paper by Ortiz (Ortiz *et al.*, 2009). But it is extremely difficult to outline general principles from these studies, especially between buildings of different regions or countries (Horvath, 2004).

A LCA study of a building of 18 stories (with 5 stories of underground parking and with a reinforced concrete frame structure) made in Canada with ATHENA software (described in detail in Chapter 5) acknowledges the importance of this methodology ((Trusty & Horst, 2002) cited by (Pinheiro, 2006)). This study also shows the different contribution of the components of the building in its environmental performance, especially of the structure. The effects are evaluated in terms of embodied energy, solid wastes, air and water pollution indexes, and are based on the method of critical measures of volume and greenhouse gas emissions, which are indicators of the “global warming potential”. The estimation of energy and emissions does not include operation energy.

Another detailed LCA, focused on the energetic component, was made on a house in Michigan, in the USA ((Blanchard & Reppe, 1998) cited by (Pinheiro, 2006)). This study considered a service life of 50 years for the building and had, as its most distinctive result, the evidence that the energetic life cycle impact of new houses can be reduced by a factor of 2.8, by promoting incremental changes and reducing the embodied energy in the use phase and its energy consumption. For that, it is necessary to improve the building envelope and the heating and cooling systems (namely using energetically efficient equipment).

Professor Arpad Horvath, from the University of California - Berkeley (also in the USA), supervised a LCA study of a building located in Finland ((Junilla, 2004) cited by (Pinheiro, 2006)). This work comprises the quantification of the most important features of the environmental performance of a new office building (used by technology companies) during a 50-year life cycle. The LCA study included the evaluation of the quality of the information collected and its results showed that most of the environmental impacts are associated with electricity consumption during the building’s exploitation, with the production and maintenance of construction materials, with the use of water and effluents generation and with the management of office waste. It was also possible to conclude that the construction and demolition phases have relatively irrelevant impacts.

In 2002, the Government of Hong Kong ordered a consultancy study entitled “Life-cycle Energy Analysis of Building Construction”, which was only finished in 2006. The aim of this study was the promotion of sustainable building development in this country via the development of an assessment tool (and its databases) which facilitates local building design professionals to appraise the environmental and financial life cycle performance of commercial buildings. This assessment tool is based on LCA and LCC (Liefe cycle costing) methodologies (ARUP, 2006). This study concluded that the building characteristics that can be evaluated in LCA studies include:

- Energy efficiency and renewable energy - building orientation to take advantage of solar access, shading and natural lighting; effects of micro-climate on building; thermal efficiency of building envelope and fenestration; properly sized and efficient heating, ventilation and air-conditioning (HVAC) systems; alternative energy resources; minimisation of electric loads from lighting, appliances and equipment;
- Minimisation of disturbance to the drainage basins and non-point-source pollution - effect of choice of materials on resource depletion and air and water pollution; use of indigenous building materials; amount of energy used to produce building materials;
- Resource conservation and recycling - use of recyclable products and those with recycled material content; reuse of building components, equipment and furnishings; minimisation of construction waste and demolition debris through reuse and recycling;
- Community issues - climatic characteristics as they affect design of building or building materials.

The EU-funded projects REGENER joined eight partners of five different EU countries to define a common methodology to apply LCA in the building sector, to develop a design toolbox and to perform first applications of the methods. This project was finished in 1997 and included as main outputs the following reports: “Environmental assessment at the local level - analysing the decision process and the possible uses of LCA”; “Application of the life-cycle analysis to buildings - detailed description and review”; “The integration of environmental assessment in the building design process - development of a design tool box”; “Applications by target groups - implementation of LCA by the main building actors” (Peuportier, Bruno *et al.*, 1997).

In Spain, the “Association for the Research and Industrial Development of Natural Resources” (*Asociación para la Investigación y el Desarrollo Industrial de los Recursos Naturales*, AITEMIN) developed, between 2003 and 2005, a LCA study of ceramic materials supported by “Ministerio do Fomento”. This study included the participation of 18 Spanish ceramic industries to become aware of the environmental load of these construction materials during their life cycle in a cradle to grave perspective. The declared unit defined was a tonne of ceramic product. The negative results are due to the drying and burning processes, and the emissions of the kiln. The positive results come from the use of sub-products of the same industry or other industries and from the high recycling potential of these products (Cabello, 2007). Also in Spain, two other studies were previously made concerning construction materials: one devoted to cementitious materials ((Filho, 2001) cited by (Cabello, 2007)); another one regarding granite ((Espí & Seijas, 1999) cited by (Cabello, 2007)).

2.4.2. LCA and the construction industry: state-of-art in Portugal

In Portugal, a LCI or LCA database exclusively dedicated to construction materials and assemblies for buildings, adapted to the reality of the country and developed via scientifically validated research, does not exist yet. This kind of data is needed to assess a building's sustainability, mainly at the design phase, and should be methodologically collected and calibrated in order to represent all the phases the construction materials have undergone: from the factory (cradle) to site, and from there to a new use (cradle), after the demolition of the building. As stated in section 2.2.2.3, the Portuguese version of the BEAS SBTool ($SBTool^{PT}$) contains a LCA database of the most common construction materials and assemblies for buildings, but is only available for the evaluators certified within this BEAS (Bragança & Mateus, 2008). This database is complemented by the information of the environmental impacts related to the use of heating, cooling, and water heating equipment. These LCA results were calculated using *SimaPro* software (and its databases (PRé, 2012)) and the EIAM *CML 2 baseline method 2000* (both described in detail in Chapter 5). However, none of the information collected from international databases was adapted to the Portuguese reality. The environmental impacts are shown by area of construction assembly or kg of construction material and are divided between the phases from cradle to gate and end-of-life. The "Cumulative Energy Demand" (CED) method is also used to determine the renewable and non-renewable embodied energy in each construction assembly (Mateus, 2009). Another research study used this database to compare a cavity wall and an "External Thermal Insulation Composite System" (ETICS) (each one with two different possible insulation materials and all with different thermal transmittance) in terms of environmental loads, embodied energy and initial cost (Lucas & Ferreira, 2010).

Professor Manuel Duarte Pinheiro developed a tool for the assessment of sustainable construction and a certification system for Portuguese buildings in his PhD Thesis completed at "*Instituto Superior Técnico*", at the Technical University of Lisbon: the *LiderA* system of Building Environmental Assessment (BEAS) (Pinheiro, 2008). In *LiderA*, there is only one criterion clearly related to LCA - materials with low environmental impact - which is a characteristic similar to most of the BEAS around the world (Pinheiro *et al.*, 2007). As cited in section 2.2.2.3, this BEAS has a classification system of construction products within the environmental dimension which is still in an experimental phase, and which will be based on LCA studies from 2013 on (Pinheiro, 2010).

At the same university, two researchers completed the LCA of concrete made with recycled fine aggregates with *EcoConcrete* (an Excel based LCA tool developed in 2003 by six major European Federations of construction materials). In this work, the result was compared with the LCA of a concrete made with 30% of recycled fine aggregates and with the LCA of a concrete made without recycled fine aggregates (Evangelista & de Brito, 2007).

Other research works on LCA applied to the construction industry have already been finished in Portugal, namely:

- The LCA from cradle to gate of different products of the ceramic industry (masonry units with vertical hollows, roof tiles, wall and floor tiles and sanitary ware) based on data collected from 11 sites and from international databases (described in detail in section 2.2.1.3) (Almeida, 2010; Almeida *et al.*, 2010);
- The primary energy requirements (renewable and non-renewable) and greenhouse gas emissions due to the production phase, and heating energy and maintenance requirements during 50 years of a house have been calculated considering seven alternative exterior wall solutions made with different materials but with similar thermal transmittance (Monteiro & Freire, 2010b);
- A research work completed at Aveiro University compared a traditional reinforced concrete solution for the structure of a dwelling with a solution of adobe walls and timber flooring, in terms of building cost, energy consumption and atmospheric emission of noxious gases in the production of construction materials, without referring to the thermal performance of the solutions evaluated (Murta *et al.*, 2010);
- A LCA study from cradle to grave of traditional masonry solutions for external walls, with different coatings and insulation materials, and of a glass curtain wall, was made in a PhD Thesis (Pinto, 2008);
- Another study compared the embodied energy, environmental loads and required heating energy (during one year) of a cavity wall and an External Thermal Insulation Composite System (ETICS), each one with two different possible insulation materials and all with different thermal transmittance, applied in the exterior wall of a room (Lucas, 2008);
- A cradle to grave LCA study concerning the 50-year service life of a lightweight steel dwelling compared three end-of-life scenarios, landfill, recycling and reuse, using international databases and without considering the operation phase (Gervásio & Silva, 2007a); another study also completed at Coimbra University comprised the cradle to grave LCA of a low-cost lightweight steel dwelling over a service life of 50 years using international databases, including the operation and maintenance phases and considering two end-of-life scenarios: the structure is recycled or 90% of the steel structure is reused

(Gervásio *et al.*, 2010);

- The LCA of the production of ceramic brick in accordance with data collected from different Portuguese plants and the calculation of the environmental impacts of the production of construction materials and of the use of a dwelling during 50 years (for three different solutions of external walls and four heating solutions) were both completed in the scope of the European project “Green-It: Green Initiative for energy efficient eco-products in the construction industry” (thoroughly described in section 2.2.1.1) (Green-It, 2010; Ribeiro *et al.*, 2006);
- The cradle to gate LCA study of cement production in a national, and in an Italian, plant was completed in the scope of a Ph.D. at the Technical University of Lisbon (in the *Instituto Superior Técnico*) (Blengini, 2006). This research study followed International standards on LCA, collected plant-specific data from different types of cement, and included the LCA of a building;
- The LCA from cradle to gate (including end-of-life phase) of 1 m^3 of ready-mixed concrete in the scope of the European project “STEPWISE EPD” (described in detail in section 2.2.1.3) (Concretope & INETI/CENDES, 2005);
- A Master Thesis in Minho University included the comparative analysis of six external wall solutions based only on the Primary Energy Consumption (PEC, same as embodied energy) already calculated by other researchers (Mateus, 2004);
- Another Master Thesis in the same University included the comparative analysis of four external wall solutions based on four environmental categories with data available in BEES and *Ecoinvent* databases (both described in detail in Chapter 5) (Ecoinvent, 2012; Pessoa, 2009);
- Using the work done by Mateus (Mateus, 2004) as a baseline, another study was recently finished in Portugal which added the “global warming potential” to the environmental indicators included in the comparative assessment of traditional solutions for walls and slabs with timber solutions (with different functional performance) (Marques, 2008).

The studies from those cited above that comprise the environmental evaluation of different exterior wall solutions are thoroughly described in section 2.4.3.

At Minho University, a program called *EcoBuild* was developed to compare the environmental impacts and the construction costs of a building with a reinforced concrete frame structure with an alternative structure in steel profiles. By defining the quantity of construction materials to use it is possible to calculate the environmental impacts (energy and water consumption and CO_2, SO_2 and NO_x emissions) only from the phases of production of construction materials and transport to site. The database of the program was built with information collected from national producers of cement and steel bars, aggregate suppliers and one Spanish factory of steel profiles (Peyroteo *et al.*, 2007).

One of the most important buildings of the "1998 Lisbon World Exposition", the *Pavilhão Atlântico*, had its embodied energy quantified in 1998 in a Master Thesis in Architecture in the University of East London by the researcher Pedro Bento (Bento, 2007). *Pavilhão Atlântico* is an all-event building with a capacity for 20.000 spectators and a remarkable timber roof structure. The embodied energy of this building considered the weight of all the materials used and the production, transport to the site and assembly phases.

2.4.3. External walls in LCA studies

The envelope is one of the main parts of buildings. One of its elements, the external walls, directly influence the thermal and environmental performance of the building envelope through their considerable weight in the envelope's initial embodied energy, life cycle energy consumption, life cycle cost and users comfort. They can represent up to 15% of the overall environmental impacts of a building over a 60-year life cycle ((Anderson *et al.*, 2002) cited by (Bingel *et al.*, 2006)) and this percentage can be even higher in energy efficient buildings (Peuportier, B. *et al.*, 2012), thus justifying being the object of this thesis. The environmental impacts of each external wall solution result directly from the attributes of the materials used, such as its initial embodied energy and thermal properties and the way the solution is designed and built.

This section presents a review of LCA results of more than ten years of international research studies on the environmental impact of a building's external walls (Silvestre *et al.*, 2010). These studies differ in various parameters, namely their scope, objectives, level of simplification, completeness and transparency. Nevertheless, the results of each study help to identify the most environmentally friendly solutions for external walls of buildings.

The most important studies concerning the comparative evaluation of the environmental impacts of external walls of buildings were searched for in the main scientific databases (Science Direct, CIB and ASCE using keywords such as wall, LCA, brick, PhD, thesis, building, etc. and combinations thereof). This compilation of studies includes scientific papers, theses and technical reports mainly from Europe (59%) and North and South America (19%), as shown in Figure 2.24. Most of these studies were done after 1999. This reveals the increasing concern about the environmental impact of buildings and building materials in the XXI century. Nevertheless, this review is considered incomplete as most LCA studies are made for the specific use of decision-makers and are not accessible as scientific literature (Werner & Richter, 2007).

Only a quarter of the studies compare functionally equivalent products while more than half of them (52%) do not even refer to the thermal performance of the external wall solutions being evaluated and their results cannot be compared in equal terms. Therefore, and because the former are representative of different regions of the world, the latter are just cited but not fully described nor analysed in this section of the thesis. Nevertheless, the studies that compare external walls that are not functionally equivalent but regard the operation energy are also considered.

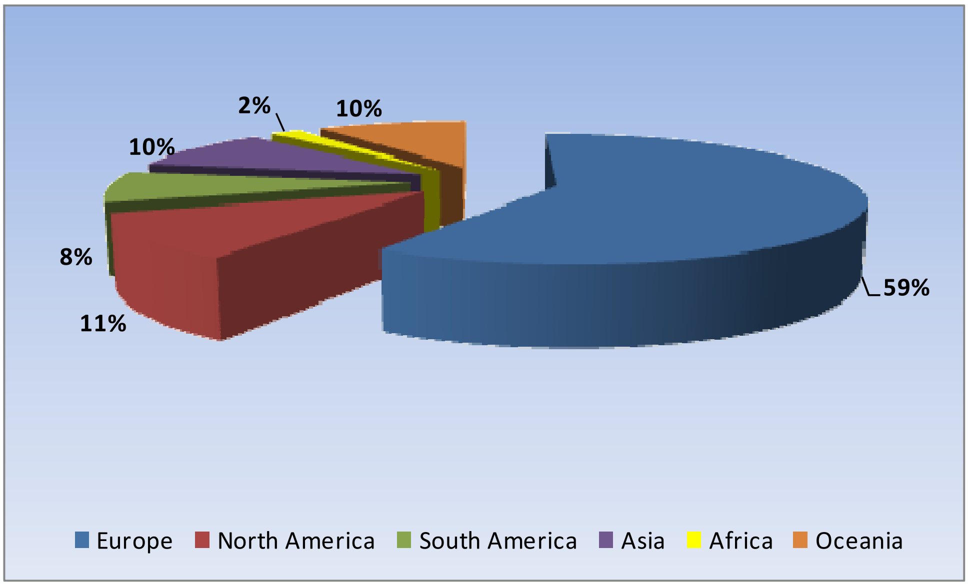

Figure 2.24 - Continent where each LCA study of external walls was made

All 63 studies found comprise the production of the construction materials and just a third include the end-of-life of the building assembly (Figure 2.25). Most of them (62%) evaluate the embodied energy of each external wall and 43% clearly refer to the use of an Environmental Impact Assessment Method (mostly *EcoIndicator 99*) and a LCA software, but just 13 of them (21%) explicitly mention that they followed the methodology described in LCA International standards.

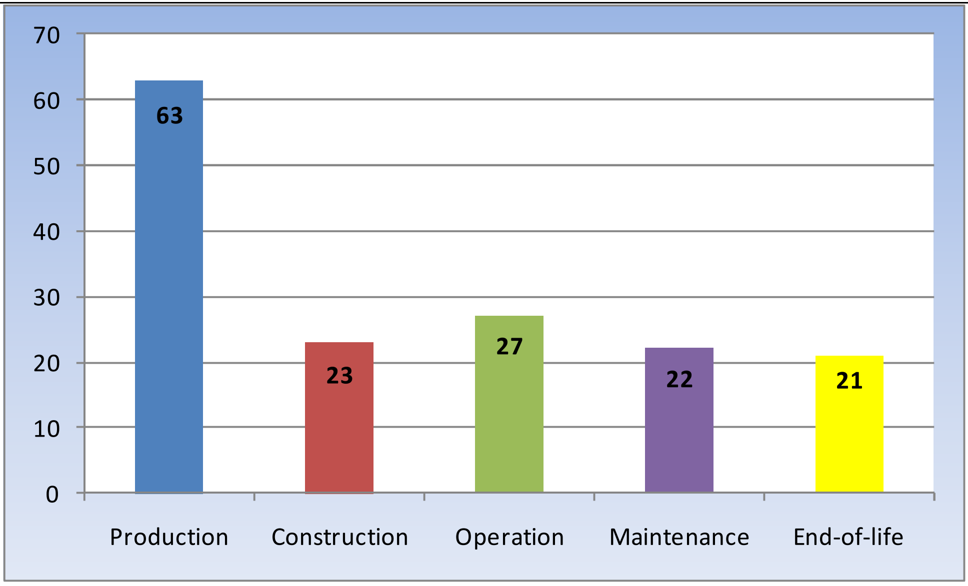

Figure 2.25 - Life cycle phases included in LCA studies of external walls

Table 2.4 presents an overview of the studies that compare functionally equivalent external walls or refer to the thermal performance of the solutions evaluated. The life cycles considered for external walls differ greatly between studies.

Within the 63 studies, less than half comprise the environmental impacts of the operation phase of the building (Figure 2.25), namely the energy use in HVAC systems calculated by a simulation tool for each external wall solution within a building. These are summarised in section 2.4.3.2, while the other ones are described below.

The results of these studies are not characterised and analysed in detail, nor compared with the ones achieved in this thesis for building products (Chapter 5) and for external walls (Chapter 7). This decision was made due to the following reasons:

- Lack of geographical representativeness - the studies are mainly from Europe, but the representation of the other continents is also significant (Figure 2.24);
- Inconsistency of methodologies - the system boundaries of the LCA studies vary from cradle to grave to cradle to gate (Figure 2.25) and just 21% explicitly mention that followed International LCA standards. Furthermore, the inventory data of some LCA studies are based in the literature, whereas others include data from producers (Table 2.4);
- Lack of critical review - most of these LCA studies were not critical reviewed. On the other hand, most of the LCA databases and EPD chosen to be compared with the results achieved in this thesis were subjected to an internal or external critical verification (see Chapter 6).

Furthermore, the number of European LCA databases and EPD with data for products used in external walls is increasing, and most of them do not present any of these limitations.

2.4.3.1. Comparative LCA studies of different solutions and materials for external walls

This section includes the studies that compare the thermal, environmental and even economic performance of complete external wall solutions or evaluate the impacts of the production phase of blocks of different materials that are normally included in these solutions. The ten studies that compare functionally equivalent products are described next.

A study of solutions for external walls with different coatings and insulation materials was made in a PhD Thesis in Portugal (Pinto, 2008). It included the LCA of the walls based on a cradle to grave LCA of individual construction materials using the methodology described in ISO 14040 (ISO, 2006c). In the same country, a master Thesis included the comparative analysis of six external wall solutions based only on the “Primary Energy Consumption” (PEC, same as embodied energy) already calculated by other researchers (Mateus, 2004). Both works mainly regarded traditional masonry solutions.

In Sweden, a value-focused thinking to support the environmental selection of external wall solutions was developed (Hassan, 2004). This model was based on LCA results and environmental categories of prior works and tried to compare concrete, fired clay and wood solutions with similar thermal transmittance. The weight of each environmental category was defined by the author.

A consultancy work ordered by three producers of construction materials was completed in Finland in 1999 (ECOBIO, 1999). This LCA study from cradle to grave (excluding only the construction phase and the energy consumption during the use phase) comprised 17 exterior wall structures placed in multi-storey buildings and single family houses. The solutions were divided in four groups, according to thermal transmittance and type of building. A critical review was made by a third party after the conclusion of the study.

A LCA evaluation of four low-weight solutions (also with similar thermal transmittance) for external walls of buildings was concluded in Italy (Monticelli, 2007). At first, this work only considered the production and end-of-life of construction materials. In a second part, the operation energy of each solution was also included.

Table 2.4 - Comparative LCA studies of external walls of buildings: functional equivalence (P - partial), wall structure Life Cycle (LC; in years) and databases used

Country	**Study**	**Functional Equivalence**	**Wall structure LC**	**Databases**		
				Software (**A**thena, **E**coinvent, **S**imaPro)	**National data**	**Prior works**
Australia	(Rouwette, 2010)	P	50	S	X	
Belgium	(Allacker & De Troyer, 2005)	X	75	X	X	
Canada	(Athena, 2009)	P	60	A		
China	(Gu, L. *et al.*, 2008; Gu, L. J. *et al.*, 2007)	X		X	X	
Finland	(ECOBIO, 1999)	X	100	S		X
France	(Lemaire, 2006)	P	100			X
Indonesia	(Utama & Gheewala, 2009)		40		X	
Israel	(Huberman & Pearlmutter, 2008)	X	50		X	
Italy	(Monticelli, 2007)	X		X		
New Zealand	(Kellenberger, Daniel, 2008, 2010)	X	50	E		
Portugal	(Pinto, 2008)	P	50	S	X	
	(Mateus, 2004)	P				X
	(Ribeiro *et al.*, 2006)	X	50	E, S		
	(Monteiro & Freire, 2010b)	X	50	E		
Sweden	(Hassan, 2004)	X	120			X
	(Thormark, 2006)	X	50		X	
United Kingdom	(BRE, 2010)		60		X	
USA	(Marceau & VanGeem, 2008)		100	S		
	(Rajagopalan *et al.*, 2009)		50	A, E, S		
	(Pierquet *et al.*, 1998)	P	30			X
	(SO-DEQ, 2009)	P	70	E	X	X

In France, a PhD Thesis developed a multi-criterion decision-aid tool that compares building products according to their environmental and health characteristics (Lemaire, 2006). This tool was applied in the evaluation of three external wall solutions with identical functional performance. The environmental and health impact categories considered in this study were the same as those included in the EPD.

A LCA from cradle to grave of two external wall solutions was included in a study that tried to define which materials and processes could be neglected in this kind of work (Kellenberger, D & Althaus, 2009). Therefore, the results only comprise the relative weight of each impact category for the wall assemblies by life cycle phase, preventing any comparison between the alternatives under analysis.

A calculator of thermal resistance and environmental impact of external walls was developed in New Zealand (Kellenberger, Daniel, 2008, 2010). The LCA of these low-weight wood solutions excluded the construction and demolition of the building and the operation energy.

The “Athena Sustainable Materials Institute” in Canada provides a free computer tool, the *EcoCalculator* (Athena, 2009). This tool performs a simplified LCA from cradle to grave of construction assemblies according to North American data.

The “Green Guide to Specification” of the “Building Research Establishment” (BRE), in the United Kingdom, contains the results of the LCA studies of more than 250 functional equivalent construction assemblies (for a service life of 60 years, considering a LCA from cradle to grave). This database was made with the support of the construction industry within the “BRE Environmental Profiles Certification” system (described in sections 2.2.1.3 and 2.2.2.1) and comprises six building types (e.g. housing, commercial, education and health). The LCA of each solution followed the BRE “Environmental Profiles Methodology” (but is not public) and is expressed in an *Ecopoint* index (between A+ and E) (BRE, 2010).

Some research works compare the environmental impact of external wall solutions with different thermal transmittance (Alías & Jacobo, 2003; Collins, R. *et al.*, 2010; König *et al.*, 2007; Lucas, 2008; Mak *et al.*, 2008; Marques, 2008; Pessoa, 2009). Other studies do not even refer to the thermal performance of the solutions evaluated (Chani *et al.*, 2003; Junnila, 2003; Lindeijer *et al.*, 2002; Mabe *et al.*, 2010; Mateus, 2009; Murta *et al.*, 2010; Nielsen, 2008; Randrianarison *et al.*, 2009; Reddy & Jagadish, 2003; Treloar *et al.*, 2001; Vandevyvere & Neuckermans, 2004; Wang *et al.*, 2003; Zami & Lee, 2010). There are also studies concerning the evaluation of the environmental impacts of the production of blocks and masonry units of different materials (Alías & Jacobo, 2003; Almeida *et al.*, 2010; Badino *et al.*, 2004; Carvalho & Sposto, 2008; Koroneos & Dompros, 2007; Kus *et al.*, 2008; Mastella, 2002; Morton *et al.*, 2005; Reddy & Jagadish, 2003; Silva, M. G. *et al.*, 2008; Spirinckx *et al.*, 2009; Zhang *et al.*, 2007). These types of studies normally consider the energy and emissions of the production of one metric tonne of product preventing any conclusions on its use in external walls.

2.4.3.2. <u>Studies concerning the LCA of entire buildings</u>

This section comprises twelve studies that compare the thermal, environmental and even economic performance of complete external walls solutions within a building.

In Portugal, the primary energy requirements (renewable and non-renewable), and greenhouse gas emissions and the LCA of a house have been calculated considering seven alternative exterior wall solutions, made with different materials (brick, concrete block and wood) but with similar thermal transmittance, and seven heating systems. This study included the production phase and the heating energy and maintenance requirements during 50 years and the LCA compared the results of two "Environmental Impact Assessment Methods" (*EcoIndicator 99* and *CML 2001*) (Monteiro & Freire, 2010a, 2010b). Also in Portugal, a study included the calculation of the environmental impacts of the production of construction materials and use phase of a dwelling during 50 years, for three alternative solutions for external walls and four heating systems (Ribeiro *et al.*, 2006).

The best external wall solution was selected for a thermally efficient building in Sweden (Thormark, 2006). The operation energy was calculated via a dynamic calculation method.

In Belgium, a decision support tool based on the environmental cost and quality of construction assemblies was developed (Allacker & De Troyer, 2005). This work included the LCA from cradle to grave of two external wall solutions within a three-floor building, including the energy consumption during use phase.

A study dedicated to the buildings of the Negev Desert in Israel calculated their "Life Cycle Energy Analysis" (LCEA), including the cumulated and operation energy and payback time of five functionally equivalent external wall solutions (Huberman & Pearlmutter, 2008).

In China, five façade solutions for an office building were compared through their energy consumption, life cycle environmental load (cost and environmental impacts during 50 years), life cycle cost, green payback time and general payback time (Gu, L. *et al.*, 2008; Gu, L. J. *et al.*, 2007).

A study concerning the materials of the external walls (two alternatives) and other assemblies, and the operation energy, was recently concluded in Indonesia (Utama & Gheewala, 2009). In 2010, a study was commissioned by Think Brick Australia to elucidate how a brick product performs over its entire life cycle, including consideration of the benefits it may bring to the "use" stage of a house. The corresponding report includes the results of the cradle to gate LCA of brick manufacturing and of the cradle to grave LCA of a brick, a brick wall and a house (including four different orientations, three different locations and five solutions for external walls) (Rouwette, 2010).

In the USA, a research study included the calculation of the embodied energy and thermal performance of twelve external wall solutions within a building in a cold climate region (Pierquet *et al.*, 1998). In the same country, two comparative LCA have been made between wall sections comprised of "Insulating Concrete Forms" **(**IF) and traditional wood frame. The first one considered all the life cycle phases from cradle to grave over a period of 100 years (Marceau & VanGeem, 2008) and the other one discarded the maintenance phase and reduced the service life of the building by half (Rajagopalan *et al.*, 2009). Also in the USA, the Department of Environmental Quality of the State of Oregon ordered a research project to evaluate the environmental benefits of potential actions to reduce materials use and prevent waste occurring in the construction, maintenance, and demolition of residential structures within this state. Three of the 25 waste prevention practices evaluated correspond to a change of the wall solution used (SO-DEQ, 2009).

A work already cited (Pinto, 2008) includes the LCA of two solutions with different and undefined thermal transmittance: a glass curtain wall and a traditional wall of fired clay hollow bricks with external insulation coating. Other studies do not clarify the characteristics of the external wall solutions evaluated (Anastaselos *et al.*, 2009; Arena & de Rosa, 2003; Collins, N. & Blackmore, 2010; Frenette *et al.*, 2007; Horne *et al.*, 2006; Itard, 2009; Massone, 2007; Nemry *et al.*, 2008; Rivela & Bedoya, 2007; Utama & Gheewala, 2006; Yu & Kang, 2009; Zold & Szalay, 2008).

2.5. Conclusion and perspectives

This chapter starts by making an introduction to the harmful effects of the built environment. This is an old, but still actual, concern. The construction industry, including the manufacturing of materials, continues to be perceived as a polluting industry. Therefore, all the initiatives that allow the collection of objective environmental information and life cycle data of construction materials and products must be encouraged. Simultaneously, a huge effort has to be made in disseminating this information to everyone who makes choices about construction materials and options in the design of buildings (CIB, 1999). This Chapter also contains the description of the increasing amount of initiatives of this kind all over the world, since the emergence of the “Sustainable Construction” concept in the 1990s, with a detailed analysis of the Portuguese condition.

The process of environmental certification of construction materials and assemblies is still absent in Portugal. However, a national programme of environmental certification of building products and services for the built environment is already in its starting point (DAPHabitat (DAPHabitat, 2012)).

There are some sector-based research projects already concluded that can be used as reference in Portugal. Moreover, national construction products with the biggest exportation potential have already had their environmental performance certified by international systems. This resulted from marketing issues but also because of possible protectionist measures from other countries. This kind of information (available or not, and more or less detailed) can be attached to further data already available from the national importers of construction materials with an environmental label (or self-declared claims). This set of environmental knowledge will allow the start of a consistent and scientifically validated database that will be an essential source of information for the building's designer who aspires to make progress on his road to sustainable construction. It will also be a starting point for the development of a voluntary system of environmental certification of construction products (or of a Type III environmental declaration programme, public or of private initiative) in Portugal, such as DAPHabitat. This programme should have as a main goal the dissemination of their EPD, which include rigorous and reliable information for the environmental assessment of buildings. These documents can also be used to show the fulfilment of environmental criteria on ecologic procurement (public or private) (Green-It, 2010; Rocha, 2010).

As stated in this chapter, the "Life Cycle Assessment" (LCA) methodology is one of the most used ways to calculate the environmental impacts of construction assemblies and buildings along their life cycle. However, there are still some barriers to overcome thanks to the particular characteristics of this industrial sector. This has stimulated the creation of software, databases and standards to support the detailed application of LCA to construction products, standardise its procedures and results, and encourage its regular use. The increasing number of initiatives and research projects included in the state-of-art presented in this chapter demonstrate the results achieved by these measures all over the world and, particularly, in Portugal.

The review concerning the LCA results of international research studies on the environmental impact of a building's external walls shows differences between them in various parameters, namely their scope, objectives, level of simplification, completeness and transparency. It also shows that, despite these differences, all LCA research studies of external wall solutions must have a definite scope and methodological approach to compare functionally equivalent products. Most of the studies included in the review do not follow these principles and prevent any inter-comparison of their results. For these reasons, it is important to develop LCA studies from cradle to grave of the traditional external wall solutions of each region, with production data from the same regional source, including the operation energy. This last feature is a powerful tool because it allows the comparison of alternatives without the need for functional equivalence of thermal performance and enlarges the amount of solutions that the designer can consider. These studies should focus more on the less-studied stages, such as construction, life-long maintenance and end-of-life (Horvath, 2004). The LCA analysis can be complemented by a whole life cost calculation for each alternative, without forgetting that all these solutions must comply with the minimum requirements of the regulations and standards (Bingel *et al.*, 2006). The LCA studies should be based on international standards, in order to enable direct comparison between them.

2.6. References - Chapter 2

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3. EXTERNAL WALLS OF BUILDINGS

3.1. Composition

This thesis is devoted to the study of the external walls of buildings, as referred to in Chapter 2, namely to the opaque areas of these assemblies (Figure 3.1). Therefore, neither the transparent areas (i.e. windows or glazed or curtain walls) of the walls nor the roof are comprised in this study, despite their important weight on the building envelope’s performance in every dimension (e.g. environmental, economic and energetic).

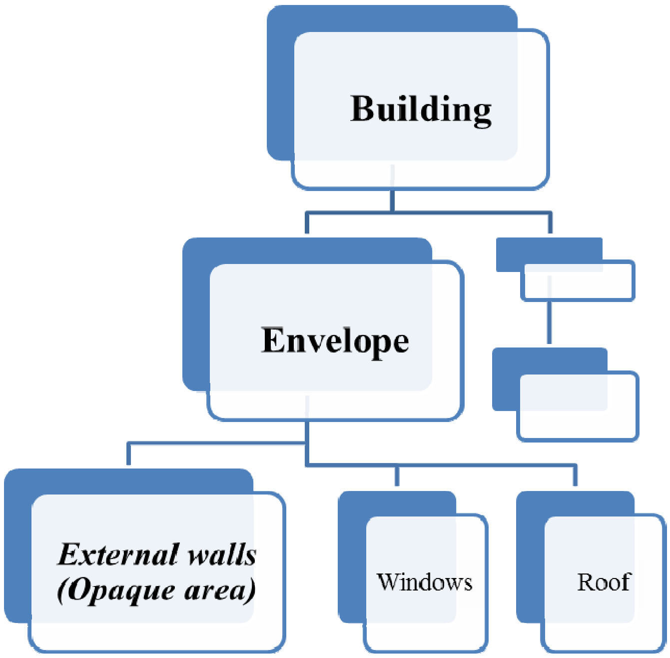

Figure 3.1 - Division of a building’s envelope into its three primary parts: external walls (the focus of this Thesis) and windows - the “vertical envelope”, where the windows represent all its transparent area, and the roof

The primary components of the opaque areas of the external walls - elements of the wall structure, insulation material, internal and external claddings and ancillary components - are described in detail in the next sections of this chapter (3.1.1, 3.1.2, 3.1.3 and 3.1.4). Then, the most common external wall solutions in Portugal are presented (section 3.1.5). In the next sections of this chapter (3.2.1, 3.2.2 and 3.2.3), the most important functional requirements (i.e. thermal performance, acoustic insulation and fire safety) that must be considered to choose an external wall solution for buildings in Portugal are described in more detail and the specific requirements of each wall element are pointed out in the next sections (3.2.5, 3.2.6 and 3.2.7). Economic concerns are also detailed for this important part of the buildings (3.2.4) and Chapter 7 complements this one by including the questions related to durability and maintenance of external wall solutions.

Eurocode 6 includes a classification of walls which lists eleven types (CEN, 2005), with a distinction between load-bearing and non-load-bearing walls and including some types which are not common in Portugal (i.e. double-leaf, grouted cavity, faced, shell bedded, shear and stiffening walls). Therefore, the remaining types of walls that are representative of common solutions for external walls are:

- Single-leaf wall, which does not have a cavity or a continuous vertical joint in its plane;
- Cavity wall, which consists of two parallel single-leaf walls, effectively tied together with wall ties or bed joint reinforcement, including a continuous space between the leaves with a cavity, or partially filled with a thermal insulating material;
- Veneer wall, which is used as a facing but not bonded or contributing to the strength of the backing wall or framed structure.

3.1.1. Elements of the wall structure

Concerning their composition, elements for the external wall structure can be classed in:

- *In situ* concrete: reinforced or unreinforced (Figure 3.2);
- Masonry: adobe, hollow fired-clay bricks, normal or lightweight concrete blocks;
- Precast panels (normal or lightweight concrete, concrete and Glass Fibre Reinforced Concrete (GFRC) with void formers, with or without a thermal insulating function).

Normal concrete blocks are not often used for external walls because of their poor thermal performance, excessive water absorption, weight, and difficulty to be cut. Therefore, these blocks are only used in load-bearing walls or when improved acoustic insulation or fire resistance are needed (Rodrigues, 2003).

Dry and stabilised (wet and ready-to-use) masonry mortars are both available in the national market. The latter are supplied to the site ready to be used within the next 24 to 36 hours, due to the use of admixtures that retard the binder’s setting. The former are more usual in Portugal and are supplied in bags or in bulk (stored on-site in silos), and mixed with water on-site (Duarte, 2007).

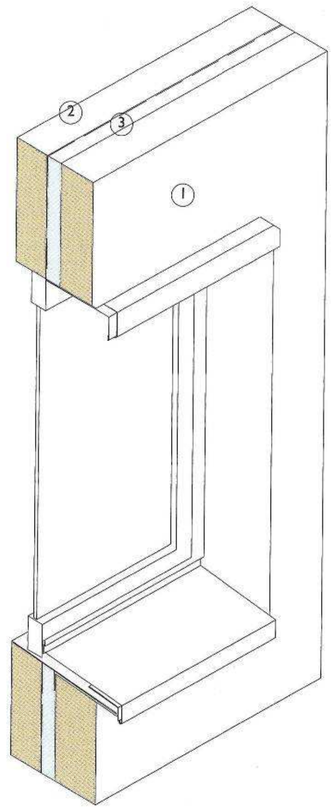

Figure 3.2 - Isometric view of an *in situ* load-bearing concrete wall: 1 and 2 - Concrete external and internal walls, respectively; 3 - thermal insulation (Watts, 2005)

3.1.2. Insulation materials

Insulation materials can be grouped in 3 families according to their chemical or physical structure: mineral/inorganic; oil-derived; and so-called “organic natural”. Furthermore, these materials can have a fibrous or cellular structure that will determine to a great extent both their mechanical and thermal properties (Table 3.1) (Kotaji & Loebel, 2010).

Mineral/inorganic materials account for 60% of the market in Europe; oil-derived materials account for about 30% (namely Extruded Polystyrene (XPS), Expanded Polystyrene (EPS) and Polyurethane/Polyisocyanurate (PUR/PIR)); and “organic natural” and other materials account for about 10% (Ardente *et al.*, 2008). In this last group, Agglomerate of Expanded Cork (Insulation Cork Board - ICB) can be highlighted as Portugal is the world’s largest producer and exporter of cork-based materials. This material can be used as insulation but also as an external cladding (Figure 3.3 and Figure 3.4). More exotic materials, such as transparent and dynamic insulation, ‘ecological’ materials based on agricultural raw materials, and gas-filled and vacuum insulated panels, have found limited acceptance in the market, mainly because of their high cost (various references cited by (Ardente *et al.*, 2008)).

Table 3.1 - Classification of insulation materials by chemical and physical structure

Physical structure / **Chemical composition**	**Fibrous**	**Cellular**	**Granular**
Mineral "inorganic"	Mineral wool - MW (Glass/Stone wool - GW and SW)	Foam glass (CG)	Expanded perlite; Expanded vermiculite; Light Expanded Clay Aggregate (LECA)
Oil-derived "organic synthetic"	-	EPS; PUR/PIR; XPS	EPS and XPS regranulate
Plant/animal derived "organic natural"	Cellulose; Wood wool; Cotton/Sheep wool; Duck feathers; Flax; Hemp; Straw bale; Recycled paper or denim (Figure 3.5)	ICB; Recycled paper (Figure 3.6)	ICB regranulate; Recycled paper (Figure 3.6)

Figure 3.3 - Portuguese Pavilion at the Xangai exhibition (Stylepark, 2011)

Figure 3.4 - External cladding of ICB at the Portuguese Pavilion at the Xangai exhibition (AI, 2010)

Figure 3.5 - Insulation consisting almost entirely of natural denim and cotton fibres (90% post-consumer) that are 100% recyclable (BL, 2011)

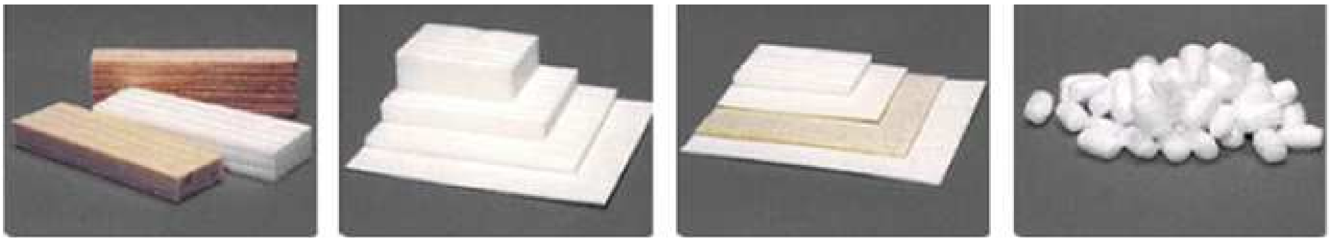

Figure 3.6 - Paper insulation with different shapes: board (low, medium and high density, corresponding to the first, second and third figure, respectively) and filling type particles (last picture) (Kang *et al.*, 2008)

Insulation materials can also be made in different shapes including loose-fill, blanket, bat or roll form, rigid, foamed in place, or reflective form (Table 3.2). For example, paper insulation can be found in South Korea in the shape of a board (low, medium and high density) or filling type particles (Figure 3.6). The cellulose from waste paper is mixed with starch and polypropylene resins; it then undergoes a process of expansion using steam and a press moulding process (Kang *et al.*, 2008). The choice of the insulation materials’ type and shape depends on the intended application as well as the target’s physical, thermal and other properties (Al-Homoud, 2005).

Table 3.2 - Classification of insulation materials concerning their trading shape

Insulation material trading shape	Insulation material
Loose-fill that can be blown-in	CG and SW
Loose-fill	Expanded perlite or vermiculite; LECA; EPS, XPS and ICB regranulate; Cellulose
Mineral fibre blankets, bats and rolls	MW, GW and SW
Rigid boards foamed or sprayed in-place (PUR/PIR)	ICB, EPS, XPS and PUR/PIR and GW
Other insulating solutions	Lightweight concrete blocks; Precast concrete with a rigid insulation foam placed in the core (sandwich panel - Figure 3.7); Insulated Concrete Forms (ICF - Figure 3.8); Reflective materials (aluminium foil or ceramic coatings)

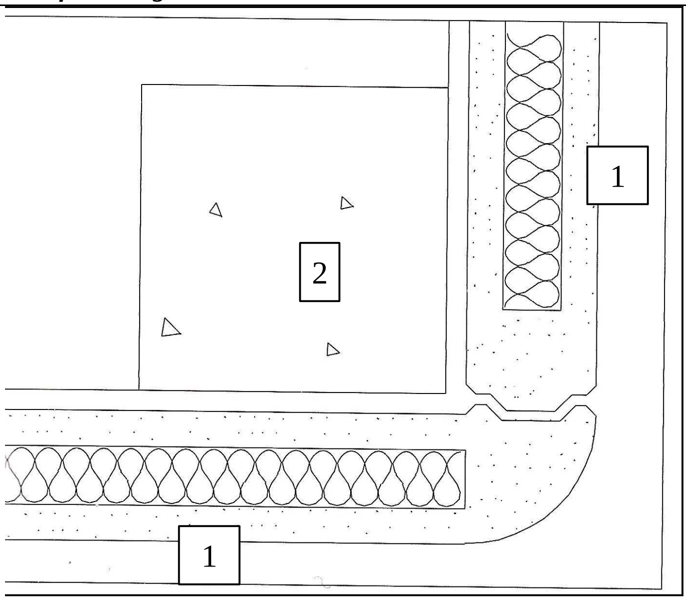

Figure 3.7 - Detail of the corner and of the panel-to-panel joint of a precast concrete wall: 1 - Precast concrete panel with a rigid insulation board between layers; 2 - Concrete column (Watts, 2005)

Figure 3.8 - Insulated Concrete Forms (ICF) (R&R, 2011)

Lightweight granular materials can be classed in organic (natural or synthetic), inorganic (not-transformed and transformed materials, not-transformed and transformed by-products) and mixed solutions (e.g. the so-called expanded cork - ICB - regranulate (APCOR, 2012), or black regranulate of expanded cork, in a cement mortar matrix). These materials have the advantages of: using raw materials that do not need significant production processes to be used; promoting recycling of scraps or wastes of different industries, by shredding or other methods; valorizing natural resources and industrial by-products. Some examples are:

- EPS granulate resulting from the pre-expansion stage of EPS board production;

- EPS or XPS regranulate resulting from shredding of wastes, scraps or non-conforming boards;
- Cellulose fibres recycled from discarded journals;
- ICB regranulate or triturated raw cork.

One of the disadvantages of these materials is that their final performance strongly depends on the application quality (e.g. complete filling of the cavity). Their thermal performance can also be affected by water absorption, adsorption, and settlements (which occur more easily when the initial void index is high and when internal cohesion, dimension of the particles or deadweight are low). Settlements can be caused by the weight of the insulation material, because of a building’s vibrations or hydro-thermal variations. These materials can be supplied in bulk, without packaging and with lower costs of loading at the plant and discharge on-site, but are normally sold in bags of 50, 100 or 500 litres (Santos, Carlos Pina, 1993).

In order to be insulated by lightweight granular materials, cavity walls should have the following characteristics (requirements specified in British and French Standards) (Santos, Carlos Pina, 1993):

- A minimum thickness (30 mm or higher) and a maximum height (6 m or 12 m above the ground, without interruptions) of the cavity;
- Outer wall with a minimum thickness of 0.11 m.

Concerning the use of insulation materials in external walls, the next requirements are highlighted:

- When the thermal insulation is placed inside a cavity wall, it should be mechanically fastened to the external face of the inner leaf (Santos, C. Pina & Matias, 2006);
- When an insulation material more sensible to the action of the water is used (i.e. ICB, MW and some PUR/PIR foams), some additional elements should be used to ensure protection against the risk of prolonged contact of the insulation with water and the infiltration of rainwater (Santos, C. Pina & Matias, 2006);
- Reflective insulation must face an air-filled, gas-filled, or evacuated space to be effective; this type of insulation solution reduces heat transfer by radiation and is therefore more effective in hot climates with predominant cooling requirements (Al-Homoud, 2005).

3.1.3. Claddings

The functional requirements of external and internal wall claddings are significantly different and therefore the systems used in both layers are usually not the same. This justifies the division of this section of the Thesis in two sub-sections which describe the most commons solutions used as external and internal cladding of external walls of buildings. There are only a few cladding systems that can be used on both sides of an external wall with a satisfactory performance, and these systems are appropriately identified in this section of the Thesis.

3.1.3.1. External cladding systems

The envelope of the building is a key element because it strongly influences its comfort, safety and aesthetics. Because it is in close contact with the environment it is constantly affected by the weather and atmospheric pollution, which can speed up the degradation rate, with likely serious implications for safety and user comfort. External cladding is the first and outermost layer that separates the inner space from environmental agents and is therefore particularly prone to failures and defects, with direct consequences for the quality of urban space, user comfort, and repair and maintenance costs (Silvestre *et al.*, 2012).

The solutions for continuous external thermal insulation of the wall (e.g. External Thermal Insulation Composite System - ETICS - or Ventilated Rainscreen Façades - VRF) are non-traditional and therefore should comprise systems evaluated by recognised institutions with compatible and proper components that can lead to satisfactory and durable global performance. In these systems, treating singular areas (e.g. corners, connections, and periphery) is essential to guarantee the expected service-life. The National Laboratory of Civil Engineering (LNEC) imposes, in the technical appreciation of these systems, a minimum of 0.20 m of thickness (excluding claddings) for the external wall element in which they are applied and using complementary measures to limit the propagation of fire (through the cladding, the insulation or the cavity) between floors (Santos, Carlos Pina, 2007).

ETICS contain an insulation panel applied over the substrate (glued, mechanically fixed, or both), above which one or two thin layers of reinforced render (normally a mixed one with cement, resin and aggregates, with a thickness of 3 to 5 mm, but a cement render - thickness of 8 to 10 mm - are also used) are applied (Figure 3.9). The latter can also be used to glue the insulation material (through spot, band, or whole bonding) and should have good adherence to the substrate, high resistance to cracking, low capillarity and significant mechanical resistance to perforation and impacts. The finishing layer is normally a special paint or a thick plastic cladding with a synthetic binder (or mineral or mixed) and fine calibrated aggregates of high resistance. This layer gives a significant contribution to the resistance to impacts and watertightness of the system, but should not excessively reduce water vapour permeability. An additional reinforcement can be applied on the ground floor to increase ETICS impact resistance (Veiga, 2004; Veiga & Santos, 2009).

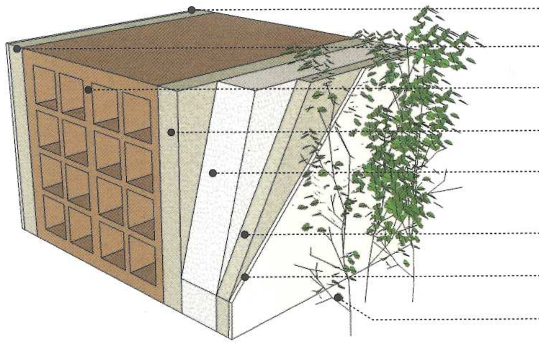

Figure 3.9 - Detail of an external wall with ETICS (Tirone & Nunes, 2007)

ETICS can present different thicknesses and compositions, particularly concerning the percentage of organic matter of the cladding layers, reinforcement materials (nets - e.g. of glass fibre with alkalis protection/polyester covered - and metallic profiles, normally of perforated aluminium) and fastening solution (adhesive, mechanic or mixed) (Veiga & Santos, 2009). On the ground floor, a stronger reinforcement can also be used within the render (over the insulation board) to prevent degradation because of impact actions (Veiga, 2004). This system (Figure 3.10) has not yet been covered by a European Standard, but there is already a “European Technical Approval Guide” (ETAG 004) edited by the “European Organisation for Technical Approvals” (EOTA) which allows for the producer to ask for a “European Technical Approval” (equivalent to a CE marking) of its own ETICS system in the homologated institute of its country (Duarte, 2007). This procedure enables the characterisation and evaluation of all the components of the construction system and of the significant aspects of its global performance (Veiga & Santos, 2009).

Figure 3.10 - ETICS applied in a building in Lisbon, Portugal (Veiga, 2004)

Ventilated rain screen façades (VRF) comprise a discontinuous external cladding mechanically settled to an independent bearing structure (with single spots or linear and visible or hidden (Dutra, 2010)), a thermal insulation glued or mechanically fastened to the substrate and a cavity between them that eases the diffusion and elimination of humidity (Figure 3.11, Figure 3.12 and Figure 3.13). The independent bearing structure is composed of metallic elements with an anti-corrosive treatment which are fixed to the substrate with mortar or mechanically connected. The discontinuous external cladding can be of natural or cast stone, ceramic tiles, aluminium, wood-based or several composite materials and are fastened to the bearing structure using steel clips. Cladding joints are normally left open but can also be closed by profiles or made by element encasement or overlapping (Veiga, 2003).

Figure 3.11 - Ventilated rainscreen façade which comprises a cladding made of natural stone (mechanically fastened to the wall structure through metallic elements) and a layer of insulation material partially filing the cavity (projected PUR)

The usual thickness of thermal insulation is between 30 mm and 40 mm in ETICS and in VRF, with higher thicknesses (50 mm to 60 mm) gaining momentum because of the pursuit of the energetic efficiency of buildings (Santos, Carlos Pina, 2007; Veiga & Santos, 2009). The insulation material used is combustible, despite having normally an additive to improve fire performance (in low or high percentage). This additive increases the difficulty of ignition of the material when exposed to a small flame but, in real circumstances with adverse conditions, the combustion can be significant. Therefore, the Portuguese regulation concerning Fire Safety in Buildings (Law decree No. 1532/2008, of 28 of December - Technical regulation of fire safety in buildings) lists minimal European classes of reaction to fire for elements of VRF (thermal insulation material, its bearing structure and cladding of the external surface and of the surfaces that confine with the cavity) and ETICS (complete system and thermal insulation) which depend on the height of the building in which they will be applied (Santos, Carlos Pina, 2009).

Figure 3.12 - Ventilated rainscreen façade - detail of the fastening system of a natural stone cladding

In Portugal, the most common types of ornamental rocks are granite (eruptive) and limestone (sedimentary), both available in mines all around the country and used mainly as wall (Figure 3.14) and floor claddings in buildings. The former has a compressive strength between 150 MPa and 240 MPa, while the latter can have a compressive strength between 30 MPa and 110 MPa (or even above 110 MPa on very hard limestone). Marble (metamorphic) is also used as a wall cladding, but it is more restricted in terms of availability and suitability (Nero, 2001a).

Figure 3.13 - Ventilated rainscreen façade - view of the lower part of the façade with the "mortar bed" for water drainage and opening for ventilation

Nowadays, natural stone claddings are based on pieces with a reduced thickness (equal or smaller than 3 cm) but most of the properties of this material (e.g. mechanical strength, water absorption, porosity and hygroscopicity) are volume-related. This forces the process of selection, prescription and application of this type of cladding to be strict and to consider every functional requirement of each specific use. The prescription of natural stone claddings should also include the description of the standards that must be followed to verify the compliance of the material with these requirements. However, the properties of natural stone and its performance in different environments are defined by their origin and the natural conditions in which they were "produced". These conditions depend on the location of the quarries and cannot be reproduced in another time or space. Therefore, despite the indicative values of the properties of natural stone listed in reference tables, these properties (essentially those volume-related) must be validated before prescription or application. This validation can prevent pathological conditions caused by the different performance of the same material with different thicknesses. Therefore, stone plates for wall cladding should have CE marking (3/4 system) in accordance with the corresponding European standard (EN 1469:2004 - Natural stone products - Slabs for cladding - Requirements).

There are types of ornamental rocks that are not suitable for external claddings, mainly sedimentary stones or stones with a heterogeneous structure, because of the alterations they can show over time (five to ten years after installation) on their surface due to the exposure to ultraviolet radiation and absorption of water (Nero, 2001a, 2001b). For this kind of use, the stone plate chosen should have a greater water tightness and resistance to environmental agents ((Paiva *et al.*, 2006) cited by (Neto, 2008)).

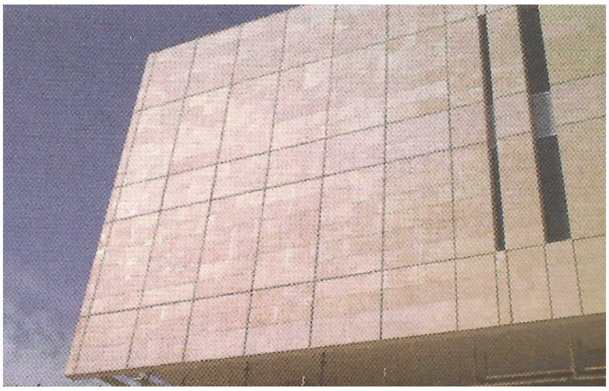

Figure 3.14 - Building with a ventilated rainscreen façade and a cladding made of natural stone (Faria, 2008)

The prescription of a natural stone cladding requires the definition of the thickness of the joints between pieces and of the type of connection to the substrate. The thickness of the joints depends on the coefficient of thermal expansion and on the thickness of the stone, and on the exposition and required water tightness, but should not be smaller than 5 cm. The joint can be open (e.g. in mechanically fixed systems with a cavity) or filled by a mortar or mastic (Neto, 2008). The type of connection to the substrate can be: glued, mechanical, mixed or with an middle structure, using a VRF system. A glued connection of a stone plate is not suitable for pieces with higher dimensions and for medium to tall buildings with a structure of reinforced concrete because the high flexibility of these buildings can lead to cracking of the cladding (Nero, 2001b; Veiga, 2004). A mechanical connection can be made through steel fastening clips (not suitable to fix stone to blocks without a proper reinforcement solution), which can create a cavity between the cladding and the substrate, and/or using adhesive spot bonding (Veiga, 2003).

Cement (mineral-based binders) renders are the most usual wall coating and are considered a waterproofing solution. The corresponding mortar can be applied manually or projected in one or two layers, with different options for the texture. When premixed at factory (industrial mortars), this material should have CE marking (4 system), in accordance with the corresponding European standard (EN 998-1:2010 - Specification for mortar for masonry - Part 1: Rendering and plastering mortar).

The increasing request for an improved thermal performance of building envelopes has led to the development of cement renders, including one-coat mortars, with some thermal insulation properties (Duarte, 2007). Therefore, external renders are classed in EN 998-1:2010 in accordance with their compressive strength (Duarte, 2007) and divided in six main groups: general purpose (GP), lightweight (LW), coloured (CR) one-coat (OC), renovation (R) and thermal insulation mortars (T) (Matos, 2008). Insulating renders are composed of premixed mortars with a mineral binder and a high percentage of lightweight aggregates (e.g. expanded polystyrene, perlite, vermiculite or cork) that reduces the thermal conductivity of the render. Only mortars with density lower than 600 kg/m^3 and thermal conductivity lower than 0.1 W/(m.ºC) can be classed as thermal insulating mortars. However, even these need to be applied with a considerable thickness in order to account for a significant complement of thermal insulation, and the reduced mechanical resistance of this material can make it more vulnerable to impacts (Veiga & Santos, 2009).

Dry mortars are the most common external waterproofing wall cladding in Portugal, are available in a broad range of options, and are mixed with water on-site. They are composed of a binder (cement, lime or synthetic, such as a water solution of acrylic polymer), aggregates (siliceous, limestone or lightweight), admixtures (waterproofing, air-entraining, plasticising, water retention, thickeners, bacterial fungicides or pigments) and other components (e.g. mineral fibres or pozzolans), together with the required reinforcement solutions (metallic or glass fibre nets) in discontinuous areas of the substrate. The application of a primer before the application of the mortar in the wall is mandatory, followed by a layer of two or three crossed coats of mortar (the reinforcement, when applicable, is placed between these coats) and, in some cases, a finishing layer (Veiga, 2003).

Stabilised (ready-to-use) cement plasters are also used as wall renders but are normally of only one kind. One-coat mortars (*monocouche*) are coloured cement renders that are widely used in France and in all the European Union. They belong to the dry mortar group, despite their higher cost and need of skilled labour, and are only supplied in bags (Duarte, 2007).

Adhesive ceramic tiling can be used both as internal (water-resistant) or external (finishing) wall cladding. Excluding the use of ceramic tiles within a VRF solution, this material is always glued to the substrate. A regularisation render should be applied to the substrate before the adhesive. The latter can be reinforced in areas with discontinuities of the substrate (Veiga, 2003).

Nowadays, only dry mortars are used as adhesives and joint materials on glued discontinuous wall claddings in Portugal. The former should have CE marking (3 system) in accordance with the corresponding European standard (EN 12004:2007 - Adhesives for tiles - Requirements, evaluation of conformity, classification and designation) and are classed according to the raw materials used in their production (based on cement and admixtures, cement and resin), and with their performance (e.g. pot life or curing time). Premixed adhesives are also available in a paste of resin in aqueous dispersion, with or without cement (Duarte, 2007; Veiga, 2003). Joint materials are normally coloured and have a significant role in the stability of a discontinuous cladding by absorbing the stress transmitted by the tiles, particularly in walls, and by providing water vapour permeability to the cladding. There is already a European standard suitable for this group of materials (EN 13888:2009 - Grout for tiles - Requirements, evaluation of conformity, classification and designation) but CE marking is not yet mandatory (Duarte, 2007).

Composite insulating panels are normal sandwich panels of two layers of metallic sheets, normally thermo lacquered, with an insulation panel between them (Veiga & Santos, 2009), and are mainly used as external cladding of industrial buildings. Reflective claddings of thermal protection (e. g. metallic sheets) do not reduce the thermal conductivity but have a high reflectivity (> 0.80) and a low emittance (> 0.20) in the infrared light range that reduces the heat transmitted by radiation, but only if there is an adjacent air space. Therefore, this cladding can only be applied in façades within their cavity and has to be maintained clean and polished to present a continuous performance (Veiga & Santos, 2009).

3.1.3.2. Internal coating systems

Gypsum plasters are the most common solution for regularisation or finishing coating of internal walls (and internal faces of external walls). This solution is supplied on-site ready-mixed and including gypsum (for some suppliers, mixed with lime), aggregates (siliceous and limestone calibrated sand) and admixtures (hardening retarders, plasticising or water retention). Some suppliers also include lightweight aggregates and/or fibres in the mix. The application comprises a regularisation (1 to 2 cm) and a finishing layer (1 to 3 cm) (Veiga, 2003).

The continuous internal thermal insulation of the external walls is normally based on gypsum or wood boards and on a thermal insulation panel. The latter is placed between the inner surface of the external wall element and the boards. The boards are normally bolted to a structure of metallic profiles. However, a composite solution of gypsum plasterboards glued to insulation panels is already available on the market, which can also be bolted to an independent structure already fastened to the wall. The use of an “internal” ETICS is not usual or advisable mainly because of the need for an appropriate mechanical resistance of the inner coating (Santos, Carlos Pina, 2007). LNEC advises the use of a minimum of 0.20 m of thickness (excluding claddings) for the external wall element, and a thermal insulation not sensible to the water (or a cavity with a drain between it and the external wall element, with the protection of the bottom of the insulation), when a continuous internal thermal insulation system is chosen. To treat singular areas (e.g. corners, connections, and periphery) in these systems, it is also essential to guarantee the expected service-life (Santos, Carlos Pina, 2007).

Paints are composed of mineral fillers, pigments, a binder or vehicle (e.g. oil or resin) and a volatile vehicle (e.g. water in water-based paints, solvent or diluent) and can be used as a finishing layer of external or internal claddings (Eusébio, 2003). On the contrary, phase change materials (PCM) incorporate small particles of different materials (e. g. micro-particles of paraffin, encapsulated in polymers) which change phase at air temperatures in the threshold of discomfort, with heat absorption or release, allowing for some thermal correction but only when used as internal coating (Veiga & Santos, 2009).

Wood derivate panels are also used in Portugal as external wall claddings, particularly High-Pressure Laminate (HPL or phenolic panels) and marine plywood. Both solutions should have CE marking in accordance with the corresponding European standards (EN 438-7:2005 - High-pressure decorative laminates (HPL) - Sheets based on thermosetting resins (usually called Laminates) - Part 7: Compact laminate and HPL composite panels for internal and external wall and ceiling finishes and EN 13986:2004 - Wood-based panels for use in construction. Characteristics, evaluation of conformity and marking) and are composed of wood fibres or kraft paper sheets, a binder (e.g. synthetic resin) and admixtures (e.g. bacterial fungicides or fire retardants). In external applications, additional requirements should be added to those provided by the European harmonised standards, namely dimensional and chromatic stability, physical integrity and water resistance in the long-term. These panels are normally applied through VRF solutions, but a careful detailing of the top protection and of the cavity ventilation should be taken into account (Cruz & Machado, 2008).

3.1.4. Ancillary components

Some external walls comprise additional ancillary elements, namely linking elements between walls with a cavity, panels or membranes for noise insulation, ventilation (Figure 3.15) or drainage systems (Figure 3.16), fire or water protection systems, vapour barriers (membranes or films) and closers (e.g. for the interface with the windows, for one or both leaves - see Figure 3.17) (CT, 2011).

The higher the material’s moisture content, the higher its thermal conductivity and, therefore, vapour retarders are commonly used to prevent moisture penetration into low-temperature insulation. Vapour retarders are used on the inside of insulation in cold climates and on the outside of insulation in hot and humid climates (allowing for the moisture to escape from the other side). The vapour retarder’s location, however, is a challenge in mixed climates (Al-Homoud, 2005) and their use presupposes that a proper ventilation system is available in the interior of the building.

Because of the warm climate, the use of waterproofing membranes in external walls is not usual in Portugal, except in singular areas (e.g. window periphery).

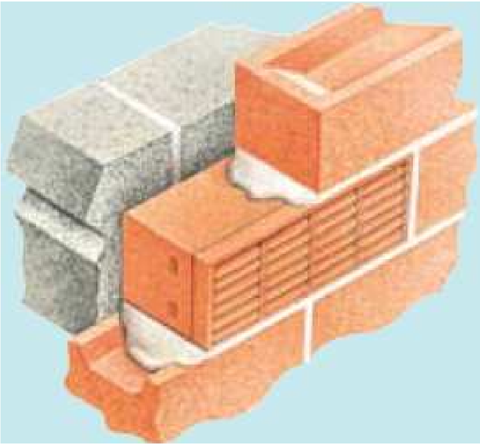

Figure 3.15 - Air-brick, which promotes the ventilation of a cavity wall via a front louvered grid, can be used when the external leaf is a brick veneer (CT, 2011)

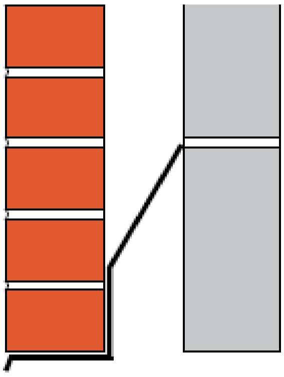

Figure 3.16 - Polypropylene profile to be used over a window lintel of a cavity wall (external leaf on the left side) in order to ease its drainage (CT, 2011)

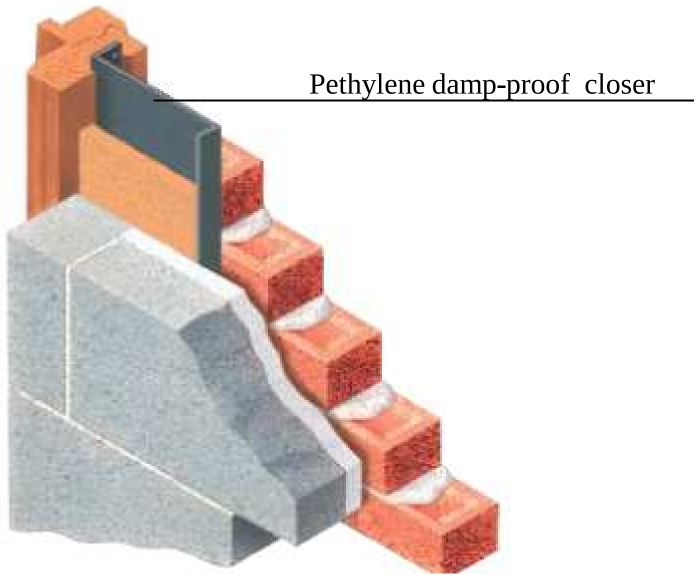

Figure 3.17 - Pethylene damp-proof closer also preventing thermal bridging in the interface between the wall (insulated in the cavity, with the insulation leaning on the internal leaf) and the opening through the overlap of insulation boards (CT, 2011)

3.1.5. Composition of the most common solutions in Portugal

In this chapter, the construction systems used in external walls of buildings have already been characterised in terms of materials and performance. Among these solutions, only the most common in the design and construction of buildings in Portugal will be assessed and evaluated in Chapter 7 and will have their materials characterised in terms of life-cycle inventory in Chapter 4. To select the most common solutions for external walls of buildings in Portugal, the starting point was the LNEC publication used as reference in the energy certification system (Santos, C. Pina & Matias, 2006). Therefore, the composition, dimensions and thermal performance of the outer wall solutions included in this publication are presented in Appendix 3.I and their summarised description is made in the next sections of this Chapter (3.1.5.1 and 3.1.5.2). Only passive thermal solutions were considered in the group of external walls of buildings studied in detail. Therefore, active thermal solutions that are not yet considered by the Portuguese thermal regulation (e.g. PCM used as internal wall coatings, Trombe walls or Double Skin Façades (DSF)) are beyond the scope of this study.

3.1.5.1. Single-leaf wall

Concerning the elements for the wall structure, masonry, and *in situ* concrete (unreinforced or reinforced, with thickness from 0.10 m to 0.20 m - Figure 3.18) walls were considered for single-leaf walls. The former includes hollow fired-clay bricks (thickness from 0.20 m to 0.24 m and horizontally perforated) and normal and lightweight (with LECA) concrete blocks (thickness from 0.20 m to 0.30 m and vertically perforated). Concerning the claddings, two alternatives were considered: adherent on both faces (i.e. gypsum or cement-based, ceramic or natural stone) or fastened to a bearing structure (continuous or discontinuous - metallic sheet, wood-based, ceramic or natural stone, creating a cavity that is considered ventilated in the external face and non-ventilated in the internal).

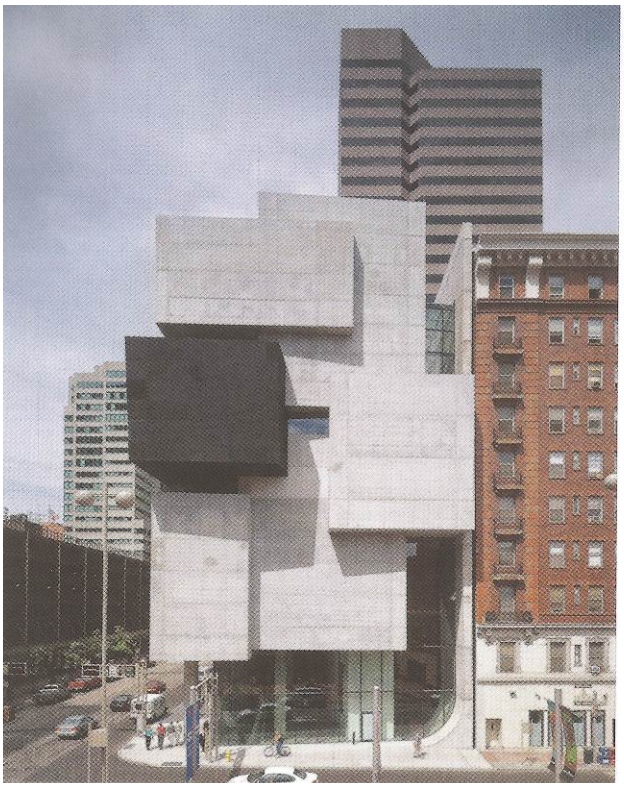

Figure 3.18 - In situ load bearing external concrete wall (CAC Museum, Cincinnati, USA, from Arch. Zaha Hadid) (Watts, 2005)

When the thermal insulation is placed on the external face of the wall, two solutions were considered: ETICS (Figure 3.19, with insulation of EPS or MW) and VRF (with insulation of EPS, ICB, MW, PUR/PIR and XPS and continuous or discontinuous cladding). For the VRF it was considered that the thermal insulation material is fastened to the wall element and interrupted (in single spots or along lines) by the supporting structure of the external cladding (e.g. natural stone, ceramic, metallic, plastic or wood-based).

When the thermal insulation is placed on the internal face of the wall, both the cladding over insulation without cavity (Figure 3.20, with insulation of EPS or MW) and independent cladding with a thermal insulation in the non-ventilated cavity (adherent to the wall element or to the cladding) were considered. The claddings considered include gypsum plasterboards or wood-based boards (with different configurations and materials for the bearing structure) and the thermal insulation materials include EPS, ICB, MW, PUR/PIR and XPS.

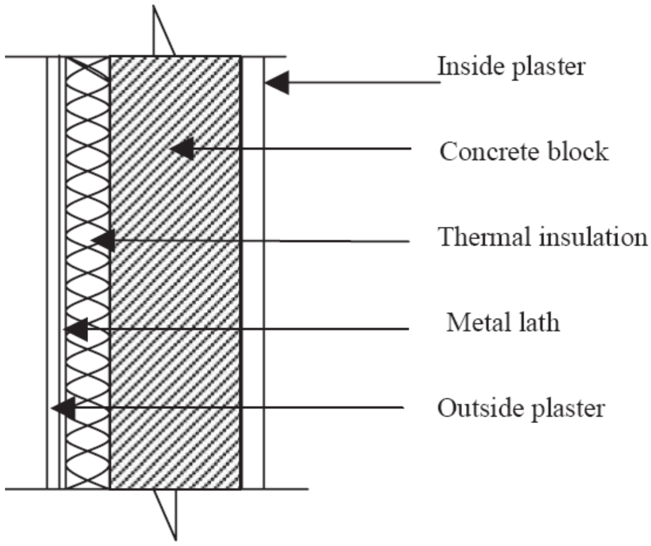

Figure 3.19 - External insulation of single-leaf wall using an ETICS system, with the insulation material protected by a metal lath (Al-Homoud, 2005)

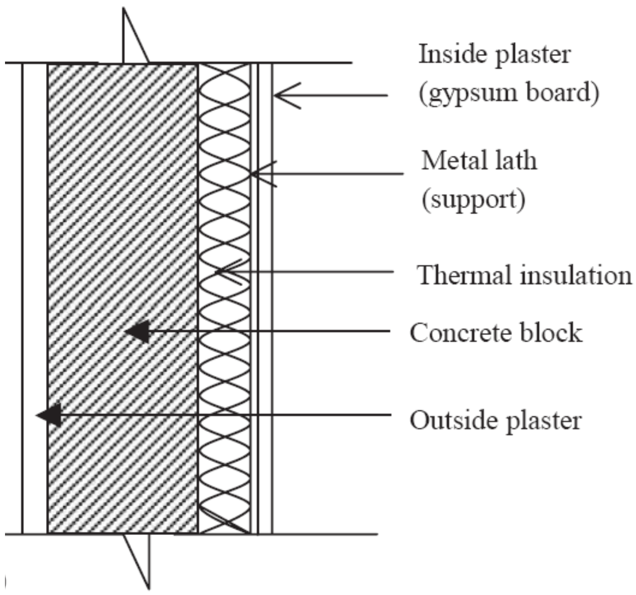

Figure 3.20 - Internal insulation of single-leaf wall covered by a gypsum plasterboard (Al-Homoud, 2005)

3.1.5.2. Cavity walls

Concerning the wall structure, masonry in both walls and *in situ* concrete (unreinforced or reinforced, with thickness of 0.10 m to 0.20 m) in one of the walls were considered. The former includes fired-clay (hollowed or not) bricks or normal or lightweight (with LECA) concrete blocks in both walls and the latter can include any of these materials in one of the walls. Concerning the claddings, gypsum plasters or plasterboards or wood-based boards on the inner face and cement-based renders, ceramic, natural stone or an apparent wall element (of concrete - Figure 3.18 - or clay brick - Figure 3.21) in one or both faces were considered.

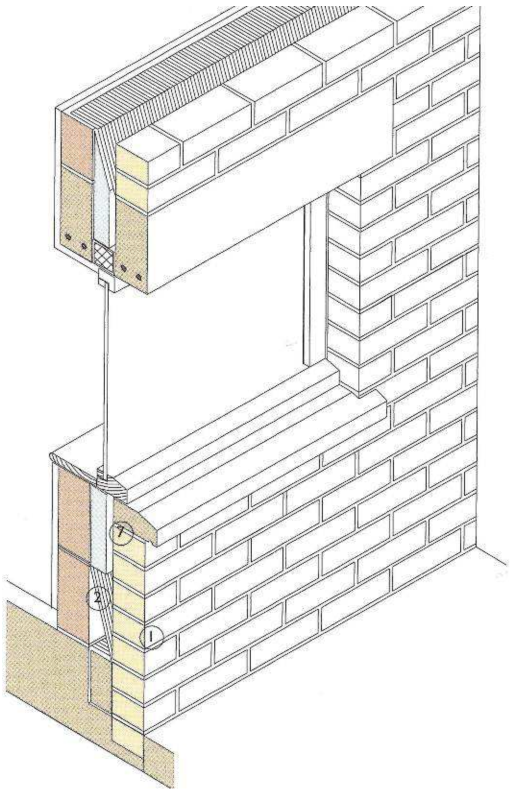

Figure 3.21 - Brick cavity wall with an apparent wall element: 1 - brick veneer; 2 - inner brick leaf; 7 - thermal insulation partially filling the cavity (Watts, 2005)

The cavity should have a minimum thickness of 30 mm (50 mm is advised, with a void minimum thickness of 20 mm) and should be ventilated and have a drainage system. EPS, ICB, MW, PUR/PIR (projected, injected or in boards) and XPS were considered as insulation (partially or totally filling the cavity - Figure 3.22).

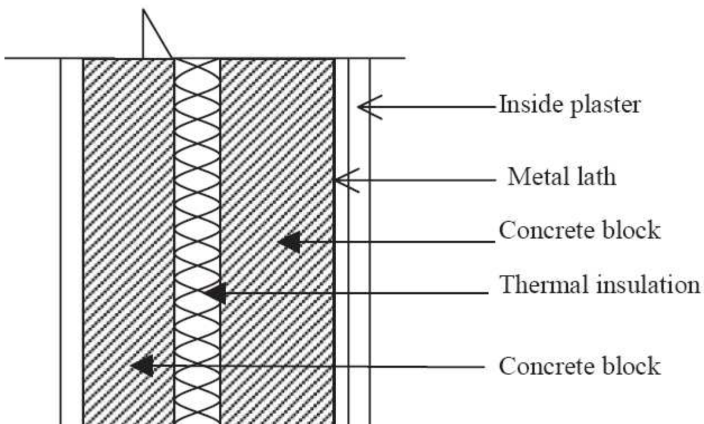

Figure 3.22 - Insulation completely filling the cavity between wall leaves (Al-Homoud, 2005)

3.2. Functional requirements

Several national, European and international building regulations contain requirements for the performance of the building envelope. Most of these requirements, particularly the national ones, directly reduce the range of solutions that can be used as external walls. However, modern regulations are more performance-based than prescriptive which broadens the number of solutions for external walls that can be taken into account in the design phase. The performance-based principle includes the definition of the functions that the construction material has to achieve in each specific use, the identification of the characteristics that condition their performance and the index of the quantification and evaluation methods (based on relevant standards) that should be used to verify the compliance of the material with these requirements (Veiga, 2003). In Europe, the Construction Products Directive context (EC, 1988) lays down certain essential performance criteria for buildings (as a whole and in their separate parts) under six essential requirements: mechanical resistance and stability (ER1); safety in case of fire (ER2); hygiene, health and the environment (ER3); safety in use (ER4); protection against noise (ER5), and energy economy and heat retention (ER6). Those requirements must be satisfied during an economically reasonable working life (period of time during which the performance of the works will be maintained at a level compatible with the fulfilment of the essential requirements) when subjected to proper maintenance (Flores-Colen, 2009).

The most important functional requirements of an external wall can be divided into three groups: safety requirements (structural, fire and intrusion safety), healthcare and comfort requirements (hydrothermal, acoustic, visual and tactile comfort, water and airtightness and hygiene) and economic requirements (initial and maintenance costs, adaptability and versatility, and durability and functionality). Some of these requirements are fulfilled by the external wall as a whole (e.g. intrusion safety and hydrothermal comfort), and other ones are fulfilled by only one or two of its elements (e.g. visual and tactile comfort). Concerning the opaque area of external walls, the bottom and the upper part (wall top or cornice) can have additional requirements (e.g. supplementary resistance against mechanical and chemical agents for the former and protection of the façade and drainage of the roof for the latter) (Flores-Colen, 2009). However, this study is focused on the overall opaque area of external walls.

3.2.1. Thermal performance

The national "Regulation of the characteristics of thermal behaviour of buildings" (RCCTE, 2006), one of the regulations that transposes the Energy Performance of Buildings Directive (EPBD) (EC, 2002) to national law, provides maximum allowable values for two fundamental thermal indexes indirectly related with the thermal performance of the building envelope: Nic (nominal annual heating needs per square meter of net floor area of the flat (kWh/m^2*year)) and Nvc (nominal annual cooling needs per square meter of net floor area of the flat (kWh/m^2*year)).

Ni (kWh/m^2.year) is the limit value for Nic and depends on the severity of winter weather in the building's location (represented by HDD - number of Heating Degree Days) and of the compactness of the dwelling or apartment (building shape expressed by the ratio between the envelope area and the net indoor volume) being analysed. Nv (kWh/m^2.year) is the limit value for Nvc and only depends on the climatic characteristics of the building's location.

RCCTE divides Portugal in three climatic regions depending on the winter conditions: I1, including mainly the coastal centre and the south of Portugal; I2, including the interior centre and the coastal North; and I3, including the Northeast region of the country. Then, this regulation provides maximum admissible values for heat transfer coefficients (U) of the opaque areas of the envelope (which mainly corresponds to the external walls) in order to lessen the risk of condensations in the inner face of these envelope elements in each of these three climatic regions (Santos, Carlos Pina, 2007). These limit values are presented in Table 3.3 and are easily fulfilled both by new and old buildings. However, the introduction of RCCTE had the positive effect of cutting off by half the allowed heat transfer coefficients (U-value) of the opaque areas of the envelope of the buildings in Portugal, when compared with the older buildings (built before 2006). Both conclusions can be reached by analysing Figure 3.23, Figure 3.24 and Figure 3.25.

Table 3.3 - Maximum admissible values for heat transfer coefficients (U) of the opaque areas of the envelope, U [W/(m^2.ºC)] (RCCTE, 2006)

Envelope element	**Climatic region**		
	I1	**I2**	**I3**
Vertical external opaque areas	1.8	1.6	1.45

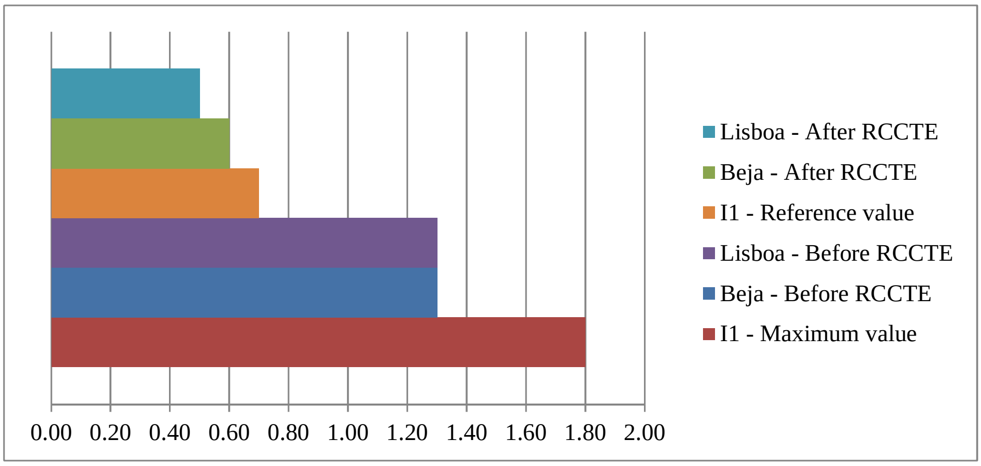

Figure 3.23 - Comparison between the average values of the heat transfer coefficients (U) of the opaque areas of the envelope of buildings in winter region I1, before and after the introduction of RCCTE, U [W/(m^2.ºC)] (Santos, P. & Baptista, 2011)

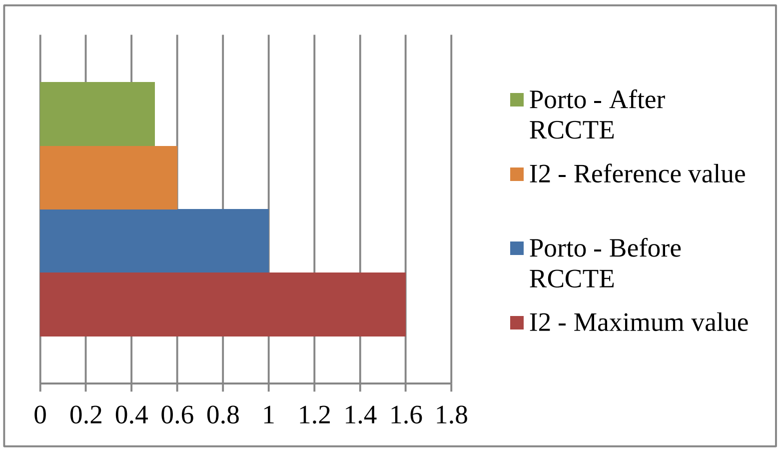

Figure 3.24 - Comparison between the average values of the heat transfer coefficients (U) of the opaque areas of the envelope of buildings in winter region I2, before and after the introduction of RCCTE, U [W/(m^2.ºC)] (Santos, P. & Baptista, 2011)

The definition of the values for Ni was made considering reference values of the heat transfer coefficients (U) which mainly correspond to traditional external wall solutions (Table 3.4) with thermal insulation components with a thickness between 30 mm and 60 mm (depending on the winter climatic region - I1 to I3). The new buildings already comply with this requirement and really use it as a reference (Figure 3.23, Figure 3.24 and Figure 3.25) (Santos, P. & Baptista, 2011) and, therefore, all the outer wall solutions presented in Appendix 3.I have heat transfer coefficients (U-value) lower than 0.7 W/(m^2.ºC). However, the use of these solutions is not mandatory to comply with the regulation because the contribution of the vertical opaque areas of the envelope to the fulfilment of the regulatory requirements is low. The winter heat losses due to air renovation, and through windows, roofs and linear thermal losses (in the connections of envelope elements) as a whole are significantly more important than the losses through external walls (Santos, Carlos Pina, 2007). Moreover, thermal insulation of external walls has a higher contribution in the summer (by reducing solar gains and cooling losses) than in the winter (in which they only reduce thermal losses) to the thermal performance of the building.

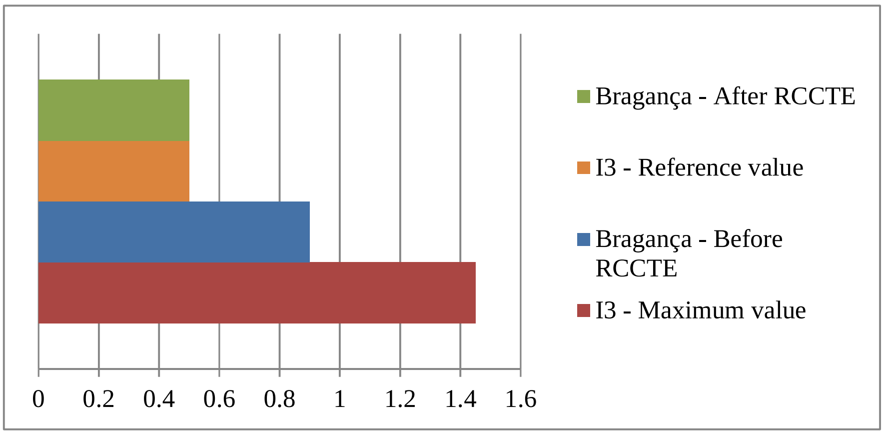

Figure 3.25 - Comparison between the average values of the heat transfer coefficients (U) of the opaque areas of the envelope of buildings in winter region I3, before and after the introduction of RCCTE, U [W/(m^2.ºC)] (Santos, P. & Baptista, 2011)

Table 3.4 - Reference values for heat transfer coefficients (U) of the opaque areas of the envelope, U [W/(m^2.ºC)] (RCCTE, 2006)

Envelope element	**Climatic region**		
	I1	**I2**	**I3**
Vertical external opaque areas	0.7	0.6	0.5

RCCTE also provides the method of calculation of the heat transfer coefficient (U) of construction assemblies composed of one or more materials with constant thickness (RCCTE, 2006), which is presented in equation (3.1):

$$U = \frac{1}{R_{si} + \sum_j R_j + R_{se}} \quad [\mathrm{W/(m^2.ºC)}] \tag{3.1}$$

Where

R_j thermal resistance of the layer [(m^2.ºC)/W];

R_{si} and R_{se} internal and external superficial thermal resistances, respectively [(m^2.ºC)/W] (for external walls, these constant values are considered to be R_{si} = 0.13 and R_{se} = 0.04).

For layers of homogeneous materials, R_j is calculated as the ratio between the thickness of *j* layer - d_j, in meters - and the thermal conductivity of the corresponding material - λ_j [W/(m.ºC)]. Thermal resistance of non-homogeneous materials and layers should be calculated following standardised methods or based on reference tables. The conventional design values of thermal conductivity of the most common construction materials and the conventional design values of thermal resistance of the most used non-homogeneous layers are already published in Portugal in a reference report of LNEC (Santos, C. Pina & Matias, 2006). The conventional design values are different from those declared within CE marking because, to determine the former, the specific conditions of the expected final use (i.e. water content, natural ageing and average temperature) are taken into account and worsens the final result (Santos, C. Pina & Matias, 2006).

Concerning planar thermal bridges (e.g. in columns, boxes of roller shutters and beam edges), RCCTE defines two limits for the maximum admissible values of heat transfer coefficients (U) of these areas: it cannot be greater than the maximum admissible value of U for the regular external wall area; it cannot be greater than two times the U of the opaque area of the external wall which the planar thermal bridges belong to. Therefore, only the use of an external (e.g. ETICS or VRF) or internal (based on gypsum or wood boards connected to a thermal insulation, precast or assembled *in situ*) continuous thermal insulation of the wall enables complying with this requirement. The former has the advantages of taking profit of the thermal inertia of the structure and of the wall element (and protecting these elements from the thermal shock and the indirect action of the rain) to keep the warmth of the indoor temperature of the building. External thermal insulation also reduces in a more satisfactory manner the influence of linear thermal bridges, which results in a minimisation of the risk of internal superficial condensations. Internal thermal insulation has the disadvantage of reducing the useful indoor area of the building, and allowing for a fast warming or cooling, but with low comfort and efficiency (Tirone & Nunes, 2007).

A summary of the effect of the position of the thermal insulation in an external wall on its useful thermal mass and inertia, on thermal bridge correction, on the time to respond to heating and cooling, on the potential location of condensation spots and on the durability and resistance of the thermal insulation is presented in Table 3.5. RCCTE (2006) valorises the thermal mass and inertia of external walls with external insulation by considering the mass of wall that is inward of the thermal insulation as the superficial useful mass (M_{si}) and reducing the economic and environmental weight of the corresponding heating and cooling needs.

Other non-traditional solutions can also comply with all RCCTE requirements for the vertical opaque areas of the envelope, but do not yet have a significant market share (Santos, Carlos Pina, 2007; Veiga & Santos, 2009). Among them, there are solutions based on single walls with “distributed insulation” (e.g. ceramic or lightweight concrete blocks with high thickness and void quantity - Figure 3.26), which in some cases avoid the use of an insulation panel in the external wall, Insulated Concrete Forms (ICF) (thermal insulation panels used as lost formwork) or precast concrete blocks with an insulation board introduced coupled in the production phase (Figure 3.27).

Table 3.5 - Effect of the position of the thermal insulation in an external wall on different parameters of thermal performance and on the durability and resistance of the thermal insulation (the best solution for each parameter is presented in italics) (Cabello, 2007; Tirone & Nunes, 2007)

Position of the thermal insulation	Useful thermal mass and inertia	Thermal bridges correction	Time to respond to heating and cooling	Local of potential occurrence of condensations	Durability and resistance of the thermal insulation
External	*Very good*	*Easy*	Slow	Within the wall	Medium
Cavity	Good	Difficult	Medium	*Cavity*	*Good*
Internal	Very bad	Medium	*Fast*	Interiors	Medium

The use of cavity walls with an insulation material in the cavity has the advantage of providing a better mechanical protection of the insulation material but demands an additional care with planar thermal bridges, in order to prevent a discontinuity in the thermal insulation between these areas and the regular area of the external wall which can become a linear thermal bridge (de Freitas, 2007). Therefore, one of the wall leaves (inner or outer, each with a minimum of 0.13 m of thickness and the outer with a recommended thickness of 0.15 m) - together with the insulation material - must correct planar thermal bridges. Some examples of this correction are presented in Figure 3.28, where the first, fourth and fifth solutions can result in an increase of 0.40 to 0.45 m of the external wall thickness and a reduction in the building’s available area (and an increase of thickness in some accessories for windows) and the second and third solutions create linear thermal bridges. However, some of them do not supply a proper thermal protection of the structural element (Santos, Carlos Pina, 2007).

Figure 3.26 - Lightweight concrete blocks with high thickness and void quantity (Artebel, 2011)

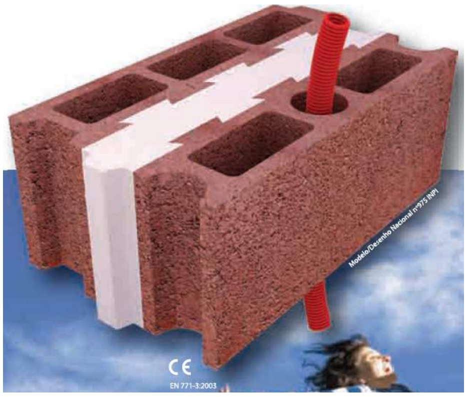

Figure 3.27 - Concrete blocks with an EPS insulation board between its two own “leaves” (Previcon, 2011)

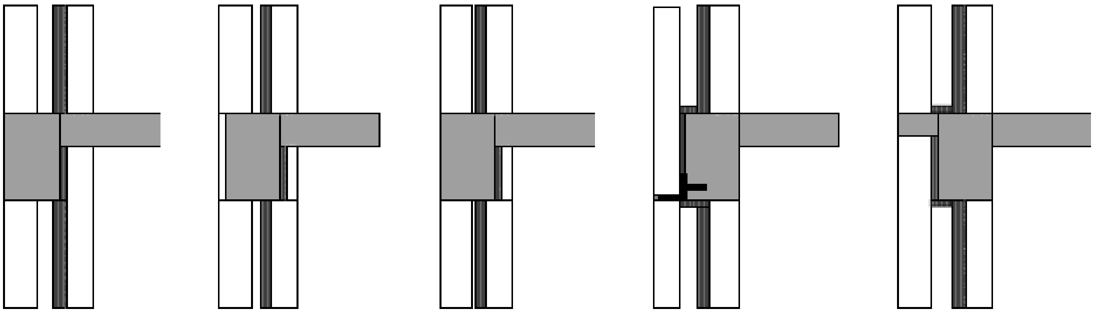

Figure 3.28 - Schematic examples of cavity walls with correction of planar thermal bridges (Santos, Carlos Pina, 2007)

3.2.2. Acoustic insulation

The national “Regulation of acoustic requirements of buildings” (RRAE, 2002) lists minimum values for the “index of acoustic insulation of aerial noise, normalised” - $D_{2m,n}$ - of external walls. This index accounts for the difference between the medium levels of sound pressure measured outside and inside the building. Therefore, together with the verification of this requirement in the design phase, a measurement should be made *in situ* after the construction of the building (Santos, Carlos Pina, 2007).

The acoustic insulation of external aerial noise does not only rely on the external wall solution but is also conditioned by the characteristics of the openings (and their accessories, such as ventilation holes or boxes of roller shutters around windows) and other discontinuities that are located in the complementary area of the envelope (Almeida, 2009). However, this research work only covers the detailed study of the requirements for the opaque areas of external walls. Therefore, the solutions presented in Table 3.6 can be used as a reference to comply with the minimum values for the “index of acoustic insulation of aerial noise” of external walls (e.g. for rooms and living rooms of residential and mixed buildings and hotels - 33 dB in mixed or sensitive areas and 28 dB in sensitive areas - paragraphs c), d) and e) for the former, and paragraph b) of the latter, of nº 1 of article 11th of the General code of noise (RGR, 2007)) (RRAE, 2002).

Table 3.6 - Estimation of the index of acoustic insulation of aerial noise (Rw) of solutions for external wall structure (Santos, Carlos Pina, 2007)

External wall structure	**Nominal thickness, excluding cladding (m)**	**Surface density (kg/m^2)**	**Rw (dB)**
Lightweight concrete blocks	0.2	190	41-45
Hollow fired-clay bricks	0.15	180	40-44
	0.22	220	44-48
Cavity wall of fired-clay bricks (0.07) and hollow fired-clay bricks(0.15)	0.07+0.15	270	44-48
Cavity wall of hollow fired-clay bricks	0.11+0.11	225	41-44
	0.11+0.15	265	44-48
	0.15+0.15	305	45-49
Concrete masonry units	0.2	280	48-52
Concrete wall	0.15	375	53-57

3.2.3. Fire protection

The national regulation of fire protection of buildings (RGSCIE, 2007) adopts the requirements of fire performance already published in Decisions of the European Commission: 2000/147/EC and 2003/632/EC - classification system of the reaction-to-fire performance of construction products; 2000/367/EC and 2003/629/EC - classification system for resistance-to-fire performance for construction products and construction works (Santos, Carlos Pina, 2007).

Concerning the reaction-to-fire performance, the elements of the wall structure (such as masonry and concrete blocks and reinforced concrete), masonry and coating mortars, natural stone, gypsum-based coatings and some insulation materials (lightweight aggregates made from expanded clay, vermiculite or perlite) are classed as non-combustible (European class A1 according with EN 13501-1:2007 - Fire classification of construction products and building elements - Part 1: Classification using data from reaction to fire tests). Moreover, if one of these materials or products is covered by an inorganic layer, they are still considered non-combustible. However, if their content in organic matter (homogeneously distributed) is greater than 1% (in mass or volume, considering the most conditioning), or if a construction product is not covered by these groups defined by a Decision of the European Commission, a preliminary reaction-to-fire set of tests in a recognised institution is mandatory to define their reaction-to-fire classes. Some non-traditional masonry and coating mortars are included in this group and they are normally classed in European classes A1 or A2 of reaction-to-fire, class s1 (limited production of smoke) and class d0 (without occurrence of burning droplets) (Santos, Carlos Pina, 2007).

Concerning an external wall solution, organic-based claddings and insulation materials are the elements that can ease the fire deflagration and promote its propagation in the building and to neighbouring buildings (Santos, Carlos Pina, 2007).

Concerning the resistance-to-fire performance, the requirements for external walls rely on several factors such as the height, use, risk classification and category of the building. Therefore, the requirements in terms of prevention of passing-through flames and hot or combustible gases (E parameter), thermal insulation to high temperatures (I parameter) and load bearing capacity (R parameter), can vary between 30 and 180 minutes. To prevent fire propagation through the envelope of the building, for example, the requirement which applies to external walls corresponds to EI 60 or REI 60 (the latter applies when external walls are load-bearing). The first requirement is easily achieved by a traditional non-load bearing wall (hollow fired-clay bricks with 0.11 m of thickness covered on both sides by a cement or gypsum plaster 15 mm thick) which has a resistance-to-fire class of EI 90. This classification should be based on tests made in recognised institutions, on reference values or on recognised calculation methods (Santos, Carlos Pina, 2007).

3.2.4. Economic performance

The external walls of buildings directly influence the thermal and environmental performance of the building envelope, because of their considerable weight in the envelope's initial embodied energy, life-cycle energy consumption, users comfort, and also the envelope's whole-life cost. Whole-life costing (WLC) is defined as "all significant and relevant initial and future costs and benefits of an asset, throughout its life cycle, while fulfilling the performance requirements" (ISO, 2008). Therefore, the economic performance of each external wall solution results directly from the attributes of the materials used, such as its initial cost, maintenance needs and reference and real service life.

WLC methodology can aid in the choice of more sustainable construction solutions by enabling the economic consideration of their parallel benefits such as reduced energy consumption in the operation of a building. This methodology can also enable the adoption of innovative construction materials and assemblies which may have higher initial costs, but offer cost efficiencies over time. Therefore, "Building Component WLC" designates tools that can provide useful financial assessments of different component or system options. One example of this kind of tool is the "Whole Life costing (+CO_2)" (developed by the "Forum for the Future” in partnership with “Fife Council”) that provides access to the WLC and CO_2 emissions of any product or service that consumes electricity (or any combustible) or water, including non-construction projects, at the evaluation stage of the procurement process (SCI-NETWORK, 2011). Another example, both at component and at building levels, is EUROLIFEFORM, a probabilistic approach to predicting Whole life-cycle costing (WLCC) of buildings and civil infrastructure that uses a stochastic WLCC model (with probabilistic WLCC results) in conjunction with deterioration analysis algorithms (based on the forecasted effects of component deterioration and maintenance and replacement works) and a decision tool to support the optimisation of the WLCC in the design process (Kirkham *et al.*, 2004).

The economic performance from “cradle to cradle” of each external wall solution can be estimated using the WLC methodology (ISO, 2008). This methodology was used in this Thesis, while also taking into consideration current Portuguese practices and following most of the principles already specified in the draft standard FprEN 15643-4:2011: “Sustainability of construction works - Sustainability assessment of buildings - Part 4: Framework for the assessment of economic performance” (CEN, 2011). The application of WLC to each stage of the life cycle of the external walls solutions studied in this thesis is presented in Chapter 7. This includes the market acquisition cost in year 0, the expense in energy use for heating and cooling during each year, the maintenance, repair and replacement operation costs of each wall and its claddings and insulation materials, and the end-of-life costs, namely the transport and disposal and the costs and/or revenues from reuse, recycling, and energy recovery of the demolition wastes.

3.2.5. Functional requirements - Elements of the wall structure

Concerning their function, all types of elements for external wall structure described in section 3.1.1 can be used either as resistant or non-resistant. However, masonry bricks and blocks cannot have a void percentage (in a plane perpendicular to the voids) greater than 70%, and the Italian seismic regulation for buildings does not allow for the use of clay units in load-bearing walls in seismic regions with a void percentage greater than 45% (RWTH, 2006). The European standards valid for the most used types of bricks and blocks are: EN 771-1:2011 - Specification for masonry units - Part 1: Clay masonry units and EN 771-3:2011 - Specification for masonry units - Part 3: Aggregate concrete masonry units (dense and lightweight aggregates). Both standards are harmonised and allow for CE marking of these construction products according to systems 2+ or 4, depending on the relevance of the factory production control. These standards define the requirements, for each characteristic that influences the final performance, that each type of block should comply with, namely: apparent density, compressive strength, thermal conductivity, water absorption, reaction to fire and water vapour permeability (Matos, 2008).

The connection between masonry blocks is made through a masonry mortar. This material should have CE marking (2+ system) according with the corresponding European standard (EN 998-2:2003 - Specification for mortar for masonry - Part 2: Masonry mortar). This standard defines three classes of mortars: G, for generic uses; T, for rectified blocks (thin joint); L, lightweight, with a dry density lower or equal to 1300 kg/m^3 and improved thermal performance. Within each class, masonry mortars are divided in groups according to their compressive strength and must have a compressive strength above 5 N/ mm^2 to be used in load-bearing walls (Matos, 2008).

3.2.6. Functional requirements - Insulation materials

Usually, only materials with a thermal conductivity lower than 0.065 W/(m.ºC) and a thermal resistance above 0.30 (m^2.ºC)/W are considered thermal insulations (RCCTE, 2006). However, other materials or products (e.g. lightweight granulates or concrete) can contribute significantly to the thermal insulation of the building's envelope or, with a thickness greater than common insulation materials, supply *per se* the thermal insulation of these elements (Santos, C. Pina & Matias, 2006). The U-value or thermal transmittance is defined as the thermal conductivity of the insulation material divided by its thickness. To achieve the same U-value, different thicknesses are needed for each insulation material. Considering design values (Santos, C. Pina & Matias, 2006), Figure 3.29 shows the thickness of each insulation material that is needed to achieve the same performance as 5 cm of ICB. The same thermal performance can only be achieved, for example, with 2.22 m of reinforced concrete or with 1.17 m of concrete with LECA.

Together with thermal performance, other characteristics have to be taken into account when an insulation material is chosen for a specific use in a building, particularly for external walls, as very few are capable of performing all functions (CIB, 2010). Water absorption, durability, mechanical and fire resistance, sound absorption, and release of hazardous substances, particularly during a fire, are some of the characteristics that must be evaluated together with the environmental performance to make a conscientious choice of the most adequate solution possible (Al-Homoud, 2005).

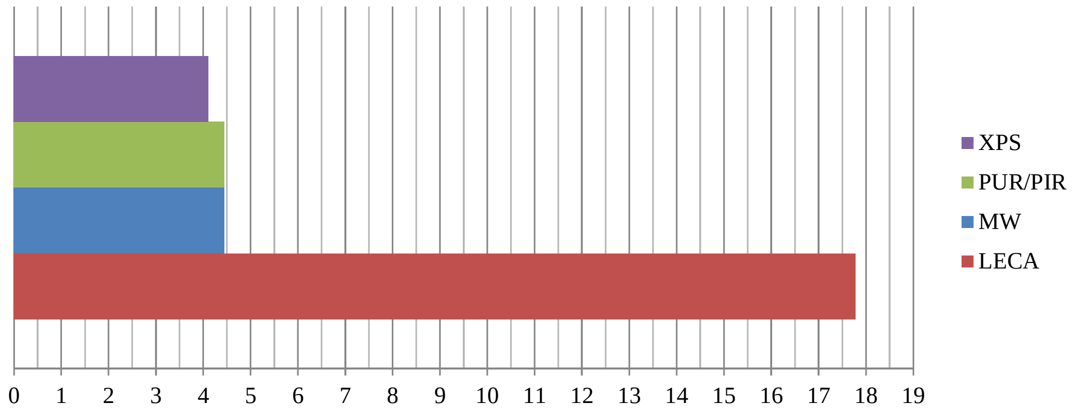

Figure 3.29 - Thickness of each insulation material with the same thermal performance as 5 cm of ICB (cm)

Most insulation materials should have CE marking based on the corresponding European harmonised standards (EC, 1988). Table 3.7 presents a non-exhaustive list of these standards. All the precast insulation materials supplied in boards, rolls or mats must have a certification of conformity (without random tests) when fire retardants are included in their composition, or organic material content is limited during the production process, in order to improve their reaction to fire classification. The producers of insulation materials must declare the target thermal resistance - R_d (under standard hydro-thermal conditions and considering a service life of 25 years) for each thickness of product available on the market (Santos, C. Pina & Matias, 2006) because most thermal insulation materials exhibit heat flows by a combination of modes (i.e. conduction, radiation, and convection) resulting in a variation of properties with material thickness. The term *apparent* is implicit in the term thermal conductivity of insulating materials and the presumption of a pure conduction mode is not valid (Al-Homoud, 2005).

Table 3.7 - Non-exhaustive list of European harmonised standards for CE marking of insulation materials

Insulation material	Harmonised standard
Thermal insulation products for buildings - Factory made mineral wool (MW) products - Specification	EN 13162:2008
Thermal insulation products for buildings - Factory made mineral wool (MW) products - Specification	EN 13163:2008
Thermal insulation products for buildings - Factory made products of extruded polystyrene foam (XPS) - Specification	EN 13164:2008
Thermal insulation products for buildings - Factory made rigid polyurethane foam (PUR) products - Specification	EN 13165:2008
Thermal insulation products for buildings - Factory made cellular glass (CG) products - Specification	EN 13167:2008
Thermal insulation products for buildings - Factory made products of expanded cork (ICB) – Specification	EN 13170:2008
Thermal insulating materials and products - In-situ formed expanded clay lightweight aggregate products (LWA) - Part 1: Specification for the loose-fill products before installation	EN 14063-1:2004

Some insulation systems have not yet been covered by a European Standard, but the producer can ask for a “European Technical Approval” (equivalent to a CE marking) or for a homologation in the corresponding institute of its country (EC, 1988). Insulating foams projected *in situ* and some thermal insulation materials based on vegetal or animal fibres are within this group.

3.2.7. Functional requirements - Claddings

Wall claddings have different functional requirements. Among them, there is stability to normal and accidental actions, fire safety (e.g. fire reaction and release of toxic products and smoke), watertightness (to water and to water vapour), visual and tactile comfort, hygiene, in-use safety (e.g. toxicity, tactile safety and adherence to the substrate), acoustic protection, economy of energy (e.g. thermal insulation), durability and suitability to the use (e.g. impact, water and weather resistance, compatibility with the support and economy, including initial and maintenance costs) (Veiga, 2003). However, the contribution of the cladding to the accomplishment of the functional requirements of the external wall solution depends on its type. Renders, for example (Flores-Colen, 2009):

- Only contribute to the fulfilment of the portion of fire safety related with the reaction to fire of claddings by being non-combustible materials, while resistance to fire can only be provided by the elements of the wall structure;
- Have an insignificant contribution to acoustic and thermal insulation, unless they contain a raw material or a layer with insulating characteristics;
- Are used on traditional facade systems, with a small degree of flexibility and adaptability.

However, the cladding of external walls of buildings has optical characteristics which affect the thermal performance of the envelope and that are determinants of the heat gain and loss per building envelope unit of area, due to exterior temperature and solar radiation. These characteristics are the coefficient of absorption and the permeability and reflectivity of solar radiation (Bostancioglu, 2010).

3.3. Conclusion and perspectives

This chapter starts by putting into perspective the object of this Thesis - the opaque areas of the external walls of buildings - and making the distinction between them and the other components of the building envelope. The object is thereafter divided in its primary components: the elements of the wall structure, the insulation material, the internal and external claddings and the ancillary components. Each of these groups of materials is described in detail, particularly the different solutions that are normally used in each layer and their corresponding characteristics. This section of the chapter ends with the presentation of the most common external wall solutions in Portugal, which have their composition, dimensions and thermal performance summarised in Appendix 3.I. A part of these solutions will be assessed and evaluated in Chapter 7 and will have their materials characterized in terms of life-cycle environmental performance in Chapters 4 and 5. In a simple way, these solutions can be divided in single-leaf and cavity walls, depending on the number of leaves of elements of the wall structure (one or two, respectively).

The second main section of this chapter details the functional requirements that the external walls of buildings have to achieve. These requirements are specified in national, European and international building regulations and directly reduce the range of solutions that can be used as external walls, despite being more performance-based than prescriptive by comparison with old ones. Therefore, this section lists the requirements of thermal, acoustic and fire performance that the opaque area of external walls must accomplish as a whole. Concerning the economic performance, there are not yet limits or reference figures. Therefore, this section only comprises the presentation of the methodology that will be used in Chapter 7 to calculate the whole-life cost from “cradle to cradle” of each external wall alternative studied in this thesis. This methodology is based on the relevant European and International standards and considers all costs that occur during the period of study of the life cycle of each external wall.

The final section of this chapter corresponds to the description of the functional requirements that should be accomplished by each part of the external wall and by the different materials that can be used in them. Thus, specific requirements concerning the elements of the wall structure, insulation materials and internal and external claddings are presented in detail.

The external walls of buildings have a significant contribution to different dimensions of the performance of the building during its whole life cycle. This contribution comes from the external wall as a whole, for some requirements, but also from each of its individual components - claddings, insulation materials and elements of the wall structure - for several other significant requirements. Therefore, only the holistic characterisation and assessment of the external wall solution and of each of its layers can lead to a satisfactory result in the several dimensions of the building performance.

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4. LIFE CYCLE INVENTORY ANALYSIS (LCI)

4.1. Life Cycle Inventory analysis (LCI) methodology

Section 2.3 “Life Cycle Assessment (LCA) methodology” of Chapter 2 already introduced the “Life Cycle Inventory analysis” (LCI) phase as a part of the global LCA methodology. However, the description in detail of LCI is only presented in this section of the Thesis and a simplified representation of the procedures that have to be done during a LCI is presented in Figure 4.1 (except for some iterative steps that are not included in this Figure).

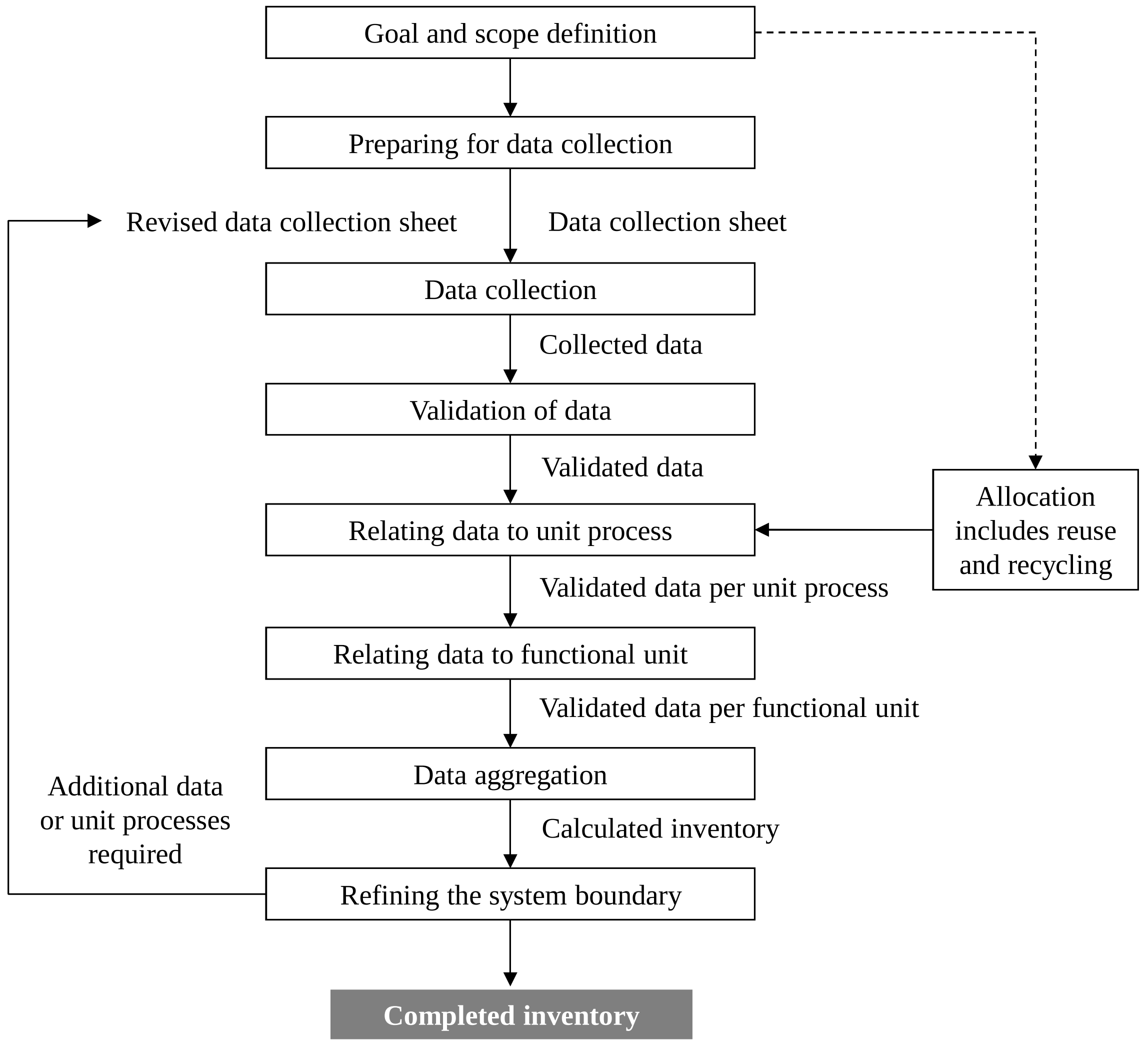

Figure 4.1 - Simplified representation of the procedures included in a LCI (ISO, 2006b)

LCI follows the definition of the goal and scope of the assessment, namely the description of the product to be assessed, the boundary of the associated system and the functional unit. LCI comprises the inventory, quantification, and compilation of the relevant inputs and outputs of the processes included along the life cycle of the product (or product system) being studied. Therefore, to complete the LCI of a product, each flow (e.g. of mass - quantification of materials, energy, and emissions to the air, water or soil) has to be identified, quantified and compiled for each life cycle and its corresponding processes (Figure 4.2).

It is important to highlight that the process of conducting a LCI is iterative. In fact, data collection procedures can be adjusted as soon as more data is collected and a better understanding of the product system is acquired. These adjustments may result from the identification of new data requirements or limitations that can prevent the goals of the study from being met.

4.1.1. Data collection

The data collection step must consider the available qualitative and quantitative data of each unit process included within the system boundary. The data collected represents inputs or outputs and can result from a measurement, calculation or estimation. Therefore, the method of derivation must be referenced, along with the source of data (e.g. company, public source, etc.). Moreover, relevant details about the data collection process, data collection period, and complementary information (e.g. data quality indicators and verification of agreement with data quality requirements) should also be noted down for data that "may be significant for the conclusions of the study" (ISO, 2006b, p. 11). The modelling of each life cycle stage of the product system must be divided in a sequence of disjointed unit processes, in order to avoid double counting. A description of the unit process must be kept with the data collected in order to maintain its usefulness (e.g. for data validation or reuse) and avoid misunderstandings (e.g. double counting) (ISO, 2006b).

To provide a uniform and consistent understanding of the system to be modelled, some procedures must be put into practice (ISO, 2006b):

- Description of each unit process, namely including the listing of relevant flows, the factors influencing inputs and outputs, and relevant data for operating conditions;
- Drawing of a system flowchart representing all unit processes to be modelled and their interrelationships;
- Definition of the units to be used in data collection for each type of flow.

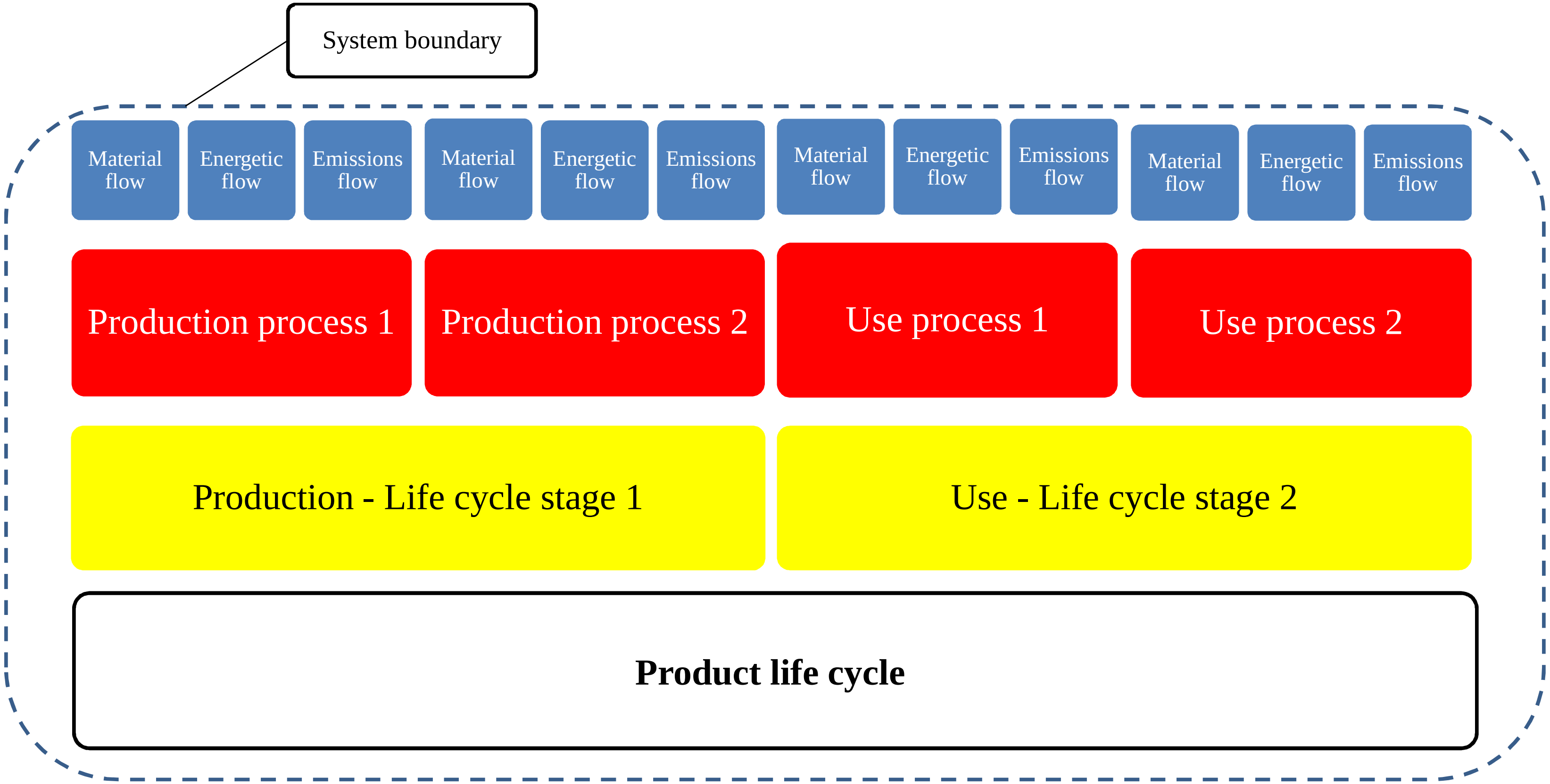

Figure 4.2 - Simplified representation of the stages and unit processes composing a product life cycle (or product system), including the corresponding flows

Collected data for each unit process can be compiled using the following major headings (ISO, 2006b): energy inputs, raw material inputs, ancillary inputs, other physical inputs; products, co-products and waste; releases to air, water and soil; and other environmental aspects. Data collection files can be used to aid the compilation of this high quantity of data and also to ease its consultation and the confirmation of its sources (Ferrão, 2009).

The initial flowchart can be modified during data collection, particularly via the decomposition of processes into elementary sub-processes, or their grouping because of lack of detailed information. However, when trying to reach a certain level of detail, the influence of data on the results can be low, while the workload is high. Therefore, the production of goods (such as machines and buildings) associated to a production site is normally not taken into account in LCI. These infra-structures are used in the production of a high number of products, their impact being low when each individual product is considered (Ferrão, 2009).

4.1.2. Data calculation

Calculation procedures must be "consistently applied throughout the study" (ISO, 2006b, p. 13) and documented, along with the clear statement and explanation of the assumptions made. At least three operational steps are completed for data calculation (Ferrão, 2009; ISO, 2006a, 2006b):

1. Validation of data - to confirm and provide evidence of fulfilment of data quality requirements for the intended application (e.g. mass or energy balances, comparative analyses of release factors) and quantify partial errors associated with the analysis;
2. Relating data to each unit process and functional unit - this step starts with the determination of an appropriate flow for each unit process and with the calculation of quantitative input and output data of the unit process in relation to this flow. Then, the flows of all unit processes are related to the reference flow based on the system flowchart and on the flows between unit processes. This guarantees that all the results of the calculations are referenced to the functional unit of the product system that is to be modelled. It is important to pay attention to the level of aggregation of the flows in order to confirm whether it is consistent with the goal of the study and that data related to equivalent substances and similar environmental impacts are aggregated;
3. Refining the system boundary - LCA has an imminent iterative nature and, therefore, the system boundary of the study defined in the first stage of LCA ("Definition of the goal and scope of the assessment" - see section 2.3) can be revised during LCI. Nevertheless, any inclusion or exclusion of data (e.g. representing a flow, a unit process or a life cycle

stage) at this stage has to be based “on a sensitivity analysis to determine their significance”, and the corresponding results must be documented.

Even if a refining of the system boundary is not necessary, the processes that are supposed to be responsible for relevant environmental impacts, but for which there is not significant data available, must be identified. The system flowchart resulting from this stage must include the interaction between the system and the environment and between the product system and the unit processes (e.g. when co-production, recycling or waste treatment occurs) (Ferrão, 2009).

Data collected (measured, calculated or estimated) may be submitted to a sensitivity analysis in order to evaluate the consequences of their inherent error. To apply this procedure, it is important to consider that the achieved results cannot be more accurate than the data used to attain them.

4.1.3. Allocation procedure

The need for allocation typically arises when it is necessary to divide the environmental impacts of the operation of a plant by the different products manufactured there in order to attribute a proportion to the product system under study (Ferrão, 2009). This need also results from industrial processes involving multiple products and recycling systems (e.g.: producing more than one product; recycling intermediate products, or using discarded ones, as raw materials) (ISO, 2006a).

According with International standards, an allocation procedure must be established, explained and documented, such as its application in the distribution of inputs and outputs to different products. The application of an allocation procedure must be uniform for similar inputs and outputs of the system. A sensitivity analysis can aid the choice between allocation alternatives by illustrating their consequences (ISO, 2006b).

After the identification of the processes being studied that are shared with other product systems, allocation must be avoided whenever possible by (ISO, 2006b, p. 14): “dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes”; or “expanding the product system to include the additional functions related to the co-products”, taking into account the system boundary of the study. When it is not possible to avoid allocation, two main approaches can be followed to implement the allocation procedure (ISO, 2006b):

1. Partitioning of system flows between its products or functions in order to reflect the essential physical relationships between them (i.e. influence of quantitative changes in the products or functions delivered by the system in the inputs and outputs);
2. Partitioning of system flows between its products or functions in order to reflect the other relationships between them when “physical relationship alone cannot be established or used as the basis for allocation” (e.g. allocation between co-products in proportion to their economic value).

When an output is partly co-products and partly waste, the ratio between both flows must be identified in order to allocate the inputs and outputs only to the co-product part.

A summarized description of the allocation procedure followed in the LCI studies completed in the scope of this thesis is presented in section 5.4.1.6, taking also into consideration the procedures included in the most recent European standards (CEN, 2012).

4.1.4. Life Cycle Inventory analysis

The LCI stage ends with the analysis of the inventory obtained. In fact, the LCI or overall account of environmental interventions (e.g. emission to air - Chlorofluorocarbons - CFC, CO, CO_2, Halon, and Methane - CH_4) of the product system must result from this stage in order to be considered in the next stage of LCA methodology (“Life Cycle Impact Assessment” - LCIA - phase). Therefore, the quantification of these flows, for every unit process, must be grouped *per* substance in an inventory table (e. g. sum of NO_x identified for unit processes in order to obtain the value to be included in the inventory table and corresponding to the reference flow of the functional unit (Ferrão, 2009)). The inventory table can also provide the quantification of each type of flow (e.g. material and energetic) *per* life cycle stage or unit process (ISO, 2006b).

4.2. LCI of building products

4.2.1. The stages of building products life cycle

The LCA of buildings can be applied to both individual construction materials and assemblies, or to the process of construction of the whole building (Ortiz et al., 2009). Figure 4.3 shows the comparison between both perspectives, where the presuppositions that have to be taken into account in each one are implicit: different temporal horizons, levels of complexity and aims.

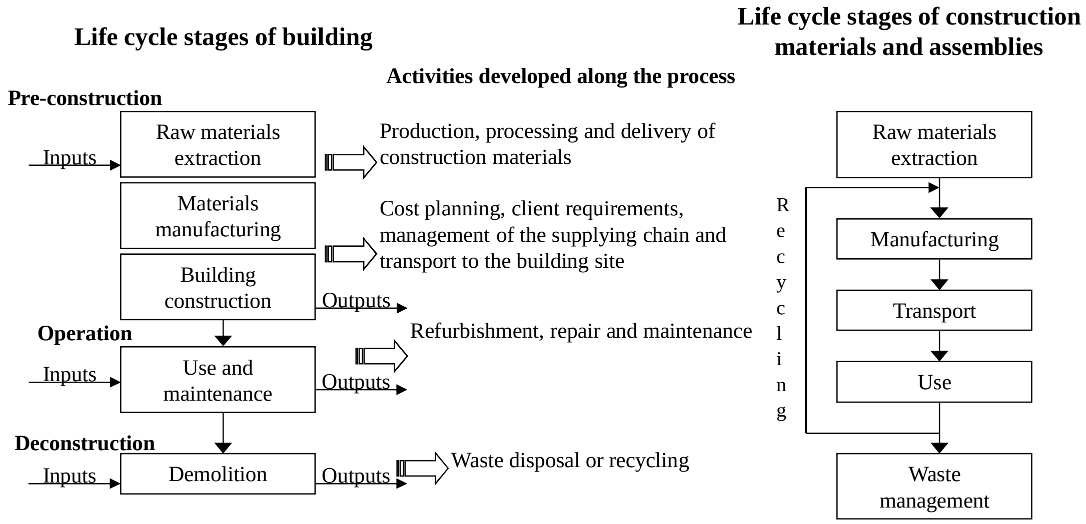

Figure 4.3 - Building *versus* construction materials and assemblies LCA (adapted from (Ortiz et al., 2009))

A standardised nomenclature of life cycle stages of buildings (and also of building products) is defined in European standards. At the same time, other standards such as the French standard NF P01-010 (AFNOR, 2004) followed by the “*Programme de Déclaration Environnementale et Sanitaire pour les produits de construction*” (called “*Fiches de Déclaration Environnementale et Sanitaire*“ (FDES)), define a different nomenclature and aggregation of these stages (Silvestre & Lasvaux, 2012). Therefore, Table 4.1 summarises and compares both approaches - the French and the European ones - and Table 4.2 shows in detail the disaggregation of life cycle stages of buildings and building products specified in European Standards.

Table 4.1 - Life cycle stages (or LCA information module D) classification based on French and European standards (AFNOR, 2004; CEN, 2012)

LCA boundaries			**Standard**	
			NF P01-010	**EN 15804:2012**
Cradle to cradle	**Cradle to grave**	**Cradle to gate**	Production	Product stage (A1-A3)
		Gate to grave	Transportation	Construction process stage (A4-A5)
			Implementation	
			Utilisation	Use stage (B1-B7)
			End-of-life	End-of-life stage (C1-C4)
				Benefits and loads beyond the system boundary (D)

In the LCA of building products, namely for Environmental Product Declarations (EPD), the information related with all the stages after the production (B, C or D) are based on scenarios, mostly built and assessed using generic LCA data (similarly to the approach commonly used for modelling upstream processes, such as the production of raw materials)

(Table 4.3). Following this approach, generic data for scenarios must be “as realistic as possible and properly documented (covering the present or anticipated situation), rather than idealistic or "carefully selected” (CEN, 2010), and the assumptions made for each stage must be inter-related. For instance, construction process scenarios are important not only for the construction stage, but also for the use and end-of-life stages. On the other hand, scenarios describing the end-of-life stage (downstream processes – see Table 4.3) must reflect the existing technology, current regulations, today's average practice and a mix of different end-of-life treatments available at the national or regional level (CEN, 2010).

Table 4.2 - Detailed life cycle stages classification based on European standards (CEN, 2012)

Modules	**Life cycle stage designation and description**	
Product stage (A1-A3)	A1	raw material extraction and processing, processing of secondary material input
	A2	transport to the manufacturer
	A3	manufacturing
Construction process stage (A4-A5)	A4	transport to the building site
	A5	installation into the building
Use stage - information modules related to the building fabric (B1-B5)	B1	use or application of the installed product
	B2	maintenance
	B3	repair
	B4	replacement
	B5	refurbishment
Use stage - information modules related to the operation of the building (B6-B7)	B6	operational energy use
	B7	operational water use
End-of-life stage (C1-C4)	C1	de-construction, demolition
	C2	transport to waste processing
	C3	waste processing for reuse, recovery and/or recycling
	C4	disposal
Benefits and loads beyond the system boundary (D)	D	reuse, recovery and/or recycling potentials

Table 4.3 - Type of data - generic and site-specific - used on EPD for each life cycle stage (CEN, 2012)

Modules	**Product stage (A1-A3)**		**Construction process stage (A4-A5)**	**Use stage (B1-B7)**	**End-of-life stage (C1-C4)**	**Benefits and loads beyond the system boundary (D)**
	Production of raw materials (A1)	**Product manufacture (A3)**				
Process type	Upstream processes	Processes the manufacturer has influence over	Downstream processes			
Data type	Generic data	Manufacturer’s average or site-specific data	Generic data			

According to the synthesis presented in Table 4.3, the information related with product manufacture (A3) should be based on site-specific data (LeVan, 1995). Therefore, section 4.3 only includes the description of the “Product stage” (A1-A3) of building products for which data have been collected from Portuguese plants, while the remaining stages of the life cycle of these products are characterised, assessed and evaluated in Chapter 7 based on scenarios.

4.2.2. Main environmental impacts in each phase of the life cycle of building products

Following the nomenclature of life cycle stages of building products defined in European standards (Table 4.2), this section summarises the factors that determine, to a great extent, the severity and type of environmental impacts that may result from each stage of the life cycle of building products. There is nomenclature for LCA of buildings prior to European standards related with the embodied effects at each stage of the life cycle (Trusty, 2003):

- Initial embodied effects - impacts related with the manufacture, transport and installation of the materials used to make the building;
- Recurring embodied effects - impacts related with maintenance and replacement activities during the building life cycle;
- Final, or end-of-life, embodied effects - impacts due to demolition and disposal of the building.

A study presented in Portugal in 2010 summarised the environmental issues and corresponding impacts and benefits at each stage of the life cycle of a building, and is presented in Table 4.4.

Table 4.4 - Potential environmental impacts related with the activities developed at each stage of a building life cycle (adapted from (Trindade & Duarte, 2010))

Environmental issues	**Example of potential environmental impacts (P - positive, or N - negative impact)**	**Life cycle stages (see Table 4.2)**
Materials, energy and water consumption	Natural resources over-exploration (N)	(A1-A3), A5, B, C1
CO_2 emissions	Contribution to greenhouse effect (N)	(A1-A3), A5, B, C1
Emission of dust or harmful substances	Air quality deterioration (N)	(A1-A3), A5, C1
Solid wastes creation	Land pollution (N)	A5, C1
Emission of untreated waste water	Water pollution (N)	A5, B
Efficient waste management	Materials reuse/recycling (P)	A5, B, C1
Chlorofluorocarbons (CFC) emissions	Ozone layer depletion (N)	B
Low or no emission of harmful substances for human health	Human health improvement (P)	B

Construction and demolition waste (CDW) is referred to in Table 4.4 either for its potential environmental impacts (land pollution) and avoided impacts resulting from an efficient waste management (through material reuse or recycling). In fact, flows related with

CDW are responsible for around 13% of all solid waste deposited in landfills worldwide, 1/3 of this quantity corresponding to construction waste (CIB, 1999). Thus, the impact of this type of flow must be higher during end-of-life than during the construction stage.

Despite the fact that the design stage does not have a share in a building's environmental impacts, the severity and type of these impacts are in a great extent determined by the decisions taken during this stage. In fact, design choices influence the impacts related with land and material use and a building's energy and water needs (Rovers - Editor in chief, 2003). Therefore, LCA from cradle to cradle of different design alternatives - including available materials and their suppliers - must be analysed in detail using appropriate scenarios for use and end-of-life stages (Duarte, 2009; Pinheiro, 2006). The aim is to achieve a sustainable design by optimising the use of resources (materials, land, energy and water), namely following the five principles of sustainable construction ((Kibert, 1994) cited by (Pinheiro, 2006)):

1. Reduce resource consumption;
2. Maximise resource reuse;
3. Recycle materials at a building's end-of-life and use recyclable resources;
4. Protect natural systems and their functions during all activities;
5. Eliminate toxic materials and sub-products at all life cycle stages.

4.2.2.1. Product stage (A1-A3)

The product stage comprises three sub-stages (Table 4.2): raw material extraction and processing, processing of secondary material input (A1), transport to the manufacturer (A2) and manufacturing (A3). Therefore, inventory data required to evaluate the environmental impacts of this stage includes: raw materials, recycled and reused materials and intermediate product flows essential to the manufacturing of the product being studied and of its raw materials; energy flows and emissions or releases occurring during A1 and A3 sub-stages (ARUP, 2006). When someone refers to the embodied energy of a building, it must correspond to the energy consumed in the production of building materials and components, including mining and manufacturing of materials and equipment (UNEP, 2007).

The environmental impacts from stage A2 are increasingly high as the resources near the factories start to be totally consumed (Cabello, 2007).

Mineral materials, for example, are extracted from open-pit quarries (A1 sub-stage) with unavoidable effects on the landscape, such as topographic changes, and acoustic and atmospheric contamination (Cabello, 2007). During manufacturing (A3 sub-stage), environmental impacts are more significant for products using pulverulent raw materials or needing a significant quantity of energy to be produced (i.e. are normally more complex or require a higher level of processing, thus having higher embodied energy). The corresponding environmental incidences are dust and CO_2 emissions, waste water emissions and too excessive consumption of energy (Cabello, 2007; UNEP, 2007).

4.2.2.2. Construction process stage (A4-A5)

The construction stage comprises both the transport of construction materials and products to the building site (A4) and their installation into the building (A5) (Table 4.2). Different alternatives for the same function can lead to different environmental impacts during transport, unloading, storage and installation. During the latter sub-stage, the appropriate choice of the construction process can lead to a lower material, energy and water consumption, waste creation rate and recyclability potential (Cabello, 2007; Gaspar, 2004). However, energy for stocking, lifting and other processes required to install a building product are “much more dependent on site conditions and building type than on the product itself” (Chevalier & LeTeno, 1996, p. 490). Building construction can also include other indirect impacts such as land clearing, earthmoving with dust emissions, discharges and energy consumption of construction machinery (Duarte, 2009; Rovers - Editor in chief, 2003).

The energy consumed during the installation stage (A5) can be divided in direct and indirect consumption. Direct consumption is related with the activity at the construction site. Indirect consumption includes the production and maintenance of the equipment used on site and the transport of workers and equipment to and from the construction site. Direct consumption can also be divided in two groups: energy consumed on site (e.g. mechanical equipment and lightning); and equivalent energy spent by workmanship (e.g. a worker can spend 360 kJ, or 100 W/h (Berge, 1999) cited by (Mendonça, 2005)) (Mendonça, 2005).

The distance between the factory and the construction site is important, in conjunction with the type of transportation chosen, to define the magnitude of the environmental impacts of A4 sub-stage. Therefore, the person responsible for the selection of the products to be used in the construction of a building must be aware that local materials can be advantageous in environmental terms, as well as the choice of the means of transportation with lower environmental burdens.

4.2.2.3. Use stage - information modules related to the building fabric (B1-B5)

The use stage comprises the following sub-stages (Table 4.2): use or application of the installed product (B1); maintenance (B2); repair (B3); replacement (B4); and refurbishment (B5). The environmental impacts during these stages can be dependent on the materials chosen in the design stage, namely on their durability, easy maintenance, functionality and aesthetic quality. However, it is important to highlight the unpredictable nature of the environmental impacts at this stage of the life cycle and their strong correlation with extrinsic conditions (e.g. climate, type of user and change of use) (Chevalier & LeTeno, 1996). As soon as a building component reaches its end-of-life, it must be (entirely or partially) replaced, increasing the environmental impacts of the building, and of the component, from a life cycle perspective (Gaspar, 2004).

It is also important to be aware of the potential long-term impact of construction materials on the health of building inhabitants, mainly because of their continued exposure to harmful substances released during use (e.g. formaldehyde, ammonia, carcinogens or volatile organic compounds - VOC - in indoor areas (Cabello, 2007; Rovers - Editor in chief, 2003)) and maintenance (e.g. chemicals used for cleaning operations (Rovers - Editor in chief, 2003)) of the building (Gaspar, 2004). However, these kinds of impacts are not often included in LCA studies.

4.2.2.4. Use stage - information modules related to the operation of the building (B6-B7)

Both the operational energy (B6) and water (B7) uses are included in the information modules related to the operation of the building during its use stage (B6-B7) (Table 4.2) (Gaspar, 2004).

The environmental impacts of operational energy (sub-stage B6) are directly related with the thermal performance of the building as a whole, and of all its parts, but also with the thermal behaviour of each building assembly, namely of its external walls. In fact, it can be an option to increase the environmental impact of a building during the product and construction stages by selecting a higher thickness of insulation of the envelope but knowing beforehand that this will provide a lower operational energy used for heating and cooling, and a lower environmental load from a life cycle perspective. Thermal performance of buildings, and specifically the contribution of external walls to the fulfilment of this requirement, has already been described in detail in section 3.2.1. Operational energy also includes lighting, cooking, ventilation needs during the building use stage (UNEP, 2007).

By the year 2000, operational energy (sub-stage B6) was responsible for almost 90% of the energy consumption during the life cycle of a building, either an office or a house (Monteiro, 2010), according to several LCA studies completed all over the world ((Junilla, 2004) cited by (UNEP, 2007)). However, because of the increasing public incentive for the implementation of measures to improve the energy efficiency of buildings, namely in Europe, the embodied energy (excluding therefore construction and use stages) can nowadays account for 30% of a building's energy consumption ((Bribián *et al.*, 2009) cited by (Monteiro, 2010)). This trend will continue in the next years with the increase of oil prices. Thereafter, all other stages of a building's life cycle will continue to gain momentum - particularly the product stage - and each environmental improvement in these stages will have a higher impact on the overall building's environmental performance.

4.2.2.5. End-of-life stage (C1-C4)

The end-of-life stage (C1-C4) of a building and of its elements can be divided into four sub-stages (Table 4.2): de-construction or demolition (C1), transport to waste processing (C2), waste processing for reuse, recovery and/or recycling (C3) and disposal (C4).

As stated in Chapter 2, the application of the cradle to cradle perspective in LCA of construction materials and products is necessary to create cyclic metabolisms (Braungart & McDonough, 2009; Farrall, 2010). In fact, closing material loops can result either from designing buildings for deconstruction or from developing disassemblable building products, which are both issues increasingly being addressed in the context of green buildings (IEA, 2004; Kibert, 2007). De-construction (or deconstruction) (C1) can be defined as a "rational demolition" in which the building is disassembled into its primary components. This activity also eases the reuse of building materials and components by promoting their split-up by type from the beginning, and allows for a cradle to cradle viewpoint in the life cycle of these products, thus preventing matter and energy loses (Santos, A. L. d. & de Brito, 2007). C1 and C2 stages account for, on average, 10% of the amount of energy consumed in construction materials life cycle from cradle to cradle ((Berge, 1999) cited by (Mendonça, 2005)).

The development of proper solutions for the end-of-life of construction materials and products can also include the use of CDW to increase the recycled content of different products, either within the construction industry or in other industries (Industrial Symbiosis). But some CDW are dangerous (e.g. asbestos and mineral fibres, and concrete solvents and admixtures) and must be adequately processed and disposed of (Cabello, 2007).

The environmental impacts of the subsequent sub-stages (C3 and C4) can be reduced if a search for the best alternatives for recovery, recycling or energetic valorisation of each construction element is completed before demolition operations (C1) begin (Gaspar, 2004). From a theoretical point of view, the four alternatives for CDW treatment included in the C3 and C4 stages - waste processing for reuse, recovery and recycling, and disposal (including physical pre-treatment and management of the disposal site) (CEN, 2012) - are in increasing order of environmental impacts. However, this axiom has to be proven for each construction material and product and for CDW treatments available in each national context.

4.2.2.6. Benefits and loads beyond the system boundary (D)

To characterise the environmental performance of construction materials and products from cradle to cradle it is necessary to take into account not only the impacts related to this stage “End-of-life stage“ (C), but also the “Benefits and loads beyond the system boundary” (D) (Table 4.1). The evaluation of the latter includes the quantification of the potential environmental impacts and avoided burdens that can result from the reuse, recovery and/or recycling potentials at the end-of-life of construction materials and products. The inclusion of the supplementary information related with module (D) in a LCA study provides a higher level of transparency for the “environmental benefits or loads resulting from reusable products, recyclable materials and/or useful energy carriers leaving a product system” (e.g. such as secondary materials or fuels) (CEN, 2012, p. 24). For instance, this module must include the benefits and loads from flows leaving the product system that have not been allocated as co-products and have passed the “end-of-waste” state (see section 5.4.1.5.2 and 7.1.5.5), but must not include the avoided impacts from allocated co-products (CEN, 2012).

4.3. The “Product stage” (A1-A3) of the building products studied in this Thesis

This section includes the qualitative description of the “Product stage” for each building product for which a LCI study has been completed in this Thesis. A quantitative description of this stage (e.g. a mass balance of the main flows, inputs and outputs occurring at each stage of this system process) is not presented for each building product due to confidentiality reasons.

First, it is important to highlight the reasons behind the choice of these 12 materials. In the first plan of this Thesis an analysis of international LCA databases was included to allow for the identification of the building materials with the most significant environmental impact and with a higher geographical variability of results. The materials identified at this stage would be chosen to be studied in detail using data from Portuguese plants, mainly those whose international LCA data is not directly applicable to the Portuguese context. However, due to the limited dimension of the Portuguese market and because of the difficulty in receiving a positive answer from some companies to collaborate on this Thesis, the approach that justified the choice of the materials chosen changed during the Thesis development. In fact, the final range of products was defined based on the companies that gave a prompt response to the request made by the author and also on the degree of innovation of the products both at a national and international level. This last requirement was taken into account to define the companies contacted to collaborate on this Thesis in order to guarantee an innovative contribution of this Thesis in the field of study related with the LCA of the construction sector (and one of the contacts with this aim resulted on a winning proposal for a national research project (Flores-Colen - Coord., 2011)). It was also an option of the author to only study a product from each plant. This choice was done to fulfil three objectives:

1. To guarantee that a LCI study was completed with each company;
2. That the learning process of completing each LCI study was useful both for the company and the author;
3. To allow for the inclusion and characterisation in this Thesis of a range of LCI studies presenting a multiplicity of constraints, limitations and need for methodological choices. This last objective allowed for the improvement of the skills of the author in doing LCI studies and for the maximisation of the variety of case studies included in this Thesis.

Each of these studies was based on present production by a Portuguese company (their names, plant locations and range of products are not presented in detail due to confidentiality reasons; their geographic distribution is illustrated in Figure 4.4) in order to guarantee a proper representativeness and innovation of this research study. In fact, 12 LCI - and corresponding LCA - studies of building products are presented in this thesis while no more than five of this type of study are publicly available in Portugal to date (Almeida, 2010; Almeida *et al.*, 2010; Concretope & INETI/CENDES, 2005). The overall goal and scope of these LCI studies precedes the description in detail of each “Product stage”.

To develop the LCI studies with each company, the author used a pragmatic approach taking into account the following presuppositions (Ferrão, 2009; ISO, 2006a):

- Each study is resource-intensive and involves the collection of information related to several unit processes, each one with their specificities;
- A part of the necessary information is often not available;

- It is necessary to implicate a third-party in the data collection process and these only have a partial interest in the results of the study or can even feel threatened by them.

Figure 4.4 - Map of Portugal (partial) with the geographic distribution of the companies whose building products were studied in this Thesis

These assumptions and limitations forced the author to spend a significant amount of time and resources in the preparation of the form that supported the collection of data of each LCI study, and in the sensitisation of the participants to the aim of the study and the use that would be made of the results. This preparation included the reading and systematisation of the information available in reference literature (e.g. scientific papers, LCA studies, environmental labels and EPD) about the environmental performance of each building product studied.

Each LCI was thereafter an iterative process, namely the identification of relevant inputs and outputs occurring within each stage of the production of the materials being studied (ISO, 2006b). The first approach was always the form for data collection already referred to, which was based on the first visit of the author to the production line and meeting with the company representative. A fuller identification and quantification of flows was only possible after additional data collection during the course of each study, namely in the subsequent contacts with the company representative (e.g. meetings at - and visits to - each plant) to clarify doubts and answer pending questions.

4.3.1. Goal and scope of the study

As stated in Chapter 2, the definition of the goal and scope of a LCA study must include the following issues related with the LCI phase (ISO, 2006a):

- The definition of the goal of the study;
- The intended audience and application, including whether the results are intended to be used in comparative assertions planned to be disclosed to the public;
- The product to be assessed;
- Allocation procedures;
- Cut-off criterion;
- The functional or declared unit;
- The boundary of the associated system;
- The strategy for data collection;
- Data quality requirements;
- The assumptions and limitations of the study.

The way of dealing with each of these issues in this Thesis is described next, except for the “product to be assessed”, which is specific to each of the LCI studies included in this section of the Thesis, and for the “assumptions and limitations of the study”, which are described within each of the following sub-sections and also in the description of each of the LCI studies.

4.3.1.1. <u>Goal of the study, intended audience and application, and methodological procedures</u>

The following paragraphs explain the general goal of these studies, identify the intended audience and describe the methodological procedures followed.

The goal of these studies includes:

- The conclusion of several LCA studies of building products, from which additional research studies can be completed in order to study specific issues of each process;

- The verification of the contribution of each life-cycle stage for the environmental impacts from cradle to gate;
- The contribution for the learning process of the company and the author.

Despite the fact that LCA studies completed in this thesis have a research purpose and are not intended to be used directly in EPD, it is expected that some producers will use them to apply for this type of declaration in some European programme, namely within the Portuguese one (see DAPHabitat description in Chapter 2). Despite of several national EPD programmes already on-course in Europe (see section 2.2.1.3), there is yet no harmonisation of their general procedures or Product Category Rules (PCR). Therefore, the methodological procedures used in this research work may be in accordance with the main parts of the these PCR, but furthermore and above all, they comply with European and International LCA standards (CEN, 2011; ISO, 2006a, 2006b).

Concerning the intended audience and application, this Thesis is a research work and LCA studies completed within are planned to be used in comparative assertions (particularly in Chapter 7 but also in future research works) and to be disclosed to the public. Therefore, profiting from the extensive, detailed and varied LCI studies completed of the 12 Portuguese plants and following the procedures specified in International standards (ISO, 2006b), several simulations can be done (using suitable LCA software) to provide interesting results both in industrial and scientific terms. These simulations correspond to a sensitivity analysis[1] of the different methodological alternatives for different issues, such as the cut-off criterion (mass, energy and environmental significance criteria), allocation (e.g. mass or economic), system boundaries or potential environmental improvements of every producer. Despite the fact that the study in detail of all these issues is outside the scope of this thesis, simulations are presented in Chapters 5, 6 and 7 for some methodological alternatives.

Therefore, considering the limitations and specificities of this research work described, the system boundary was defined but a restricted cut-off criterion or allocation procedures were not. This can be an advantage by allowing for a broad awareness of the potential environmental improvements of each production process, corresponding to an eco-design practice. Therefore, the methodological procedures defined for the LCI phase were:

- To maintain the consistency among the LCI studies completed in each plant and for each type of material;
- To not define a cut-off criterion but collect and quantify all available data. Only the unit processes or flows that the company stated that are residual - and are not dangerous, or for

[1] **Sensitivity analysis** - procedure to determine how changes in data and methodological choices affect the results of the Life Cycle Impact Assessment (LCIA) (ISO, 2006b, p. 22).

which there is not sufficient information available, are not quantified but their occurrence were noted down, along with an explanation of the implications of their omission (a cut-off criterion excludes flows with significance - in mass, energy or contribution to the emission of substances with environmental impact - lower than a specified percentage of the total amount of the system process) (Ferrão, 2009; ISO, 2006b);

- To define the most appropriate allocation method (e.g. mass or economic) for each product and corresponding production process, but, at the same time, collect all available data to allow for a future simulation of the consequences of different allocation procedures.

Finally, it is important to highlight that this thesis is a research work and therefore the goal of each individual LCI study is complex and multipurpose, and therefore not easy to outline individually. However, it is considered that the goal of these studies was achieved, despite the limitations described in this section that made difficult this desideratum.

4.3.1.2. Functional or declared unit

"The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related" (ISO, 2006a, p. 12). Therefore, a declared unit is considered for each product studied in this section of the thesis and is directly related with the reference flow - related to mass or volume (e.g. flows per kg or m^3 of product) - that characterise each type of plant. A functional unit is not defined because it is not necessary to identify at this stage the function of each product when applied into the building (CEN, 2012). The declared unit that are used to assess and evaluate the external wall solutions in Chapter 7 is a square metre of wall and the LCA results presented in Chapter 5 are then converted in accordance with the physical characteristics of each material (i.e. density, thickness, etc.).

4.3.1.3. System boundary and data collection

The system boundary of each LCI study corresponds to the "Product stage (A1-A3)" (Table 4.1) and, therefore, the study of each product was completed from cradle to gate. Raw material extraction and processing, processing of secondary material input (A1), transport to the manufacturer (A2) and manufacturing (A3) are included in the product stage, and the last sub-stage includes the packaging of the product (when applicable) but, wherever a disaggregation is possible, do not include infrastructures (e.g. production plant and related flows, such as lighting and heating). The unit processes included in the manufacturing (A3) of each material studied are described in the corresponding sub-section of this Chapter of the Thesis, including the corresponding inputs and outputs considered. However, all outputs that do not leave the system process (e.g. re-used or recycled production waste, or re-used waste water, within the plant), and all the flows that were allocated to sub-products (e.g. waste from insulation board cutting process that is grinded, packed and sold) and that were not considered in the LCI of the production of the materials studied, were not included in these descriptions[2]. Sub-stages A1 and A2 of each material studied, and the process of choice of generic LCA datasets to model them, are presented in more detail in Chapter 5 and Chapter 6 of this Thesis. In fact, sub-stages A1 and A2 were modelled using generic datasets, following the common procedure used in EPD (Table 4.3), while site-specific data was used for the manufacturing process (A3). Nevertheless, processes from generic database used in all sub-stages of these LCI studies were modified (e.g.: electricity production mix; transport modelling and distances and origin of raw materials - when information was available from the company; waste disposal and treatment processes, namely packaging of raw materials) in an approach known as "contextualisation" (Peuportier et al., 2011), to improve their representativeness to the Portuguese context (Ibáñez-Forés et al., 2011). LCA software (SimaPro 7.3.3 – see section 5.3.4 (PRé, 2012)) was used to collect and store the data from each LCI study and, furthermore, to support the subsequent LCA study whose results are presented in Chapter 5.

Site-specific data used for the manufacturing process (A3) is a mix of data obtained or calculated from internal company reports or databases (e.g. average data from a production day, month or year), data measured in the plant from one or more unit processes or estimated data based on insufficient company information (ISO, 2006b). The mode of collection of the data, and its temporal representativeness, was noted down for each LCI study along with its quantification.

4.3.1.4. Data quality requirements

Data quality requirements were considered in each LCI study in order to achieve LCA results representative of current production practices (namely with an appropriate technological representativeness) in Portuguese plants. Therefore, each company was requested to supply production data with an extensive temporal representativeness (e.g. last year of production). But when these figures were not available, the option was to collect or estimate data directly from the production line and quantify the current input and output flows (guaranteeing that the totality of each flow is considered - fulfilling a completeness requirement (ISO, 2006b)). This procedure was followed to aid in the interpretation of the

[2] In fact, the description of the referred flows is only presented in Appendix 4.I for the manufacturing process of one of the products studied.

outcome of each study and ensure the reliability of the results of this Thesis (ISO, 2006a), but the limitations in data collection found in each plant restricted its implementation. Other data quality requirements were also considered (ISO, 2006b):

- Precision - site-specific data was not characterised in terms of its variability (e.g. variance), not even when corresponding to an average of a production day, month or year, and only the average figure was taken into account;
- Geographical representativeness - all inventory data was collected from Portuguese plants, but the national market share - or geographical representativeness of the selected product - of each of these companies is not identical. Therefore, the national market share of each company - or geographical representativeness of each LCI study - is included in the integrity field of Table 4.6 for the companies that provided this information;
- Reproducibility - a form was built to support each LCI study (see an example in Appendix 4.I). This document includes the characterisation and quantification of the individual flows of each unit process based on the data provided by the company. Therefore, it is considered that this form, along with the methodological principles described in this section of the Thesis, “allow an independent practitioner to reproduce the results reported in the study” (ISO, 2006b, p. 10);
- Uncertainty of the information and missing data - practical constraints on data collection such as LCI uncertainty (e.g. data, models and assumptions) or missing data and corresponding treatment (e.g. estimation based on unit processes employing similar technology available in the bibliography) were always noted down to allow for an uncertainty analysis[3] in subsequent phases of the LCA study.

Concerning the filled out forms of each LCI study, it was not possible to present them for all the building products studied due to confidentiality reasons. Nevertheless, an example of one of these forms is presented in Appendix 4.I (Ferrão, 2009; ISO, 2006b). Along with the characterization and quantification of each flow, it also includes some notes about the options of the author in the modelling of the product system. When the form was sent to the company, it also included specific instructions for data collection and for filling it in (see Appendix 4.I). The company was asked to describe the inputs in detail (to help further characterisation of their nature) along with the “quality” of each figure included in the form (how it was derived - measured/calculated/estimated - and its uncertainty). Companies are also usually asked to include the date in which the information for each unit process was collected and who was re-

[3] **Uncertainty analysis** - procedure to determine how uncertainties in data and assumptions progress in the calculations and how they affect the reliability of the results of the Life Cycle Impact Assessment (LCIA) (ISO, 2006b, p. 22).

sponsible for the collection. However, this information was not considered to be mandatory in this thesis because the author only has one interlocutor at each company that centralises all the information related with the LCI study on one form and the company is responsible for all the data provided (Ferrão, 2009; ISO, 2006b).

Ferrão (2009) proposes a method to classify the quality of information used in a LCA study. This method (reproduced in Table 4.5) includes the most important indicators to evaluate the quality of data collected and it was applied in the classification of the information used in the LCI studies presented in this section of the Thesis (Table 4.6).

4.3.2. Elements of the wall structure

From the description made in Chapter 3, the most common solutions for external wall structures can be classed as *in situ* concrete, masonry elements or precast panels. Of these solutions, those studied in this Thesis were: lightweight - with LECA - concrete blocks (vertically perforated); precast panels made of Glass Fibre Reinforced Concrete (GFRC) with void formers (of EPS). A stabilised (wet and ready-to-use) masonry mortar was also studied. This cement mortar can furthermore be used as an external render or internal coating.

Concerning the LCI of each of these building products, a summary of the main issues related with the data collection and the quality of the information provided by each company was presented in Table 4.6. Therefore, this sub-section provides a technical characterisation of each product plus a summarised description and qualitative illustration of their production processes.

4.3.2.1. Lightweight concrete blocks (with LECA and vertically perforated)

The main technical characteristics of the lightweight concrete block studied in this thesis (composition, dimension, apparent density, weight, declared thermal performance and CE marking) are presented in Table 4.7. It is a block with improved thermal characteristics for use in single-leaf external walls.

Table 4.5 - Quality of the information used in a LCA study (adapted from (Ferrão, 2009))

Scale	**Confidence**	**Integrity**	**Temporal correlation**	**Geographic correlation**	**Technological correlation**
1	Verified [a] data and based on measurements [b]	Data representing a sufficient [c] number of companies, during a period that allows for the elimination of fluctuations	Maximum difference of 3 years from the year being studied	Data from the region being studied	Data from the company being studied
2	Partially verified data and based on hypothesis [d], or not verified but based on measurements	Data representing a small number of companies, but for appropriate periods	Less than 6 years of difference	Average data from a region greater than the one being studied, but comprising it	Data from the same processes/materials but from other companies
3	Not verified data and partially based on hypothesis	Data representing a proper number of companies, but for short periods	Maximum difference of 10 years	Data from a region with similar production conditions	Data from the same processes/materials but from a different technology
4	Verified or qualified estimations (done by experts)	Representative data but from a small number of companies and from short periods, or incomplete data from a suitable number of companies and period lengths	Difference lower than 15 years	Data from a region with production conditions with some similarities	Data from similar processes/materials but analogous technology
5	Not verified nor qualified data estimations	Unknown representativeness, or incomplete data from a small number of companies and/or short periods	Unknown age of data or difference higher than 15 years	Data from an unknown region, or from a region with very different production conditions	Data from similar processes/materials but different technology

Notes to Table 4.5:

[a] Data can be verified by comparison with original documents, by repeating the calculations, by comparison with other sources, by material or energy balances, etc.

[b] Experimental measurement techniques must be described in the report.

[c] In order to be representative, in a statistical sense, data does not need to be complete. However, the chosen sample must be randomly chosen and have an appropriate dimension in order to be reproducible and truly reflect the characteristics of the whole population.

[d] The considered hypothesis must also be specified in the report.

Table 4.6 - Quality of the information used in the LCI of the building products studied in this Thesis

Company that produces: (Average value - AV)	**Quality of the information used in the LCI of the building products studied in this Thesis (based on Table 4.5)**				
	Confidence (AV = 2.2)	**Integrity (AV = 3.1); market share (%)**	**Temporal correlation (AV = 1.2)**	**Geographic correlation (AV = 1)**	**Technological correlation (AV = 1)**
Lightweight concrete blocks (1.6)	1 - Verified data (internal documents and visit to the production line) and based on measurements	4 - Representative data but from a small number of companies (one) and from short periods (one month maximum and data measured from the process); 100% of national production for this geometry	1 - 2011	1	1
GFRC precast panels (1.4)	2 - Partially verified data (internal documents and visit to the production line) and based on hypothesis	2 - One company and a two-year period; 30% of national production and sales	1 - 2010 and 2011 (data collection of an order for the construction of a particular building)	1	1
Stabilised mortar (1.2)	1 - Verified data (internal documents and visit to the production line) and based on measurements	2 - One company and one-year and half period (and data measured from the process)	1 - 2010 and 2011	1	1
LECA (1.2)	1 - Verified data (internal reports and visit to the production line) and based on measurements	2 - One company and a two-year period 33% of national production and sales	1 - 2010 and 2011	1	1
XPS boards (1.4)	2 - Not verified (but including a visit to the production line) but based on measurements	2 - One company and a two-year period; 50% of national production and 30% of sales	1 - 2010 and 2011	1	1
EPS boards (1.6)	2 - Partially verified data (internal documents and visit to the production line) and based on hypothesis	2 - One company and a three-year period	2 – 2008, 2009 and 2010	1	1
PUR boards (2.4)	5 (and not including a visit to the production line)	4 - Representative data but from a small number of companies (one) and from short periods (data measured from the process); 100% of national production for the construction sector	1 - 2012	1	1
ICB boards (1.6)	2 - Not verified (but including a visit to the production line) but based on measurements	2 - One company and a two-year period; most important company in the national market	2 - 2008 and 2010	1	1
One-coat mortar (1.8)	2 - Not verified (but including a visit to the production line) but based on measurement	4 - Representative data but from a small number of companies (one) and from short periods (data measured from the process); 75% of national production and sales	1 - 2011	1	1

Company that produces: (Average value - AV)	Quality of the information used in the LCI of the building products studied in this Thesis (based on Table 4.5)				
	Confidence (AV = 2.2)	**Integrity (AV = 3.1); market share (%)**	**Temporal correlation (AV = 1.2)**	**Geographic correlation (AV = 1)**	**Technological correlation (AV = 1)**
WPC boards (2.4)	5 (and not including a visit to the production line)	4 - Representative data but from a small number of companies (one) and from short periods (one month maximum and data measured from the process); 100%	1 - 2012	1	1
Two-component adhesive (1.8)	2 - Not verified (but including a visit to the production line) but based on measurement	4 - Representative data but from a small number of companies (one) and from short periods (data measured from the process)	1 - 2012	1	1
Gypsum plasterboards (1.8)	2 - Not verified (but including a visit to the production line) but based on measurements	4 - Representative data but from a small number of companies (one) and from short periods (data measured from the process); 100% of national production	1 - 2012	1	1

Table 4.7 - Main technical characteristics of the lightweight concrete block

Composition	Size (cm)	Apparent density of the block; density of concrete (kg/m^3)	Weight (kg/piece)	Declared thermal performance - U-value [$W/(m^2.ºC)$]	CE marking (standard)
Lightweight concrete block, with LECA as coarse aggregate	Length - 35; height - 19; width - 38	752; 1117	19	0.42 (EN 1745:2002; ISO 6946:1996)	Yes (EN 771-3:2003/A1:2005)

Concerning the "Product stage" of this block, a description of the unit processes included in this "system process" (production of lightweight concrete block) is presented below and illustrated in a flowchart in Figure 4.5. This graph represents each stage (unit process) of lightweight concrete block manufacturing (A3) and their inter-relationships within plant boundaries, and also summarises the main flows (elementary and product inputs and outputs) occurring at each of these stages. A1, A2, A4 and A5 sub-stages (raw material extraction and processing, processing of secondary material input; transport to the manufacturer; transport to the building site; and installation into the building, respectively) are only identified in the graph. It is always helpful to use a flowchart to illustrate a production process and to use it as a basis for data collection in a LCI study (ISO, 2006b).

The declared unit used for this LCI study was "one finished block". The production process begins with the reception and storage of raw materials. LECA and other aggregates are conveyed to pass through a sifting process before being mechanically mixed in an industrial mixer with the other components. Then, the mix (ready-mixed lightweight concrete) is discharged into a press, with a metallic mold specially designed for this company-exclusive block. Following the pressing (and molding) stage, wet blocks are transported by large conveyor belts to be stored on trays (nine blocks per tray). Trays of blocks are then conveyed to an automated stacker to be placed into a curing rack. The stacker waits for the filling of each rack to transport it to the curing kiln. The (steam) kiln is a closed space having the capacity of making the simultaneous curing of a high quantity of blocks. Curing conditions are controlled using a ventilation and moist air exhaust system that provides the permanent regulation of temperature and humidity conditions. The final stage of the production process corresponds to the palletisation of each set of 45 blocks on a wood pallet. An automatic pallet cuber is used in this process, and also places a low width PET (Polyethylene terephthalate) strap band at two different heights of the filled pallet. Then, stackers transport each pallet to an open air storage area.

4.3.2.2. Glass Fibre Reinforced Concrete (GFRC) precast panels with void formers (filled with EPS)

The Glass Fibre Reinforced Concrete (GFRC) precast panels studied in this Thesis are not produced on a daily-basis but on request. In fact, the data collected for this LCI study was from an order for the construction of a particular building. The main technical characteristics of these panels (composition, dimensions, volume of each component, estimated weight and thermal performance and CE marking) are presented in Table 4.8. These panels have improved thermal characteristics due to the placement of EPS boards filling the voids between frontal and posterior GFRC layers. In fact, these panels can either be considered as an element of the wall structure or as a cladding because they are mechanically fixed on site to the structure (a cavity remaining between them and the external single-leaf wall) and provide the thermal insulation and cladding of this wall.

This sub-section includes a description of the manufacturing (A3) process of GFRC panels. Table 4.9 and Table 4.10 summarise the main flows, inputs and outputs, respectively, occurring at each stage of this system process. Solid (e.g. natural resources, products used as raw materials, recovered, auxiliary and packaging materials), liquid (e.g. natural resources - water, products used as raw materials, auxiliary materials and fuels), gaseous (e.g. products used as raw materials and auxiliary materials) and energetic (e.g. electricity, auxiliary equipment and/or corresponding fuels) inputs and solid (e.g. production waste or packaging from products used as raw materials), liquid (e.g. production waste or waste water), and gaseous (e.g. air emissions from specific equipment or operations) outputs are described in these tables (Blengini, 2006).

Table 4.8 - Main technical characteristics of GFRC precast panels with EPS as void formers

Composition	Dimensions (m)	Estimated volume of each component (m^3/piece)	Estimated weight (kg/m^2)	CE marking
GFRC, with EPS as void formers	Height - 4.5; width - 3; thickness - 0.15	GFRC - 0.72; EPS - 1.3	129.3	No

The declared unit chosen for this LCI study was “one square metre of finished panel”. The production process begins with the reception and storage of raw materials. Cement, sand and admixtures are then mechanically mixed with water in an industrial mixer to be used in the spray-up process of GFRC application: the referred cement mortar is applied by spray gun against the metallic mold of the panel (previously pulverised with a concrete mold release agent) while glass fibre strands are cut within the spray gun to the required size (Ferreira & Branco, 2007). This layer of mortar is also reinforced by a glass-fibre mesh. Following the curing of the bottom layer of the panel (corresponding to its exposed surface), EPS boards, metallic connectors (to allow for the fixing of the panels on-site to the building’s structure), metallic accessories for lifting panels, glass-fibre mesh and PVC pipes (to provide ventilation between pieces of EPS boards) are put into the designed places. Cement, sand and admixtures are again mechanically mixed with water, and also with glass fibres, in an industrial mixer to be used in the pre-mixed process of GFRC application (Ferreira & Branco, 2007). The mortar produced using this method is already reinforced and is applied to the mold over the spray-up layer and EPS boards through normal concrete pouring. Heat curing of the panels is often used to accelerate this stage of the production process. Thereafter, the panels are released from the mold and transported to a covered storage area.

4.3.2.3. Stabilised (wet and ready-to-use) masonry mortar

Since 2008, a national company has produced in several plants all over Portugal an innovative stabilised (wet and ready-to-use) cement-based mortar. This mortar can be used in the setting of masonry elements (in accordance with EN 998-2:2003 - Specification for mortar for masonry - Part 2: Masonry mortar) or as an external render or internal coating (in accordance with EN 998-1:2010 - Specification for mortar for masonry - Part 1: Rendering and plastering mortar).

The main technical characteristics of the stabilised mortar (composition, density, declared thermal performance and CE marking) are presented in Table 4.11. The innovative nature of this product relies on being supplied on-site - discharged - and stored in metallic containers supplied by the company, without packaging and ready-to-use. Then, this product can be used in the next 24 to 48 hours, depending on the weather, humidity and admixtures used in the mix. Next, a description of the manufacturing (A3) process of stabilised mortar is presented, while the main flows that occur at each stage of this system process are summarised in Table 4.12 and Table 4.13.

The declared unit chosen for this LCI study was "one cubic metre of mortar". The production process begins with the delivery and storage of raw materials. Raw materials and admixtures are then transported to an industrial mixer, in which they are mechanically mixed. This mixer is also used for ready-mixed concrete production. When the mix is ready, it is discharged by gravity into a concrete mixer truck.

4.3.3. Insulation materials

From the classification presented in Chapter 3, insulation materials studied in this Thesis include: mineral/inorganic materials (LECA); oil-derived materials (XPS, EPS and PUR/PIR); and "organic natural" (Agglomerate of Expanded Cork or Insulation Cork Board - ICB). The inclusion of the Agglomerate of Expanded Cork (ICB) in this group of materials is important for Portugal, given that this insulation material has a great potential of exportation. It has also potential environmental advantages, but these are not yet reproduced in LCA studies and need to be quantified using scientific rigorous methods and compared with the most common insulation materials, in order to be unequivocal accepted at national and international levels.

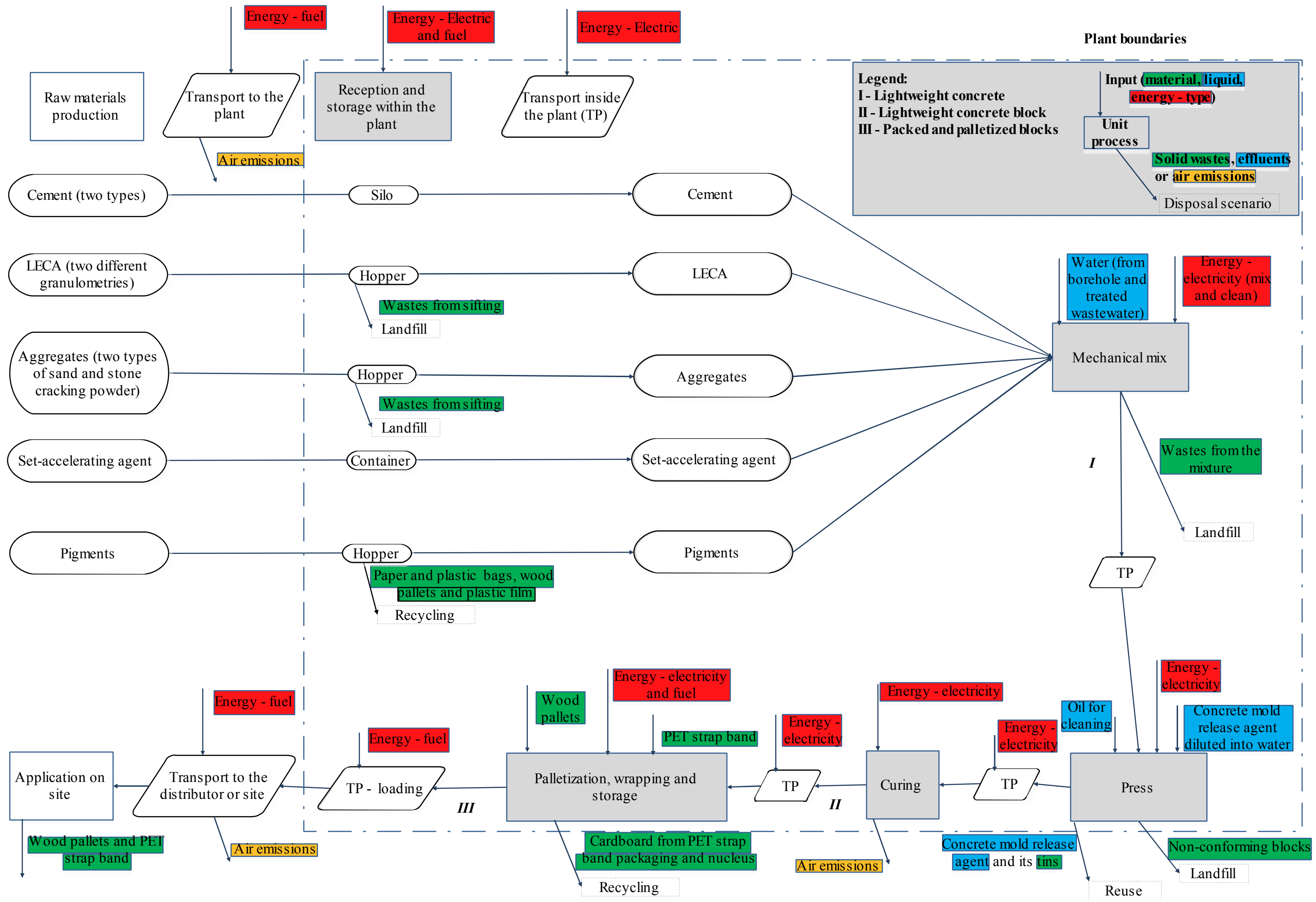

Figure 4.5 - Flow-chart of lightweight concrete block production

Table 4.9 - Input flows at each stage of production of GFRC precast panels with EPS as void formers

Production stages (unit processes)	**Identified flows**		
	Solid	**Liquid**	**Energetic**
1. Raw materials delivery and storage	- Cement - Sand	- Admixtures (for fibres protection and a super plasticiser)	- Diesel stacker
2. Mechanical mix and spray-up	- Glass strands - Glass-fibre mesh	- Concrete mold release agent - Fresh water (for cleaning and for the mix)	- Electricity
3. Mechanical mix and GFRC pouring using the premix method	- Glass fibres pieces - EPS - Metallic connectors and accessories - PVC pipes		- Electricity
4. Curing, concrete mold release and storage	-	-	- Electricity - Propane gas

Table 4.10 - Output flows at each stage of production of GFRC precast panels with EPS as void formers

Production stages (unit processes)	**Identified flows**	
	Solid	**Liquid**
1. Raw materials delivery and storage	- Metal and plastic bins, cardboard, plastic bags, polyethylene film (packaging of admixtures, EPS and glass fibres)	- Water from cleaning silos
2. Mechanical mix and spray-up	- Concrete waste	- Waste water
3. Mechanical mix and GFRC pouring using the pre-mix method	- Concrete waste	- Waste water
4. Curing, concrete mold release and storage	-	-

Table 4.11 - Main technical characteristics of the stabilised mortar

Composition	**Density (kg/m^3)**	**Declared thermal performance – $\lambda_{10, dry}$ (P=90 %[a]) [W/(m.K)]**	**CE marking (standard)**
Cement-based mortar	1650 (wet); 1700 (hardened)	0.85 (EN 1745)	Yes (EN 998-1:2003 and EN 998-2:2003)

Notes to Table 4.11:

[a] At least 90% of the volume of mortar produced has this thermal conductivity or lower.

Table 4.12 - Input flows at each stage in the production of stabilised mortar

Production stages (unit processes)	Identified flows		
	Solid	**Liquid**	**Energetic**
1. Raw materials delivery and storage	- Cement - Sand	- Air entraining and retarding admixtures	- Electricity - Loader
2. Mechanical mix		- Concrete mold release agent - Water from borehole (for cleaning operations and for the mix)	- Electricity
3. Loading of concrete mixer truck	-	- Water from borehole (for cleaning operations)	-

Table 4.13 - Output flows at each stage in the production of stabilised mortar

Production stages (unit processes)	Identified flows	
	Solid	**Liquid**
1. Raw materials delivery and storage	- HDPE and polypropylene bins (admixtures packaging)	-
2. Mechanical mix	- Polypropylene bins (concrete mold release agent packaging)	- Water used for cleaning operations
3. Loading of concrete mixer truck	-	- Portion of the mix not loaded into the truck - Water used for cleaning operations

A summary of the leading issues related with data collection and the quality of the information provided by each company during LCI studies, is presented in Table 4.6. As such, this sub-section includes the technical characterisation and manufacturing (A3) process of each insulation material studied in this Thesis.

4.3.3.1. Light Expanded Clay Aggregate (LECA)

Light Expanded Clay Aggregate (LECA) studied in this Thesis can be used in the insulation of several building elements, including double-leaf external walls in which the 8-16 label is used (Table 4.14). Therefore, this size of granules was chosen to be studied in detail in this Thesis. It is important to highlight that this construction material is also used as a raw material in the production of lightweight concrete blocks (see sub-section 4.3.2.1). The main technical characteristics of LECA (available and studied sizes and labels, bulk density, declared thermal performance and CE marking) are presented in Table 4.14.

Table 4.14 - Main technical characteristics of LECA

Product	**Available (real sizes) labels (mm)**	**Bulk density (kg/m^3)**	**Declared thermal performance - λ [W/(m.K)]**	**CE marking (standard)**
LECA	0-2 (0.25-2)	550	-	Yes (EN 13055-1[4])
	2-4 (4-8)	258	0.11	
	3-8F (6.3-12.5)	331	0.11	
	3-8 (8-12.5)	303	0.11	
	8-16 (8-16 - studied size)	297	0.10	

The manufacturing (A3) process of LECA is described next and the main flows that occur at each stage of this system process are summarised in Table 4.15 and Table 4.16.

The declared unit chosen for this LCI study was "one cubic metre of LECA". The production process begins with the delivery and storage of raw materials and admixtures. The main raw material, the clay, is then converted into pellets via a complex process that includes: the mix with the admixtures (liquid - mineral oil, and solid - stone cracking powder), disaggregation, grinding, lamination, and extrusion. Then, clay pellets are conveyed to the kiln to start the expansion process. The heat is produced in the kiln using three different fuels: coke, fuel oil and cork cutting powder. The temperature inside the kiln reaches 1200 ºC in order to create the fusion of clay pellets that leads to the production of a gas in their interior that causes their expansion (Santos, C. P., 1993). After leaving the kiln, LECA is conveyed to pass through a sifting process. The final stage of LECA production corresponds to the filling of LECA bags and palletisation. LECA is available on the market both in Poly-

[4] **EN 13055-1:2002** - Lightweight aggregates - Part 1: Lightweight aggregates for concrete, mortar and grout.

ethylene (PE) (50 liters) and Polypropylene (PP) bags (open big-bags with 1.5 or 3 m^3 of capacity). Only the former are palletised (60 bags per wood pallet) in an automatic pallet cuber. This process includes the placement of a layer of PE shrink film around each pallet. Then, a stacker transports the pallets, and also the PP bags, to a covered storage area.

4.3.3.2. Extruded Polystyrene (XPS)

Extruded Polystyrene (XPS) boards are available on the market with different labels and finishings, but the references studied in this thesis are suitable for application in external walls (within ETICS or internal thermal insulation, namely glued to gypsum plasterboards). The main technical characteristics of the XPS boards studied in this Thesis (available thicknesses, density, declared thermal performance and CE marking) are presented in Table 4.17.

The main flows that occur at each stage of this system process are summarised in Table 4.18 and Table 4.19 and the manufacturing (A3) process of XPS boards is described next.

The declared unit chosen for this LCI study was "one cubic metre of XPS board". The production process begins with the delivery and storage of the gaseous blowing agents, raw materials and admixtures. Then, solid raw materials and admixtures are heated (at around 200 °C) and melted, after which they are placed inside the first extruder in which gaseous blowing agents are injected under high pressure. The final mix is then placed in a second extruder in which a cooling process takes place. The final extrusion and expansion of the mix occurs thereafter, when the XPS foam is placed on a large conveyor belt. During these processes, the pressure rapidly drops down to atmospheric pressure while the foam is extruded through a horizontal hole that calibrates its final thickness.

The continuous XPS board with homogeneous and closed cell structure is then prepared through lateral milling and cut to the demanded length. Each XPS board is thereafter conveyed through a continuous sequence of processes, all or only partially completed depending on the intended finishing:

- Peeling, and/or grooving or "wafer" pattern (of the upper and/or lower faces in order to remove the smooth foam skin resulting from the extrusion process; to improve the adhesive strength to a given coating, e.g. concrete, mortar, or construction adhesives);
- Longitudinal edge cutting;
- Milling and/or special cutting (creation of grooves - "L-shaped" or male/female slotted edges - for easy lap joint) of one or both longitudinal edges;

Table 4.15 - Input flows at each stage in the production of LECA

Production stages (unit processes)	Identified flows		
	Solid	**Liquid**	**Energetic**
1. Raw materials delivery and storage	- Clay - Admixture (stone cracking powder)	- Admixture (mineral oil)	- Loader
2. Clay preparation and extrusion		- Water (clay humidification)	- Loader - Electric energy
3. Baking	- Coke - Cork cutting powder	- Fuel oil	- Loader - Electric energy
4. Selection and packaging	- Polyethylene bags - Polypropylene bags - Wood pallets - PE shrink film	-	- Diesel stacker - Electric energy

Table 4.16 - Output flows at each stage in the production of LECA

Production stages (unit processes)	Identified flows	
	Solid	**Gaseous**
1. Raw materials delivery and storage	-	-
2. Clay preparation and extrusion	-	-
3. Baking	-	- Air emissions from the kiln
4. Selection and packaging	- Waste from the sifting process - Polyethylene shrink film, cardboard, polyethylene, polypropylene bags and plastic strap bands (packaging of packaging products)	- Air emissions from the sifting process

Table 4.17 - Main technical characteristics of XPS boards studied in this Thesis

Company - Product	Available thicknesses (mm)	Density (kg/m^3)	Declared thermal performance - λ [W/(m.K)]	CE marking (standard)
XPS boards	30	28 (walls); 30 (roofs; production average)	0.034	Yes (EN 13164; EN 13172[5])
	40		0.035	
	50		0.035	
	60		0.035	
	80		0.036	
	100		0.038	
	120		0.038	

[5] **EN 13172:2001** - Thermal insulating products. Evaluation of conformity.

Table 4.18 - Input flows at each stage of XPS board production

Production stages (unit processes)	Identified flows			
	Solid	Liquid	Gaseous	Energetic
1. Raw materials delivery and storage	- Expandable polystyrene - Solid admixtures (organic and inorganic nucleators, fire retardant and pigment)	- Ethanol	- Blowing agents (difluoro-ethane, dimethyl ether, carbon dioxide and ethanol)	- Electricity
2. Fusion, mix and extrusion	- Recycled production waste (pellets)	-	- Nitrogen	- Electricity - Diesel stacker
3. Cut and milling	-	- Ink, make-up and solvent	-	- Electricity
4. Packaging and palletisation	- XPS bars - Polyethylene shrink film	- Glue - Printing chemicals	-	- Electricity - Diesel stacker

Table 4.19 - Output flows at each stage of XPS board production

Production stages (unit processes)	Identified flows		
	Solid	Liquid	Gaseous
1. Raw materials delivery and storage	- Polystyrene and polyethylene bags, plastic film and wood pallets (expandable polystyrene packaging), polystyrene bags, plastic film, cardboard and wood pallets (admixtures packaging)	-	- Air emissions from the recycling of production waste
2. Fusion, mix and extrusion	-	-	-
3. Cut and milling	- Cardboard and plastic bottles (paint, make-up and solvent packaging)	- Solvent	-
4. Packaging and palletisation	- Cardboard, plastic bags and nucleus, polyethylene film, wood pallets (packaging of packaging products)	-	-

- Special cutting (creation of grooves - "L-shaped" or male/female slotted edges - for easy lap joint) of one or both top edges.

The lot, label, and date of production are stamped (using ink) directly on the board, at the end of production line. The final stage of XPS board production corresponds to pallet-isation. This process starts by the placement of a layer of Low Density (LD) PE shrink film around each group of boards. Then, each of these sets is placed in an oven to produce PE film shrinkage. An automatic pallet cuber covers these packages with another layer of Low density Polyethylene (LDPE) and four XPS bars are manually glued to their bases to resemble a pallet. At the end, a stacker transports these pallets to an open-air storage area.

4.3.3.3. Expanded Polystyrene (EPS)

The main technical characteristics of EPS boards studied in this thesis (available thicknesses, density of the product studied, declared thermal performance and CE marking) are presented in Table 4.20.

Table 4.20 - Main technical characteristics of EPS boards studied in this Thesis

Product	**Available thicknesses (mm)**	**Density (kg/m^3)**	**Declared thermal performance - λ [W/(m.K)]**
EPS boards	60; 80	15 (EPS 60)	0.0396

The main flows that occur at each stage of this system process are summarised in Table 4.21 and Table 4.22 and the manufacturing (A3) process of EPS boards is described next.

The declared unit chosen for this LCI study was "one cubic metre of EPS board". The production process begins with the delivery and storage of the only raw material - expandable polystyrene beads, with pentane as a blowing agent. These beads are heated by steam in two pre-expansion stages that lead to their expansion (the final volume is 50 to 80 times higher than the initial one (Santos, C. P., 1993) due to their blowing agent content). The beads undergo a conditioning step in silos between these stages, and after the last pre-expansion, during which a part of the water vapour and of the blowing agent are released. Then, the beads are placed into a closed parallelepiped mold (with 4 x 1 x 0.5 m) to suffer a final expansion (also using steam). During this process, the fusion and union of the beads occurs (due to the absence of expansion volume), leading to the production of EPS blocks. These blocks are then placed into a covered pavilion to enable their curing. When the curing is complete, the blocks are "transformed" in boards using hot wire cutting. The final stage of EPS board production corresponds to packaging. Each group of boards is packed into Polyvinyl chloride (PVC) shrink bags, welded using a welding torch. Then, each bag is manually placed in a covered storage area.

4.3.3.4. Polyurethane/Polyisocyanurate (PUR/PIR)

Polyurethane/Polyisocyanurate (PUR/PIR) boards are available on the market with different labels, but the reference studied in this thesis is suitable for application in external walls. The main technical characteristics of PUR boards (available thicknesses, density, declared thermal performance and CE marking) are presented in Table 4.23.

The main flows that occur at each stage of this system process are summarised in Table 4.24 and Table 4.25 and the manufacturing (A3) process of PUR boards is described next.

The declared unit chosen for this LCI study was "one cubic metre of PUR board". The production process begins with the delivery and storage of raw materials in deposits: polyol and isocyanate. These deposits feed the injection machine, which mixes both components and conducts the liquid - resulting from the mix - to a parallelepiped mold. This liquid continues developing a chemical reaction inside the mold until it becomes solid and molded as a block. The block is extracted from the mold and placed into a chamber with controlled temperature and humidity to undergo a curing process. When the curing ends, the block is cut in boards using an abrasive cutting wire. The boards can furthermore suffer a process of fine-tuning of their thickness, when necessary. The final stage of PUR board production corresponds to their manual packaging and transport to a covered storage area. The boards are superposed until a height of 500 mm, and each of these sets are then packed using four carton board corners and an external layer of PE film.

4.3.3.5. Agglomerate of Expanded Cork (ICB)

The main technical characteristics of Agglomerate of Expanded Cork (Insulation Cork Board - ICB) boards studied in this thesis (available thicknesses, density, declared thermal performance and CE marking) are presented in Table 4.26.

Concerning the manufacturing (A3) process of ICB boards, the declared unit chosen for this LCI study was "one cubic metre of ICB board". The production process begins with the delivery and storage of a single raw material - the "falca". "Falca" is the waste wood that results from periodical paring and pruning operations of cork oak trees (Sofalca, 2012).

Table 4.21 - Input flows at each stage of EPS board production

Production stages (unit processes)	Identified flows		
	Solid	**Liquid**	**Energetic**
1. Raw materials delivery and storage	- Expandable polystyrene beads	-	- Electricity
2. Pre-expansion		- Water from borehole - Naphtha (for the boiler)	- Electricity
3. Intermediate conditioning	-	-	- Electricity
4. Expansion and moulding	-	- Water from borehole - Naphtha (for the boiler)	- Electricity
5. Curing	-	-	- Electricity
6. Cut	-	-	- Electricity
7. Packaging	- Polyvinyl chloride shrink bags	-	- Electricity - Propane gas (welding of plastic bags)

Table 4.22 - Output flows at each stage of EPS board production

Production stages (unit processes)	Identified flows	
	Solid	**Gaseous**
1. Raw materials delivery and storage	- Polystyrene bags and cardboard (Expandable polystyrene packaging)	-
2. Pre-expansion	-	- Air emissions from the boiler
3. Intermediate stabilisation	-	-
4. Expansion and moulding	-	- Air emissions from the boiler
5. Curing	-	-
6. Cut	-	-
7. Packaging	- Wood pallets (PVC bags packaging)	-

Table 4.23 - Main technical characteristics of PUR boards studied in this Thesis

Product	Available thicknesses (mm)	Density (kg/m^3)	Declared thermal performance - λ [W/(m.K)] (standard)	CE marking (standard)
PUR boards	20-60	35	0.023 (EN 13165:2008 - 21 days)	Yes (EN 13165:2008)

Table 4.24 - Input flows at each stage of PUR board production

Production stages (unit processes)	Identified flows		
	Solid	Liquid	Energetic
1. Raw materials delivery and storage	-	- Polyol - Isocyanate	- Electricity - Diesel stacker
2. Mix, injection and moulding	- LDPE	- Methylene chloride	- Electricity
3. Curing of the blocks	-	-	- Electricity
4. Cut	-	-	- Electricity
5. Packaging and palletisation	- Cardboard - Polyethylene film	-	-

Table 4.25 - Output flows at each stage of PUR board production

Production stages (unit processes)	Identified flows
	Solid
1. Raw materials delivery and storage	- Metal bins (raw materials packaging)
2. Mix, injection and moulding	- Plastic bins (methylene chloride packaging)
3. Curing of the blocks	-
4. Cut	- Boards cutting waste
5. Packaging and palletisation	- Cardboard, polyethylene film, wood pallets (packaging of packaging products)

Table 4.26 - Main technical characteristics of ICB boards studied in this Thesis

Product	Available thicknesses (mm)	Density (kg/m^3)	Declared thermal performance - λ [W/(m.K)]	CE marking (standard)
ICB boards	40 - 150	110	0.04	Yes (EN 13170; EN 13172)

"Falca" is stored in bulk - in the open-air in the plant's external area and also in covered pavilions. This raw material passes through a "cleaning" process in order to supply only natural cork to the next unit process. Therefore, soil, gravel and wood waste are set apart during "falca cleaning". Natural cork pieces are then granulated through a mechanic process and stored in silos. These granules are discharged into autoclaves in which the expansion and agglomeration process takes place. Water vapour is injected after the autoclaves are closed in order to force the cork to release its natural resin. The suberine is released from the granules at a temperature of 300 ºC and enables their natural agglomeration, while their volume increases (Santos, C. P., 1993).

When this process is completed, the autoclave is opened and an ICB parallelepiped is lifted from the autoclave bottom to the surface. The ICB block is conveyed to a closed cooling chamber in which it passes through hot water jets. After leaving this chamber, the blocks are kept in a stabilisation (of temperature and humidity) process, before being cut. The cutting process starts by the squaring of the blocks, followed by the horizontal cut into boards and/or by polishing of board faces. The final stage of the production process corresponds to palletisation. A layer of PE shrink micro-perforated film is placed around each group of boards, and these sets are then manually stored on wood pallets. The pallets can be either stored in a covered area or in an open-air storage area.

4.3.4. Claddings

External and internal wall claddings were separated in Chapter 3 into two subsections. However, the aim of this section is different and therefore the cladding solutions studied in this Thesis are not separated but their application field is explicitly referred to (External Cladding Systems - ECS; Internal Coating Systems - ICS).

Considering that Table 4.6 already presented a summary of the main issues related with data collection and quality of the information of each LCI study, this sub-section includes the technical characterisation and production process of external cladding and internal coating systems studied in this Thesis.

4.3.4.1. One-coat mortar - ECS

The main technical characteristics of the one-coat dry mortar studied in this thesis (composition, density, available colours, declared thermal performance and CE marking) are presented in Table 4.27. This cement-based mortar has improved thermal characteristics due to the incorporation of an expanded aggregate and can be applied as an external render in a broad range of colours.

Table 4.27 - Main technical characteristics of the one-coat mortar

Product	Composition	Dry / hard-ened mortar density (kg/m^3)	Available colours	Declared thermal performance - λ (P=50 %[a]) [W/(m.K)]	CE marking (standard)
One-coat mortar	Cement-based one-coat dry mortar	1500 / 1400	24	0.47	Yes (EN 998-1)

[a] At least 50 % of the volume of mortar produced have this thermal conductivity or lower.

Concerning the “Product stage” of this mortar, a description of the unit processes included in this “system process” (production of one-coat mortar) is presented below and illustrated through a flowchart in Figure 4.6. This graph represents each stage (unit process) of one-coat mortar manufacturing (A3) and their inter-relationships, including the main flows (elementary and product inputs and outputs) that occur at each of these stages. A1, A2, A4 and A5 sub-stages (raw material extraction and processing, processing of secondary material input; transport to the manufacturer; transport to the building site; and installation into the building, respectively) are only identified in the graph.

The declared unit used for this LCI study was “one ton of dry mortar”. The production process begins with the reception and storage of raw materials (cement, hydrated lime, aggregates, admixtures and pigments), thereafter mechanically mixed in an industrial mixer. Then, the mix is directly discharged into bags made of two layers of paper with a thin LDPE layer between them. Each bag holds 30 kg of dry mortar and, after being closed by the filling machine, is conveyed to an automatic pallet cuber. This machine completes the palletisation of the bags by placing 42 of them on each wood pallet and covering it with a PE shrink film layer. Then, stackers transport each pallet to a covered storage area.

4.3.4.2. Wood-plastic extruded boards - ECS and ICS

Wood-plastic extruded boards (Wood-Plastic Composite - WPC) are available on the market with different labels, but the reference studied in this thesis is suitable for application in internal and external walls, and also in ceilings. The main technical characteristics of WPC boards (dimensions, colours, density and CE marking) are presented in Table 4.28.

Concerning the manufacturing (A3) sub-stage of the “Product stage” of these boards, a description of the unit processes included in this “system process” (production of WPC boards) is presented below and their main flows are summarised in Table 4.29 and Table

4.30. The declared unit chosen for this LCI study was “one ton of WPC board”. The production process begins with the delivery and storage of the main raw materials into silos: pellets of post-consumer plastic and sawdust (and other wood waste). Admixtures are delivered and stored in their own bags. Wood waste passes through a “cleaning” process, in order to supply only natural wood to the next unit process, and is furthermore treated using a proper admixture. Wood and plastic pellets are then placed into an industrial mixer, along with a set of admixtures. This mixer feeds an extrusion line where the wood-plastic profiles are formed. The wood-plastic profiles are then cut into boards according to the intended lengths. The final stage of WPC board production corresponds to their packaging and transport to a covered storage area. The boards are packed on wood pallets and protected by a layer of LDPE wrapped by a High Density (HD) PE strap band.

4.3.4.3. Stabilised (wet and ready-to-use) masonry mortar- ECS and ICS

This building product has already been included in the “Elements of wall structure” group (see 4.3.2.3), but can furthermore be used as an external render or internal coating (according with EN 998-1:2010 - Specification for mortar for masonry - Part 1: Rendering and plastering mortar). Therefore, this product is also considered in the claddings group, but the description of the data taken into account in the LCI study has already been done in sub-section 4.3.2.3 and is not repeated in this sub-section of the Thesis.

4.3.4.4. Two-component adhesive (for ceramic tiles and natural stone) - ECS and ICS

The main technical characteristics (composition and CE marking) of the two-component adhesive studied in this thesis are presented in Table 4.31. This cement-based adhesive can be used both for fixing all types of ceramic tiles and natural stone to walls and laying of indoor and outdoor paving. Both components of the adhesive - the powder (component A) and the resin (component B) - are sold separately and mixed on-site.

Concerning the manufacturing (A3) sub-stage of the “Product stage” of this two-component adhesive, a description of the unit processes included in this “system process” (production of two-component adhesive) is presented below and their main flows are summarised in Table 4.32 and Table 4.33. The declared unit used for this LCI study was “one ton of component”, for both the solid (the powder, component A) and for the liquid (the resin, component B) components.

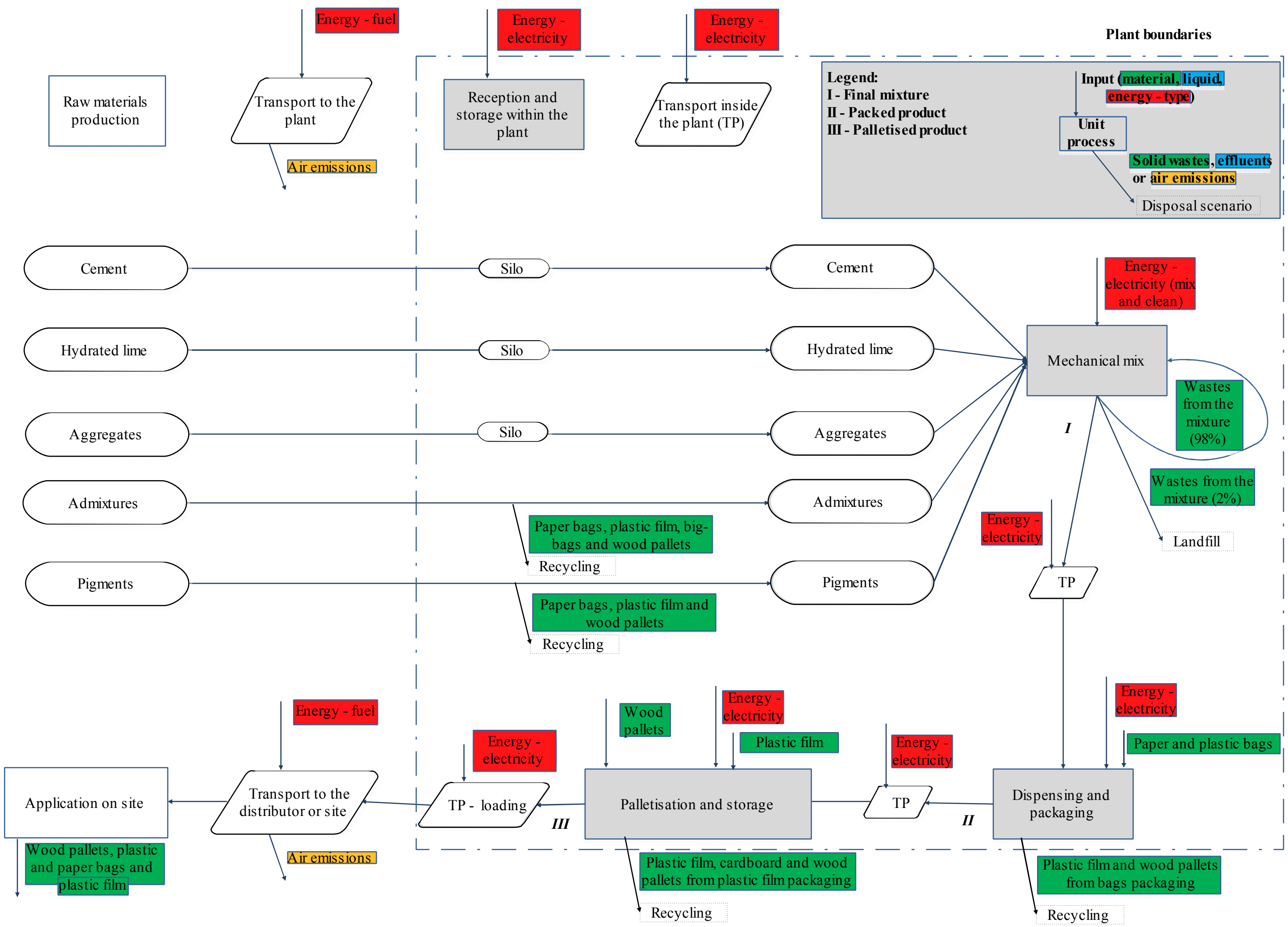

Figure 4.6 - Flow-chart of one-coat mortar production

Table 4.28 - Main technical characteristics of WPC boards studied in this Thesis

Product	**Dimension (cm)**	**Thickness (mm)**	**Colours**	**Density (kg/m^3)**	**CE marking (standard)**
WPC	15,8 x 250	14 (maximum)	Five standard colours and several other on-demand	1200	No

Table 4.29 - Input flows at each stage of WPC board production

Production stages (unit processes)	**Identified flows**		
	Solid	**Liquid**	**Energetic**
1. Raw materials delivery and storage	- Wood waste - Pigments - Admixtures	-	- Liquefied petroleum gas (stacker) - Electricity
2. Wood treatment and stabilisation		-	- Electricity
3. Mechanical mix	- Pellets of post-consumer plastic - Admixtures	-	- Electricity - Liquefied petroleum gas (stacker)
4. Extrusion and cutting	-	- Fresh water	- Electricity - Liquefied petroleum gas (stacker)
5. Packaging and storage	- Polyethylene film - Polyethylene strap band - Wood pallets	-	- Electricity - Liquefied petroleum gas (stacker)

Table 4.30 - Output flows at each stage of WPC board production

Production stages (unit processes)	**Identified flows**
	Solid
1. Raw materials delivery and storage	- Wood pallets, plastic bags, plastic film and big-bags (raw materials and admixtures packaging)
2. Wood treatment and stabilisation	- Wood pallets, paper and plastic bags and plastic film (raw materials and admixtures packaging)
3. Mechanical mix	-
4. Extrusion and cutting	-
5. Packaging and storage	- Plastic film and cardboard (packaging from packaging materials)

The production process of component A begins with the reception and storage of raw materials (cement, aggregates and admixtures), which are thereafter mechanically mixed in an industrial mixer. Then, the mix is directly discharged into bags made of two layers of kraft paper with a thin LDPE layer between them. Each bag holds 20 kg of powder (component A) and, after being closed by the filling machine, is conveyed to an automatic pallet cuber. This machine completes the palletisation of the bags by placing 60 of them on each wood pallet and covering it with two PE shrink film layers (lateral plus top layer). Then, stackers transport each pallet to a covered storage area.

The production process of component B begins with the reception and storage of raw materials (resin and admixtures), which are thereafter mechanically mixed by a small industrial mixer. Then, the mix is transported in a container and discharged by a stacker into a big plastic dispenser. The filling and closing of each plastic bucket with 5.25 kg of component B is manual, as is the transport of these buckets to the automatic pallet cuber. This machine does the palletisation of the buckets by placing them on wood pallets and covering them with two PE shrink film layers (lateral plus top layer). Then, stackers transport each pallet to a covered storage area.

4.3.4.5. Gypsum plasterboard - ICS

The gypsum plasterboard studied in this thesis is suitable for cladding of internal walls, ceilings and partitions. Its main technical characteristics (dimensions, weight, declared thermal performance and CE marking) are presented in Table 4.34.

During the LCI study of these boards, the author also collaborated with the national company that produces them in the development of a winning application for the "Good Environmental and Energetic practices" award promoted by the "Portuguese Entrepreneurial Association" (*Associação Empresarial de Portugal* - AEP) in the scope of the "BenchMark A+E" project (AEP, 2012)). The awarded environmental practice corresponds to the optimisation of the gypsum transport. This material is transported by train from the thermoelectric central to the plasterboards plant and the return trip is used to supply limestone for the desulfurization of the thermoelectric central emissions.

Concerning the manufacturing (A3) sub-stage of the "Product stage" of these boards, a description of the unit processes included in this "system process" (production of gypsum plasterboard) is presented below and their main flows are summarised in Table 4.35 and Table 4.36. The declared unit used for this LCI study was "one square metre of finished board". The production process begins with the reception and storage of raw materials, followed by the process of stucco preparation. All the gypsum (calcium sulphate dehydrate) used is flue-gas desulphurisation (FGD) gypsum. This material results from the desulfurization process of thermoelectric central emissions. Therefore, only the transport to the manufacturer (A2 – Table 4.2) was considered in this study, and no impacts from A1 stage were therefore taken into account. Gypsum is discharged from a hopper to a grinding mill and the resulting gypsum grains are conveyed to a silo. Gypsum grains are then transported to a calcining mill to continue the grinding process and heated to remove chemically bound water and become stucco. Stucco passes through a separator and a cooler before being stored in a silo. Stucco slurry is then obtained from the mixing of stucco with water and solid and liquid admixtures. This mix is discharged over a sheet of paper, and another piece of paper is thereafter placed over the uniform horizontal layer of stucco slurry and two lateral bands are glued to the board while it is carried along a vibratory conveyer. The boards are then cut according to the intended lengths and placed into curing stacks to enter the dryer.

Dry boards are placed again on a conveyer belt to have their tops rectified (cut) and to be joined as a set of two (face-to-face). The final stage of the production process corresponds to the palletisation of the boards. An automatic pallet cuber places piles of boards over recycled wood bars, which are positioned perpendicularly to the board’s length. Each pile is then “transformed” into a pallet when wrapped with a layer of plastic film. Then, stackers transport each pallet to a covered storage area.

4.4. Conclusion and perspectives

This chapter starts by describing in detail the “Life Cycle Inventory analysis” (LCI) phase of the “Life Cycle Assessment (LCA) methodology”. This includes the main procedures to be followed at each LCI step, such as data collection and calculation, allocation and the final analysis of the inventory obtained.

Table 4.31 - Main technical characteristics of two-component adhesive

Product	Composition	Density (kg/m^3)	CE marking (standard)
Two-component adhesive	Cement, silica and admixtures (component A)	1700 (component A)	Yes (Class C2TE - NP EN 12004)
	Aqueous-dispersion resin and admixtures (component B)	1007 (component B)	

Table 4.32 - Input flows at each stage of the two-component adhesive’s production

Production stages (unit processes)		Identified flows		
		Solid	Liquid	Energetic
Component A	**1. Raw materials delivery and storage**	- Cement - Sand - Admixture	-	- Electricity - Diesel stacker
	2. Mechanical mix		-	- Electricity
	3. Dispensing and packaging	- Plastic and paper bags	-	- Electricity - Diesel and electric stacker
	4. Palletisation and storage	- Polyethylene shrink film (two types) and wood pallets	-	- Electricity - Diesel and electric stacker
Component B	**5. Raw materials delivery and storage**	-	- Resin - Admixtures	- Electric stacker
	6. Mechanical mix	-	- Fresh water (for cleaning operations and for the mix)	- Electricity - Electric stacker
	7. Dispensing and packaging	- Plastic buckets	- Fresh water (for cleaning operations)	- Diesel and electric stacker
	8. Palletisation and storage	- Polyethylene shrink film (two types) and wood pallets	-	- Electricity - Diesel and electric stacker

Table 4.33 - Output flows at each stage of the two-component adhesive’s production

Production stages (unit processes)		Identified flows	
		Solid	Liquid
Component A	**1. Raw materials delivery and storage**	- Plastic and paper bags (admixture packaging)	-
	2. Mechanical mix	-	-
	3. Dispensing and packaging	- Polyethylene film and wood pallets (bags packaging)	-
	4. Palletisation and storage	- Cardboard, polyethylene film and wood pallets (polyethylene shrink film packaging)	-
Component B	**5. Raw materials delivery and storage**	-	-
	6. Mechanical mix	-	-
	7. Dispensing and packaging	- Polyethylene film and wood pallets (buckets packaging)	- Effluents from cleaning operations
	8. Palletisation and storage	- Cardboard, polyethylene film and wood pallets (polyethylene shrink film packaging)	-

Table 4.34 - Main technical characteristics of the gypsum plasterboard studied in this thesis

Product	Dimensions (m)	Weight (kg/m^2)	Declared thermal performance - λ [W/(m.K)]	CE marking
Gypsum plasterboard	Length – between 2 and 3; width - 1.2; thickness - 0.0125	7.8	0.25	Yes (A type - EN 12524[6]; EN 520[7])

Table 4.35 - Input flows at each stage of gypsum plasterboard production

Production stages (unit processes)	Identified flows		
	Solid	Liquid	Energetic
1. Raw materials delivery and storage	- Gypsum	-	- Loader and diesel stacker
2. Stucco preparation		-	- Electricity and diesel stacker
3. Stucco slurry preparation	- Recycled paper - Admixtures - Glass fibre	- Water from borehole (for cleaning operations and for the mix) - Glue - Admixtures	- Electricity - Natural gas
4. Drying and finishings	-	-	- Electricity - Natural gas
5. Palletisation	- Wood bars - Polyethylene film	-	- Electricity and diesel stacker

Table 4.36 - Output flows at each stage of gypsum plasterboard production

Production stages (unit processes)	Identified flows		
	Solid	Liquid	Gaseous
1. Raw materials delivery and storage	-	- Effluents from wastewater treatment plant	-
2. Stucco preparation	-	-	- Air emissions from gypsum calcination and cooling processes
3. Stucco slurry preparation	- Plasterboard production waste - Wood pallets, plastic and cardboard (raw materials and admixtures packaging)	- Effluents from wastewater treatment plant	-
4. Drying and finishings	- Plasterboard production waste	-	- Air emissions from the drying process
5. Palletisation	- Wood pallets (wood bars packaging)	-	-

[6] **EN 12524:2000** - Building materials and products. Hygrothermal properties. Tabulated design values.
[7] **EN 520:2004+A1:2009** - Gypsum plasterboards - Definitions, requirements and test methods.

The specificities of the LCI of building products are treated in detail in the second main section of this chapter. Firstly, the stages of the life cycle of these products are defined based on European standards. Then, the leading environmental impacts that can result from each life cycle stage of building products are enumerated based on reference literature.

The third main section of this chapter is devoted to the description of the "Product stage" for each of the 12 building products studied in this Thesis based on the actual production by a Portuguese company. It starts with the definition of the overall goal and scope of these LCI studies, including the declared unit, system boundary, and data collection procedure and quality requirements. This section was divided in three sub-sections, concerning the principal function of the building products: elements of the wall structure, insulation materials and claddings (internal and external).

The description of the "Product stage" of each product starts with the description of its main technical characteristics, including the range in which it is available on the market. The description of the unit processes included in the "system process" (production of the building product) is presented below and illustrated through tables or flowcharts. These objects represent each stage (unit process) of the production and their inter-relationships, including the main flows (elementary and product inputs and outputs) occurring at each of these stages. This description is presented in more detail in Appendix 4.I, which presents an example of a form that was filled in during the LCI study of one of these products. This appendix, include: specific instructions for data collection and for filling it in; the characterisation and quantification of the individual flows that occur at each unit process, based on the data provided by the company; some notes about the choices done by the author in the modelling of the product system.

From the 12 LCI studies completed, the author confirmed the time-intensive and iterative nature of data collection and the importance of giving permanent attention to allocation in many system processes. Data quality can vary a lot for each system process studied, and this issue was confirmed by the characterisation of the quality of the information provided by each of the 12 companies for the LCI studies of their corresponding products.

This Chapter provides a thorough explanation of the LCI procedure, both in theoretical and practical terms. LCI constitute a significant part of the LCA studies whose results are presented in Chapter 5 of this Thesis. Therefore, the principles chosen by the author to be applied in the LCI of each building product, following the guidelines defined in standards, are of foremost importance to guarantee the scientific validity of the results achieved in each LCA study.

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5. LIFE CYCLE IMPACT ASSESSMENT (LCIA)

5.1. Life Cycle Impact Assessment (LCIA)

Section 2.3. “Life Cycle Assessment (LCA) methodology” has already presented the “Life Cycle Impact Assessment” (LCIA) phase as a part of the global LCA methodology. However, the description in detail of LCIA is presented only in this section of the Thesis. LCIA limitations are described, and its mandatory and optional stages are then presented in the corresponding sub-sections.

Firstly, it is important to highlight that LCA is based on a multi-disciplinary approach, and each of its application phases requires knowledge from different fields of expertise, as shown in a simplified form in Figure 5.1. The Life Cycle Inventory (LCI) requires an understanding of the production processes and an ability to detect and quantify physical flows, which are both typical of engineers. However, the LCIA requires knowledge in the field of natural and physical sciences that allows the understanding if and to what extent the use of resources and the release of pollutant substances can be harmful to the environment. In the final stage of this phase, the main concern becomes distinguishing the conceptual and practical differences between environmental issues (i.e. their global or local nature) taking into account their complexity. Therefore, social science expertise becomes essential in order to allow justified aggregate judgements in different environmental fields (Blengini, 2006).

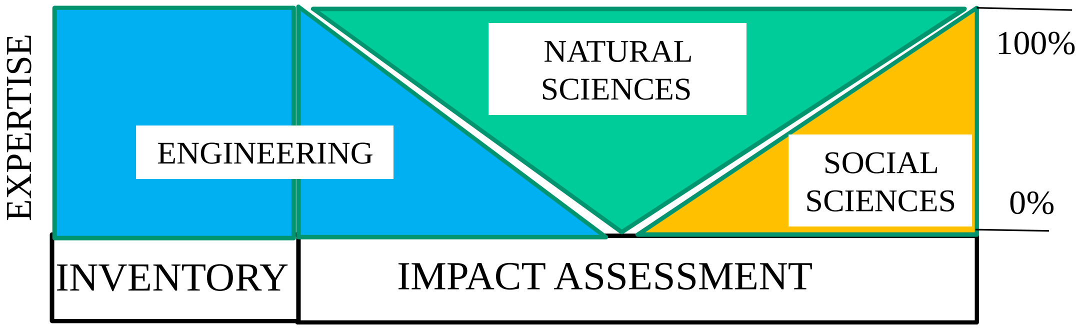

Figure 5.1 – Simplified representation of the procedures included in a LCA ((ISO, 2006b) adapted from (Blengini, 2006))

LCIA is not a complete assessment of all environmental issues of the product system under study because the level of detail, choice of impacts evaluated and methodologies used depend on the goal and scope of the study (ISO, 2006a). It is also important to highlight that LCIA results “only indicate potential environmental effects but do not predict actual impacts on category endpoints, the exceeding of thresholds or safety margins or risks” (ISO, 2006a).

LCIA possible omissions and sources of uncertainty include (ISO, 2006b):

- The level of quality of the LCI data and results (e.g. a system boundary that does not encompass all possible unit processes for a product system or does not include all inputs and outputs of every unit process due to cut-offs and data gaps, uncertainties or differences in allocation and aggregation procedures, or limitations in the collection of inventory data appropriate and representative of each impact category), which should be sufficient to conduct the LCIA in accordance with the goal and scope of the study;
- "The environmental relevance of the LCIA results is decreased due to the LCI functional unit calculation, system wide averaging, aggregation and allocation" (ISO, 2006b, p. 16).

Subjectivity in issues such as choice, modelling and evaluation of impact categories must be avoided by describing and reporting with transparency all assumptions made (ISO, 2006a). LCIA has other limitations, such as: it "cannot always demonstrate significant differences between impact categories and the related indicator results of alternative product systems", namely due to limited development of the characterisation models, sensitivity analysis and uncertainty analysis for the LCIA phase. LCIA results can also be uncertain due to the lack of spatial and temporal dimensions in the LCI results. This uncertainty varies with the spatial and temporal characteristics of each impact category. Moreover, models for impact categories are in different stages of development and there are yet no largely accepted methodologies (ISO, 2006a).

The separation of the LCIA phase into different elements is helpful and necessary, namely to allow a quality assessment and critical review of the LCIA methods, assumptions and other decisions (e.g. value-choices) for each LCIA element (ISO, 2006a). Each mandatory and optional LCIA element is described in detail in sections 5.1.1 and 5.1.4, respectively.

5.1.1. LCIA mandatory elements

The LCIA phase starts with the selection of impact categories, category indicators and characterisation models. This procedure should be justified and consistent with the goal and scope of the LCA. All the information related with the chosen entities, and corresponding sources, should be referenced. For instance, LCI flows other than mass and energy (e.g. land use) should be identified along with the determination of their relationship with the corresponding category indicators (Figure 5.2). There are several other recommendations related with this stage of LCIA and two of them can be highlighted for their utmost importance (ISO, 2006b):

- “The impact categories, category indicators and characterisation models should be internationally accepted”, namely via international agreements or approval of a competent international body;
- “The characterisation model for each category indicator should be scientifically and technically valid, and based upon a distinct identifiable environmental mechanism and reproducible empirical observation”.

The classification procedure assigns LCI results (or contribution of each environmental intervention, such as chlorofluorocarbons – CFC’s, carbon dioxide - CO_2, or Methane - CH_4 (Ortiz *et al.*, 2009)) to the selected impact categories. To exemplify this procedure, the amounts of SO_2, HCl and NO_x per functional unit are assigned to the “Acidification” impact category and the amount of greenhouse gases per functional unit is assigned to the “Global warming” impact category (Figure 5.2; see 5.1.3 for a detailed description of environmental impact categories). There are, however, LCI results that are related with more than one impact category and that can be assigned to parallel mechanisms (e.g. SO_2, which can contribute to both the “Human health” impact category and “Acidification”), or assigned to serial mechanisms (e.g. NO_x, which can contribute to both “Photochemical Ozone Creation” and “Acidification”) (ISO, 2006b).

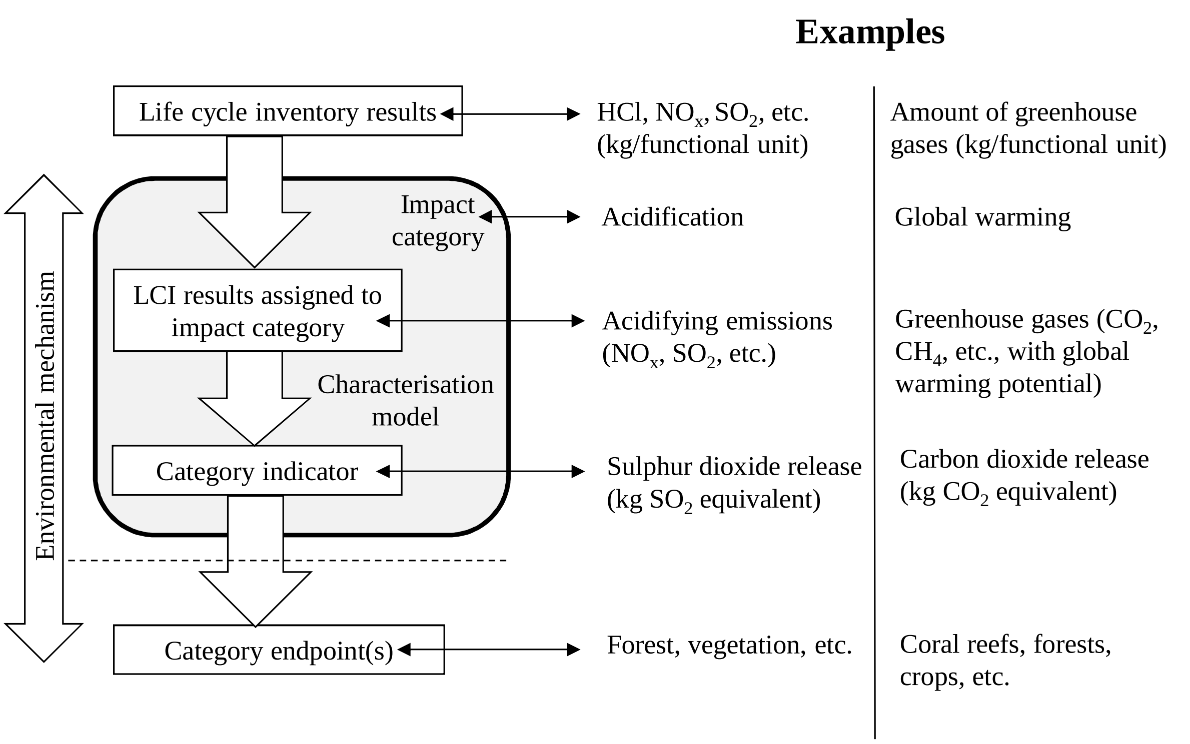

Figure 5.2 – Concept of category indicators for midpoint categories based on environmental mechanisms (adapted from (Blengini, 2006; ISO, 2006b))

The calculation of each category indicator result is made during the characterisation stage, which is summarised in Figure 5.2. A characterisation model (alone or within an "Environmental Impact Assessment Method" (EIAM) – see 5.1.2) converts LCI results assigned to a given environmental category to common units, by assuming a cause-effect relationship. This assumption includes adequate characterisation factors (within a conversion matrix and provided by the characterisation model of each impact category) for each pair intervention-environmental impact. A chosen EIAM then aggregates these figures to calculate the indicator result in that environmental category. This can result either in midpoint (e.g. acidification or global warming) or endpoint (e.g. damage to human health or to the ecosystems – see Figure 5.2) impacts (Ferrão, 2009; ISO, 2006b).

The LCIA phase also provides information for the life cycle interpretation phase (ISO, 2006a). Therefore, a compilation of the LCIA category indicator results for all impact categories – or LCIA profile - should be compiled after characterisation. This compilation should be complemented by elementary flows from inventory results that have not been assigned to impact categories (e.g. due to lack of environmental relevance) and data that does not represent elementary flows. Optionally, a LCIA profile can be subjected to a data quality analysis at the end of the LCIA phase in order to provide a better understanding of the reliability of the collection of indicator results (ISO, 2006b). This procedure can include the isolated or joint application of techniques such as gravity, uncertainty and sensitivity analysis, depending on the accuracy and detail needed to fulfil the goal and scope of the LCA study. Gravity analysis (e.g. Pareto analysis) consists of a statistical procedure that identifies the greatest contributors to the indicator result, indicating a priority for their investigation to ensure that sound decisions are made. The mode uncertainties (in data and in assumptions) progress in the calculations, and how they affect the reliability of the results of the LCIA, can be determined using uncertainty analysis. Sensitivity analyses allow the determination of the way in which LCIA results are affected by changes in data and methodological choices. The LCI phase can be revised depending on the result of this LCIA data quality analysis, which is in line with the iterative nature of LCA (ISO, 2006b).

5.1.2. Environmental Impact Assessment Methods (EIAM)

The main function of "Environmental Impact Assessment Methods" (EIAM) in LCA methodology is to provide LCA results from LCI flows. The LCIA phase starts with the selection of impact categories, category indicators and characterisation models or, alternatively, with the selection of an EIAM that includes a set of all these entities (each impact category includes a category indicator and a characterisation model - or environmental mechanism). The selection of the impact categories often implies the choice of an EIAM because most of the latter are associated with a set of environmental categories.

Two types of EIAM can be chosen depending on the phase of the characterisation models for which the indicators (of their impact categories) are defined. In fact, category indicators can quantify properties more related to the environmental intervention (and be known as midpoint indicators) or to its environmental impact (and be known as endpoint indicators) (Ferrão, 2009). Figure 5.3 illustrates environmental mechanisms that provide midpoint and endpoint category indicators from LCI environmental interventions. Therefore, an EIAM can be based on midpoint indicators (e.g. CML 92, CML 2001, EDIP 97/2003 and IMPACT 2002+ (Ortiz *et al.*, 2009)) and use a problem-oriented approach, or can be based on endpoint indicators and use a “damage-oriented” approach, i.e., with a focus in environmental burdens or final consequences (e.g. EPS, Eco-indicator 99 and also IMPACT 2002+ (Ortiz *et al.*, 2009)) (Ferrão, 2009). EIAM based on midpoint indicators provide reliable calculations but present significant problems in the process of “Grouping” (see section 5.1.4) by including impacts categories (e.g. potential of ozone layer depletion or greenhouse effect) that can be less significant in the interpretation stage. On the other hand, EIAM based on endpoint indicators are less reliable and more uncertain because they demand the analysis of complex characterisation models, despite providing results for impacts categories that are more relevant at the interpretation stage (Ferrão, 2009; Ortiz *et al.*, 2009). In fact, impact categories based on endpoint indicators ease and speed up their “Grouping” (in groups such as damage to human health or to the ecosystems), which is an important characteristic in terms of LCA applicability and in the communication of its results to support decision-making processes (Ferrão, 2009).

In fact, and regardless of the approach chosen, EIAM uncertainties are still significant. They can rely on model and parameter uncertainties. Model uncertainty is related with the accuracy of the model and can be determined via evaluation studies. Parameter uncertainty is connected with input data and is frequently determined through techniques such as Monte Carlo analysis. Therefore, endpoint models can be less certain due to model and parameter uncertainty, and midpoint methods can be more certain ((Bare *et al.*, 2000) cited by (Pargana, N. G. S. C., 2012)).

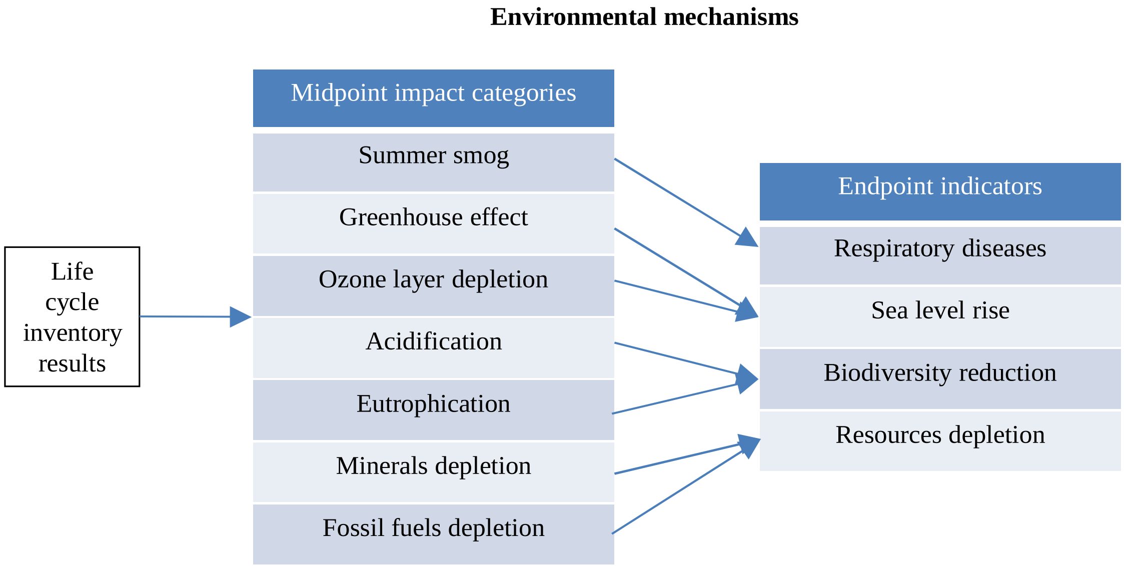

Figure 5.3 – Examples of environmental mechanisms and corresponding midpoint impact categories and endpoint indicators (adapted from (Ferrão, 2009))

CML 92, for example, is an EIAM that uses a problem-oriented approach and includes category indicators highly related with environmental interventions. It was developed in the Netherlands by the “Institute of Environmental Sciences” (CML) of Leiden University. The “Acidification” impact category, for instance, is characterised based on the emission of H^+ protons per substance released into the environment. However, this category indicator is measured using another unit: “kg SO_2 equivalents”. Nevertheless, the contribution of each environmental intervention to a given impact category is established by comparing its potential effect with the reference environmental intervention (e.g. kg SO_2 for “Acidification”) (Ferrão, 2009).

On the other hand, Eco-indicator 99 is an EIAM based on endpoint indicators and therefore oriented for environmental burdens or final consequences. It was developed by a Dutch consortium and is an upgrade of Eco-indicator 95 (that has environmental impact categories similar to CML 92, except for toxicity that is distributed into heavy metals, carcinogenic substances, pesticides and winter smog (Kellenberger & Althaus, 2009; PRé, 2008)). This EIAM expresses in a single score the weighted impacts of the use of resources and of emissions on human health, on the ecosystems and on resource quality. In this EIAM, the category indicator for the “Greenhouse effect” impact category is expressed as “Disability Adjusted Life Years” (DALY), which corresponds to the consequences that the “Greenhouse effect” can have in the reduction of the life expectancy (estimated in time) of the human being. This quantification demands a complex characterisation model that can be less reliable than the calculation of the equivalent CO_2 emissions (a midpoint indicator), but is closer to the problems that affect people (Ferrão, 2009).

Among the EIAM most used in LCA software tools (see section 5.3), the following ones can be highlighted (ENSLIC, 2012; Gervásio, 2010; Kellenberger & Althaus, 2009; Massone, 2007; PRé, 2008):

- ILCD 2011 Midpoint method (European Commission - EC) – this EIAM was released by the Institute for Environment and Sustainability of the Joint Research Centre of the EC in 2011 and supports the correct use of the characterisation factors in 16 midpoint impact categories as recommended in the ILCD guidance document (EC-JRC, 2011, 2012);
- CML 2001 (or CML-IA, Netherlands) – also developed by the (CML) of Leiden University, was updated in November 2012 (based on the spreadsheet version 4.0) and is oriented to intermediate environmental effects (via a midpoint approach);
- TRACI (USA) - the “Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts” was developed by the U.S. EPA (Environmental Protection Agency) to provide a midpoint approach;
- Environmental Design of Industrial Products (EDIP 97/2003 / UMIP in Danish - Denmark) – developed in 1996 and updated in 2003 by the “Institute for Product Development” of the Technical University of Denmark. This EIAM comprises a midpoint approach in the first version, but the updated one (2003) follows an end-point approach for most of the impact categories;
- IMPACT 2002+ (Switzerland/USA) – is a combination of IMPACT 2002, Eco-indicator 99 (with completely recalculated toxicity factors), CML 2000 and IPCC that allows both midpoint and endpoint approaches, and was developed by the “Risk and Impact Modelling group” of the University of Michigan and at the Swiss Federal Institute of Technology, in Lausanne (EPFL);
- EPS 2000 (Sweden) - developed by the Centre for Environmental Assessment of Products and Material Systems (CPM) of the Chalmers University of Technology, EPS is the acronym of “Environmental Priority Strategies in product design”, and considers four types of environmental damages (Human Health, Ecosystem Production Capacity, Biodiversity and Abiotic Stock Resources) to apply an end-point approach that considers monetarization (willingness to pay) in the “weighting” step (see section 5.1.4);
- Ecoscarcity Method – Eco-Points (Switzerland) – this method of environmental scarcity - also called the Swiss Eco-Points method – was developed by the Federal Office of the

Environment, Forests and Landscape of this country and the most recent updated version is from 2006. It provides an end-point approach to achieve a single score for LCA, which results from the comparison between each quantified flow and its corresponding annual critical quantity in a defined area.

There are also “single issue” EIAM that allow the evaluation of a particular category of impact. One of the most used is the “Cumulative Energy Demand” (CED) method developed by Ecoinvent (Althaus *et al.*, 2007) that estimates the renewable and non-renewable parcels of the energetic resources consumed in a given system process. The Intergovernmental Panel on Climate Change (IPCC 2007, of the United Nations) also developed a single issue method to characterise the contribution of gaseous emissions for global warming according to three temporal perspectives: 20, 100 and 500 years (PRé, 2008).

5.1.3. Environmental impact categories

As described, LCI results are assigned to each impact category (classification procedure) to calculate the value of each category indicator (in the characterisation stage), using characterisation factors provided by the characterisation model of each impact category (Ferrão, 2009; ISO, 2006b). This theoretical procedure aims to represent the complexity of the main environmental mechanisms that occur in nature as a consequence of the occurrence of each LCI flow from the system process under study. In fact, each environmental impact (category) is associated with one or more elementary flows (Blengini, 2006).

Impact categories can be classified as global, regional or local, depending on their scale or influence but also on their causative mechanism and on the physical and chemical characteristics of related “pollutants” (LCI flows associated with a given impact category). Global Warming, for example (see 5.1.3.2), is considered an environmental impact category that has an effect at a global scale, because local CO_2 emissions contribute to its occurrence worldwide (Blengini, 2006). LCA is more effective in studying environmental impacts at a global scale, while regional scale effects require extra attention on geographical areas of influence and time boundaries. For the study of environmental impacts at a local scale, LCA does not supply additional information or substitute other methodologies such as “Environmental Risk Analysis” or “Environmental Impact Assessment”, despite being a good complement to them (Blengini, 2006).

Environmental impact categories are usually divided in three main groups depending on their effects (Blengini, 2006): Resource Depletion (e.g. mineral or energetic); Ecosystems (corresponding to several effects on Ecology); Human Health (i.e. effects on human health and safety). However, some impact categories can result in burdens to more than one of these groups. The midpoint impact categories most used in LCA studies (Gervásio, 2010) are described in detail in the next sub-sections.

5.1.3.1. Abiotic depletion

Resource depletion corresponds to the use of both mineral and energetic (or fossil) resources. The materials extracted from nature (with and without energetic content, such as total primary energy or raw materials, respectively) for a given system process are quantified in the LCI stage. The effect of this consumption in the depletion of each resource is estimated according to the available (known and economically or technically extractible (Peuportier *et al.*, 2011)) stock of the latter at a global scale, given that the resource is considered as non-renewable (Blengini, 2006) or finite. Some EIAM also consider the extraction rate (e.g. the category abiotic depletion potential – ADP – in CML) or are based on the marginal increase of cost or energy surplus (e.g. Eco-indicator 99). In fact, consuming a resource increases the cost or the energy needed to continue extracting it as the reserves needing the lowest effort are exploited first (Peuportier *et al.*, 2011).

5.1.3.1.1. Depletion of energetic resources (or fossil fuels)

Concerning the energetic analysis of systems, several definitions can be found, namely related with different types of “energy” that characterise each energy carrier (“substance or phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes” (CEN, 2010)). For instance, a fuel can be described by its “direct energy”, which is “the energy content of fuel that depends on its low calorific value” or “the energy that can be obtained using or burning it” (Blengini, 2006, p. 82). On the other hand, “indirect energy” is “the energy that must be spent to extract primary fuels from the earth and then to transport and transform them into a useful form of energy” (Blengini, 2006, p. 82). “Capital energy” is “the quantity of energy that can be associated with the production of equipment and infrastructures necessary to produce fuels”, and “feedstock energy” is “the energy embedded in products or materials that could, theoretically, be recovered at the end-of-life through incineration” (i.e. associated to the materials as potential fuels) (Blengini, 2006, p. 82). The “total amount of energy” or “Gross Energy Requirement (GER)” can be associated to the production of a given product and is the sum of capital, indirect, direct and feedstock energies (Blengini, 2006, p. 82). As GER is the total amount of energy necessary to produce a given product, the GER value can be used as an indicator for the abiotic depletion of energy resources (Blengini, 2006).

If energetic analysis of systems is applied to construction materials, "feedstock energy" corresponds to the heat from combustion of a raw material that is not used as an energy source (e.g. the calorific value of a timber piece, which might be burned and converted into energy at some point of its life cycle) (Nebel, 2006). "Process energy" is therefore the energy input during product manufacturing, excluding energy inputs for production and delivery of this energy. The "production and delivery energy" represent the energy required to extract, process, refine and deliver energy or material inputs to a given process (e.g. the fuel required to run a truck), and the "total primary energy" corresponds to the sum of the feedstock, process and production and delivery energies. "Total primary energy" is usually assessed in LCA studies because this amount corresponds to an aggregation of all the energetic resources used (Nebel, 2006). Nevertheless, an analysis of each of its components is of paramount importance, namely in eco-design studies at an industrial level.

Other approaches introduce one of the most used concepts in environmental assessment of construction materials, "embodied energy", which includes all energetic inputs in the manufacturing process of a given product, and may also include its assembly on-site (as referred in Chapter 4 at the building level). In effect, this amount can be divided into initial and recurrent embodied energy, when analysing buildings and related products. The latter includes the consumption of energy in maintenance, repair, restoration and replacement operations of the materials and systems during the building service life. Initial embodied energy corresponds to the consumption of non-renewable energy in the extraction of raw materials, processing, manufacturing, transportation to site and assembly on-site of construction materials. This type of energy can be divided in two components: direct, for the transport to site and assembly stages, and indirect, for the preceding stages (i.e. extraction of raw materials, processing and manufacturing, including transport processes related with these stages) (adapted from (Nebel, 2006; Pinheiro, 2006)).

As referred in Chapter 4, the energy consumed during the installation stage (A5) can be divided in direct and indirect consumption. The former is related with the activity at the construction site, while the latter includes the production and maintenance of the equipment used on site and the transport of workers and equipment to and from the construction site. Direct consumption can also be divided in two groups: energy consumed on site (e.g. mechanical equipment and lighting); and equivalent energy spent by workmanship (Mendonça, 2005).

5.1.3.2. Global warming

This impact is well-known as the “greenhouse effect” and relies on a mechanism originated by the “greenhouse gases” present in the atmosphere. These gases reflect or trap the heat emitted by the Earth’s surface, such as the infrared reflection of solar radiation, resulting in an increase of the global mean temperature. This effect increases sideways with the rise of the concentration of these gases and can result in several other climate changes that affect ecosystems and human health at a global scale, according to the IPCC ((Guinée *et al.*, 2001) cited by (Blengini, 2006)).

The most important “greenhouse gases” are Carbon dioxide (CO_2), Methane (CH_4), Halocarbons (CFC and HCFC), Nitrous oxide (N_2O) and Ozone (O_3 – see section 5.1.3.6) (Blengini, 2006)).

Carbon dioxide is, in its anthropogenic form, the most important one (is responsible for more than a half of the anthropogenic – not naturally generated – greenhouse effect) and results mainly from burning of fossil fuels (oil, gas and coal) (Blengini, 2006)).

Methane is the second most important one with a share of around 20%. The molecules of this gas have a significant heat absorption capacity (20 times higher than carbon dioxide) and their greenhouse effect is therefore substantial, even when in small concentrations. Natural emissions of methane take place when bacterial decomposition of organic material occurs in anaerobic conditions (without the presence of oxygen) mainly in wet regions (swamps) (Blengini, 2006)).

The third most important “greenhouse gases” are Chlorofluorocarbons (CFC) and Hydro-chlorofluorocarbons (HCFC) with a cumulative share of about 14% (Blengini, 2006)). CFC, a synthetic material, seems to be more linked with the ozone layer depletion than to global warming and was almost completely banned from industrial processes. Nowadays, HCFC is therefore the material that replaces CFC (e.g. in spray cans, insulation materials and refrigerants in refrigerating equipment) because it does not destroy the ozone layer. However, it has a greenhouse effect 20,000 times higher than carbon dioxide (Blengini, 2006)).

Nitrous oxide has a mass contribution of around 6% for global warming and has an effect more than 3,000 times higher than carbon dioxide. It results from the microbial transformation of nitrogen available on Earth, the latter increasing due to agriculture, industry and transport operations (Blengini, 2006)).

5.1.3.3. Stratospheric ozone depletion

The significance of this impact category in LCA has decreased since CFCs were banned from industrial processes. However, HCFC emissions are also harmful for the ozone layer and must be kept continuously under control, along with other emissions.

The depletion of the stratospheric ozone layer corresponds to its thinning due to anthropogenic emissions, resulting in and increasing in the fraction of the Ultraviolet B radiation that can reach the Earth's surface. This radiation has a great potential of causing harmful effects in human and animal health, and in ecosystems, at a global scale (Blengini, 2006)).

5.1.3.4. Acidification

Burning fossil fuels generates anthropogenic acidifying emissions, such as sulphur dioxide (SO_2), nitrous oxides (NO_x) and reduced nitrogen (NH_X), because of their content in sulphur. Sulphur compounds – the most harmful for acidification – deposit within two to four days after emission and, therefore affecting areas close to the emission source (i.e. industrial or densely populated areas). NO_x affect a wider area – up to a regional level - because of their longer time decay that allows their long-distance transportation by the wind (Blengini, 2006)).

Acidifying emissions also result from agriculture and, therefore, the impacts of this category can affect the soil, ground and surface waters, animals, ecosystems and also the building environment (Blengini, 2006)).

5.1.3.5. Eutrophication

This category represents consequences of the excessive accumulation of macronutrients (within which nitrogen – N – and phosphorous – P – are the most important) in both aquatic and terrestrial ecosystems both at a local and at a regional scale. This accumulation – also known as nutrient enrichment – may lead to: an undesirable shift in species composition; a higher biomass production, which causes additional consumption of oxygen during their decomposition in aquatic ecosystems, therefore reducing the availability of oxygen in these environments; the contamination of surface waters making their use as drinking water impossible (Blengini, 2006)).

Emissions of degradable organic matter are also considered in this category due to their similar effects. These emissions can result from the use of fertilisers in agriculture and from industrial and urban releases rich in N and P compounds, but their impact must be analysed separately for surface water and soil ((Guinée et al., 2001) cited by (Blengini, 2006)).

5.1.3.6. Photochemical ozone creation

Photochemical oxidation produces several reactive chemical compounds (or photo-oxidants), but the most important are Peroxyacetylnitrate – PAN, and Ozone. Ozone occurs naturally but can also result from the photochemical oxidation of gases emitted by vehicles (i.e. photochemical oxidation of Carbon monoxide – CO and Volatile organic compounds – VOC, which are produced mainly by the incomplete burning of different types of fuels and by the use of chemical solvents - in the presence of NO_x) in urban areas. Ozone can therefore reach significant concentrations in the summer (when the sun shines for many hours), when its accumulation at low heights (close to the Earth- in the lower troposphere, being known as “summer smog”) has a direct effect on human health and ecosystems - due to its toxic nature - both at a local and at a regional scale, and accelerates the greenhouse effect (Blengini, 2006)).

5.1.4. LCIA optional elements

The LCIA phase can also include optional elements, such as normalisation, grouping or weighting. The application and use of these procedures shall be consistent with the goal and scope of the LCA and all methods and calculations used shall be documented to provide transparency (ISO, 2006b).

Normalisation comprises the calculation of the magnitude of each category indicator in relation to reference information (Figure 5.4). It improves the understanding of the relative magnitude of each indicator in order to help in verifying inconsistencies or in the communication of the relative significance of the indicator results, for example. This procedure commonly uses selected reference values (e.g. “the total inputs and outputs for a given area on a *per capita* basis”) to divide each indicator result (ISO, 2006b).

To identify the key environmental impacts of the product stage of construction materials and products, LCA results were calculated using the Ecoinvent database (Ecoinvent, 2012) and were then normalised. Ecoinvent version 2.2 is a generic LCA database developed by the “Swiss Centre for Life Cycle Inventories” (see section 5.3.1.1), and is included in the LCA tool SimaPro (Silvestre, J. & Lasvaux, 2012). Appendix 5.I includes the environmental impacts in six categories after normalisation (using CML 2001 v. 2.04 – see section 5.1.2, and West Europe - 1995 as a reference for normalisation) of several construction materials and products, divided in four groups:

1. Construction materials - cement, concrete, gravel and sand, gypsum and reinforcing steel;
2. Insulation materials - Expanded Polystyrene (EPS), Light Expanded Clay Aggregate (LECA), Polyurethane/Polyisocyanurate (PUR/PIR), Stone Wool (SW) and Extruded Polystyrene (XPS);
3. Elements of the wall structure - hollow fired-clay bricks and lightweight concrete blocks;
4. Wall claddings - ceramic tiles, dry pre-mixed mortar, Glass Fibre Reinforced Concrete (GFRC) panels, gypsum plasterboards, gypsum plasters, paint and two-component adhesive.

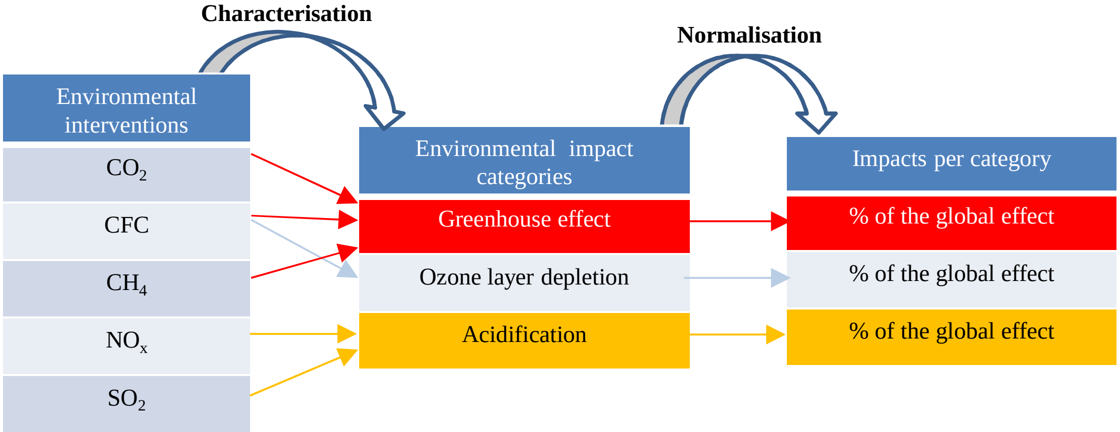

Figure 5.4 – Simplified representation of normalisation procedure (adapted from (Ferrão, 2009))

From Appendix 5.I it is possible to conclude that Global Warming Potential (GWP) is the most important environmental impact of cement and concrete production in a European context. For all the other materials and products, the most important environmental impact category can be considered to be Abiotic Depletion Potential (ADP). From these results, it can be concluded that the use of virgin raw materials is responsible for the greatest share of the environmental impacts of most construction materials, including cement-based materials, when compared to average values of all productive sectors (through normalisation of the results of each environmental category - Appendix 5.I). In fact, only cement and concrete present a significant contribution of A3 sub-stage (manufacturing) in their product stage account of environmental impacts.

Impact categories can be sorted and possibly ranked using a “Grouping” procedure. This process results in the assignment of impact categories into one or more sets using two alternative procedures (ISO, 2006b):

- Sorting the impact categories on a nominal basis (e.g. by characteristics or global, regional, and local spatial scales);
- Ranking the impact categories in a given hierarchy (e.g. high, medium, and low priority) based on value-choices.

The “Weighting” procedure includes the conversion of the results of the indicators (or normalised results) using selected weighting factors based on value-choices. These value-choices may or may not be scientifically based. Therefore, it is desirable to evaluate the consequences in LCIA results of using different weighting methods (e.g. via a sensitivity analysis). This procedure can also be followed by an aggregation across impact categories. Even when weighting is applied to LCIA results, data prior to its application should remain available together with the weighting results to allow decision-makers to have access to the complete range of LCIA results (ISO, 2006b).

International standards provide special recommendation for LCIA “intended to be used in comparative assertions intended to be disclosed to the public”. In fact, this type of LCIA should employ a suitable and ample set of category indicators and their comparison must be presented separately. Moreover, LCIA limitations should be highlighted (e.g. value-choices and the variation in precision among impact categories) and these results have to be complemented by additional information to limit the impact of these limitations. This care is indispensable when the aim is to disclose a comparative assertion to the public of overall environmental superiority or equivalence. The category indicators have to be chosen following the rules described in 5.1.1, weighting (see 5.1.3) should not be used, an analysis for sensitivity and uncertainty of the results should be conducted, and the “Life Cycle Impact interpretation” should include the interpretation of this analysis (ISO, 2006b).

5.2. Life Cycle Impact interpretation

Section 2.3. “Life Cycle Assessment (LCA) methodology” has introduced the “Life Cycle Impact Interpretation” phase as a part of the global LCA methodology. However, its description in detail is presented only in this section of the Thesis.

The “Life Cycle Impact interpretation” phase comprises two procedures (that should be implemented in accordance with the goal and scope definition and supplemented by the results of data quality analysis) (ISO, 2006b):

- The identification of flows or environmental indicators that can cause more concern, based on the results obtained in the LCI and LCIA phases;
- The completeness, sensitivity and consistency check which provides an evaluation of the LCA study (namely of the results obtained in the LCI and LCIA phases).

For the first procedure, the results from the LCI and LCIA phases are structured in order to ease the identification of the most significant issues (i.e. inventory data - energy, emission or waste; impact categories – climate change or other; life cycle stage contributions – unit processes or group of processes, such as transport or energy production or use) of these phases. This has to be done in conjunction with the second procedure, namely taking into account the implications of the methods used and assumptions made during the preceding phases (ISO, 2006b).

The evaluation – second procedure of “Life Cycle Impact interpretation” – has the aim of establishing and enhancing confidence in, and the reliability of, the results of the LCA or the LCI study, including the significant flows or environmental indicators found in the first procedure. The results of this procedure should provide a clear view of the outcome of the study. Three techniques can be used to achieve this goal. The first one:

- Confirms the availability and completeness of all relevant data and information needed for interpretation;
- Concludes about - and justifies - the need for collecting more data, or completing the available one, in order to satisfy the goal and scope of the LCA study.

This can result in a change in goal and scope, in the revisiting of the LCI or LCIA phases, or in the justification of why the missing information is unnecessary. The second technique - sensitivity check – determines how final results and conclusions are affected by uncertainties (e.g. in the data, allocation methods, or calculation of category indicators) to assess their reliability. This check procedure should include the results of preceding sensitivity or uncertainty analyses, when available. It can conclude with the need for a more “extensive and/or detailed sensitivity analysis“. The last technique tries to determine if the assumptions, methods and data are consistent with the goal and scope via a consistency check (ISO, 2006b).

These procedures of “Life Cycle Impact interpretation” result in conclusions, identification of limitations, and recommendations that can be included in the LCA report. The drawing of conclusions can be initiated by the identification of significant issues, and followed by the evaluation of the methodology and results (via a completeness, sensitivity and consistency check), resulting in preliminary conclusions. These can be considered as final when consistent with the goal and scope of the study. The interpretation should also reflect the fact that the LCIA results “only indicate potential environmental effects but do not predict actual impacts on category endpoints, the exceeding of thresholds or safety margins or risks” (ISO, 2006a), as it has already been referred to.

5.3. LCA tools

According to a study from the “International Energy Agency”, tools for environmental evaluation of buildings and their components should be based on scientific principles. These tools should also allow a global and integrated vision, by considering the whole life cycle of the chosen construction assemblies (IEA, 1997). As such, tools for environmental assessment of buildings may be based on LCA methods (Graham, 2003), despite LCA being a method that complies with the described requirements.

LCA tools emerged as computer-supported conversions of already existing calculation or evaluation methods (IEA, 1997). These tools provide (Graham, 2003): an interface for introduction of design information; an easy access to calculation and inventory databases (LCI of raw material production or other elementary processes); environmental impact evaluation; and adequate data representation and exportation, thus enabling the practical application of the methodology.

There are several directories of LCA tools available on the internet, of which the ones from the “International Energy Agency” (SCC, 2002), from the “United States Department of Energy” (USDE, 2007), and from the European Commission (EC, 2009b) can be highlighted.

The tools for environmental assessment (e.g. LCA) of products, and namely of buildings and corresponding elements, can be divided in three main groups (Trusty, W., 2004):

- Level 1 - tools devoted to individual products or simple construction assemblies (e.g. windows or floor coverings) and that are used in comparisons of environmental and economic performance, being therefore useful at the design stage;
- Level 2 - tools focused on complete and complex construction assemblies or on the whole building, can be considered decision-support tools that provide the evaluation of the life cycle economic - or environmental - performance (of assemblies or buildings) or of the building’s operational energy;
- Level 3 - systems or platforms that allow a wider evaluation of the whole building using environmental, economic and socially relevant criterions.

Sections 5.3.1, 5.3.2 and 5.3.3 present a detailed analysis of level 1, 2 and 3 software-based tools most used at an international level for LCA of construction materials and assemblies in order to characterise their functionalities in the execution of the sequential LCA steps and identify the most adequate to be used in this research work, namely to allow the LCA from cradle to cradle of construction materials and assemblies of buildings in Portugal.

5.3.1. Level 1 LCA tools

Level 1 tools allow the comparison of the environmental performance of individual products or simple construction assemblies, being useful essentially at the design stage. However, these tools can also: allow the optimisation of the production process; provide data for qualitative tools for the environmental assessment of other stages of the building life cycle (like level 2 or 3 tools); be used for refurbishment interventions; and support end-of-life decisions (CfD, 2001b). The greatest part of these tools corresponds to LCA generic software that can be applied in the construction sector – namely to construction materials and assemblies. Among the level 1 tools available worldwide, GaBi in Germany (more oriented to engineering applications (PE, 2012)) and SimaPro in the Netherlands (more directed to the optimisation of industrial processes (PRé, 2012)) can be highlighted. The TEAM (Tools for Environmental Analysis and Management, from PricewaterhouseCoopers) software is available in France and was already used in several European projects in areas such as agriculture, construction and waste management. TEAM has a level 2 version devoted to the LCA of buildings – the TEAM Bâtiment (CfD, 2001b).

Concerning the construction-specific tools, "Building for Environmental and Economic Sustainability" (BEES) was developed in the USA by the National Institute of Standards and Technology (NIST). This free-of-charge tool is LCA-based and allows the choice of cost-efficient and environmentally preferable construction materials to be used in a building. These components can be selected among the 230 available in its database - which is based on LCA studies made according to international standards, and can be used in "Building Environmental Assessment Systems" (BEAS – see 5.3.3) (Erlandsson & Borg, 2003) and also in level 2 or 3 tools (Trusty, W. B., 2004). Boustead software is a general LCA tool available in the United Kingdom whose main focus is the construction sector (EA, 2000b).

The usefulness of Level 1 tools for each specific field of application (e.g. construction sector, eco-design of products or industrial processes) is highly dependent on the LCI and LCA databases included in their software packages. For this reason, both types of databases are described in detail in the next sub-section, namely the most used for LCA studies at an international level.

5.3.1.1. LCI and LCA databases

LCA of a product system needs data related to inputs and outputs of the materials, products or components under analysis. This data corresponds to energy and mass flows within the system boundary or the life cycle. The collection of the necessary information to characterise these flows is, simultaneously, time and resources-consuming. This concern leads to the development of generic databases to model an adequate LCI, supporting therefore LCA activity (CfD, 2001b).

Level 1 (and also levels 2 and 3) LCA tools are characterised by the databases included in their standard version but also by the databases that can be bought individually and additionally. The possibility of importing data included in commercial (external) databases is also an important advantage, along with the option of editing available databases and creating new ones. An LCA study can be developed using data from a single database, or from the combination of information from several databases (ENSLIC, 2012). In fact, databases are a critical issue in LCA of buildings because their availability (or absence), within the software tool, allows (or avoid) the supplying of the necessary information for an adequate environmental evaluation of the building (CfD, 2001b). An updated directory of databases to support LCA, from the European Commission, is available on the internet (EC, 2009a).

According to Ferrão (1998), databases can be non-bibliographic (including information related to energy consumption, emissions and chemical, biologic and toxic effects), institutional (from governments or private entities, in order to ease the access to several databases and bibliographic references) or bibliographic (including bibliographic references for real data that should be extracted from referenced sources). According to another source (CfD, 2001b), databases can be divided in three groups according to the data that they include. Each of these groups is presented next, in conjunction with the description of the most relevant databases for LCA (in the construction sector) comprised within each group.

Group 1 databases, known as “materials and processes”, include inputs and outputs of the production of materials (e.g. aluminium) and of their processing (e.g. hot lamination), as well as the corresponding data related to upstream (i.e. energy and transportation) and downstream processes (e.g. disposal or recycling), in order to allow the modelling of the system process of a given product through the association of materials and processes. The most relevant databases included in this group are (ACLCA, 2009; CfD, 2001b; EC, 2009a;

EFCA, 2012; ENSLIC, 2012; Ferrão, 1998; Gervásio, 2010; PlasticsEurope, 2012; PRé, 2009; SERT, 2012; Silva *et al.*, 2007):

- Aluminium LCA (Australia) – developed for the “Aluminium Council”;
- APC/EPIC (USA/ Canada) – LCI of the American plastics industry, supported by the “American plastics council” (APC) and by the “Environment and plastics institute of Canada” (EPIC);
- BHP Steel LCA (Australia) – developed by “Broken Hill Proprietary Company” (BHP) and available in the LCA tool LISA (also developed by BHP), it includes environmental impact data from the LCI of more than 65 materials (e.g. consumption of energy and fuels, emission of greenhouse gases and of other substances, and water consumption);
- Boustead (United Kingdom) – includes general and building specific data from nearly 13,000 individual processes completed by Dr. Ian Boustead and available in the software with the same name (namely eco-profiles of the European aluminium and plastics industries - ordered by the corresponding industrial associations, and data from the production and processing of fuels from all over the world);
- Centre for Design at Royal Melbourne Institute of Technology (RMIT, Australia) – public database with information related to the origin of energy, processes, transportation, fuels, construction materials, glass and plastic of the Australian industry;
- Data for Environmental Analysis and Management (DEAM, France) – database of the LCA tool TEAM that includes information related to the energy, transportation, materials, production and end-of-life of more than 30 industrial sectors, namely from North America, Asia and Europe;
- Ecoinvent version 2.2 (Switzerland) – developed by the Swiss Centre for Life Cycle Inventories, updated in 2010 and included in the most commonly used LCA tools, it includes LCI data and extensive background reports from 4,000 industrial processes (including energy-related data - energy mix of more than 25 European countries, transportation, construction materials, metals, wood-based and chemical products, paper and cardboard, and waste management) built with data mainly from Switzerland and Western Europe (average industry, survey or literature based, but also processes from the compilation of other databases such as BUWAL 250 database of packaging materials and ESU ETH 96);
- Embodied energy data (School of Architecture and Design, Deakin University, Australia) – produced by Graham Treloar and used by the CSIRO Sustainable Ecosystems (CSE) in its building modelling tool (CSIRO - embodied energy 3D CAD tool);

- EMPA (Switzerland) – developed by the "Federal Laboratories for Materials Science and Technology", it includes data from energy, input and output flows for different processes, transportation and electricity production;
- Envest (United Kingdom) – database included in the tool with the same name and that includes information from energy suppliers, production and transportation, setting up life cycles from cradle to grave of a limited number of chemical, plastic and wood-based products;
- European Life Cycle Database version 2.0 (ELCD; European Union - EU) – being an open access database developed with funds from the EU (European Platform for LCA), constantly updated and with a focus on data quality, consistency, and applicability. It includes the LCI of 300 processes supplied by associations of producers from the EU and by other sources for the most common materials, energy suppliers, transports and waste management (EC, 2009a);
- Eurofer (Belgium) – free LCA database that includes data specifically for carbon and stainless steel products;
- European Federation of Concrete Admixtures Associations (EFCA) - this organisation freely provides detailed eco-profiles (EPD) of six types of concrete admixtures (plasticisers, superplasticisers, retarders, accelerators, air entraining and water resisting admixtures);
- Franklin (USA) – LCI database for metals and plastics, last updated in 1998, including data related to energy, transport and processing, which was developed by "Franklin Associates";
- GaBi (Germany) – data records included in the LCA tool with the same name - and developed by the same company (PE International), that include data on several energy supplies, and production and end-of-life data of materials (e.g. metals, organic and inorganic intermediate products, plastics, minerals and construction materials);
- Inventory of Carbon and Energy version 1.6a (ICE, United Kingdom) – developed at the Department of Mechanical Engineering of the University of Bath, it includes an inventory of embodied energy and carbon of about 170 building materials and of other primary and secondary materials, which is freely available in a PDF file;
- IDEMAT 2001 (Netherlands) – developed by Dr. Hans Remmerswaal from the Faculty of Industrial Design Engineering of the Delft University of Technology, and last updated in 2001. It includes data from 508 processes, namely from materials (metals, metallic alloys, plastics and wood), energy and transportation;

- KCL-EcoData 11 (Finland) – included in the software KCL-Eco, includes files from 215 wood-based products with data from the extraction of raw materials, processing and waste management;
- Kerbside disposal LCA (Australia) – developed for EcoRecycle;
- Plastics Europe – this organisation freely provides detailed eco-profiles of almost every plastic product available on the market, which are also available in Ecoinvent and ELCD database;
- SimaPro (PRé, Netherlands) – data records included in the LCA tool SimaPro - and developed by the same company, that include energy, transportation and waste management data of materials and processes based on several public sources;
- PVC-LCA (Australia) – developed for the Australian vinyl industry;
- Sustainable Product Information Network for the Environment (SPINE, Sweden) – developed by the "Swedish Competence Centre" of the "Centre for Environmental Assessment of Product and Material System (CPM), it includes data to support the environmental evaluation of the Swedish industry (e.g. electricity, heating, fuels, chemicals, natural materials, polymers, metals, construction materials, painting processes and sustainability reports);
- US LCI Database (USA) – developed by the "National Renewable Energy Laboratory" (NREL) and by Athena (Sustainable Materials Institute in Canada), this open access database was last updated in 2008 and contains inputs and outputs (material and energy flows) for common unit processes (e.g. metals, wood, energy, transportation and waste management, including a group devoted to building and construction products), which were critically reviewed.

Group 2 databases, named "components" (e.g. construction assemblies), include inputs and outputs of elements constituted from different individual materials and processes (e.g. sandwich panel). This information allows the comparison of products with similar functions without the need for detailing their raw materials and corresponding production processes. In the construction sector, these databases ease the LCA application in levels 2 and 3 tools, dispensing the use of level 1 tools. Some relevant databases included in this group are (CfD, 2001b; EC, 2009a; ENSLIC, 2012; Ferrão, 1998; ITEC, 2012; PRé, 2009):

- Athena (Canada) – LCI database used in the level 2 tool with the same name, it includes data for energy use and related air emissions for on-site construction, maintenance, repair and replacement, demolition and disposal for two main groups of components: structural elements (i.e. wood, steel or concrete elements) and elements of the envelope (e.g. discontinuous elements, gypsum plasterboard and corresponding finishing, insulation materials, windows, curtain walls and paints);

- BEDEC (Spain) – developed by “Institut de Tecnologia de la Construcció de Catalunya”, includes the energy (and also the economic) cost, CO_2 emissions, and application and packaging waste of 565,000 elements for new and refurbished buildings and for other construction works;
- IVAM 2.0 (Netherlands) – developed by “IVAM – Environmental Research”, last updated in 2005 and used in LCA tools Eco-Quantum and SimaPro, it includes information related to energy, transportation and waste management of about 1,350 processes from 350 materials, including construction processes (corresponding to a compilation of APME database of plastics and chemical products, of BUWAL 250 database of packaging materials and of ESU ETH database), mainly according to the Dutch reality;
- LCAid (Australia) – included in the level 3 LCA tool with the same name and developed according to the “Boustead Life Cycle Assessment Method”, it includes data for 97 building assemblies (including floors, walls and roofs).

Group 3 databases contain operational and performance data, namely information concerning the mix of energy consumed and water consumption, orientation, insulation, use and lighting of buildings. Relevant databases included in this group are (CfD, 2001b; EC, 2009a; Ferrão, 1998; PRé, 2009):

- Australian Residential Building Sector Greenhouse Gas Emissions 1990 – 2010 (Australia);
- Ecotect (a tool developed in Australia but acquired by Autodesk, in the USA) – available in the modelling tool with the same name, it includes energy and water consumption;
- LCAid (Australia) – available in the LCA tool with the same name, it includes average temperature, rainfall and water consumption of several Australian regions;
- Lipasto (Finland) – database of emissions from vehicle traffic depending on the type of load (persons or materials), which is applicable to road, railways, water and air transportation;
- Nationwide House Energy Rating Scheme (NatHERS, Australia) – Australian system for the certification of a building’s energy modelling tools.

5.3.2. Level 2 LCA tools

Level 2 LCA tools can be used to support decisions during the design process based on LCA data of construction assemblies or of the whole building. In fact, these tools provide oriented and objective data that can be used from the early to detail design stage. OF the most used tools of this group, ATHENA (Environmental Impact Estimator for buildings) was developed in Canada by the "Sustainable Materials Institute" (Athena, 2009). This tool allows the determination of the LCA of the whole building from "cradle to grave", considering the construction assemblies (structure and envelope elements, such as external walls) chosen in the design stage and using data from North America.

Envest 2 is an LCA tool developed in the United Kingdom by the "Building Research Establishment" (BRE) as a web-based tool to be used in building design. It includes a generic LCI database, and provides the LCA, and the corresponding cost of each alternative building assembly (CfD, 2001a; EA, 2000a; Edwards & Anderson, 2002; Erlandsson & Borg, 2003; Graham, 2000).

A detailed comparative study was completed for five level 2 building LCA tools: The Environmental Load Profile (ELP), BEE 1.0, Eco-Quantum, BEAT 2000 and EcoEffect (Forsberga & Malmborg, 2004). These five tools have in common the fact of: being applicable to the whole life cycle of products; being software-based with an emphasis on mathematical modelling; having the aim of proving the best option for a given use; and having been developed in the North of Europe using governmental funds (Forsberga & Malmborg, 2004).

The Swedish tool (ELP) differentiates itself for being applicable at the neighbourhood level. In fact, it was developed to evaluate and supervise the environmental performance of new (or refurbished) buildings of a neighbourhood in Stockholm. The outputs of this tool correspond to the socio-economic effects (*per capita* or square metre of built-up area) calculated from the estimation of repair costs. The Finish tool BEE 1.0 also has a restricted application field, being used to analyse the proposals for a national Architecture competition from an environmental perspective (Forsberga & Malmborg, 2004).

In the Netherlands, the Eco-Quantum tool (developed by IVAM and W/E consultants) already has a commercial purpose and provides weighted results (in comparison with a reference building) for the complete life cycle of new or refurbished buildings. This tool has a weighted mode which can be chosen depending on the intended use: by material, by assembly, or by life cycle stage; by unit of built-up area or of volume, or *per capita*. It is based on relevant environmental information of construction materials supplied by producers and in the LCA modelling used in SimaPro software (see 5.3.1), but it is only available in Dutch (Forsberga & Malmborg, 2004).

The Danish commercial tool BEAT 2000 allows the optimisation of the environmental performance of new or refurbished buildings by providing the results by construction material, *per capita* or by square metre of built-up area. This tool uses LCA data from national producers of construction materials and data from scientific reference literature for imported materials (Erlandsson & Borg, 2003). The EcoEffect tool (only available in Swedish and not commercialised) allows the environmental evaluation of existing buildings and the determination of their WLC (presenting the results *per capita* or by square metre of built-up area) (Forsberga & Malmborg, 2004).

All five tools include the building materials and processes (i.e. construction materials and assemblies and corresponding construction processes), the life cycle stages (e.g. operation of the building, maintenance actions and demolition - only BEE 1.0 does not include the latter stage) in the environmental assessment. Commercial tools Eco-Quantum and BEAT 2000 allow the user to define a service life for the components and for the whole building.

As described in Chapter 2, a program called EcoBuild was developed at Minho University (in Portugal), to compare the environmental impacts and the construction costs of a building with a reinforced concrete frame structure with an alternative structure in steel profiles. The environmental impacts (energy and water consumption and CO_2, SO_2 and NO_x emissions) from the phases of production of construction materials and transport to site can be calculated by defining the type and quantity of each construction material used (but there is no information available concerning the commercialisation of this tool). The database of the program was built with information collected from national producers of cement and steel bars, aggregate suppliers and one Spanish factory of steel profiles (Peyroteo *et al.*, 2007; Torgal & Jalali, 2007).

5.3.3. Level 3 LCA tools

Level 3 LCA tools use either objective (based on level 2 tools, namely on LCA of construction assemblies) or subjective inputs to make the evaluation of the building’s global performance. Chosen environmental, economic and social criterions are therefore subjectively weighted to achieve a single indicator that can be used to aid design choices (Trusty, W., 2004).

According to Cole (2005), building environmental assessment techniques should be divided in two groups (and not in three levels): construction LCA tools and “Building Environmental Assessment Systems” (BEAS). BEAS (first in chronological order and presented in detail in Chapter 2) can be considered level 3 LCA tools, but only when they include environmental performance criterions in their structure that are explicitly evaluated using LCA standardised methodology (from a cradle to grave or cradle to cradle perspective). However, the majority of BEAS do not yet consider criterions compulsorily evaluated using this methodology because it is necessary to (Pinheiro *et al.*, 2007):

- Develop a wide and significant database, and an information repository (e.g. appropriate LCA database), associated with LCA practice. This information should be compiled and maintained with the permanent support of the professionals from the industry of construction material production, but the majority of companies from this sector are not available to supply this data;
- Develop case studies of different types of common buildings in different regions to be used as reference. Therefore, the entity responsible for the BEAS has to define the methodology to compare the results of each building with the reference building according to the BEAS structure.

The BEAS that includes the greatest quantity of LCA practices and methods is SBTool (former GBTool) (Pinheiro *et al.*, 2007). This system (already presented in detail in Chapter 2) includes LCA within its assessment criterions, based on the quantification of the embodied energy of construction materials and assemblies per square metre of built-up area. This environmental burden can be quantified using LCI data provided by the system or using an external LCA tool. The Portuguese version of this BEAS - SBTool^{PT} - contains an LCA database of the most common construction materials and assemblies of buildings. This database includes only the LCA results (by built-up area of construction assembly or kilogram of construction material, and divided by the stages from cradle to grave and "demolition/waste treatment") for the most common environmental impact categories used in EPD based on generic international LCA data sets (see 5.3.1.1) (Bragança & Mateus, 2008; Graham, 2003; Mateus, Ricardo, 2009; Pinheiro, 2006).

A potential development of the use of LCA data in the BEAS relies on the increasing systematisation of environmental performance data of construction materials and assemblies, which can progressively make the integration of this dimension in building assessment for all BEAS unavoidable (Pinheiro, 2006). A summary of the LCA use in the most important BEAS all over the world (these BEAS have already been presented in detail in Chapter 2), which correspond mostly to criteria related to the evaluation of the environmental performance of construction materials and assemblies chosen for the building, is presented next:

- BREEAM (United Kingdom) – the "Building Research Establishment Environmental Assessment Method" includes the evaluation of the environmental impact of finishing materials along their service life in the criteria related with the responsible source of the materials chosen (Pinheiro *et al.*, 2007). The “Code for Sustainable Homes” is the BREEAM version for residential buildings and includes a “Green Guide” for the prescription of building products, which is easy to use and is based on LCA studies (Mateus, R. & Bragança, 2008; Pinheiro, 2008);

- Green Globes (Canada) – includes LCA in several criterions (use of construction materials and assemblies of low environmental impact and minimisation of resource consumption), including a LCI database developed by the “Athena Sustainable Materials Institute” (ASMI). However, the correlation between the LCI profiles and the environmental assessment criterions was not disclosed to the public (Bragança & Mateus, 2008);
- HQE (France) – includes the use of LCA in the criteria related with the integrated choice of construction materials, processes and systems, in order to decrease the environmental impacts of building construction (Pinheiro *et al.*, 2007);
- LEED (EUA) – this BEAS does not include LCA-based criteria, but it values construction materials produced locally, with recycled content, that do not produce wind-blown dust during the construction process and do not decrease the indoor air quality (Bragança & Mateus, 2008; Sharrard, 2007; Trusty & Horst, 2002);
- LiderA (Portugal) – version 1.02 includes only two criteria that explicitly accept LCA results (from an external software) corresponding to the use of construction materials produced locally (less than 100 km, minimising the effects of transportation) or with low environmental impact (environmentally certified, recycled or with better environmental performance) in building construction (Pinheiro, 2008). The future versions of this BEAS will have increased focus on LCA and WLC.

The need for LCA integration in BEAS to replace current criterions for the assessment of the environmental performance of construction materials and assemblies should be considered, namely because existing criteria are prescriptive and solutions are performance-oriented, instead of assessment-oriented (e.g. to advise the use of 100% of recycled material may not always lead to the improvement of the environmental performance because of the energy needed for recycling, but an LCA study from cradle to grave of the alternatives can lead to the best option) (Pinheiro *et al.*, 2007). Typical criteria are also “qualitative” (e.g. natural, local, renewable or recycled materials, and certified wood) and not even based on an LCA study from cradle to grave. These criteria can lead to the selection of: a natural material with less durability; a less efficient local material; a renewable material with higher impact during manufacturing; a recycled material with higher impact due to recycling; certified wood from abroad with significant impact from transportation (Campioli & Lavagna, 2007).

Therefore, the trend can either be to incorporate LCA methods in BEAS, or the complementary use of BEAS and levels 1 and 2 LCA tools in a robust and satisfactory solution for the effective assessment of buildings, these tools being the providers of objective data related with the environmental performance of construction materials and assemblies to be used in the corresponding BEAS criterions (Trusty & Horst, 2002). However, it is possible to go further and consider the replacement of current BEAS by new ones that totally incorporate LCA and that can be decision-support tools in building design (Pinheiro *et al.*, 2007).

LCA tools integrated with or within “Computer-aided design” (CAD) software can also be included in this category. These tools can read information concerning construction materials or assemblies included in CAD drawings and calculate the corresponding environmental impacts. Usually, they can also have modelling capacities, therefore being known as hybrid tools. In ideal terms, these tools should have the precision of detailed LCA devoted tools, a simplified interface and the ability of handling three dimensional data. Some examples of the tools already all over the world that belong to this group are provided below (CfD, 2001b; Chevalier *et al.*, 2010; Graham, 2003):

- CSIRO (Sustainable Ecosystems – CSE) / embodied energy 3D CAD tool (Australia) – building modelling tool that includes ”Embodied energy data” produced by Graham Treloar (School of Architecture and Design, Deakin University);
- Ecotect (USA) – a tool developed in Australia but acquired by Autodesk (owner of Autocad software) and used mainly for modelling buildings at the conceptual design stage (including the analysis of solar exposure, lighting, energy consumption, shading, natural ventilation and acoustic comfort) using a three dimensional interface. This tool is linked to LCAid (level 3 LCA tool) software in order to provide information related with the LCA of the alternative construction assemblies represented in three dimensions, including the embodied energy, greenhouse gases and costs;
- ELODIE (France) – developed by the “Centre Scientifique et Technique du Bâtiment” (CSTB), this tool is based on the “Building Information Model” (BIM) and provides the evaluation of the environmental impacts of construction materials and assemblies at the building design stage (using, since 2007, the information of the EPDs available in the public national database INIES) and the estimation of the water and energy consumption during the building design life;
- ENER-RATE (USA) – updated version of ENER-WIN (thermal and energetic building simulation tool) to analyse the environmental performance of buildings at the conceptual design stage, generating environmental impact profiles which can be compared with a

reference building (which can be an existing building introduced by the user), the user having the possibility of defining weights for each environmental category. The annual energy consumption, heating and cooling needs, annual and monthly energetic costs, energy use, CO_2 emissions through the service life, whole-life costing and embodied energy of envelope elements, can all be estimated depending on the geometry, location and type of building;

- LCAid (Australia) – developed by the "New South Wales Department of Public Works and Services – Environmental Services", combines LCA results of construction materials with the building modelling capacities of Ecotect tool.

Beyond levels 1, 2 and 3 tools, there are many other software tools to support the sustainable design of buildings. Energetic simulation tools can be highlighted among them, despite that this function can be included in all-inclusive LCA tools, namely in level 3 ones. However, tools such as the "Energy Express for Architects" of "CSIRO Sustainable Ecosystems" (CSE) (an Australian tool that replaced BUNYIP) BEAVER/ ESPII and DOE 2.2 tools in the USA allow the dedicated assessment of the buildings thermal performance (Graham, 2003). The "U.S. Department of Energy" (USDE, 2007) provides a directory of the tools (available worldwide) for the energetic analysis of buildings.

5.3.4. Definition of the LCA tool to be used in this thesis

The analysis of LCA tools presented in section 5.3 allowed the characterisation of the main general and specific LCA software available at an international level. These tools can support the LCA of construction products and assemblies, namely of the ones studied in this thesis. However, to allow the detailed LCA study (including editing of process flow data) of single products and their arrangement in assemblies, level 1 tools are the most adequate option (ARUP, 2006). These tools support the modelling of the production stage using process-specific data but also the evaluation of the contribution of the remaining life cycle stages (i.e. transportation to the building site, on-site construction, and construction and demolition waste disposal) and of each material included in a component or building (ARUP, 2006). They also include databases that provide data to model upstream processes (e.g. transportation and energy supply) of the life cycle of the products using generic data adequate to each country. Then, the LCA of the corresponding construction assemblies can be completed considering the service life predicted for each construction material.

Level 1 LCA tools that were considered the most adequate to be used in this thesis (from the ones described in 5.3.1) are characterised in Table 5.1.

A comparative study between LCA tools was foreseen in the first research plan of this thesis. This study would include the simulation of the LCA of two of the most common solutions for external walls of buildings in Portugal using demo versions of GaBi and SimaPro software. Then, their databases would be exhaustively tested, the results achieved using each tool would be analysed and compared, and the capabilities of these tools would be confirmed. However, this study was not completed due to the limitation of features and databases available in the demo version of these LCA tools.

LCA tools differ according to their scope and geographical origin, transparency and quality of the included inventories. Therefore, the choice of the most adequate LCA tool should take into consideration (Ferrão, 1998; Oliveira *et al.*, 2008):

- The contribution of the tool to the arrangement of data and to minimise the effort necessary for the inventory analysis or the evaluation of impacts;
- The reliability of the inventories needed for the analysis and the quality of data management, because these issues directly influence the quality of the results;
- The compatibility or the tool with other software tools, in order to allow the LCA results to be used in the most adequate manner to support design choices.

Taking into account these preliminary reflections, the LCA tool chosen to be used in this thesis was SimaPro, in its version 7.3.3 (PRé, 2012). This tool was chosen because of:

- Its international market share (which guarantees an adequate longevity and support of this software);
- The offer of (paid) training courses for new users;
- The availability of a fully functional Academic – PhD – version, including all necessary LCI and LCA databases (namely the widest range of LCI and LCA databases available worldwide in a LCA software (ARUP, 2006));
- The flexibility of “contextualising” the processes included in the databases (namely adapting background data such as energy and transport processes to a national context) and switching between available impact assessment methods (ARUP, 2006).

The use of the most adequate LCA tool is essential in achieving the LCA of the system processes being studied according to International and European standards, namely to provide innovative LCA data from cradle to cradle of construction materials and assemblies used in buildings in Portugal.

Table 5.1 – Characterisation of level 1 LCA tools: GaBi and SimaPro (CfD, 2001b; EA, 2000b; EC, 2009b; Pinheiro, 2006; USDE, 2007)

Software	GaBi	SimaPro
Country (Organisation)	Germany (Institute for Polymer Testing and Polymer Science at the University of Stuttgart and PE Europe GmbH)	Netherlands (Pré-Consultants)
Webpage	http://www.gabi-software.com/international	http://www.pre-sustainability.com/content/simapro-lca-software/
Main features	- Modelling and LCA of processes - Whole-life cost - Data exportation to external spreadsheets - LCA database of construction materials (e.g. aggregates, minerals – including concrete-based products, claddings, windows, wood-based materials and by-products, insulations, metals and plastics, construction and demolition wastes disposal scenarios, concrete pumping, among others) developed in collaboration with the *German building materials association* (BBS) - Ecoinvent database not included in the standard version	- Modelling and LCA of complex life cycles following ISO standards (ISO, 2006a, 2006b) via the detailed analysis of the production processes, of the assembling of the products, and of the waste disposal and recycling scenarios - Sensitivity analysis of different scenarios using charts and flowcharts - Table and chart exportation to external spread sheets and word processors - LCI data of 4,000 industrial processes (from the Swiss and Western European industry, but also other LCI databases available worldwide), including the production of construction materials (namely from Ecoinvent database) in all versions

5.4. LCIA of the “Product stage” (A1-A3) of the building products studied in this thesis

Nowadays, the main aim of LCA of construction materials (using level 1 tools – see 5.3.1) is the determination of the environmental performance of the building in level 3 tools, namely to be used in BEAS (see 5.3.3) (Pinheiro, 2008). To provide a more controlled, realistic and precise building LCA, the approach has to be changed in order to be focused on the main parts of the building – complete construction assemblies – in accordance with the methodology of level 2 tools and using LCA data on construction materials available in level 1 tools. To put this approach into practice, this thesis proposes the beginning of this research work, starting with one of the construction assemblies of the building envelope: the external walls.

The first step to provide reliable LCA data of external wall solutions is the collection of LCA results for building products included in Portugal in this type of assembly. However, as stated in Chapter 4, no more than five LCA studies of building products are publicly available in Portugal to date (Almeida, 2010; Almeida *et al.*, 2010; Concretope & INETI/CENDES, 2005). This fact justified the need to complete a considerable number of additional LCA studies of products from national plants in the scope of this thesis using the LCI methodology described in Chapter 4. The corresponding LCA results, together with the ones already available, provide consistent and up-to-date LCA data of several solutions for external walls of buildings in Portugal.

LCA results for building products included in external walls are presented in two different sections of this thesis. LCA results from the studies completed in the scope of this thesis are presented next in this chapter, right after the description of many important presuppositions that have been considered in the LCIA phase of these studies. LCA results for building products that have not been included in the field work of this thesis were chosen from available data sets (including LCA studies publicly available in Portugal to date) using an innovative methodology (NativeLCA) proposed in Chapter 6 of this thesis.

5.4.1. Preliminary considerations concerning the modelling procedure

Many options made during the LCI stage (i.e. in the modelling of the manufacturing of the products studied in the scope of this thesis) have consequential and significant influence on the corresponding LCA results achieved. The discussion of these issues is included in this chapter (instead of Chapter 4, related with LCI) because they are more related with the modelling of the production processes in the software and with the LCA results than with the LCI procedure (e.g. data collection, calculation or analysis). Finally, the description of these presuppositions establishes a coherent methodology for all the studies completed in the scope of this thesis.

Modelling is considered to be the most demanding stage of a LCA, namely because of including the following sub-stages (adapted from (Blengini, 2006)):

- Creation of unit processes and their inter-linkage;
- Assignment of input and output flows to each process, verifying whether mass and energy balances are observed and internal and external recycling loops are properly generated;
- Definition of LCA calculation rules to allow the software to provide the correct quantity of environmental interventions (e.g. of energetic and non-energetic resources, pollutant emissions and solid wastes) to each process.

While site-specific data was used to model the manufacturing process (A3, as described in Chapter 4) for each material studied, raw material extraction and processing, processing of secondary material input (A1) and transport to the manufacturer (A2) were modelled using generic LCA data available in SimaPro software. Nevertheless, generic data sets were also used to provide background data to model the A3 sub-stage (e.g. energy or water supply, transportation processes or infrastructures). This section of the thesis includes, therefore, a self-justified description of the process of selection of generic data sets to model these upstream processes. Some of these data sets were also modified after being selected (e.g.: electricity production mix; transportation modelling; waste disposal and treatment processes) in an approach known as “contextualisation” (Peuportier et al., 2011), to improve their representativeness for the Portuguese context (Ibáñez-Forés et al., 2011).

5.4.1.1. Processes for modelling the “raw material extraction and processing of secondary material input” (A1)

The selection of the LCI data sets to model the background process of the “production” of a raw material for a given product is of paramount importance in any LCA study. The choice is even more important when the manufacturing (A3) is not energy intensive and most of the environmental impacts come from the A1 sub-stage. The practitioner always relies on available data sets (namely in the ones available in his LCA software) to make his choice and, therefore, it is not easy to have a straightforward and coherent approach in this procedure, despite the cases where only one data set is available for that specific raw material. This question thus arises very frequently during a LCA study and, not only because of its frequency but also due to the influence of its answer in the final results of the study, it is of paramount importance in providing a decision framework for the practitioner to make his choices always coherent and based on a scientifically robust methodology.

The author has identified the need for such a methodology when modelling the production processes of the construction products studied in this thesis and has also found that the increasing number of LCI and LCA data sets available in Europe (namely in databases but also from EPD and environmental profiles from industrial organisations) turn it into an more increasingly required tool. Consequently, an innovative methodology - NativeLCA - with the aim of answering this need of LCA practitioners (namely of those working in the building sector) was developed in the course of this thesis and is presented in detail in Chapter 6. The selection of the LCI data sets to model the background processes of “production” of raw materials for the construction products studied in this thesis was already made using NativeLCA methodology and is summarised in Table 5.2. Examples of the application of this methodology for some of these products (i.e. cement, LECA and EPS) are presented in section 6.2 of Chapter 6.

It is also important to highlight that the use of background data taken from available databases (e.g. for extraction/production and transportation of raw materials, and for electric energy) in most of the LCA studies of construction products, namely for EPD, corresponds to an almost unavoidable limitation due to time and resource constraints. However, this practice always influences the LCA results, even when the data used for the manufacturing sub-stage (A3) is based on questionnaires answered by manufacturers (Pargana, N. G. S. C., 2012).

5.4.1.2. Infrastructure processes

As described, generic data sets were used to model “product stage”, namely energy or water supply or transportation (for upstream processes of the A1 and A2 sub-stages and to provide background data for the A3 sub-stage). Each of these generic processes includes therein other processes usually designated as “infrastructure processes”. Infrastructure processes correspond to all capital equipment and machinery (i.e. factories, equipment and machine) used to: extract and process materials; manufacture products; produce and supply energy, supply water, process waste and transport goods (EeBGuide, 2012, p. 69). These are also known as “capital goods” - goods that are a one-off investment (e.g. trucks or machines) (PRé, 2010).

Actually, generic data sets can include or exclude infrastructure processes depending on their policy or cut-off rules (EeBGuide, 2012). Ecoinvent, for example, has the principle of including these processes for energy (e.g. wind and hydropower) and transport systems (PRé, 2010). Then, when this database is used in SimaPro software, it is optional to include them in the calculations. But this option only has consequences for “Ecoinvent unit processes” (where all flows are individually visible, including their uncertainty data), because “Ecoinvent system processes” (whose content correspond only to the final output flows) work as not modifiable “black boxes” with fixed LCA results (PRé, 2010).

In fact, the inclusion of infrastructures is especially important for processes used as background data, such as energy (e.g. not including infrastructures when modelling energy from hydropower, wind turbines or photovoltaic cells corresponds to using an empty model) and transport systems, and should not be discarded when generic data sets are used in LCA calculations, namely due to the application of cut-off rules (EeBGuide, 2012; PRé, 2010). Infrastructure processes were therefore considered for the generic data sets used in the studies included in this thesis, whenever they were available in the corresponding database (except for some life cycle stages of transportation processes - see 5.4.1.4.1). These processes were not discarded not even when their significance was low because a restricted cut-off criterion was not defined in this thesis (see Chapter 4).

Table 5.2 - LCI data sets selected to model the background processes of "production" of raw materials (A1) with significant contribution for environmental impacts of the building products studied in this thesis (geographical area codes: European area – RER; United States of America – US; Ecoinvent codes: U for unit and S for system processes)

Building product		Raw material; process chosen (data age)	LCI/LCA databases (see 5.3.1.1)
Elements of the wall structure	**Lightweight concrete blocks**	Cement; Cimpor (Alhandra, Portugal) CEM II A-L 42.5 R (2003)	Site-specific data ((Blengini, 2006) - see section 2.4.2)
		LECA; Author data (see 5.4.3.4)	Site-specific data
	GFRC precast panels	Cement; Cimpor (Alhandra, Portugal) CEM I 42.5 R (2003)	Site-specific data (Blengini, 2006)
		Admixture for fibre protection; Polymethyl methacrylate (PMMA) beads, production mix, at plant RER (1996)	ELCD
		Glass fibre; Glass fibre, at plant/kg/RER (2003)	Ecoinvent
		EPS; Author data (see 5.4.3.6)	Site-specific data
	Stabilised (wet and ready-to-use) masonry mortar	Cement; Cimpor (Alhandra, Portugal) CEM II A-L 42,5 R (2003)	Site-specific data (Blengini, 2006)
		Fine sand; Sand 0/2, wet and dry quarry, production mix, at plant, un-dried RER S (2006)	ELCD
		Retarding admixture; Indicators for Eco-profile for 1 kg retarding admixtures, 17-46% solids (2005)	EFCA
Insulation materials	**LECA**	Clay; Clay, at mine/kg/CH (2003)	Ecoinvent
		Oil; Lubricating oil, at plant/kg/RER (2003)	
	XPS	Dimethyl ether; Dimethyl ether, at plant/kg/RER (2003)	Ecoinvent
		Polystyrene crystals; Polystyrene (general purpose) granulate (GPPS), production mix, at plant (2002)	Plastics Europe (ELCD)
		Difluoroethane; 1.1-difluoroethane, HFC-152a, at plant/kg/US (2007)	Ecoinvent
		Fire retardant; Chemicals organic, at plant/kg/GLO (2003)	
	EPS	Expandable polystyrene; Polystyrene expandable granulate (EPS), production mix, at plant RER (2003)	ELCD
	PUR/PIR	Polyol; Aromatic Polyester Polyols (APP) with Flame Retardant (2008)	PU Europe - Federation of European rigid Polyurethane Foam Associations (Schindler *et al.*, 2010)
		Isocyanate; MDI E (2000-2004)	Plastics Europe
	ICB	"Falca"; Raw cork, at forest road/kg/RER (2003)	Ecoinvent
Claddings	**One-coat dry mortar**	Cement; Cimpor (Alhandra, Portugal) CEM I 52,5 R (2003)	Site-specific data (Blengini, 2006)
		Retarding admixture; MEHEC (Methyl Ethyl HydroxyEthyl Cellulose) (2000)	International EPD system (I.EPDS., 2010)
		Pigments; Magnetite, at plant/kg/GLO and portafer, at plant/kg/RER (2007)	Ecoinvent
		Hydraulic lime; Lime, hydraulic, at plant/kg/CH (2004)	

Building product		Raw material; process chosen (data age)		LCI/LCA databases (see 5.3.1.1)
	Wood-plastic extruded boards	Recycled postconsumer plastic pellets; Recycled postconsumer HDPE pellet/kg/RNA (2010)		US LCI
		Anti-bacterial product; Chemicals inorganic, at plant/GLO S (2003)		Ecoinvent
		Ultra-violet (UV) protection product; Paraffin, at plant/kg/RER (2003)		Ecoinvent
	Two-component adhesive	Powder (comp. A)	Cement; Cimpor (Alhandra, Portugal) CEM II/A-L 42,5 R (2003)	Site-specific data (Blengini, 2006)
			Retarding admixture; MEHEC (Methyl Ethyl HydroxyEthyl Cellulose) (2000)	International EPD system (I.EPDS., 2010)
		Resin (component B)	Resin; Acrylic binder, 34% in H_2O, at plant/kg/RER (1995)	Ecoinvent
	Gypsum plaster-board	Recycled paper; Paper, recycling, with deinking, at plant/kg/RER (2003) and waste paper, sorted, for further treatment/kg/RER (2007)		Ecoinvent

Concerning the inclusion of infrastructure processes in life cycle stages for which site-specific data is used (i.e. modelling of a given manufacturing process using data collected from a specific site), there is no specific provision included in ISO or European Standards. However, the first draft of the "EeBGuide - Operational guidance for Life Cycle Assessment studies of the Energy Efficient Buildings Initiative" (EeBGuide, 2012) refers that infrastructure, capital equipment and machinery should be included in complete LCA studies, unless they have to be omitted due to the application of cut-off rules. The referred guide, based on European reference documents and Standards, also states that the option of excluding infrastructure processes from the assessment should be carefully evaluated because their relevance depends not only on the environmental category assessed but also on the nature of the manufacturing process. This recommendation is not in accordance with other sources that advise the inclusion of infrastructure processes only when they have a significant contribution to final LCA results (PRé, 2010). Capital goods can only be relevant when the number of manufactured products is very small (i.e. flow of raw materials input *versus* amount of materials used in buildings, equipment and machinery maintenance in the same period), when the capital equipment has a very short life span or the final product has extremely low impact (EeBGuide, 2012). This definition was taken into account to define the methodology followed in this thesis.

The construction products studied in this thesis do not have extremely low environmental impacts (see 5.4.3) and are manufactured at significant production rates in their production plants, while their capital equipment is not supposed to have a very short life span. Infrastructure processes were therefore not considered when site-specific data was used (e.g. the factory building and related flows, such as lighting and heating, the manufacturing or energy generation equipment or the vehicles for internal transports used in the A3 sub-stage, wherever a disaggregation was possible). The same option was also chosen in another PhD study concluded recently in Portugal (Gervásio, 2010). However, if the option was to include these processes, the corresponding data collection would be extremely time and resource consuming. In fact, even the information related to maintenance operations of the manufacturing equipment with a frequency lower than 3 years was only provided by one company, despite being requested by the author at the beginning of each individual LCI study.

If the studies included in this thesis are used for an EPD, they may have to be modified to comply with the corresponding programme rules (e.g. cut-off criterion, or inclusion or exclusion of infrastructure processes in the life cycle stages for which site-specific data is used). In the French EPD programme (FDES – see Chapter 2), for example, the procedure is similar to the one defined in this thesis: upstream processes from Ecoinvent are used, including the corresponding infrastructure processes; infrastructure processes are excluded when production processes of construction products are modelled.

Finally, it is important to clarify that the transportation of plant workers, and their water and energy consumption at plant, were also not considered for the manufacturing stage (A3) of the construction products studied in this thesis (even taking into account that a restricted cut-off criterion was not defined). This option was based on the fact that the impacts of these activities are usually minor when compared with the whole system process being studied (EeBGuide, 2012), and they are therefore also not considered in available EPD and LCA databases of construction products.

5.4.1.3. Energy processes

Processes included in the Ecoinvent database (Ecoinvent, 2012) for each energy carrier adequately represent the reality of the western countries, including Portugal, namely the interdependent network between countries that characterises the international trade of electricity (Blengini, 2006). Therefore, they were used as a basis to model the energy supply of the production processes studied in this thesis, while the corresponding quantification was made using site-specific data. Based on a specific composition of these energy carriers, the Ecoinvent database also includes processes that correspond to the national electric energy supply for residential ("Electricity, low voltage, at grid/PT U") and industrial ("Electricity, medium voltage, at grid/PT U") consumers, both based on the energetic mix of 2004. However, to accurately estimate the environmental impacts of the companies from the consumption of energy for production of the construction products studied in this thesis, the author updated these processes using the latest information available concerning the Portuguese electricity mix (data from 2011) (ERSE, 2012). The processes themselves were not actually modified, only their share in the national electricity mix. In fact, these types of processes have already been thoroughly studied in several research centres worldwide, and available LCA databases include the corresponding results (Blengini, 2006). Moreover, the modelling of energy supply systems is very complex because it involves several networks of suppliers, processing companies and distributors in a global context (Blengini, 2006). Therefore, Table 5.3 presents the differences between the Portuguese electric mix in 2004 and the updated one – of 2011, both for industrial and domestic consumption. These figures show an increasing contribution of renewable energy carriers (e.g. photovoltaic and wind power plants, the latter mainly for residential consumers) and a reduction in the most harmful technologies (e.g. hard coal and oil), which leads to a decrease of the environmental impacts of electric energy use. The use of the national electricity mix that expresses the present reality is even more important when the manufacturing (A3) is energy intensive and most of the environmental impacts of the life cycle of the product come from this stage.

Table 5.3 – Portuguese electric mix – differences between 2004 and 2011 for companies and residential consumers (Ecoinvent, 2012; ERSE, 2012)

Energy carrier	Ecoinvent (2004)	Electricity mix/PT – ERSE (2011)	
	Electricity mix/PT	Companies	Residential consumers
Hard coal, at power plant	31	25	14
Lignite, at power plant	1	0	0
Oil, at power plant	12	1	0
Natural gas, at power plant	25	26	15
Hydropower	21	21	15
Nuclear	4	8	5
Production mix photovoltaic	0	1	4
Wind power plant	3	4	32
Cogen with wood	3	4	4
Cogen with biogas	0	10	11

The collection of data of the energy consumption for the manufacturing of each declared unit was easier in some of the studies developed within this thesis because, in Portugal, industries that have a consumption of more than 1,000 tonnes of oil equivalent (toe) per year (plants named as intensive consumers of energy) have to be submitted to energy audits (Ferrão, 2009). The report of each energy audit is also a robust starting point for a LCA study (Ferrão, 2009).

5.4.1.4. Transportation modelling

The inclusion of transportation processes is mandatory for complete LCA studies. However, their environmental impacts (e.g. of the "transport of raw materials to the manufacturer") can be omitted due to the application of cut-off rules (CEN, 2012).

Several factors influence the environmental impacts of the transportation of goods (EeBGuide, 2012): the type of transport (e.g. lorry, ship, train); the loading factor/use ratio; the transport distance; and the maximum admissible load/payload (for lorries). The impact of these processes is usually more relevant for materials whose manufacturing process results in minor burdens (e.g. timber or aggregates). The impact of transport can be cut down if transport is by water instead of by train, or if it is by train instead of by road (EeBGuide, 2012).

The collection of transportation data from site-specific processes, namely from the transportation of each raw material to the manufacturer (sub-stage A2) and from each waste stream resulting from the manufacturing process (sub-stage A3), should at least include the travelled distance and the mode of transport. The transport distance of each raw material to the manufacturer should correspond to the path between the places of raw material processing all the way to the factory. For waste streams, the total distance should represent the route between the factory and the waste treatment plant (EeBGuide, 2012). Remaining data gaps can be filled with default values (i.e. use of lorry types, or even of average distances and loading factors, available in generic databases) in order to reflect the present transportation practices (EeBGuide, 2012). In fact, transportation processes have already been thoroughly studied worldwide and available LCA databases include results suitable for each geographical area, so there is therefore no need to collect primary data (Blengini, 2006).

Transportation processes were modelled (in the studies included in this thesis) mainly using data provided by the manufacturers (i.e. mode of transportation and average distances, and also lorry types and loading factors when applicable) or default values from generic data sets. These processes were not discarded, not even when their significance was low because a restricted cut-off criterion was not defined in this thesis (see Chapter 4). Then, generic datasets of transportation per kilogram*kilometre (including e.g. a typical vehicle size and payload, fuel efficiency and % of empty return or coming journeys – the latter corresponding to the trip of the lorry to the plant e.g. when it has to pick up waste for disposal (EeBGuide, 2012)) were used to calculate the environmental impact of the transportation of a specific load in accordance with the data collected on-site. The next sub-sections describe in more detail the procedure followed in this thesis to choose generic datasets for road, train and water transportation.

There were, however, two transportation processes that were not modelled in the studies included in this thesis: the transportation of the packaging of the raw materials; and the transportation of the wrapping materials of the packaging materials of each construction product. In fact, the transportation of the raw materials and of the packaging materials was modelled in accordance with the corresponding input flows per declared unit, but the transportation of their wrapping materials was not considered in the model (on the contrary, their production and final disposal were taken into account). Two main reasons led to this decision: the insignificant environmental impact of these processes; the impossibility of isolating these flows from the global packaging waste streams accounted for in each plant in order to find the corresponding packaging weight and consider the corresponding transportation.

A final remark should be made concerning “gate-to-gate” (or internal) transportations. European Standards state that the A2 sub-stage should include the environmental impacts from transportation of raw materials up to the factory gate, and also “internal transportation” (CEN, 2012). These “internal transportations” can be understood as the operations of raw material unloading at the factory gate and of their internal transportation and storage. However, in most of the studies completed in this thesis it was not possible to make such a disaggregation because the manufacturer only provided the total amount of energy and diesel consumed “gate-to-gate”, including diesel and electric stacker consumptions for the whole manufacturing process. Therefore, for the calculation of the results presented in 5.4.3 it was considered that A2 sub-stage includes only the transportation of raw materials up to the factory gate, while internal transportations were included in sub-stage A3 (namely A3.2 - see 5.4.1.5.2). This option was also justified because sub-stage A3 should include all the processes the manufacturer has influence over (see Table 4.3 – Chapter 4), and internal transportations are included in these types of processes.

5.4.1.4.1. Roadway transportation

The manufacturers characterised the transportation operation of each specific load by road describing the lorry type, payload, loading factor, average distance and return or coming trip (empty, full load or other). Then, a generic data set of transport per tonne*kilometre (which refers to a mass of 1 tonne travelling for 1 km (Blengini, 2006)) was used to model these operations and calculate the corresponding environmental impact. The generic data set chosen for road transportation of bulk commodities or packaged goods was ELCD. This option was made because this database:

- Is up-to-date and includes processes that adequately represent the European reality, namely for transportation operations (EC, 2009a);
- Considers a weighted average of lorry for emission standards from Euro classes EURO 0 to EURO 4 (from more to less pollutants, in decreasing order);
- Defines a loading factor of 85% for each transportation operation, which is considered a realistic amount (SETAC, 2003);
- Does not consider average truck journeys (including namely loaded and unloaded journeys) to also take into account the return trips;
- Includes three transportation system processes whose characteristics are suitable and sufficient to model any of these operations adequately (Table 5.4)
- Does not consider vehicle production and end-of-life treatment because these life cycle stages are considered negligible from a LCA point of view;
- Is available in SimaPro software, including the documentation of each process.

In fact, ELCD defines a lorry loading factor of 85% and does not consider average lorry journeys to take into account the return trips. Therefore, the environmental impact of each transport per km is divided by this amount (85% of the payload of each vehicle). This assumption allows the modelling of empty return trips (up to 200 km) by considering a simulated full load (85%) transport along an additional distance equal to 70% of the coming trip, resulting in a total distance of 1.7 times the latter. Only a parcel of 70% of the environmental impacts of the return trip is considered because an unloaded truck has a consumption of about 70% of a fully loaded truck (Blengini, 2006). Thus, it is possible to estimate and consider the environmental impacts of the empty return trip (considering the real distances provided by the manufacturer) and allocate them to each tonne of raw material delivered at the factory (or to each tonne of waste stream collected in the same place). The use of the Ecoinvent database does not allow this detailed and realistic modelling of empty return (or coming) trips because its transportation processes are based on average truck journeys, including therefore estimated loaded and unloaded journeys to directly take into account the return trips, no matter what is the real practice.

Table 5.4 – Characterisation of transportation system processes included in ELCD and available in SimaPro software (EC, 2009a)

Process name	Euro class	Total weight (ton)	Maximum payload (ton)	Loading factor (%)	Average load (ton)
Small lorry transport	0 to 4 mix	7.5	3.3	85	2.805
Lorry transport		22	17.3		14.705
Articulated lorry transport		40	27		22.95

Concerning the modelling of extensive return or coming trips (more than 200 km), a common criterion was applied to all system processes. It was assumed that the lorry goes in full load after 200 km of the return (coming) when the distance of this trip was higher than this value (and only from 200 km) and the manufacturer states that he left the factory empty (or arrived empty at the factory to collect a waste cargo). To model this return trip, it is again considered that an unloaded truck has a consumption of about 70% of a fully loaded truck (Blengini, 2006). For example, when a lorry delivers raw material at the factory and returns empty on a 350 km trip back to the supplier, a total transportation distance of 490 km (350 for the delivery plus 200*0.7=140 km to return) was considered. Despite the fact that the lorry left the factory empty, it was considered that it will be refilled in an average distance of 200 km from the factory. This option was taken because it is the supplier who pays for the transportation service (while the manufacturer does not have detailed information about the return trip) and it was considered that it represents a more than probable practice to optimise the transportation costs.

The option for a more detailed modelling of these kind of processes (e.g. assuming a specific Euroclass or modelling the number of deliveries of a lorry) is only justified when this stage is significantly important for the environmental impacts of the system process being studied (EeBGuide, 2012).

5.4.1.4.2. Railway transportation

Generic databases available in SimaPro software only include one process suitable to model the national reality of railway transportation of bulk commodities or packaged goods. This system process, entitled "Transport, freight, rail/RER S", includes the production, maintenance and disposal, along with the operation, of the vehicles, considering a current modern locomotive. The construction, maintenance and disposal of the railway infrastructure are also considered (Ecoinvent, 2012). Almost all data for this process was collected in Europe (15 European countries, including Portugal), and represents therefore the average train transport conditions in this area. Data for rail infrastructure and vehicle disposal reflect however Swiss conditions. Concerning the technology of vehicle operation, this process considers average data from available technologies (i.e. electric and diesel locomotives) per ton*kilometre, according to the extrapolation for the remaining countries of the technology share of the German railways (Ecoinvent, 2012). Full load return trips were always considered for the railway transportation processes used in the LCA studies completed in this thesis.

5.4.1.4.3. Sea transportation

A process from ELCD database was considered suitable to model the sea transportation of goods to and from Europe (or, more specifically, to and from Portugal). This process is entitled "Container ship ocean, technology mix, 27.500 dwt pay load capacity RER S" and is adequate to model the transportation by sea of goods in standard containers (TEU = twenty-foot equivalent units) in the European area (RER is the geographical area code) (EC, 2009a). The reference container ship has up to 27,500 dead weight tons (dwt) of payload capacity and is fuelled by heavy fuel oil. The corresponding environmental impacts are estimated by the multiplication of the mass transported times the corresponding distance (t*km – mass*distance), considering namely the fuel supply and corresponding combustion emissions (the latter based on measured data) (EC, 2009a). Full load return trips were always considered for the seaway transportation processes used in the LCA studies completed in this thesis.

5.4.1.5. Waste disposal processes

Solid waste flows are included in the outputs for which site-specific data were collected in the manufacturing (A3) stage, and their identification was made in Chapter 4 for each material studied in this thesis. The information concerning the amount of each of these flows per declared unit was collected on-site. The manufacturers also confirmed that the separation of waste flows per type is concluded at the plant in order to enable their individual transport and adequate disposal. Then, specific information about the usual destination of each of these flows was provided in the forms filled during data collection.

Waste flows can have different origins depending on the phase of the production process where they are generated. From the systematisation presented in Chapter 4 for each construction product, it is possible to draw some conclusions about the main origins and characteristics of production waste:

- Mainly, raw materials or admixtures packaging is generated during the delivery and storage of these products at the plant (e.g. metal and plastic bins, cardboard, plastic bags, polyethylene shrink film, plastic strap bands, wood pallets and plastic or cardboard core);
- Some portions of the mixture waste generated in certain production processes (e.g. concrete waste) are not re-used nor recycled within the plant;
- Some processes after the main production phases (i.e. sifting, cutting, milling) generate waste flows with a composition similar to the main product;
- The packaging and/or palletisation phases also generated different waste flows that correspond mainly to the wrapping material of the packaging products (i.e. similar to the ones generated by the delivery and storage of raw materials).

These production wastes must be classified as hazardous or non-hazardous, depending on their composition, in order to be declared in the EPD of a given construction product (CEN, 2012). A type of waste that displays one or more of the hazardous properties (e.g. explosive, irritant or toxic) listed in Annex III of the “European Waste Framework Directive” (EP, 2008) has to be classified as “hazardous”. The manufacturer also has to attribute a code to each waste flow according to the corresponding European list of waste (e.g. waste code 17 09 04 - mixed construction and demolition wastes) (EC, 2000), which also includes liquid wastes. Thus, each flow can be transported to and deposited in a site managed by a licensed operator.

5.4.1.5.1. Disposal alternatives

Concerning the disposal of each type of waste, different solutions are available at a national level. Each solid waste operator accumulates - at his own site - each type of waste, in order to have a minimum quantity that enables its processing (recycling, landfilling, or incineration – see summarised description of these processes in the next paragraphs) in an adequate waste treatment plant. This is a simplified description of a reality – the chain of processes related to solid waste treatment –which is actually complex and one of the most important of today’s environmental issues (SETAC, 2003). The Ecoinvent database includes several waste treatment processes and corresponding LCI, namely several treatment alternatives for each type of waste, adequate to the present European situation. These processes were therefore used to model the disposal of each waste stream generated during the manufacturing (A3) stage of each material studied in this thesis, according to the information provided by each manufacturer. The procedure used for the choice of the type of lorry for the transportation of each waste stream was described in 5.4.1.4.1.

Recycling operations can be very different concerning their output rate, machinery used, and emissions and waste generated (Table 5.5). The efficiency of these processes is also highly dependent on the quality, quantity and contamination rate of the waste to be recycled.

Landfilling plants are mainly used to accumulate "municipal solid waste" (MSW), resulting in harmful emissions to the air, water and soil (Table 5.5). Landfill gas emissions can be reduced, however, via the recovery and use of landfill gases as an energy resource. These emissions include, for example, methane (a potent greenhouse gas), which can be used in fuel power plants (EPA, 2012).

Incineration is one of the most common destinations of waste in Europe, namely for "municipal solid waste" (MSW). This process can generate energy whose amount depends on the calorific value of the waste and on the efficiency of the incineration plant. The final solid waste flow of the incineration process is usually sent to landfill (Table 5.5) (SETAC, 2003). Table 5.5 summarises the environmental loads resulting from each one of these waste treatment alternatives, based on the European reality.

Table 5.5 – Main environmental loads from waste treatment alternatives in Europe (adapted from (EC, 1999), cited by (SETAC, 2003))

Effect of environmental load	**Waste treatment process**		
	Landfill	**Incineration**	**Recycling**
Air emissions	CH_4, CO_2 and odours	SO_2, NO_x, HCl, HF, NMVOC, CO, CO_2, N_2O, dioxins, dibenzofurans, heavy metals (Zn, Pb, Cu, As)	Dust
Water	Leaching of salts, heavy metals, biodegradable and persistent organics to groundwater	Deposition of hazardous substances on surface water	Waste water discharges
Soil	Accumulation of hazardous substances in soil	Landfilling of slags, fly ash, and scraps	Landfilling of final waste
Landscape	Soil occupancy; restriction on other land uses	Visual intrusion; restriction on other land uses	Visual intrusion
Ecosystem	Contamination and accumulation of toxic substances in the food chain		-
Urban areas	Exposure to hazardous substances		Noise

5.4.1.5.2. LCIA of waste disposal

A more detailed approach of this issue is presented in Chapter 7 for the end-of-life of construction materials and buildings, and therefore this sub-section has only the aim of concluding about the environmental impacts (and potential benefits) related to waste disposal that should be accounted for in the manufacturing (A3) stage.

Waste processing (e.g. transport and disposal of materials leaving the system) during any stage of the product system (i.e. production, construction, use, or end-of-life stages) up to the system boundary is considered to be included in the corresponding stage, and hence within the system under study (CEN, 2012). For the A3 stage, waste processing includes the transport and disposal of final waste during the product stage, including any packaging not leaving the factory gate with the product (CEN, 2012). This standard (EN15804:2012 (CEN, 2012)) follows the "polluter pays principle", assigning waste processing to the product system that generates the waste until the "end-of-waste" state is reached. In fact, only waste processing after reaching the "end-of-waste" state is part of module D (Benefits and loads beyond the system boundary – see Chapter 4) (CEN, 2012). The "end-of-waste" state is where a secondary material or fuel crosses the system boundary during any stage of the product system, i.e. during A, B or C stages. The European Commission has defined "end-of-waste" criteria only for certain types of scrap metal (iron, steel and aluminium scrap). This type of waste only reaches the "end-of-waste" state after a sequence of treatment processes (e.g. cutting or shredding) that prepares it to be used as a direct input into the next product system (EU, 2011). Thus, no waste processing after the "end-of-waste" state is reached has yet been defined for any waste type, so as a result there are no environmental loads to be quantified beyond the system boundary and assigned to module D.

Loads from waste disposal are considered part of the product system under study. However, if this process generates energy (e.g. heat and power from waste incineration or landfill), the potential benefits of its use in the next product system are assigned to module D. The same occurs when a solid waste flow is used in the next product system (e.g. secondary material substituting a virgin material and avoiding its extraction and the "substituted production of the product") (CEN, 2012). However, "as a general rule, potential loads or benefits from A1-A3 do not appear in module D", and other methods may be chosen and adequately justified to present these effects when co-products allocation is not possible (CEN, 2012). In fact, only information modules A1 to A3 should be included in a "cradle to gate" EPD of a construction product and module D is normally not declared in this type of EPD (CEN, 2012). The potential benefits or avoided loads described above should be calculated taking into account a scenario that is consistent with the national reality and that is based on current average technology or practice (CEN, 2012).

Figure 5.5 summarises the conclusions drawn from the analysis of current regulations presented in the last paragraphs. The environmental impacts (and potential benefits) related with waste disposal that should be accounted for in the manufacturing (A3) stage are therefore (Figure 5.5):

- Impacts due to the transport of each production waste flow generated during manufacturing (including any packaging not leaving the factory gate with the product) to a site managed by a licensed operator (I_t);

- Impacts from processing (e.g. energy consumption on recycling – I_r, or emission from landfilling or incineration – I_w) of this waste in an adequate waste treatment plant;
- Benefits of the use of energy generated during production waste treatment processes in the next product system (e.g. heat and power from waste incineration or landfill, I_e being the environmental impact of supplying the same amount of energy through traditional sources);
- Benefits of the use of a solid waste flow from manufacturing in the next product system (e.g. secondary material replacing a virgin material, I_n being the environmental impact from the extraction and the “substituted production of the product”), namely after suffering a recycling treatment.

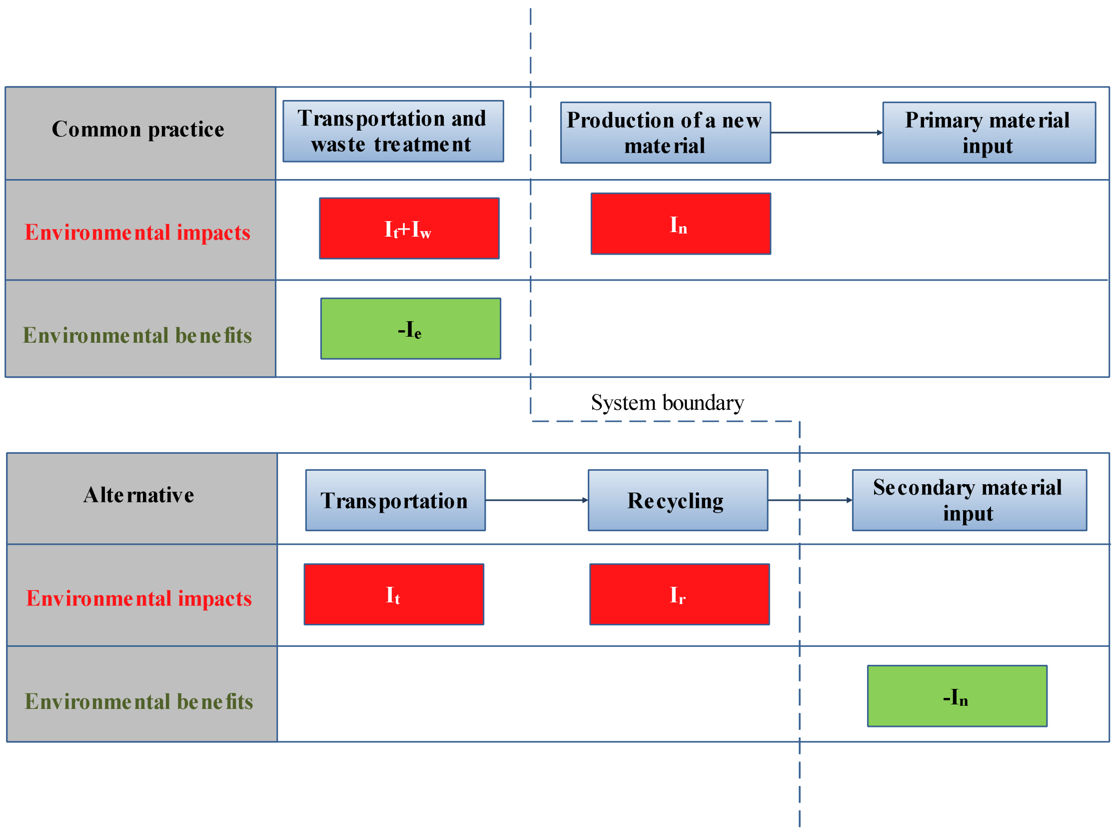

Figure 5.5 – Comparison between environmental impacts and benefits of the use of primary raw materials in a given system process with the use of recycled materials, including the definition of the LCA system boundary in accordance with European standards (based on (CEN, 2012))

For reasons of transparency and traceability, and following the recommendations of European standards (CEN, 2012), the environmental impacts and potential benefits quantified in the A3 stage are subdivided in this thesis (namely in the presentation of LCA results – see 5.4.3) into three independent information modules which characterise the manufacturing process in more detail:

- A3.1 – including the manufacturing and the transport to the factory of the packaging material that leaves the factory gate with the product;
- A3.2 – including the gate to gate manufacturing of the product being studied, and of ancillary materials, pre-products, and co-products, all internal transportations, and also the disposal of final waste (except packaging waste) generated during production (i.e. $I_t + I_w - I_e$ or $I_t + I_r - I_n$, for each waste flow – see Figure 5.5);
- A3.3 – including the production and disposal (i.e. $I_t + I_w - I_e$ or $I_t + I_r - I_n$, for each waste flow – see Figure 5.5) of raw materials or admixtures packaging, and of the wrapping material of the packaging products.

The production of raw materials or admixtures packaging (and also of the wrapping material of the packaging products) was included in the A3.3 module, and not in A3.2 (or A3.1) modules because it was impossible to isolate each of the flows from the global packaging waste streams accounted for in each plant, as referred to in 5.4.1.4.

5.4.1.6. Allocation procedure

The requirements for allocation procedure to be considered in LCI studies were described in Chapter 4, based on International standards. These requirements were taken into account in the modelling of products studied in the scope of this thesis to allow the artificial division of the input and output flows (and corresponding environmental impacts) of the operation of each plant by the different products manufactured in order to attribute a proportion to the product system under study. A summarised description of the allocation procedure followed in the LCI studies completed in this thesis is presented in this section for the products – all of them insulation materials – for which the consequences of physical (e.g. volume or mass) and economic allocation have been compared.

The allocation procedure is more critical for products: that are co-produced with other goods; for which manufacturing results in “production waste” that is recycled inside the plant and sold as co-product. The production of Expanded Polystyrene (EPS) boards includes both situations. EPS boards are jointly produced with EPS granulate until the moulding stage. All the EPS “production waste” is milled into regranulate and sold. Three allocation alternatives were considered for this manufacturing process: volume, mass and economic allocation (Table 5.6). The first option appears as the most obvious and direct, because all production flows are measured by the company based on the final production volume of each product (boards, granulate and regranulate). However, while the final volume of the boards is directly related with their density (15 kg/m^3, on average), the final volume of the other two products results from a bulk density (10.5 kg/m^3 and 9 kg/m^3 for granulate and regranulate, respectively). Therefore, the allocation based on the final volume does not express the physical relation between the products during the production process. The option was to apply mass allocation (using the final production volume and corresponding density or bulk density) between these three products, in order to correctly express the physical relation between them during manufacturing.

Table 5.6 – Manufacturing share of EPS boards, EPS granulate and regranulate depending on the allocation procedure

Allocation procedure	**Manufacturing share (%)**		
	EPS boards	**EPS granulate**	**EPS regranulate**
Volume	39	52	9
Mass	50	43	7
Economic	55	41	4

Allocation can also be economic, namely when the difference in revenue from the co-products is not low (1% or less is considered very low and more than 25% is regarded as high) (CEN, 2012). It was found in this case that the difference in revenue between EPS boards and regranulate is around 50%, and therefore high, and the difference between EPS boards and granulate is around 15% (and cannot be considered to be low). Taking into account the corresponding proceeds from these revenues (based on the procedure described by Guinee *et al.* (2004)), it was found that economic allocation can increase the share of the product system under study (EPS boards) by 5% (Table 5.6). This alternative was not selected however because it leads to final results that do not respect the underlying physical relationships between the products. Moreover, LCA results achieved using economic allocation do not express the authentic environmental impacts related to the production of each co-product. These results also cannot be compared with available LCA results for the same products (in LCA databases or EPD) because the latter are usually achieved using allocation based on physical relations. Finally, despite the fact that this research work does not follow any specific PCR rules, it was considered more accurate to apply allocation based on physical relations in all LCI studies completed, instead of applying different allocation procedures in each study.

The "production waste" from Polyurethane/Polyisocyanurate (PUR/PIR) board manufacturing is also milled and sold, therefore being a co-product of the boards. However, its final destiny and selling price depends on its quality and size: regranulate can be used as a lightening element for several uses; powder is sold for different industries (e.g. plastics recycling or cosmetic). The allocation between the boards and the "production waste" was done, in this case, directly by the company, assuming a share of 10% of all production flows for the latter. This value results from the comparison between the volume of blocks produced and the final volume of boards sold.

The manufacturing of Agglomerate of Expanded Cork (Insulation Cork Board - ICB) boards also co-produces regranulate that results from the milling of “production waste”. Three allocation alternatives were also considered for this manufacturing process: volume, mass and economic allocation (Table 5.7).The first option is again the most obvious and direct for the same reasons described for EPS boards. However, the allocation based on the final volume again does not express the physical relation between the products during the production process (the density of the boards is 110 kg/m^3 and the bulk density of regranulate is 70 kg/m^3). The option was therefore to apply mass allocation (using the final production volume and corresponding density or bulk density) between these two products.

Table 5.7 – Manufacturing share of ICB boards and ICB regranulate depending on the allocation procedure

Allocation procedure	**Manufacturing share (%)**	
	ICB boards	**ICB regranulate**
Volume	75	25
Mass	83	17
Economic	87	13

Concerning economic allocation, it was found in this case that the difference in revenue between ICB boards and regranulate is around 27%, and therefore high. Taking into account the corresponding proceeds from these revenues (Guinee *et al.*, 2004), it was found that economic allocation can increase the share of ICB boards by 4% (Table 5.7). However, this alternative was not selected for the same reasons referred to for EPS boards.

5.4.2. Choice of the Environmental Impact assessment method (EIAM) and categories

The choice of the EIAM to be used in this thesis has taken into consideration the recommendations included in International Standards (ISO, 2006b) and described in 5.1.1..

According to the present version of the European Standard that provides the core product category rules for all construction products and services – EN 15804:2012, the impact assessment should include seven categories and the corresponding characterisation factors should be the ones applied in ELCD (except for mineral and fossil abiotic depletion, for which characterisation factors from CML should be used), (CEN, 2012). However, by the time this Standard was concluded, characterisation factors still had not been defined or applied in ELCD. In fact, only in November 2011 was an EIAM defined to be applied in ELCD: the ILCD 2011 (see 5.1.2) (EC-JRC, 2011). In September 2012, CEN/TC 350 decided to amend EN 15804:2012, namely in environmental impact categories and corresponding characterisation factors to be used. Therefore, there is not a new version of this Standard yet available but the referred amendment proposes that the impact assessment includes seven categories (i.e. global warming, ozone depletion, acidification of soil and water, eutrophication, photochemical ozone creation, and depletion of abiotic resources (elements and fossil, separately, but the latter may be used and explained only if such values are known)), the characterisation factors being taken from CML-IA (based on spreadsheet version 3.9, dated November 2010). Taking these developments into account, and also that the most recent version of CML available in SimaPro software is version 2.05, dated November 2009 (based on spreadsheet version 3.2, December 2007), this EIAM and corresponding version was chosen to be used in the impact assessment of the products studied in this thesis. The characterisation models and LCIA indicators of the midpoint environmental impact categories that were used (and whose results are presented in 5.4.3) are summarised in Table 5.8. These impact categories were described in detail in 5.1.3 and they are, in fact, the most used in LCA studies (Gervásio, 2010) and EPD, allowing the inter-comparison between results for similar construction products. CML 2001 also includes additional impact categories which are not usually included in LCA results.

Table 5.8 – Indicator of each midpoint environmental impact category, corresponding characterisation models and impact indicators, based on the EIAM CML 2001 baseline - version 2.05 (EeBGuide, 2012; Guinée *et al.*, 2001; PRé, 2008)

<table>
<tr><th rowspan="2">Category indicator (abbreviation)</th><th colspan="3">Characterisation model</th><th rowspan="2">LCIA indicators</th></tr>
<tr><th>Designation</th><th>Time span</th><th>Geographical scale</th></tr>
<tr><td>Abiotic depletion potential (ADP)</td><td>Concentration reserves and rate of depletion at a global scale</td><td>-</td><td rowspan="3">Global</td><td>kg antimony (Sb) equivalents (eq.)</td></tr>
<tr><td>Global warming Potential (GWP)</td><td>Baseline model of the IPCC</td><td>100 years</td><td>kg carbon dioxide (CO_2) eq.</td></tr>
<tr><td>Ozone depletion potential (ODP)</td><td>Steady-state based on WMO (1999) model</td><td rowspan="3">Infinite</td><td>kg CFC-11 eq.</td></tr>
<tr><td>Acidification potential (AP)</td><td>Adapted RAINS 10 model</td><td rowspan="3">Varies between local and continental</td><td>kg sulphur dioxide (SO_2) eq.</td></tr>
<tr><td>Eutrophication potential (EP)</td><td>Stoichiometric procedure (Heijungs et al., 1992)</td><td>kg phosphate (PO_4^{3-}) eq.</td></tr>
<tr><td>Photochemical ozone creation potential (POCP)</td><td>United Nations Economic Commission for Europe (UNECE) trajectory model (including fate)</td><td>5 days</td><td>kg ethylene (C_2H_4) eq.</td></tr>
</table>

It is always preferable to choose a set of indicators from a robust and unified methodology (defined in this case in the CML "Operational guide to the ISO standards" (Guinée *et al.*, 2001)) than to choose each indicator from different methodologies. Gervásio (2010) justifies this statement by referring that the interdependency of the indicators is taken into account in each methodology, e.g. considering in the development of characterisation factors (for each category included in CML) that a given emission can contribute simultaneously to more than one category. Two more arguments are favourable to the choice of CML EIAM and of this set of categories for this study (Gervásio, 2010): the characterisation models were developed considering European data, which is still more important to the categories with effects at a local scale; this set of categories reflects most of the present worldwide environmental concerns.

Results presented in 5.4.3 include two more environmental categories calculated based on a single issue method published by Ecoinvent and expanded by PRé Consultants (PRé, 2008). The Cumulative Energy Demand (CED) method expresses the depletion of energy resources and its calculation is based on the higher heating value (Monteiro & Freire, 2012). It provides, in fact, the calculation of six environmental categories (Non-renewable, fossil; Non-renewable, nuclear; Non-renewable, biomass; Renewable, biomass; Renewable, wind, solar, geothermal; Renewable, water) which were grouped and presented in a simplified form by only two categories with the same unit (Mega Joule - MJ):

- Consumption of primary energy, renewable (PE-Re, or renewable energy resources depletion);
- Consumption of primary energy, non-renewable (PE-NRe, or non-renewable energy resources depletion).

5.4.3. LCA results

The description of the main technological characteristics and of the LCI of this stage for each of the building products studied in this thesis was made in Chapter 4. Chapter 4 also summarises the quality of the information used in each of the LCI studies. This section includes the presentation and quantitative analysis of the environmental impacts of the “Product stage” (A1-A3) of these products divided in three groups: elements of the wall structure, insulation materials and claddings. The results presented and analysed next in this thesis were achieved by following the LCA procedures described, namely the ones included in 5.4.1, and their figures are in accordance with the declared unit defined for each study.

These LCA results were presented by the author to each company representative in a meeting at the corresponding plant, in order to be validated jointly with the form for data collection and with the LCI model. Each of these meetings included the detailed analysis and discussion of the figures achieved, namely the relative importance of each life cycle stage and the significance of individual impact categories in the environmental profile of the product. Therefore, common conclusions were reached from these meetings in order to make final corrections in the forms for data collection and in the corresponding LCI model that made this research study and corresponding results even more robust.

The building products studied in this thesis include the insulation materials most often used in Portugal (except stone wool, for which there is already a French EPD of a Portuguese producer – see Chapter 2). This group of materials has an unquestionable significance in an external wall’s energy, environmental and economic performance (Silvestre, J. D. *et al.*, 2011). However, no LCA studies of their national production have been available until now. Therefore, a Master’s Dissertation in Environmental Engineering at Instituto Superior Técnico was supervised by the author and by his co-supervisor in order to provide up-to-date results on the environmental performance of these materials (Pargana, N. G. S. C., 2012). This research work was developed side-by-side with this thesis, following similar procedures and fulfilling the same scientific requirements. Nevertheless, the fact that it was developed in the Environmental Engineering field resulted in important conclusions which were taken into account in some methodological choices made in this thesis. The most relevant results of this interdisciplinary study are included in a paper that has been submitted for publication in a journal included in ISI-Journal of Citation Reports ((Pargana, N. *et al.*, 2012), which is presented in its present form in Appendix 5.II).

5.4.3.1. <u>Elements of the wall structure (EWS) - Lightweight concrete blocks</u>

The lightweight concrete block (with LECA and vertically perforated) studied in this thesis has improved thermal characteristics due to the inclusion of a lightweight element (LECA) and to the quantity of voids. Cradle to gate LCA results of the production of one lightweight concrete block are presented in Table 5.9. Figure 5.6 shows the relative contribution (in percentage) of sub-stages (A1-A3) to the same environmental impact categories.

Figure 5.6 proves the great influence of raw material production (A1) in the environmental impact of the production of lightweight concrete blocks (equal or higher than 80% in every category, except for PE-Re). The packaging of blocks (A3.1) also has a significant contribution to PE-Re (89%), EP and POCP (around 10% in both) categories, almost only due to wood pallets (more than 98 % of the share of this life cycle stage).

A more detailed analysis of the individual contributors to stage A1 (and A2) impacts is provided in Table 5.10. In fact, almost all the burden of each impact category results from cement and LECA production (LCA results of this last product are analysed in more detail in 5.4.3.4). This table presents the relative contribution of both raw materials to each impact category in A1 and A2 sub-stages (the contribution of the latter sub-stage being lower than 4% in every category).

Table 5.9 – LCA results for each sub-stage of the "product stage" (A1-A3) of one lightweight concrete block (with 19 kg/block)

Category indicator	Unit	Life cycle stages (total per 1 block)					
		A1-A3	A1	A2	A3.1	A3.2	A3.3
PE-NRe	**MJ**	**7.53E+01**	6.77E+01	8.73E-01	4.03E+00	2.54E+00	1.61E-01
PE-Re	**MJ**	**1.47E+01**	1.29E+00	1.17E-03	1.32E+01	2.57E-01	1.99E-03
ADP	**kg Sb eq**	**3.43E-02**	3.15E-02	4.28E-04	1.73E-03	6.37E-04	7.85E-05
AP	**kg SO_2 eq**	**2.81E-02**	2.65E-02	2.93E-04	7.81E-04	5.46E-04	5.31E-05
EP	**kg PO_4^{3-} eq**	**2.63E-03**	2.10E-03	6.71E-05	3.16E-04	1.37E-04	1.25E-05
GWP	**kg CO_2 eq**	**3.84E+00**	3.50E+00	6.19E-02	1.73E-01	8.51E-02	1.13E-02
ODP	**kg CFC-11 eq**	**6.43E-07**	6.23E-07	1.18E-10	1.14E-08	7.92E-09	4.76E-11
POCP	**kg C_2H_4**	**1.23E-03**	1.10E-03	6.88E-06	1.05E-04	1.91E-05	1.32E-06

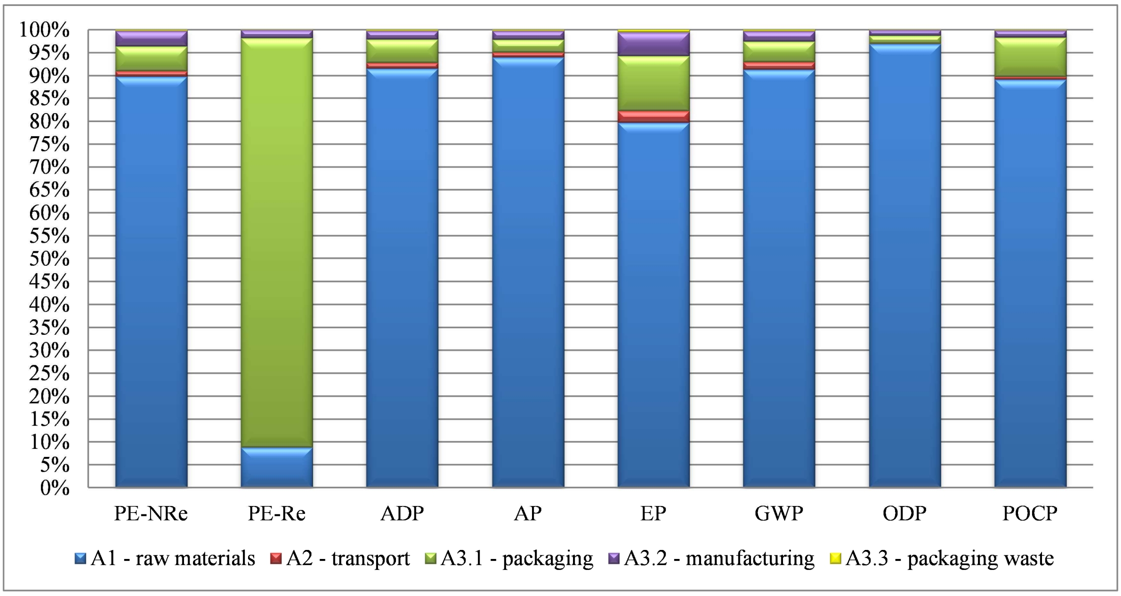

Figure 5.6 – Relative contribution of each sub-stage of the production of lightweight concrete blocks to environmental impact categories

Table 5.10 – Relative contribution (%) of cement and LECA to A1 plus A2 sub-stages of the production of lightweight concrete blocks

Category indicator	Relative contribution (%) for A1-A2	
	Cement	LECA
ADP	27	71
AP	21	77
EP	37	60
GWP	57	40
ODP	34	65
POCP	15	84

5.4.3.2. EWS - GFRC precast panels

The Glass Fibre Reinforced Concrete (GFRC) precast panels studied in this thesis have improved thermal characteristics due to the placement of EPS boards filling the voids between frontal and posterior GFRC layers. These panels can be considered either as an element of the wall structure or as a cladding.

Cradle to gate LCA results of the production of one square metre of GFRC precast panels are presented in Table 5.11. Figure 5.7 shows the relative contribution (in percentage) of sub-stages (A1-A3) to the same environmental impact categories.

Table 5.11 – LCA results for each sub-stage of the “product stage” (A1-A3) of one square metre of GFRC precast panels (with a weight of 73.5 kg/m^2)

Category indicator	Unit	Life cycle stages (total per 1 m^2)					
		A1-A3	A1	A2	A3.1	A3.2	A3.3
PE-NRe	**MJ**	**1.29E+03**	1.12E+03	2.19E+01	-	1.42E+02	4.32E+00
PE-Re	**MJ**	**3.94E+01**	2.70E+01	2.92E-02		1.12E+01	1.19E+00
ADP	**kg Sb eq**	**6.39E-01**	5.85E-01	1.07E-02		4.19E-02	1.45E-03
AP	**kg SO_2 eq**	**3.77E-01**	3.46E-01	7.06E-03		2.37E-02	1.14E-03
EP	**kg PO_4^{3-} eq**	**6.23E-02**	5.43E-02	1.61E-03		6.72E-03	-2.66E-04
GWP	**kg CO_2 eq**	**1.01E+02**	9.49E+01	1.56E+00		3.81E+00	2.37E-01
ODP	**kg CFC-11 eq**	**7.58E-06**	7.04E-06	2.95E-09		5.23E-07	1.07E-08
POCP	**kg C_2H_4**	**4.02E-02**	3.89E-02	1.69E-04		1.08E-03	3.22E-05

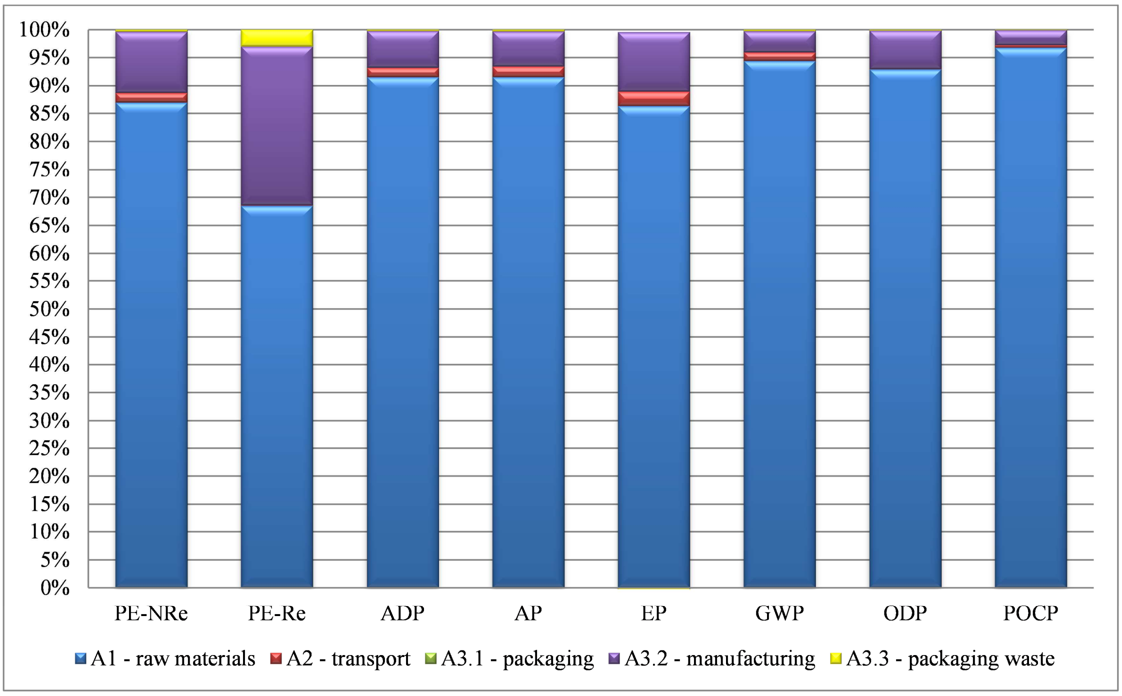

Figure 5.7 – Relative contribution of each sub-stage of the production of GFRC precast panels to environmental impact categories

GFRC precast panels are delivered on-site without packaging and the environmental impacts for A3.1 sub-stage are therefore inexistent (Table 5.11).

Figure 5.7 shows that manufacturing (A3.2) only contributes significantly to PE-Re (28%). This impact is mainly related (92%) to electric energy use during this stage, and results from the significant share of renewable technologies in the Portuguese electric mix (see 5.4.1.3). The influence of raw material production (A1) on the environmental impact of this type of product is significant (more than 85% in every category, except for PE-Re). This environmental profile is analogous to the one of the previous product analysed (lightweight concrete block) and this similarity should be related to their cement-based composition.

A more detailed analysis of the individual contributors to sub-stages A1-A2 impacts (the contribution of the latter being equal or lower than 3% in every category) is provided in Figure 5.8, Figure 5.9 and Figure 5.10, namely for three of the categories for which raw material impacts are significant (AP, GWP and POCP). Figure 5.8 shows the contribution of A1 and A2 sub-stages to AP (using a Sankey diagram with the relative contribution of each process, which results from the LCI modelling of this product made in SimaPro software). Almost half of the impact (43.4%) comes from cement production, while admixture for fibre protection (17.6%), EPS (16%, including its packaging and production waste) and glass fibre (16%, including for premix and spray-up, the latter not appearing in the diagram) have a decreasing contribution to this category. The contribution of EPS is similar for GWP (Figure 5.9) but increases for POCP (73.9% in Figure 5.10). LCA results of EPS are analysed in more detail in 5.4.3.6. Admixture for fibre protection (7%) and glass fibre (5.4%) have a lower contribution in the POCP category than in AP. Cement has its lowest contribution in the POCP category (10.7%), while GWP impacts of cement production (57.8%) are once more highlighted (Figure 5.10).

5.4.3.3. EWS - Stabilised (wet and ready-to-use) masonry mortar (also used in ECS and ICS)

Stabilised (wet and ready-to-use) cement-based mortar can be used in the setting of masonry elements or as an external render or internal coating. In the LCI description (Chapter 4) of this product it was considered that it is delivered on-site without packaging. However, this product is always stored on-site in metallic containers supplied by the producer. These containers were therefore considered as packaging material in LCA calculations, considering they are re-used 100 times.

Cradle to gate LCA results of the production of one cubic metre of this mortar are presented in Table 5.12. The relative contribution (in percentage) of sub-stages (from A1 to A3) to the same environmental impact categories is shown in Figure 5.11.

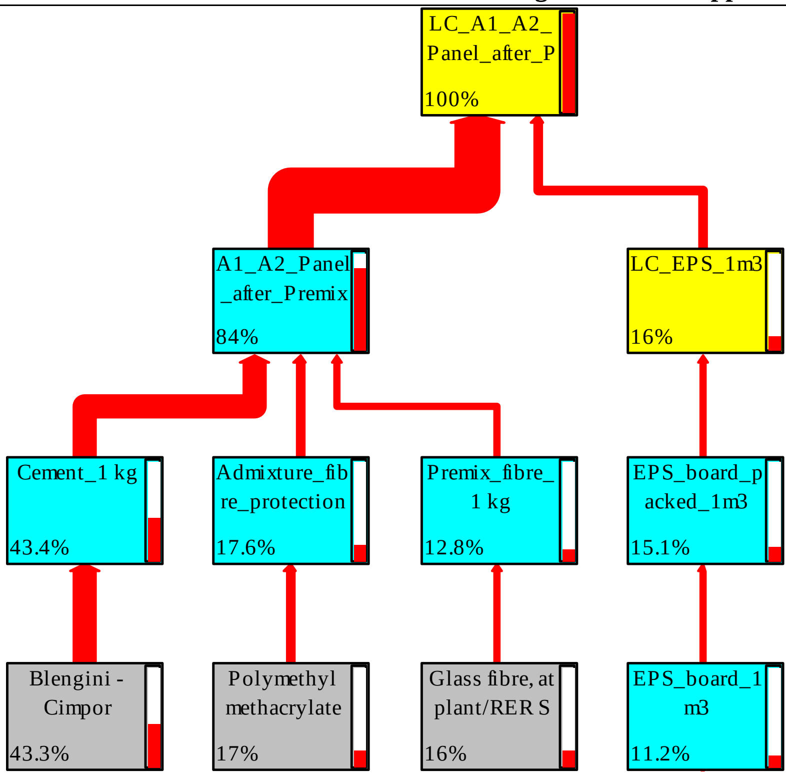

Figure 5.8 – Contribution of A1 plus A2 sub-stages of GFRC precast panel production to AP with 10% cut-off generated in SimaPro

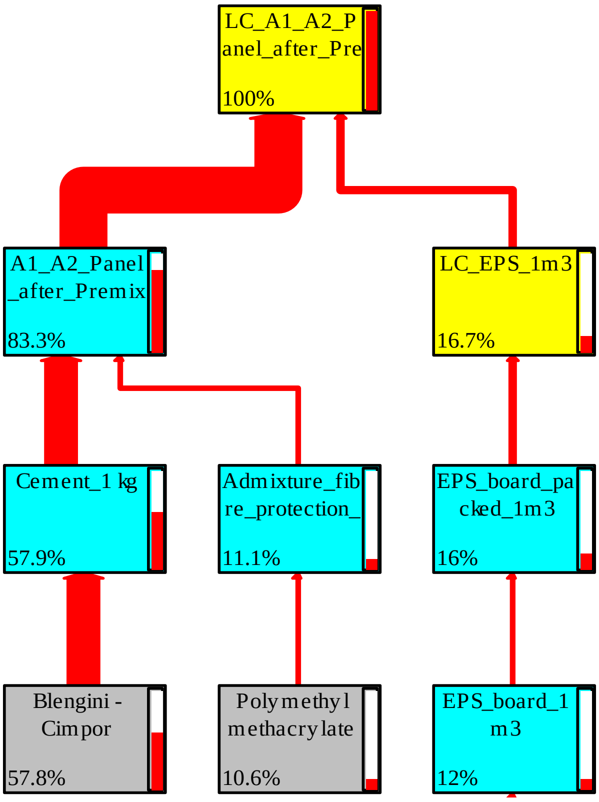

Figure 5.9 – Contribution of A1 plus A2 sub-stages of GFRC precast panel production to GWP with 10% cut-off generated in SimaPro

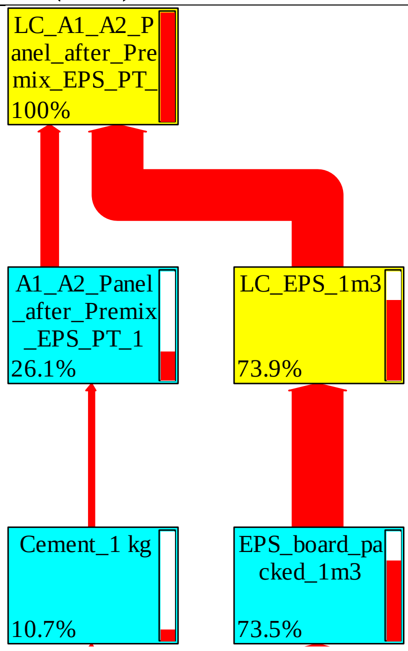

Figure 5.10 – Contribution of A1 plus A2 sub-stages of GFRC precast panel production to POCP with 10% cut-off generated in SimaPro

Table 5.12 – LCA results for each sub-stage of the “product stage” (A1-A3) of one cubic metre of stabilised masonry mortar (wet density of 1650 kg/m^3)

Category indicator	Unit	Life cycle stages (total per 1 m^3)					
		A1-A3	**A1**	**A2**	**A3.1**	**A3.2**	**A3.3**
PE-NRe	**MJ**	**1.52E+03**	1.30E+03	9.52E+01	3.15E+01	8.80E+01	6.23E+00
PE-Re	**MJ**	**5.24E+01**	4.50E+01	1.27E-01	8.18E-01	6.31E+00	1.81E-01
ADP	**kg Sb eq**	**9.52E-01**	8.45E-01	4.67E-02	1.77E-02	4.01E-02	2.89E-03
AP	**kg SO_2 eq**	**6.30E-01**	5.62E-01	3.19E-02	7.13E-03	2.81E-02	1.55E-03
EP	**kg PO_4^{3-} eq**	**9.62E-02**	7.96E-02	7.32E-03	4.45E-03	4.91E-03	-1.22E-04
GWP	**kg CO_2 eq**	**2.17E+02**	1.99E+02	6.75E+00	2.06E+00	8.55E+00	4.76E-01
ODP	**kg CFC-11 eq**	**2.14E-05**	2.04E-05	1.28E-08	7.83E-08	8.53E-07	1.14E-09
POCP	**kg C_2H_4**	**2.07E-02**	1.78E-02	7.50E-04	1.14E-03	8.84E-04	1.23E-04

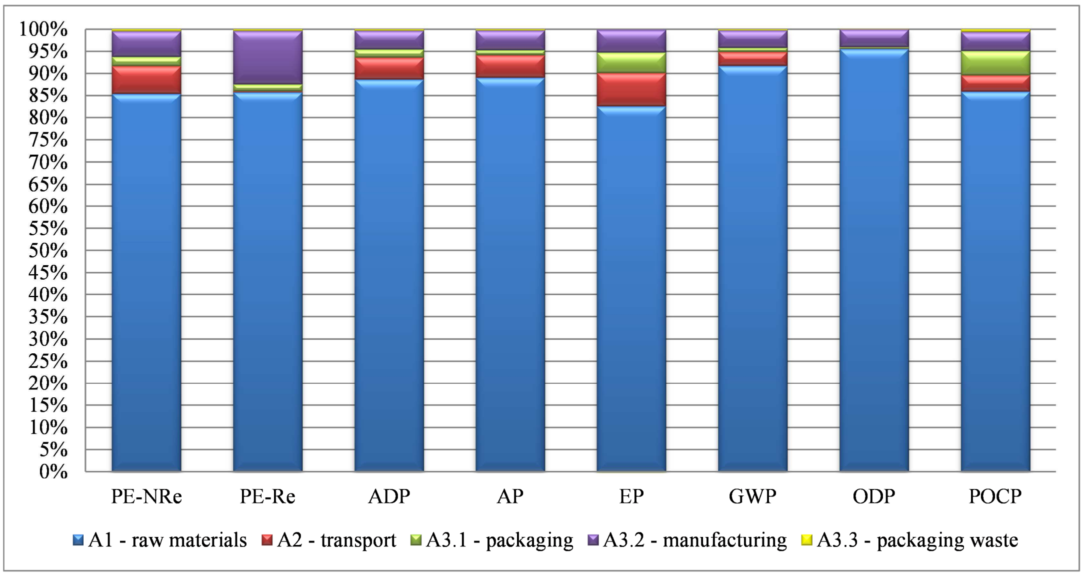

Figure 5.11 – Relative contribution of each sub-stage of the production of stabilised masonry mortar to environmental impact categories

Figure 5.11 confirms that this product belongs to the cement-based group by showing the significant contribution of raw material production (A1) to all impact categories (more than 80%). Manufacturing (A3) has a significant impact in PE-Re (12%) due to electric energy consumption (see 5.4.3.2). The impact of transport (A2, with 8% to EP and 6% to PE-NRe) relies mainly on the transportation of high quantities of aggregates for the manufacturing of this product (and is not motivated by long distance transportation). Figure 5.12 provides a more detailed analysis of the individual contributors to sub-stages A1-A2 impacts for POCP. Cement contribution is even higher for some other categories (e.g. 88% for ADP and AP, including its transportation), while fine sand (5.02%, from its extraction) and retarding admixture (8.52%, from its production) only have important contributions for this specific category.

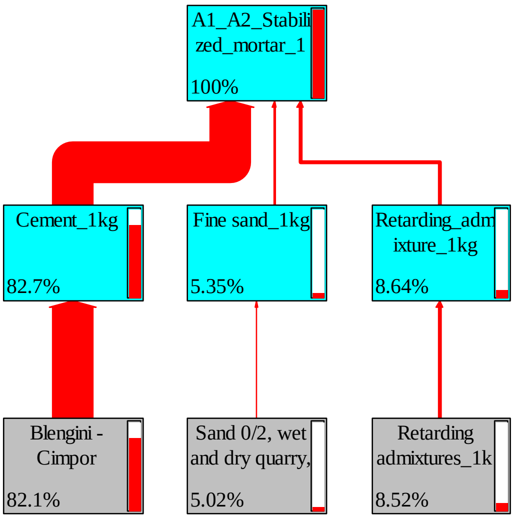

Figure 5.12 – Contribution of A1 plus A2 sub-stages of stabilised masonry mortar to POCP with 5% cut-off generated in SimaPro

5.4.3.4. Insulation materials (IM) - Light Expanded Clay Aggregate (LECA)

Light Expanded Clay Aggregate (LECA) studied in this thesis can be used in the insulation of several building elements but is also used as a raw material in the production of lightweight concrete blocks (see 5.4.3.1). LECA is available on the market both in Polyethylene (PE) (50 liters, palletised with 60 bags per wood pallet) and Polypropylene (PP) bags (open big-bags with 1.5 m^3 or 3 m^3 capacity). Therefore, cradle to gate LCA results of the production of one cubic metre of LECA are presented separately for PE and PP bags in Table 5.13 and Table 5.14, respectively. PP bags and raw materials do not generate packaging waste. Thus, the A3.3 sub-stage does not have impacts for LECA in PP bags (Table 5.14). Only the accumulated impacts (A1-A3) and the packaging ones (A3.1) are also different between these packaging alternatives.

Table 5.13 – LCA results for each sub-stage of the "product stage" (A1-A3) of one cubic metre of LECA in palletised PE bags (with a bulk density of 297 kg/m^3 for 8-16 size)

Category indicator	Unit	Life cycle stages (total per 1 m^3)					
		A1-A3	**A1**	**A2**	**A3.1**	**A3.2**	**A3.3**
PE-NRe	**MJ**	**3.03E+03**	3.77E+02	7.05E+00	2.89E+02	2.35E+03	1.02E+00
PE-Re	**MJ**	**2.49E+02**	2.43E+00	9.41E-03	2.08E+02	3.91E+01	1.20E-01
ADP	**kg Sb eq**	**1.26E+00**	1.65E-01	3.45E-03	1.22E-01	9.72E-01	3.80E-04
AP	**kg SO_2 eq**	**1.08E+00**	5.20E-02	2.24E-03	3.81E-02	9.86E-01	2.02E-04
EP	**kg PO_4^{3-} eq**	**7.46E-02**	1.14E-02	5.11E-04	9.89E-03	5.27E-02	9.76E-05
GWP	**kg CO_2 eq**	**8.07E+01**	5.97E+00	4.99E-01	9.40E+00	6.48E+01	5.14E-02
ODP	**kg CFC-11 eq**	**2.07E-05**	3.06E-06	9.49E-10	2.50E-07	1.74E-05	3.67E-09
POCP	**kg C_2H_4**	**4.95E-02**	2.60E-03	5.14E-05	2.92E-03	4.39E-02	1.15E-05

Table 5.14 – LCA results for each sub-stage of the "product stage" (A1-A3) of one cubic metre of LECA in PP bags (297 kg/m3 for 8-16 size)

Category indicator	Unit	Life cycle stages (total per 1 m^3)					
		A1-A3	**A1**	**A2**	**A3.1**	**A3.2**	**A3.3**
PE-NRe	**MJ**	**2.82E+03**	3.77E+02	7.05E+00	8.77E+01	2.35E+03	-
PE-Re	**MJ**	**4.44E+01**	2.43E+00	9.41E-03	2.79E+00	3.91E+01	
ADP	**kg Sb eq**	**1.18E+00**	1.65E-01	3.45E-03	4.11E-02	9.72E-01	
AP	**kg SO_2 eq**	**1.06E+00**	5.20E-02	2.24E-03	2.06E-02	9.86E-01	
EP	**kg PO_4^{3-} eq**	**6.63E-02**	1.14E-02	5.11E-04	1.67E-03	5.27E-02	
GWP	**kg CO_2 eq**	**7.42E+01**	5.97E+00	4.99E-01	2.97E+00	6.48E+01	
ODP	**kg CFC-11 eq**	**2.05E-05**	3.06E-06	9.49E-10	3.32E-10	1.74E-05	
POCP	**kg C_2H_4**	**4.75E-02**	2.60E-03	5.14E-05	9.43E-04	4.39E-02	

The relative contribution (in percentage) of sub-stages (A1 to A3) to the same environmental impact categories is presented in Figure 5.13 and Figure 5.14, respectively for PE and PP bags. These figures express the environmental benefit that can come from the choice of PP bags (even if only available from a minimum order of 1.5 m^3) and the impact of the packaging in (PE bags) and palletisation process. In fact, the difference of environmental impacts in A3.1 sub-stage of these two alternatives varies between 1% in ODP and 77% in PE-Re, while being also relatively significant for EP (10%) and GWP (8%).

Considering Figure 5.14, a more detailed analysis of the other life cycle stages can be made. Manufacturing (A3.2) is responsible for a great share of environmental impacts (more than 78% in every category). The main individual contributors to this sub-stage are presented in Figure 5.15, Figure 5.16 and Figure 5.17 for three impact categories (AP, EP and GWP). These figures show that the contribution of coke production to environmental impacts varies between 20.8% (AP) and almost 57% (EP). Electric energy consumption also has a share in these categories, which can vary between 5.02% (AP) and 24.7% (EP), with an intermediate value in GWP (12.9%). Environmental impacts from diesel stacker operation are around 5% in EP, while the share that is not represented (more than 70% in the AP diagram - Figure 5.15, and more than 60% in the GWP diagram - Figure 5.17) results from the impacts of the direct air emissions from the kiln during the baking process.

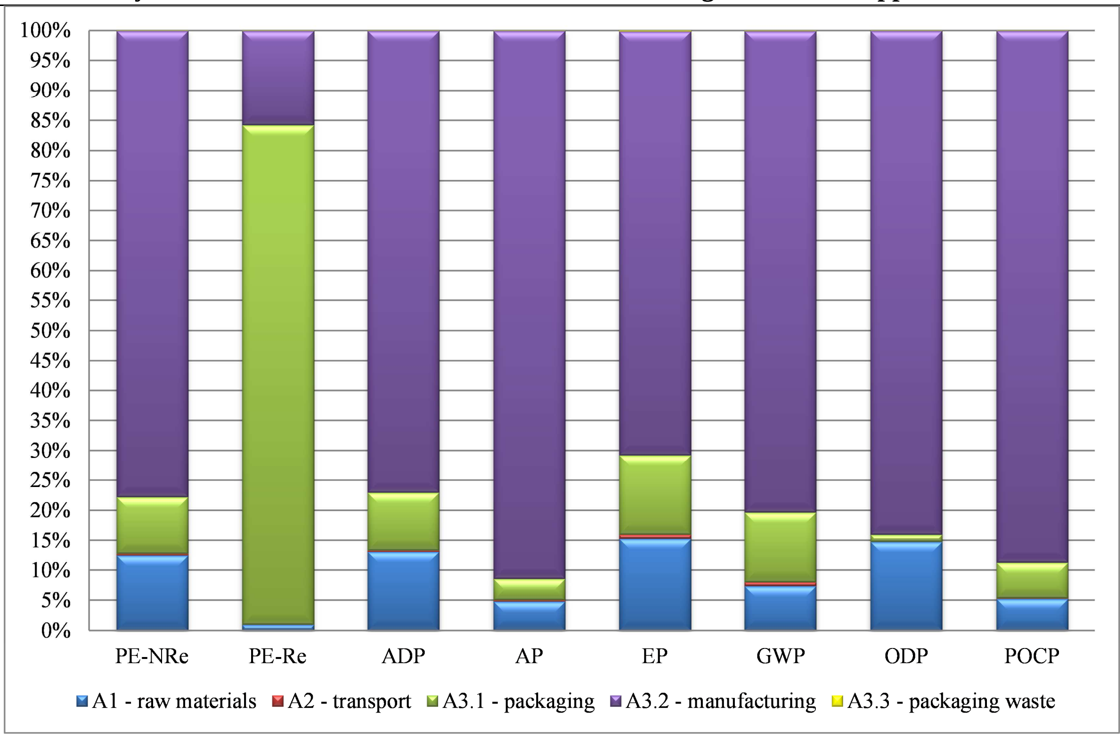

Figure 5.13 – Relative contribution of each sub-stage of the production of LECA in palletised PE bags to environmental impact categories

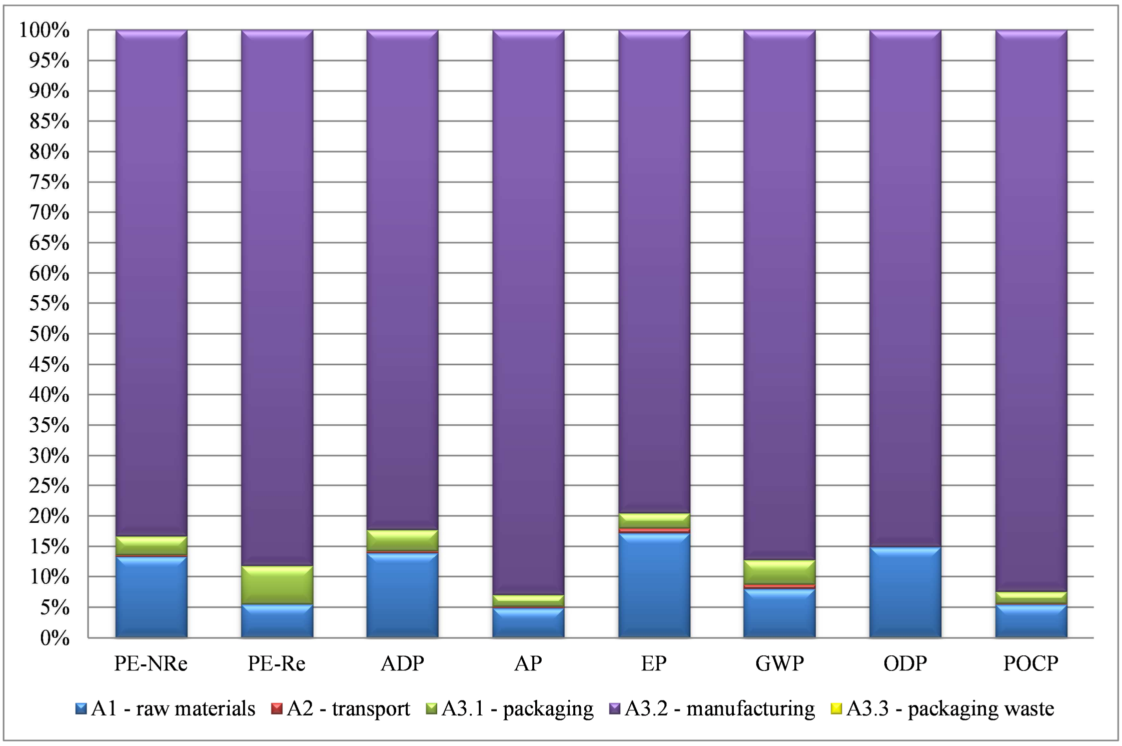

Figure 5.14 – Relative contribution of each sub-stage of the production of LECA in PP bags to environmental impact categories

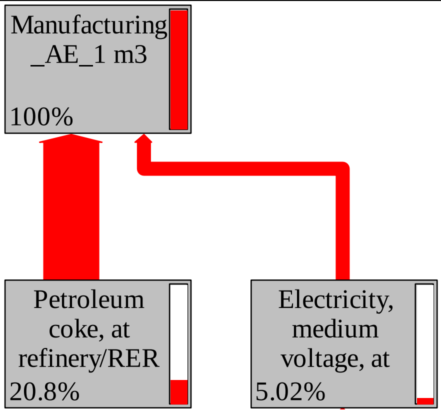

Figure 5.15 – Contribution of A3.2 sub-stage of LECA production to AP with 5% cut-off generated in SimaPro

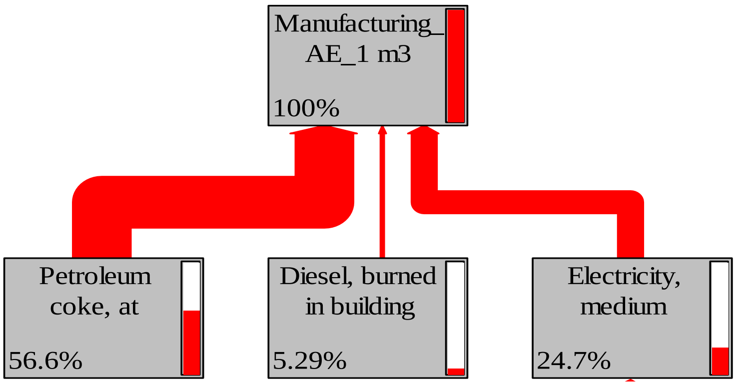

Figure 5.16 – Contribution of A3.2 sub-stage of LECA production to EP with 5% cut-off generated in SimaPro

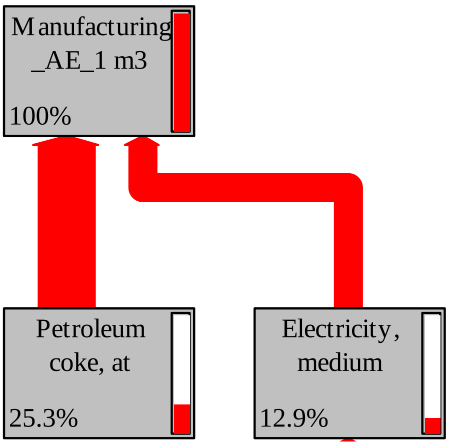

Figure 5.17 – Contribution of A3.2 sub-stage of LECA production to GWP with 5% cut-off generated in SimaPro

5.4.3.5. IM - Extruded Polystyrene (XPS)

Extruded Polystyrene (XPS) boards studied in this thesis are suitable for application in external walls (within ETICS or internal thermal insulation, namely glued to gypsum plasterboards). Cradle to gate LCA results of the production of one cubic metre of XPS depend on the final thickness of the boards, because a set of blowing agents is used for thicknesses equal or lower than 80 mm (dimethyl ether and carbon dioxide) and another one is used for thicknesses equal or higher than 80 mm (difluoroethane and ethanol). Therefore, the presentation of these results is divided in two parts.

Cradle to gate LCA results of the production of one cubic metre of this insulation material are presented in Table 5.15 for boards with thickness equal or lower than 80 mm, while Figure 5.18 shows the relative contribution (in percentage) of sub-stages (A1-A3) to the same environmental impact categories.

Table 5.15 – LCA results for each sub-stage of the "product stage" (A1-A3) of one cubic metre of XPS for boards with thickness ≤ 80 mm (with an average density of 30 kg/m^3)

Category indicator	Unit	Total per 1 m^3	Life cycle stages (total per 1 m^3)				
			A1	A2	A3.1	A3.2	A3.3
PE-NRe	**MJ**	**2.77E+03**	2.43E+03	3.22E+01	4.90E+01	2.50E+02	4.48E+00
PE-Re	**MJ**	**3.73E+01**	8.27E+00	4.29E-02	1.63E+00	2.69E+01	5.22E-01
ADP	**kg Sb eq**	**1.33E+00**	1.19E+00	1.58E-02	2.08E-02	9.78E-02	1.48E-03
AP	**kg SO_2 eq**	**4.76E-01**	3.29E-01	1.08E-02	6.10E-03	1.29E-01	8.87E-04
EP	**kg PO_4^{3-} eq**	**5.23E-02**	2.41E-02	2.38E-03	1.23E-03	2.41E-02	4.11E-04
GWP	**kg CO_2 eq**	**1.49E+02**	9.90E+01	2.28E+00	1.57E+00	4.58E+01	2.00E-01
ODP	**kg CFC-11 eq**	**1.23E-06**	4.55E-07	4.33E-09	1.89E-08	7.36E-07	1.31E-08
POCP	**kg C_2H_4**	**3.67E-01**	2.23E-02	2.52E-04	3.43E-04	3.44E-01	5.66E-05

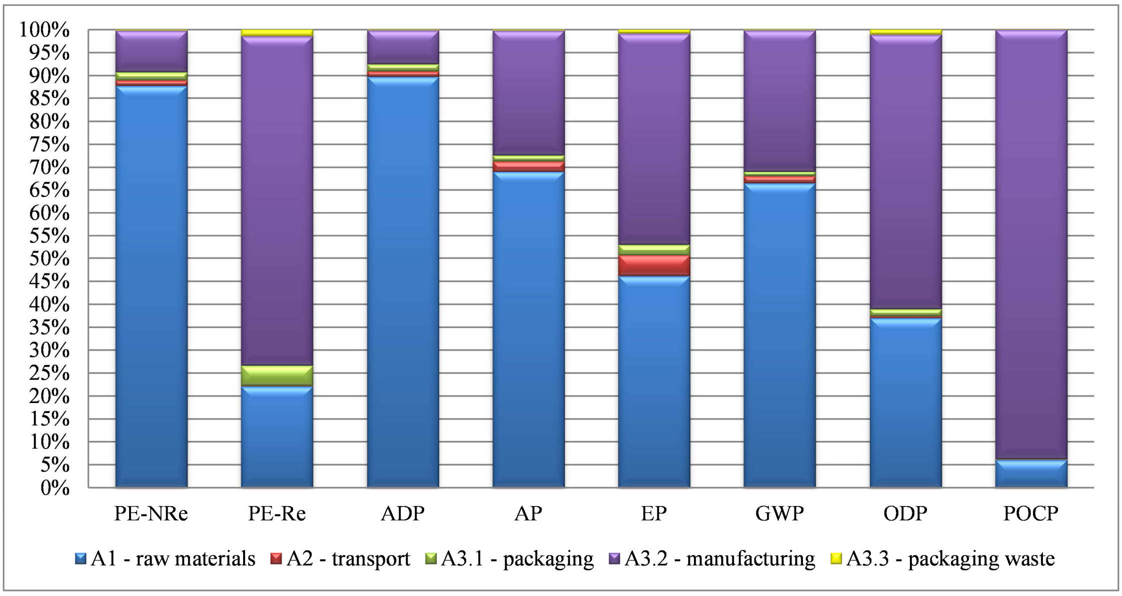

Figure 5.18 – Relative contribution of each sub-stage of the production of XPS boards with thickness ≤ 80 mm to environmental impact categories

The importance of raw material production (A1) in XPS environmental impacts is expressed in Figure 5.18. The contribution of this life cycle stage is in fact significant to many categories (more than 65% for PE-NRe, ADP, AP and GWP), and is only smaller than 40% for PE-Re, ODP and POCP. Manufacturing (A3.2) has an important impact in many categories (more than 25% for AP, EP and GWP and more than 50% for PE-Re, ODP and POCP) mainly due to electric energy consumption and air emissions during this stage. These air emissions are mainly generated during the internal recycling process of production waste and by the release of dimethyl ether during the extrusion process.

Figure 5.19, Figure 5.20 and Figure 5.21 provide a more detailed analysis of the individual contributors to sub-stages A1-A2 impacts for ADP, EP and POCP, respectively. Impact from transportation (A2) is only important in EP (8%), while raw materials (mainly polystyrene, but also dimethyl ether and flame retardant) share the remaining parcel of impacts in this and in the other two categories. Polystyrene has a higher impact in ADP and POCP (93.7% and 92.2%, respectively), having a lower contribution in the other category (76.3% in EP). Dimethyl ether, on the other hand, has its highest contribution to EP (8.93%), and it is also in this category that the impact of the flame retardant is more significant (4.32%).

Cradle to gate LCA results of the production of one cubic metre of XPS are presented in Table 5.16 for boards with thickness equal or greater than 80 mm, while Figure 5.22 shows the relative contribution (in percentage) of sub-stages (A1-A3) to the same environmental impact categories.

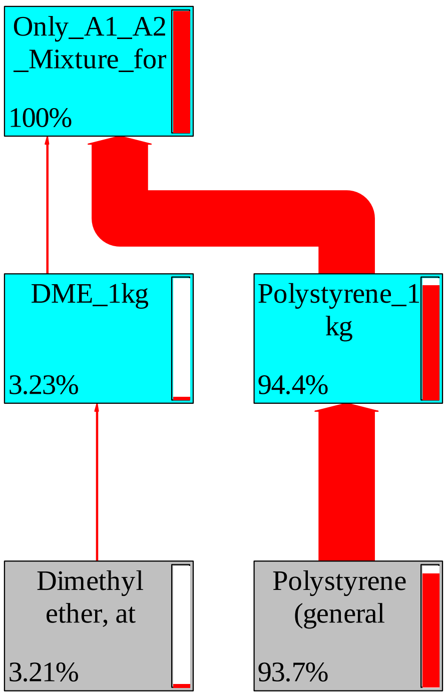

Figure 5.19 – Contribution of A1 plus A2 sub-stages of XPS boards with thickness ≤ 80 mm production to ADP with 2% cut-off generated in SimaPro

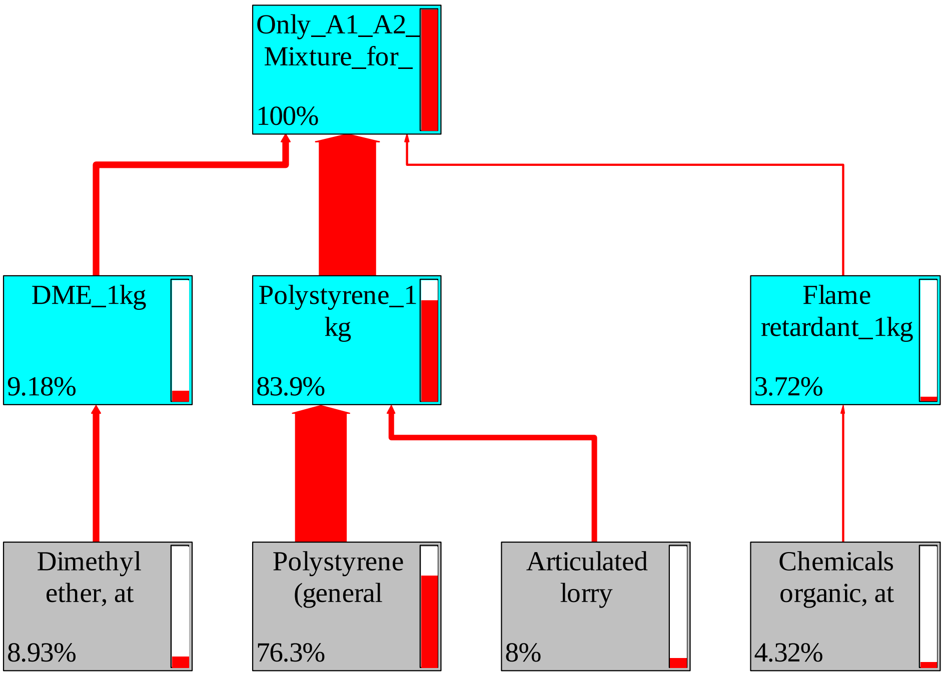

Figure 5.20 – Contribution of A1 plus A2 sub-stages of XPS boards with thickness ≤ 80 mm production to EP with 2% cut-off generated in SimaPro

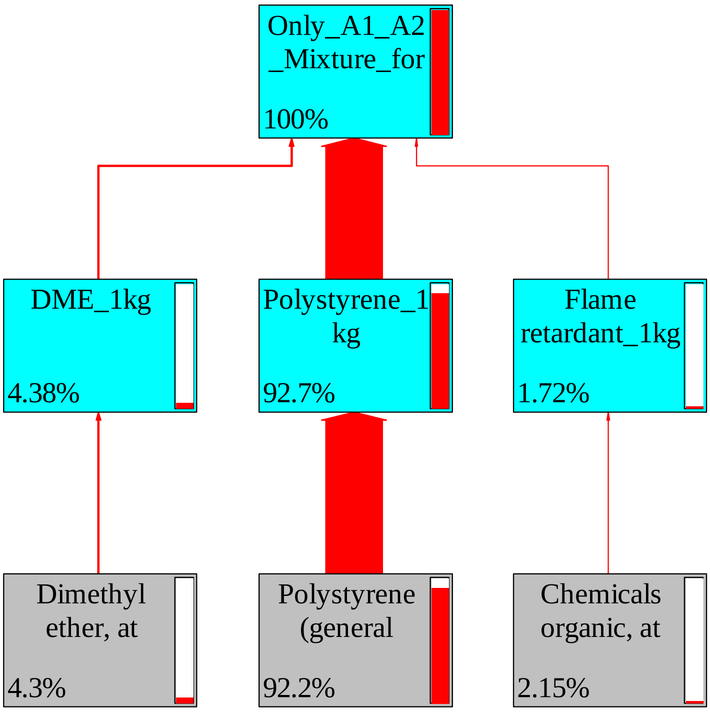

Figure 5.21 – Contribution of A1 plus A2 sub-stages of XPS boards with thickness ≤ 80 mm production to POCP with 2% cut-off generated in SimaPro

Table 5.16 – LCA results for each sub-stage of the “product stage” (A1-A3) of one cubic metre of XPS for boards with thickness ≥ 80 mm (with an average density of 30 kg/m^3)

Category indicator	Unit	Total per 1 m^3	Life cycle stages (total per 1 m^3)				
			A1	A2	A3.1	A3.2	A3.3
PE-NRe	**MJ**	**2.79E+03**	2.45E+03	3.51E+01	4.90E+01	2.50E+02	4.48E+00
PE-Re	**MJ**	**4.20E+01**	1.29E+01	4.67E-02	1.63E+00	2.69E+01	5.22E-01
ADP	**kg Sb eq**	**1.33E+00**	1.20E+00	1.72E-02	2.08E-02	9.78E-02	1.48E-03
AP	**kg SO_2 eq**	**5.89E-01**	4.33E-01	1.89E-02	6.10E-03	1.30E-01	8.87E-04
EP	**kg PO_4^{3-} eq**	**6.57E-02**	3.68E-02	3.14E-03	1.23E-03	2.41E-02	4.11E-04
GWP	**kg CO_2 eq**	**1.90E+02**	1.05E+02	2.52E+00	1.57E+00	8.06E+01	2.00E-01
ODP	**kg CFC-11 eq**	**1.22E-06**	4.42E-07	4.70E-09	1.89E-08	7.36E-07	1.31E-08
POCP	**kg C_2H_4**	**3.09E-01**	2.64E-02	4.84E-04	3.43E-04	2.82E-01	5.66E-05

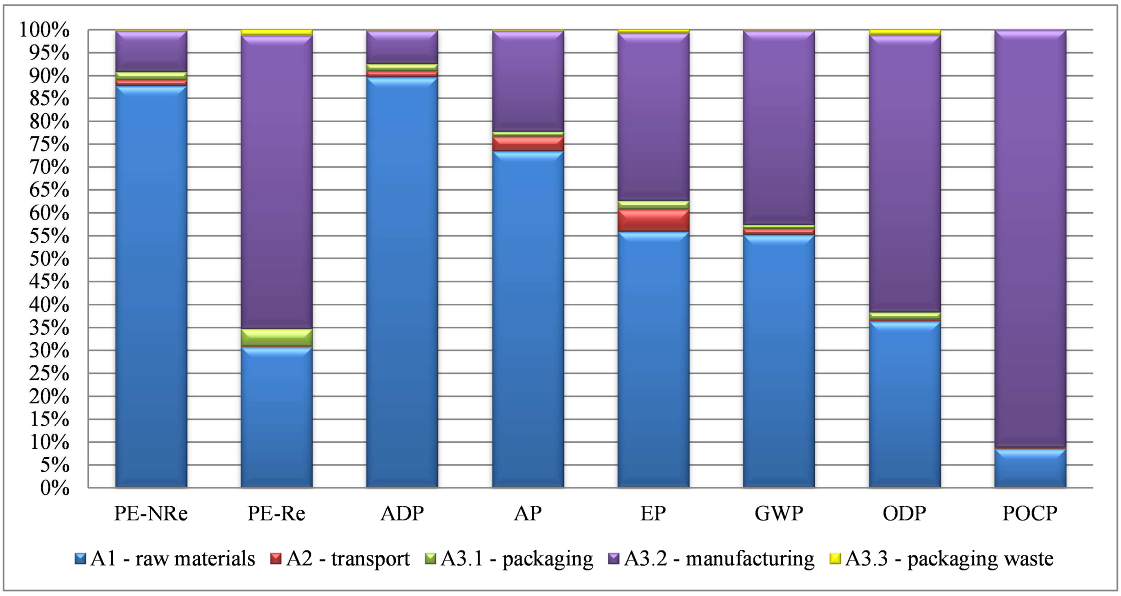

Figure 5.22 – Relative contribution of each sub-stage of the production of XPS boards with thickness ≥ 80 mm to environmental impact categories

The LCA results for XPS boards with thickness ≥ 80 mm (Table 5.16) only differ from the ones of the boards with thickness ≤ 80 mm (Table 5.15) in A1, A2 and aggregated A1-A3 stages, as expected. The importance of raw material production (A1) is also similar and significant for both groups of thicknesses (Figure 5.18 and Figure 5.22).

A more detailed analysis of the individual contributors to stage A1 (and A2) impacts is provided in Table 5.17. In fact, almost all the burden of each impact category results from polystyrene and difluoroethane production, except for ODP (with a contribution of 22.4% of the flame retardant). This table therefore presents the relative contribution of both raw materials to each impact category in A1 and A2 sub-stages (the contribution of the latter sub-stage is lower than 8% in every category).

Table 5.17 – Relative contribution (%) of polystyrene and difluoroethane to A1 plus A2 sub-stages of the production of XPS boards with thickness ≥ 80 mm

Category indicator	Relative contribution (%) for A1-A2	
	Polystyrene	Difluoroethane
ADP	94	3
AP	72	26
EP	56	40
GWP	91	8
ODP	1	69
POCP	78	19

5.4.3.6. IM - Expanded Polystyrene (EPS)

Expanded Polystyrene (EPS) boards studied in this thesis are suitable for application in several building assemblies, namely in external walls. Cradle to gate LCA results of the production of one cubic metre of EPS are presented in Table 5.18. Figure 5.23 shows the relative contribution (in percentage) of sub-stages (A1-A3) to the same environmental impact categories.

Table 5.18 – LCA results for each sub-stage of the “product stage” (A1-A3) of one cubic metre of EPS (with a density of 15 kg/m^3)

Category indicator	Unit	Life cycle stages (total per 1 m^3)					
		A1-A3	**A1**	**A2**	**A3.1**	**A3.2**	**A3.3**
PE-NRe	**MJ**	**1.86E+03**	1.45E+03	3.38E+01	6.22E+01	3.09E+02	1.17E+01
PE-Re	**MJ**	**1.59E+01**	6.39E+00	4.51E-02	1.75E+00	6.78E+00	9.59E-01
ADP	**kg Sb eq**	**8.91E-01**	7.09E-01	1.65E-02	2.79E-02	1.32E-01	4.48E-03
AP	**kg SO_2 eq**	**2.87E-01**	1.90E-01	1.13E-02	1.32E-02	6.99E-02	2.32E-03
EP	**kg PO_4^{3-} eq**	**3.41E-02**	1.87E-02	2.60E-03	1.09E-03	1.06E-02	1.13E-03
GWP	**kg CO_2 eq**	**8.22E+01**	5.65E+01	2.39E+00	2.87E+00	1.98E+01	6.03E-01
ODP	**kg CFC-11 eq**	**2.34E-06**	0.00E+00	4.55E-09	2.71E-11	2.29E-06	4.36E-08
POCP	**kg C_2H_4**	**1.47E-01**	1.14E-02	2.66E-04	6.64E-04	1.35E-01	1.30E-04

Figure 5.23 shows substantial influence of raw material production (A1) in the environmental impact of this product (except for ODP and POCP, but from 40% in PE-Re to 78% in PE-NRe). This impact is due to the production process of the only raw material used: the polystyrene expandable granulate. Concerning the other contributors to environmental impacts, the manufacturing sub-stage (A3.2) has a share between 15% (in ADP) and 98% (in ODP). This sub-stage is dominated by the impacts of the burning of naphtha in the boiler (modelled using the Ecoinvent process “Naphtha, burned in boiler 100kW condensing, non-modulating”), by the electric energy consumption and by pentane and isopentane release during manufacturing (98% of contribution to the impact of A3.2 in POCP). Table 5.19 presents the relative contribution of the first two of these processes to the remaining impact categories in A3.2 sub-stage.

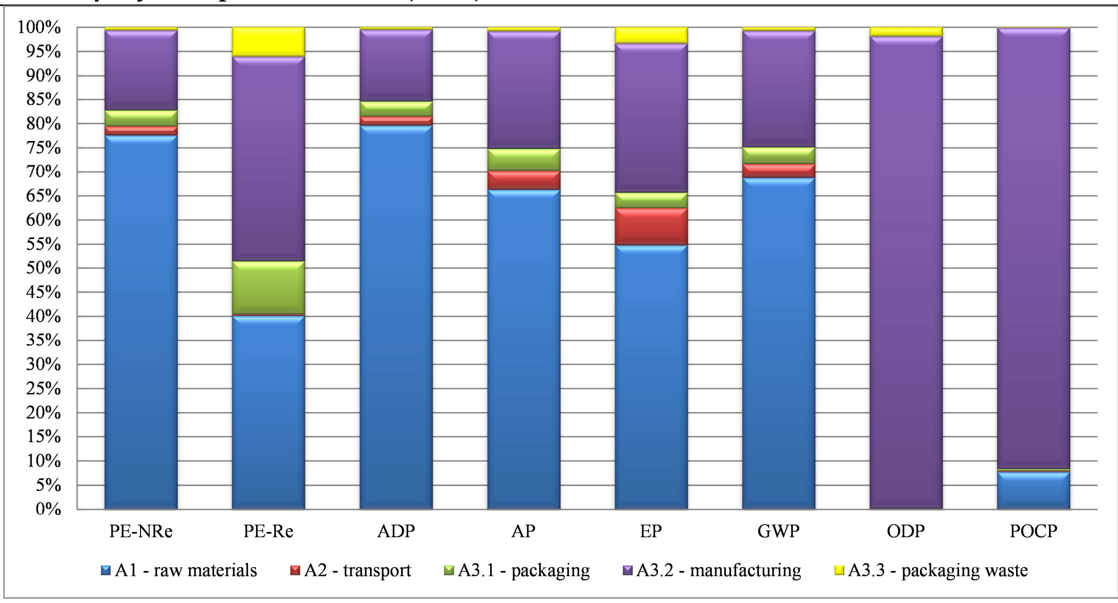

Figure 5.23 – Relative contribution of each sub-stage of EPS production to environmental impacts

Table 5.19 – Relative contribution (%) of burning of naphtha in the boiler and of electric energy consumption to A3.2 sub-stage of EPS production

Category indicator	**Relative contribution (%) for A3.2**	
	Electricity	**Naphtha, burned in boiler 100kW condensing, non-modulating**
ADP	15	83
AP	37	61
EP	47	51
GWP	14	85
ODP	7	92

5.4.3.7. IM - Polyurethane/Polyisocyanurate (PUR/PIR)

Polyurethane/Polyisocyanurate (PUR/PIR) boards studied in this thesis are suitable for application in external walls. Cradle to gate LCA results of the production of one m^3 of PUR/PIR are presented in Table 5.20. Figure 5.24 shows the relative contribution (in percentage) of sub-stages (A1-A3) to the same environmental impact categories.

The importance of raw material production (A1) in PUR/PIR environmental impacts is expressed in Figure 5.24. The contribution of this life cycle stage is in fact significant to many categories (more than 75% for PE-NRe, ADP, AP, GWP and POCP), and is only smaller than 40% for PE-Re. Manufacturing (A3.2) has an impact of 27% for the former category mainly due to electric energy consumption during this stage. The burdens related to packaging waste (A3.3) are mainly due to the fabrication of the metal bins (raw material packaging).

Table 5.20 – LCA results for each sub-stage of the “product stage” (A1-A3) of one cubic metre of PUR/PIR (with a density of 35 kg/m^3)

Category indicator	Unit	Life cycle stages (total per 1 m^3)					
		A1-A3	A1	A2	A3.1	A3.2	A3.3
PE-NRe	**MJ**	**3.59E+03**	3.01E+03	8.12E+01	5.38E+01	3.36E+02	1.06E+02
PE-Re	**MJ**	**1.46E+02**	5.71E+01	1.08E-01	2.67E+01	3.99E+01	2.25E+01
ADP	**kg Sb eq**	**1.53E+00**	1.36E+00	3.98E-02	2.22E-02	7.29E-02	4.06E-02
AP	**kg SO_2 eq**	**5.61E-01**	4.36E-01	2.72E-02	8.56E-03	5.65E-02	3.24E-02
EP	**kg PO_4^{3-} eq**	**6.77E-02**	4.19E-02	6.24E-03	2.40E-03	1.49E-02	2.21E-03
GWP	**kg CO_2 eq**	**1.45E+02**	1.21E+02	5.76E+00	1.83E+00	9.57E+00	7.16E+00
ODP	**kg CFC-11 eq**	**3.58E-06**	1.96E-06	1.09E-08	5.99E-08	7.95E-07	7.52E-07
POCP	**kg C_2H_4**	**5.07E-02**	4.60E-02	6.40E-04	4.15E-04	2.17E-03	1.45E-03

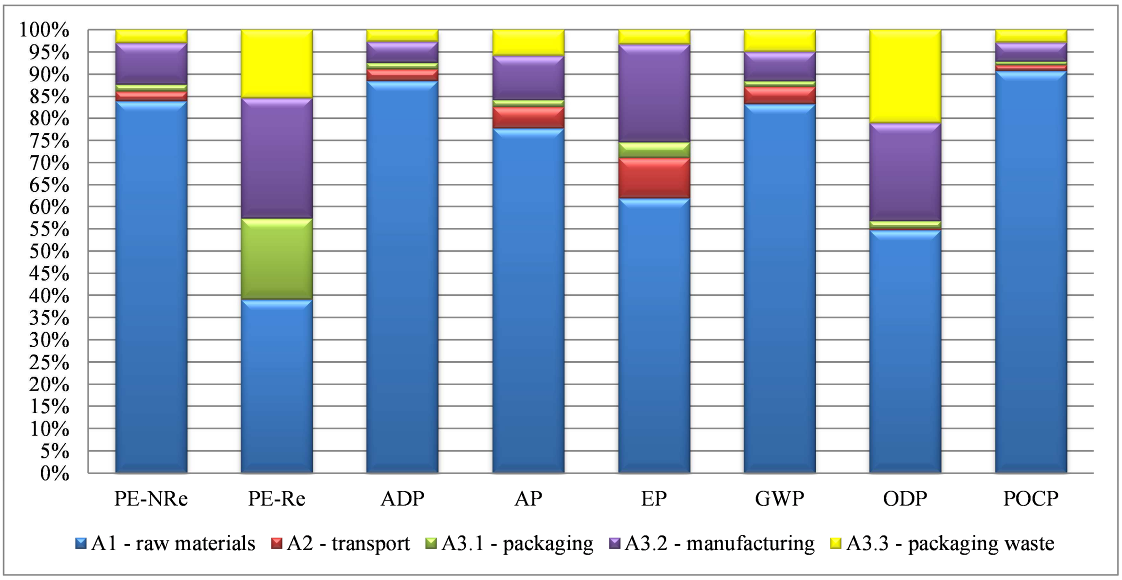

Figure 5.24 – Relative contribution of each sub-stage of PUR/PIR production to environmental impacts

Figure 5.25, Figure 5.26 and Figure 5.27 provide a more detailed analysis of the individual contributors to sub-stages A1-A2 impacts for EP, GWP and POCP, respectively. Impact from transportation (A2) is higher in EP (13%), while raw materials (polyol and isocyanate) share the remaining parcel of impacts in this and the other two categories. Polyol has a higher impact in POCP (61.6%), with a contribution of about half this value in the other two categories (EP and GWP). Isocyanate, on the other hand, has a lower contribution to POCP (37%), and is the main contributor to EP (53.7%) and GWP (63.2%).

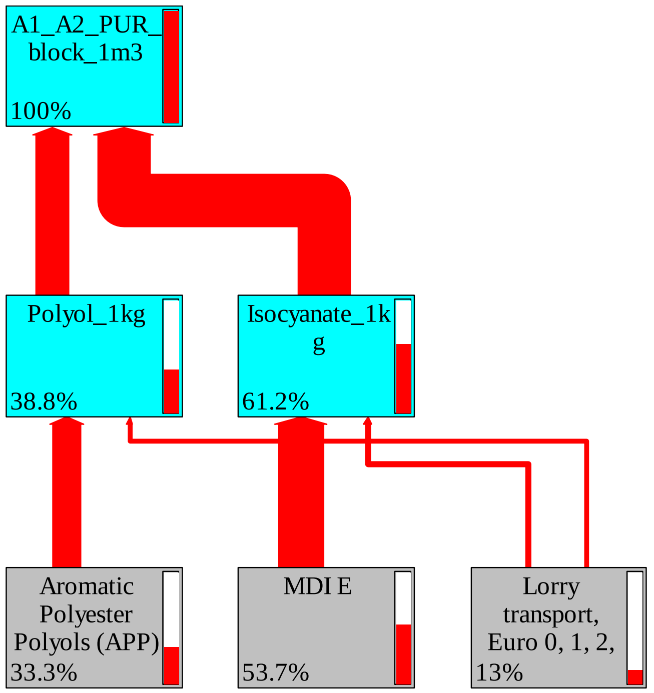

Figure 5.25 – Contribution of A1 plus A2 sub-stages of PUR/PIR production to EP with 1% cut-off generated in SimaPro

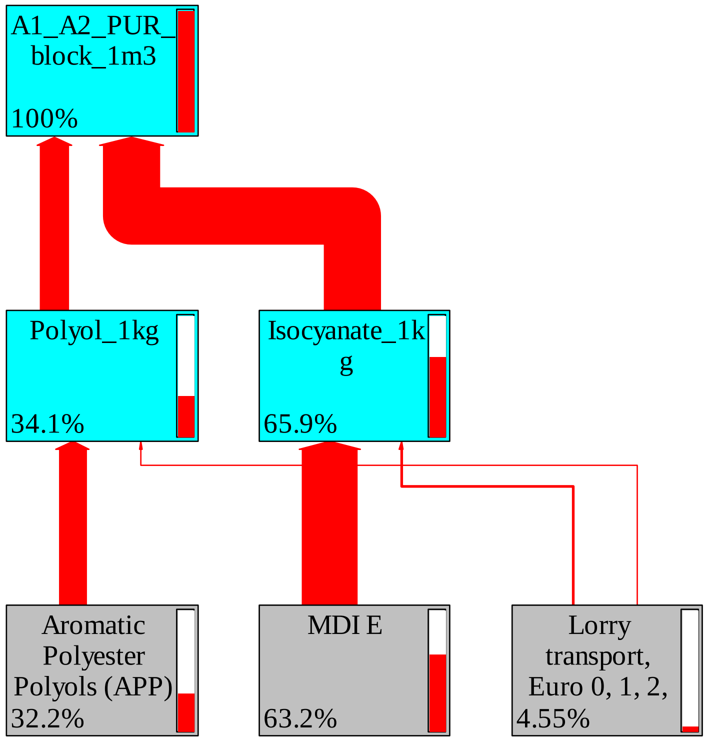

Figure 5.26 – Contribution of A1 plus A2 sub-stages of PUR/PIR production to GWP with 1% cut-off generated in SimaPro

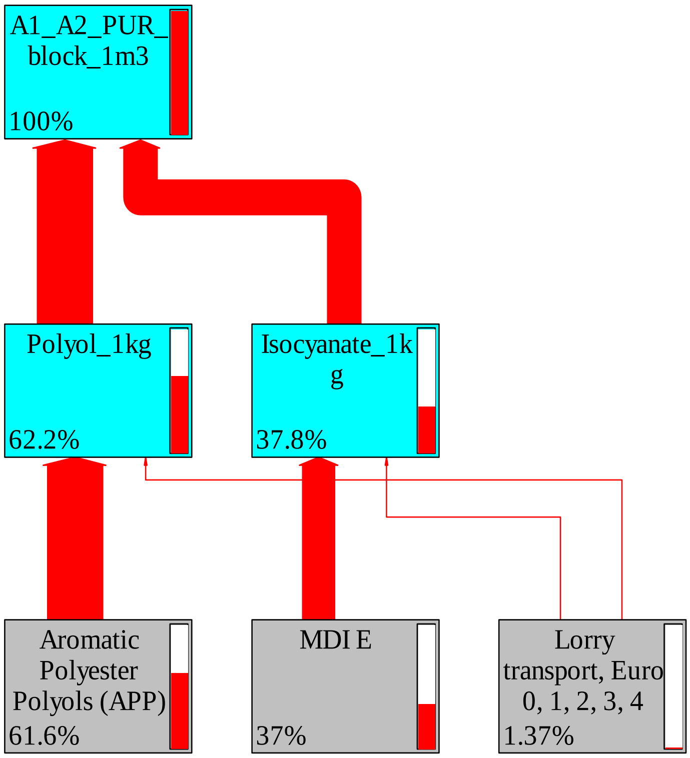

Figure 5.27 – Contribution of A1 plus A2 sub-stages of PUR/PIR production to POCP with 1% cut-off generated in SimaPro

5.4.3.8. IM - Agglomerate of Expanded Cork (ICB)

Agglomerate of Expanded Cork (Insulation Cork Board - ICB) boards studied in this thesis is an insulation material that can be used in several building assemblies, including external walls. Cradle to gate LCA results of the production of one cubic metre of ICB are presented in Table 5.21. Figure 5.28 shows the relative contribution (in percentage) of sub-stages (A1-A3) to the same environmental impact categories.

Table 5.21 – LCA results for each sub-stage of the “product stage” (A1-A3) of one cubic metre of ICB (with a density of 110 kg/m^3)

Category indicator	Unit	Life cycle stages (total per 1 m^3)					
		A1-A3	A1	A2	A3.1	A3.2	A3.3
PE-NRe	**MJ**	**8.21E+02**	1.19E+02	1.73E+01	1.54E+02	5.25E+02	5.56E+00
PE-Re	**MJ**	**7.68E+03**	6.83E+03	2.31E-02	7.53E+01	7.74E+02	1.18E+00
ADP	**kg Sb eq**	**3.31E-01**	4.91E-02	8.47E-03	6.47E-02	2.07E-01	1.76E-03
AP	**kg SO_2 eq**	**9.05E-01**	4.47E-02	5.80E-03	1.99E-02	8.34E-01	1.07E-03
EP	**kg PO_4^{3-} eq**	**4.03E-01**	1.19E-02	1.33E-03	4.87E-03	3.84E-01	4.65E-04
GWP	**kg CO_2 eq**	**4.02E+01**	7.15E+00	1.23E+00	4.92E+00	2.67E+01	2.33E-01
ODP	**kg CFC-11 eq**	**2.78E-06**	9.43E-07	2.33E-09	1.12E-07	1.71E-06	1.37E-08
POCP	**kg C_2H_4**	**6.38E-02**	7.43E-03	1.36E-04	1.33E-03	5.49E-02	4.71E-05

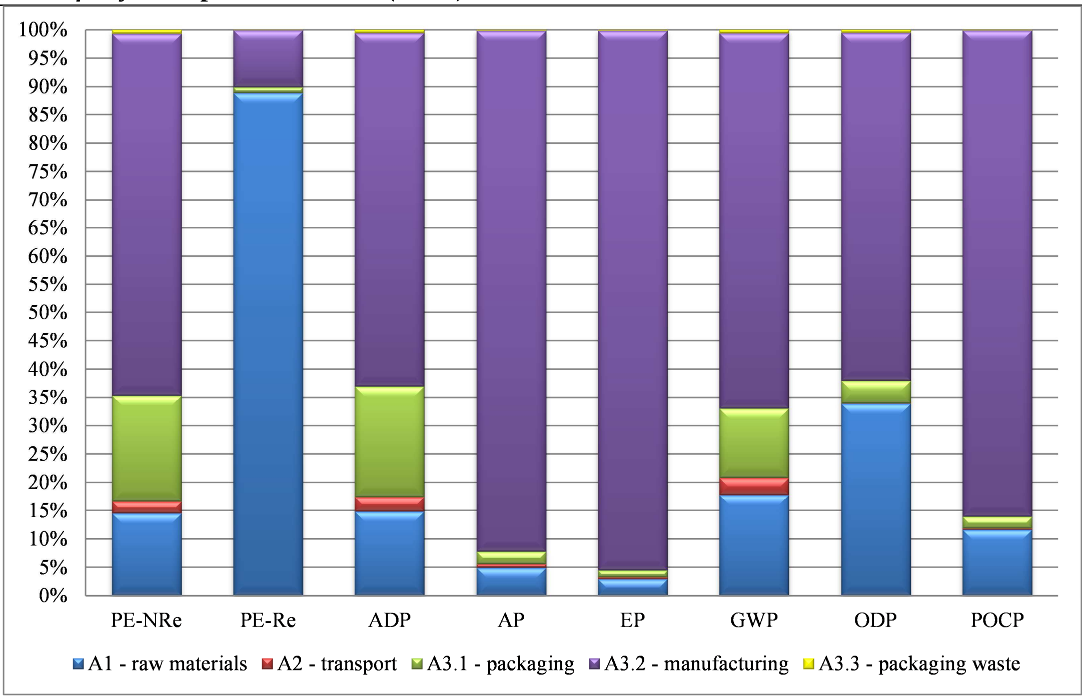

Figure 5.28 – Relative contribution of each sub-stage of ICB production to environmental impacts

Figure 5.28 reflects the fact that only one raw (and natural) material is used in ICB production - the "falca". Thus, A1 sub-stage contribution is only significant for PE-Re (88.9%) and for ODP (33.9%), the former being mainly related to forest, and forest roads, conservation and maintenance operations. On the other hand, the contribution of manufacturing (A3.2) is significant in many categories, such as AP, EP, GWP and POCP (more than 65%). Figure 5.29 and Figure 5.30 provide a more detailed analysis of the individual contributors to sub-stages A3.2 impacts for EP and GWP, respectively. However, the most important contribution to EP (about 40%) is not represented in diagrams and corresponds to the impacts of the direct air emissions from the boiler during heating of water for the expansion process. Electric energy consumption has around a 10% contribution to EP, while the disposal of wood ash mixture (from boiler) to land farming is responsible for 48.2% of the impacts in this impact category. Concerning GWP, only electric energy consumption presents a significant impact (95.8%) because the CO and CO_2 emissions from the boiler are biogenic and therefore not considered in this impact category by the EIAM used (CML).

5.4.3.9. ECS - One-coat mortar

The one-coat dry mortar studied in this Thesis is cement-based and has improved thermal characteristics due to the incorporation of an expanded aggregate. It can be applied as an external render in a broad range of colours. Cradle to gate LCA results of the production of one tonne of this mortar are presented in Table 5.22. The relative contribution (in percentage) of sub-stages (from A1 to A3) to the same environmental impact categories is shown in Figure 5.31.

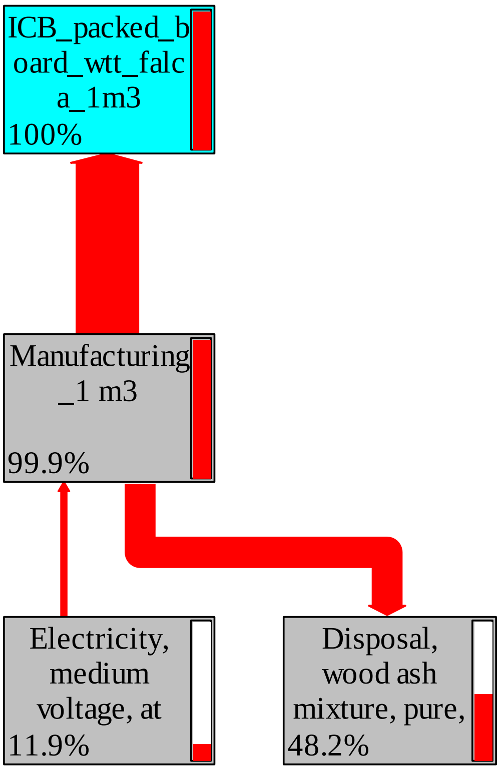

Figure 5.29 – Contribution of A3.2 sub-stage of ICB production to EP with 1% cut-off generated in SimaPro

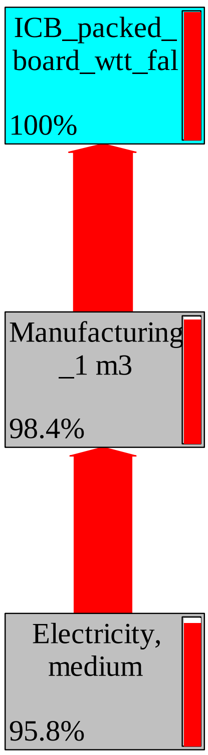

Figure 5.30 – Contribution of A3.2 sub-stage of ICB production to GWP with 1% cut-off generated in SimaPro

Table 5.22 – LCA results for each sub-stage of the "product stage" (A1-A3) of one tonne of one-coat mortar (dry density of 1.5 kg/cm^3)

Category indicator	Unit	Life cycle stages (total per 1 ton)					
		A1-A3	A1	A2	A3.1	A3.2	A3.3
PE-NRe	**MJ**	**2.61E+03**	1.89E+03	2.21E+02	2.34E+02	2.37E+02	2.02E+01
PE-Re	**MJ**	**7.42E+02**	1.75E+02	3.48E-01	5.28E+02	2.81E+01	1.05E+01
ADP	**kg Sb eq**	**1.24E+00**	9.72E-01	1.08E-01	9.76E-02	5.12E-02	8.82E-03
AP	**kg SO_2 eq**	**9.59E-01**	6.55E-01	2.09E-01	5.04E-02	3.97E-02	4.75E-03
EP	**kg PO_4^{3-} eq**	**1.99E-01**	1.40E-01	2.69E-02	1.87E-02	1.12E-02	1.71E-03
GWP	**kg CO_2 eq**	**2.35E+02**	2.01E+02	1.62E+01	9.93E+00	6.85E+00	1.08E+00
ODP	**kg CFC-11 eq**	**3.76E-05**	3.64E-05	3.30E-08	5.99E-07	5.60E-07	4.74E-08
POCP	**kg C_2H_4**	**3.87E-02**	2.67E-02	5.73E-03	4.33E-03	1.56E-03	3.50E-04

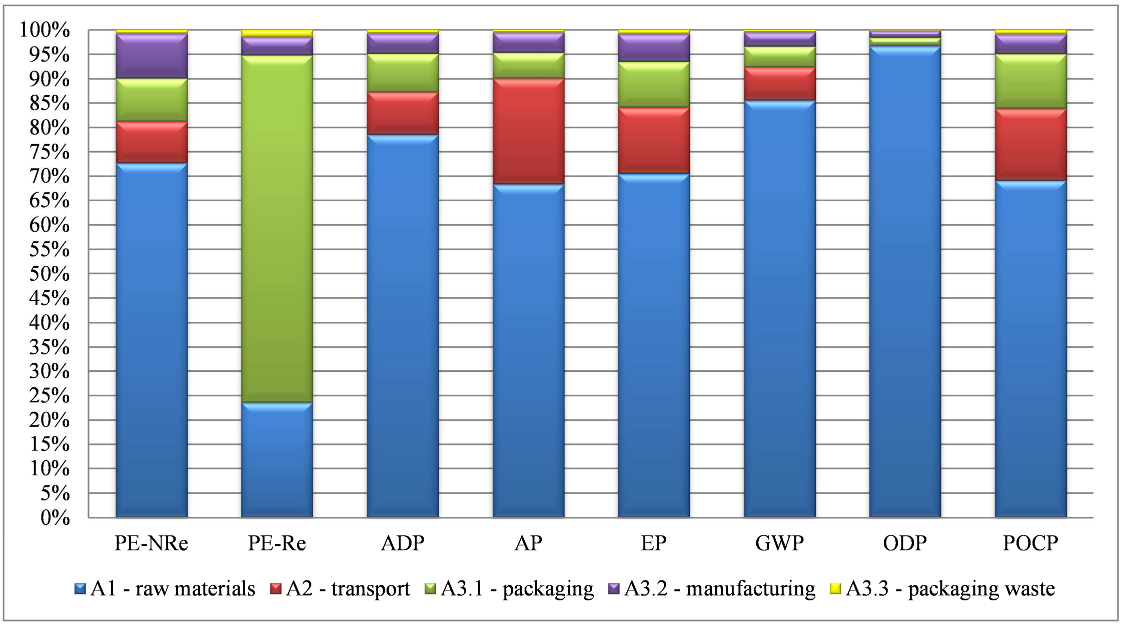

Figure 5.31 – Relative contribution of each sub-stage of the production of one-coat mortar to environmental impact categories

Figure 5.31 confirms that this product belongs to the cement-based group by showing the significant contribution of raw material production (A1) to all impact categories (more than 65%) except PE-Re. The impact of packaging (A3.1) to the latter category (71%) relies on the use of wood pallets (biomass as renewable energy). The impact of transportation (A2) to PE-NRe, ADP, AP, EP and POCP (between 8% and 22%) is mainly due to the water transportation of pigments from China and of one admixture from South Africa (Figure 5.34). Manufacturing (A3) impacts are directly related to electric energy consumption.

Figure 5.32, Figure 5.33 and Figure 5.34 provide a more detailed analysis of the individual contributors to sub-stages A1-A2 impacts for EP, GWP and POCP, respectively. Cement contribution to A1 is dominant in all impact categories: EP (32.3%), GWP (65.5%), and POCP (38.3%). Retarding admixture contribution to A1 is significant for POCP (22.6%) and EP

(11.7%), but pigments have a higher impact in this last category (18%). GWP impacts are also due to hydraulic lime production (9.57%), while pigments also influence POCP (16.9%, with 13.8% concerning the water transportation of pigments from China and of one admixture from South Africa).

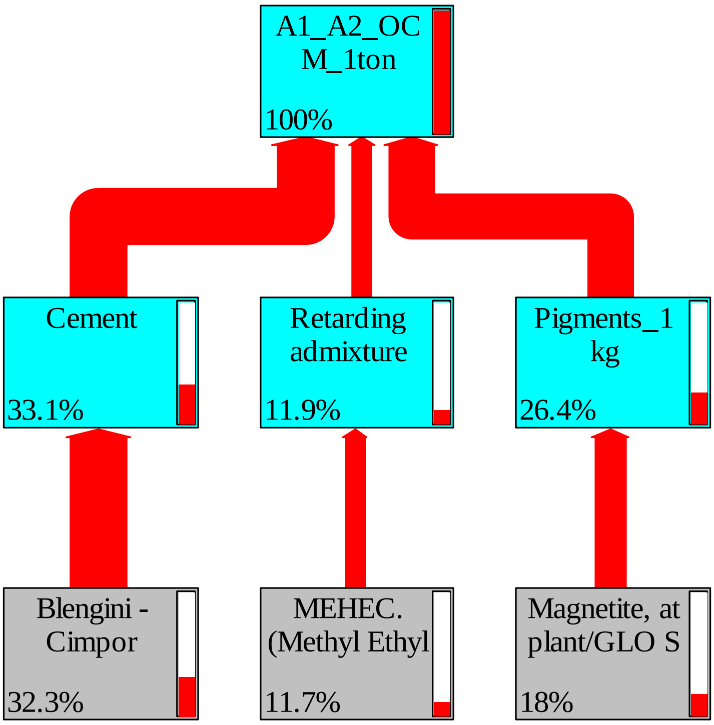

Figure 5.32 – Contribution of A1 plus A2 sub-stages of one-coat mortar to EP with 9% cut-off generated in SimaPro

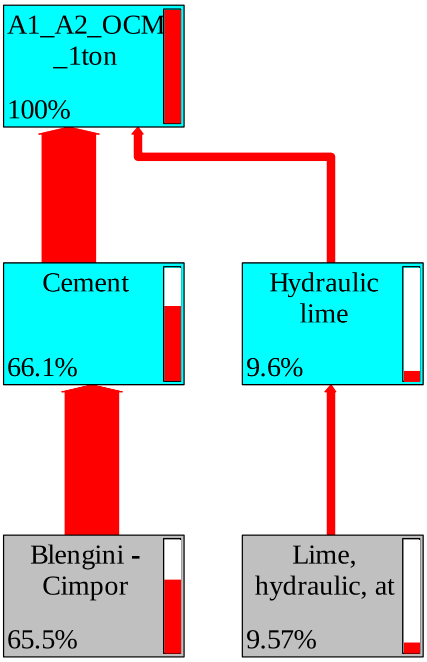

Figure 5.33 – Contribution of A1 plus A2 sub-stages of one-coat mortar to GWP with 9% cut-off generated in SimaPro

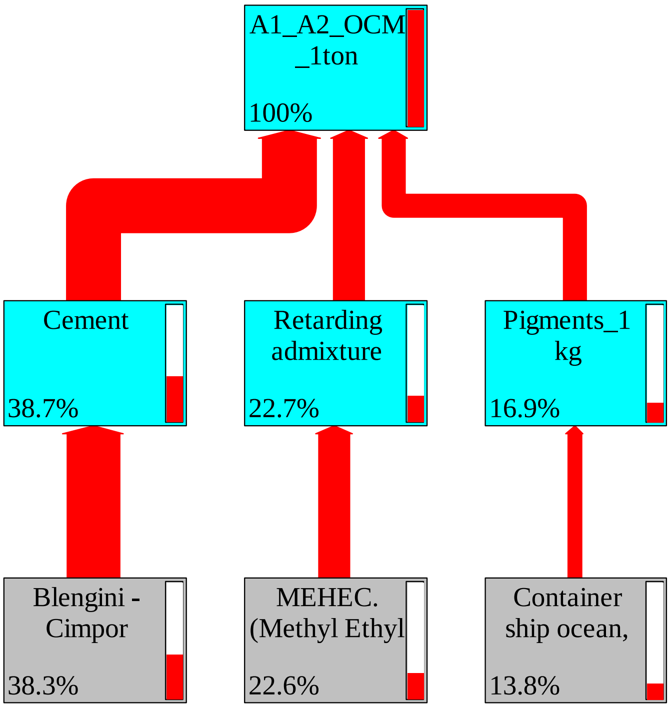

Figure 5.34 – Contribution of A1 plus A2 sub-stages of one-coat mortar to POCP with 8% cut-off generated in SimaPro

5.4.3.10. ECS and ICS - Wood-plastic extruded boards

Wood-plastic extruded boards are suitable for application in internal and external walls, and also in ceilings. Cradle to gate LCA results of the production of one tonne of wood-plastic boards are presented in Table 5.23, while Figure 5.35 shows the relative contribution (in percentage) of sub-stages (A1-A3) for the same environmental impact categories.

The importance of raw material production (A1) in wood-plastic board environmental impacts is expressed in Figure 5.35. The contribution of this life cycle stage is in fact significant (more than 75%) to all categories. Transport (A2) has an impact higher than 10% in PE-NRe, ADP, AP, EP and GWP due to the distant origin of some raw materials (Spain for wood waste and Central Europe for all the admixtures).

Table 5.23 – LCA results for each sub-stage of the "product stage" (A1-A3) of one tonne of wood-plastic boards (with a density of 1200 kg/m^3)

Category indicator	**Unit**	**Life cycle stages (total per 1 ton)**					
		A1-A3	**A1**	**A2**	**A3.1**	**A3.2**	**A3.3**
PE-NRe	**MJ**	5.75E+03	4.74E+03	6.57E+02	7.64E+01	2.06E+02	7.21E+01
PE-Re	**MJ**	1.41E+04	1.40E+04	8.77E-01	2.82E+00	1.99E+01	6.70E+00
ADP	**kg Sb eq**	2.60E+00	2.13E+00	3.22E-01	3.37E-02	8.14E-02	2.59E-02
AP	**kg SO_2 eq**	1.98E+00	1.63E+00	2.20E-01	1.06E-02	1.04E-01	1.41E-02
EP	**kg PO_4^{3-} eq**	3.26E-01	2.48E-01	5.05E-02	1.15E-03	2.03E-02	6.67E-03
GWP	**kg CO_2 eq**	2.75E+02	2.11E+02	4.66E+01	2.29E+00	1.13E+01	3.48E+00
ODP	**kg CFC-11 eq**	1.57E-05	1.46E-05	8.85E-08	1.21E-08	7.19E-07	2.41E-07
POCP	**kg C_2H_4**	1.13E-01	1.02E-01	5.18E-03	6.37E-04	3.71E-03	7.23E-04

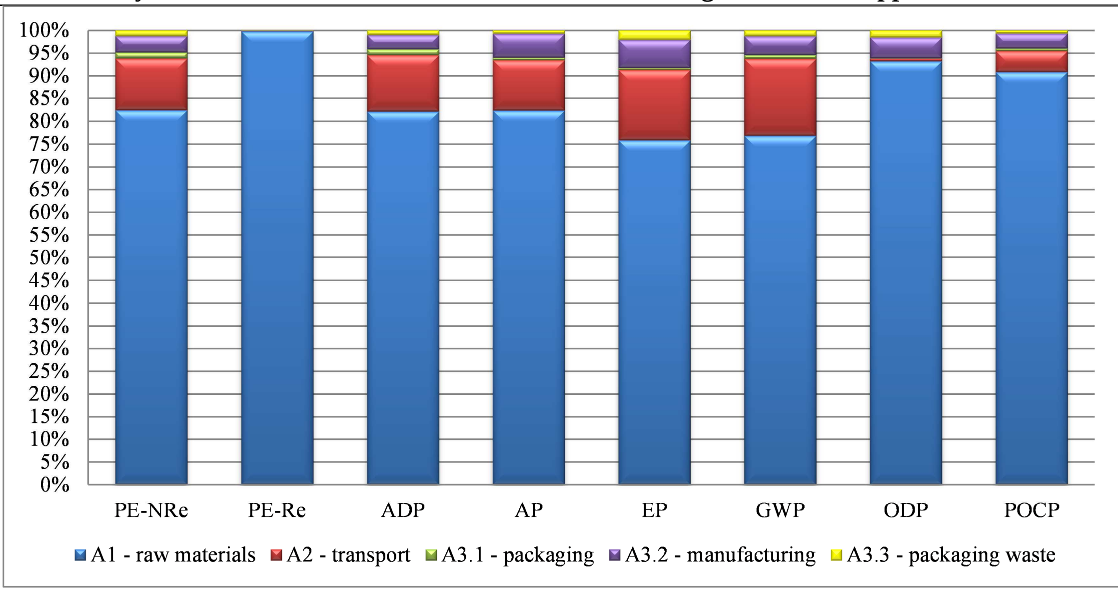

Figure 5.35 – Relative contribution of each sub-stage of wood-plastic board production to environmental impacts

Figure 5.36, Figure 5.37 and Figure 5.38 provide a more detailed analysis of the individual contributors to sub-stages A1-A2 impacts for AP, EP and POCP, respectively. The recycling of post-consumer plastic to produce pellets has a significant impact in AP and POCP (47.4 and 67.1%, respectively), while in the case of wood waste only impacts from the A2 sub-stage are significant because it is not a processed material. However, wood-protection products have a high contribution to the environmental impacts of wood-plastic boards. The anti-bacterial product has a share between 18.2 % (POCP) and 46% (EP) in the A1 sub-stage, while the ultra-violet (UV) protection product is responsible for around 10% of impacts for AP and EP.

5.4.3.11. ECS and ICS - Two-component adhesive

The two-component adhesive studied in this thesis is cement-based and can be used both for fixing all types of ceramic tiles and natural stone to walls and laying of indoor and outdoor paving. Both components of the adhesive - the powder (component A) and the resin (component B) - are sold separately and mixed on-site. LCA results of these two components are also presented and analysed separately in this section.

Cradle to gate LCA results of the production of one tonne of the powder (component A) are presented in Table 5.24. The relative contribution (in percentage) of sub-stages (from A1 to A3) to the same environmental impact categories is shown in Figure 5.39.

Table 5.24 – LCA results for each sub-stage of the "product stage" (A1-A3) of one tonne of the powder (comp. A; density of 1.7 g/cm^3)

Category indicator	**Unit**	**Life cycle stages (total per 1 ton)**					
		A1-A3	**A1**	**A2**	**A3.1**	**A3.2**	**A3.3**
PE-NRe	**MJ**	**3.16E+03**	2.71E+03	8.32E+01	3.06E+02	6.12E+01	1.51E+00
PE-Re	**MJ**	**7.79E+02**	1.95E+02	1.11E-01	5.77E+02	6.45E+00	6.33E-02
ADP	**kg Sb eq**	**1.82E+00**	1.64E+00	4.08E-02	1.32E-01	1.48E-02	6.23E-04
AP	**kg SO_2 eq**	**1.20E+00**	1.09E+00	2.65E-02	7.53E-02	1.27E-02	3.09E-04
EP	**kg PO_4^{3-} eq**	**1.97E-01**	1.62E-01	6.03E-03	2.52E-02	3.23E-03	1.58E-04
GWP	**kg CO_2 eq**	**3.95E+02**	3.71E+02	5.89E+00	1.52E+01	2.01E+00	8.64E-02
ODP	**kg CFC-11 eq**	**5.76E-05**	5.67E-05	1.12E-08	6.61E-07	1.86E-07	6.60E-09
POCP	**kg C_2H_4**	**4.48E-02**	3.86E-02	6.07E-04	5.17E-03	4.41E-04	1.92E-05

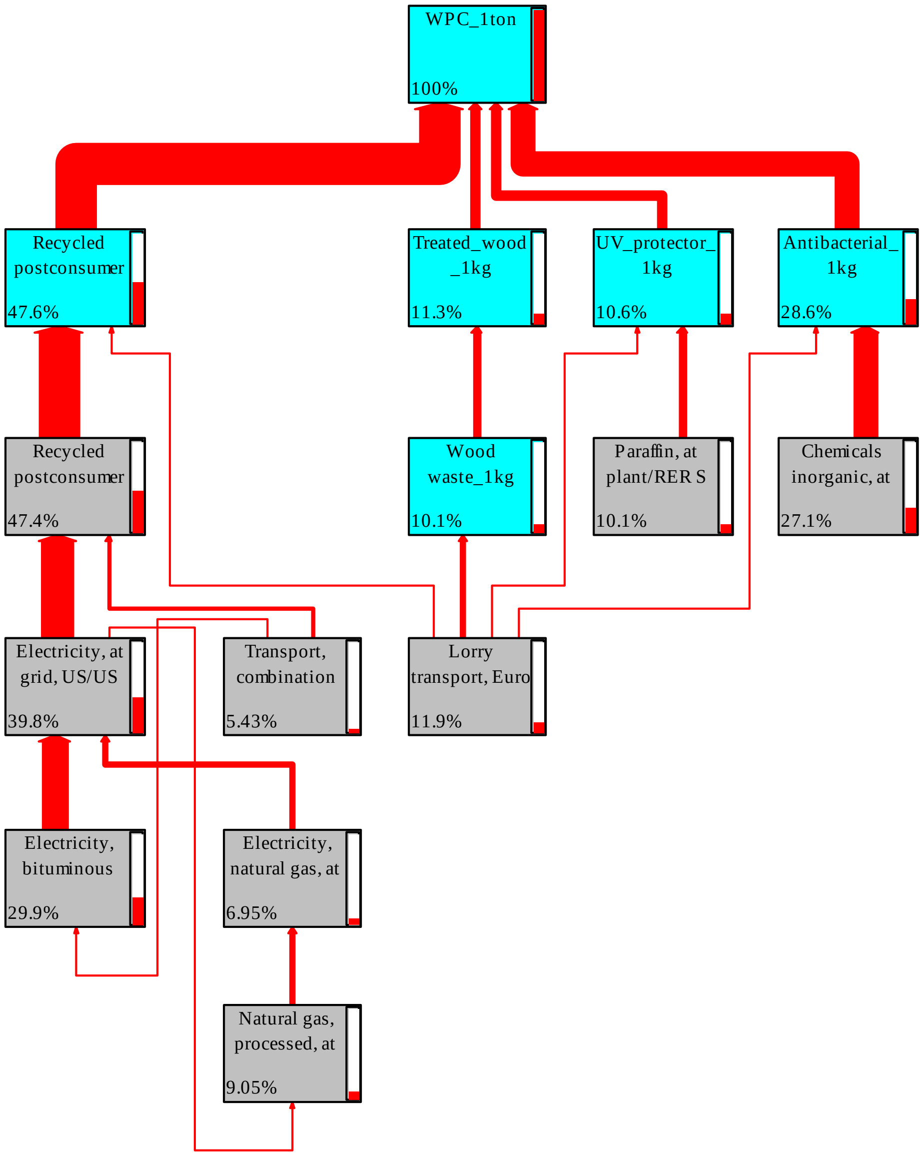

Figure 5.36 – Contribution of A1 plus A2 sub-stages of wood-plastic board production to AP with 5% cut-off generated in SimaPro

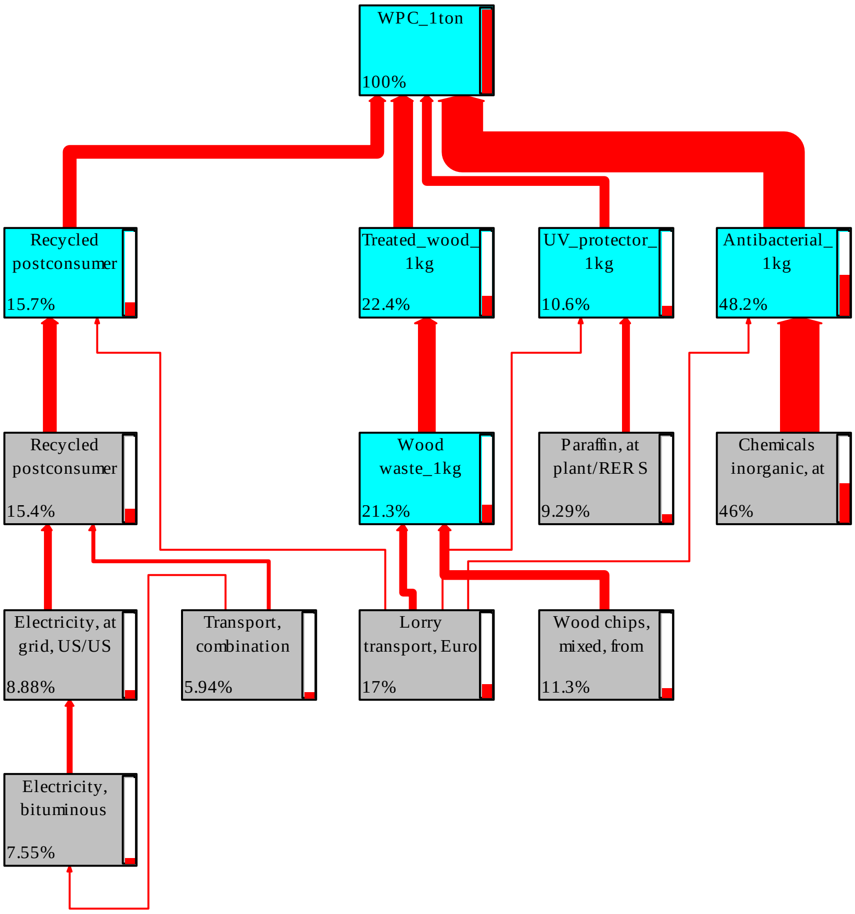

Figure 5.37 – Contribution of A1 plus A2 sub-stages of wood-plastic board production to EP with 5% cut-off generated in SimaPro

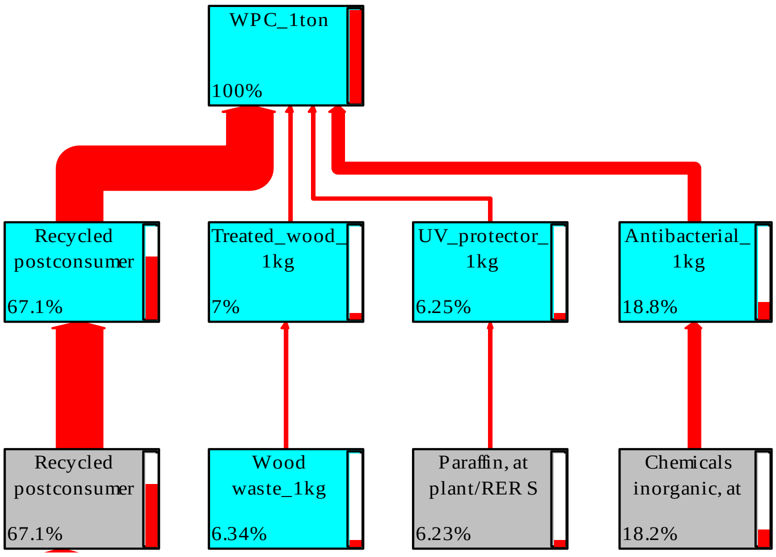

Figure 5.38 – Contribution of A1 plus A2 sub-stages of wood-plastic board production to POCP with 5% cut-off generated in SimaPro

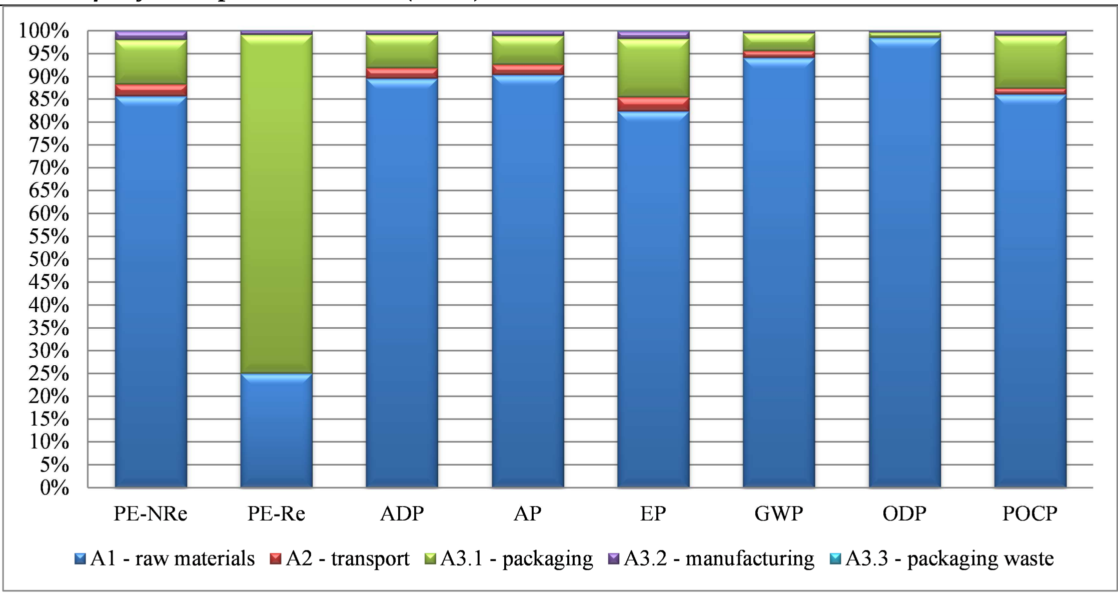

Figure 5.39 – Relative contribution of each sub-stage of the production of one tonne of the powder (comp. A) to environmental impact categories

The significant contribution of raw material production (A1) to all impact categories (more than 80%, except for PE-NRe) presented in Figure 5.39 confirms that this product is cement-based. The impact of packaging (A3.1) to PE-NRe (10%) and PE-Re (74%) is due to the use of wood pallets (biomass as renewable energy). The impact of transport (A2, with 3% to PE-NRe and EP) comes mainly from the transportation of high quantities of aggregates for the manufacturing of this product (and is not motivated by high distances transportation).

A more detailed analysis of the individual contributors to sub-stages A1-A2 impacts for AP and GWP is provided in Figure 5.40 and Figure 5.41. Cement production has the most important contribution for both categories (87.5% for AP and 94.1% for GWP). The remaining significant contributor is the retarding admixture (9.14% for AP and 3.99% for GWP).

Cradle to gate LCA results of the production of one tonne of the resin (component B) are presented in Table 5.25. The relative contribution (in percentage) of sub-stages (from A1 to A3) to the same environmental impact categories is shown in Figure 5.42.

Table 5.25 – LCA results for each sub-stage of the "product stage" (A1-A3) of one tonne of the resin (comp. B; density of 1.007 g/cm^3)

Category indicator	Unit	Total per 1 ton	Life cycle stages				
			A1	**A2**	**A3.1**	**A3.2**	**A3.3**
PE-NRe	**MJ**	**2.35E+04**	1.65E+04	4.43E+02	6.47E+03	1.17E+02	2.10E+01
PE-Re	**MJ**	**2.33E+03**	3.20E+02	5.91E-01	2.00E+03	1.20E+01	2.78E+00
ADP	**kg Sb eq**	**1.05E+01**	7.29E+00	2.17E-01	2.99E+00	2.92E-02	6.65E-03
AP	**kg SO_2 eq**	**3.48E+00**	2.27E+00	1.48E-01	1.04E+00	2.57E-02	4.01E-03
EP	**kg PO_4^{3-} eq**	**1.06E+00**	8.92E-01	3.41E-02	1.25E-01	6.61E-03	1.78E-03
GWP	**kg CO_2 eq**	**8.97E+02**	6.07E+02	3.14E+01	2.53E+02	4.38E+00	8.85E-01
ODP	**kg CFC-11 eq**	**5.03E-05**	4.82E-05	5.96E-08	1.66E-06	3.66E-07	5.46E-08
POCP	**kg C_2H_4**	**3.91E-01**	3.20E-01	3.49E-03	6.64E-02	8.78E-04	1.74E-04

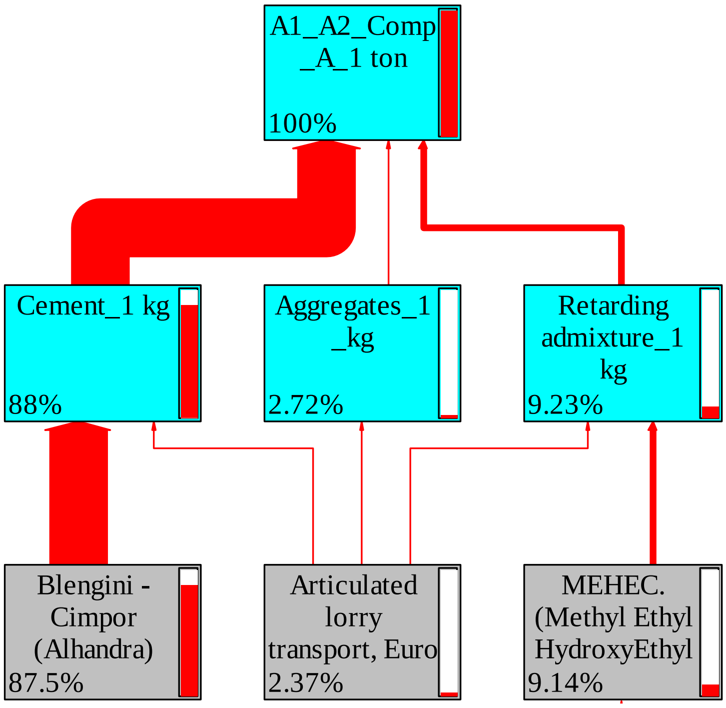

Figure 5.40 – Contribution of A1 plus A2 sub-stages of powder production (comp. A) to AP with 1% cut-off generated in SimaPro

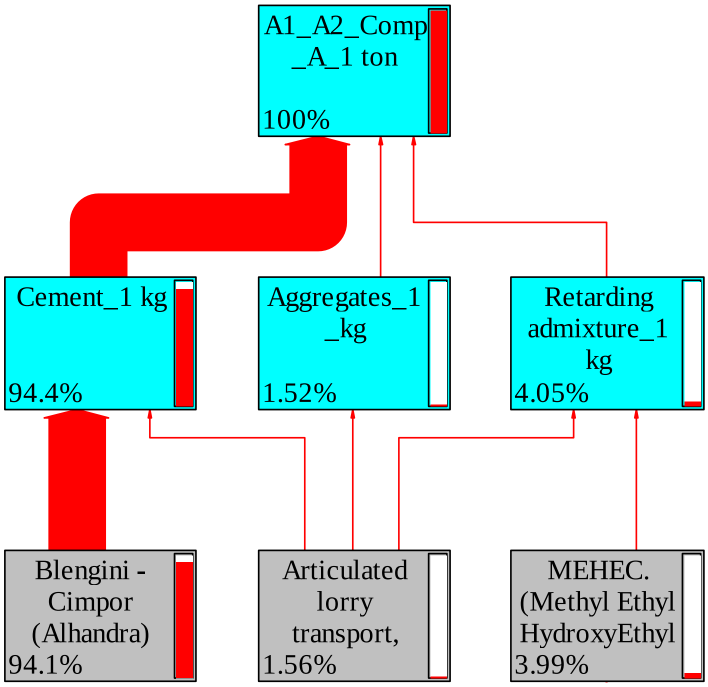

Figure 5.41 – Contribution of A1 plus A2 sub-stages of powder production (comp. A) to GWP with 1% cut-off generated in SimaPro

Figure 5.42 shows an environmental profile of this product that seems more like chemical-based materials (e.g. EPS or XPS) than cement-based ones (e.g. component A of this adhesive). Sub-stage A3.1 (packaging) has in fact a significant contribution to the environmental impacts of this product, namely with more than 25% for PE (NRe and Re, the latter with a contribution of 86% of

A3.1), ADP, AP and GWP. This burden is due mainly to the polypropylene buckets used for packing this component, but also in the two types of polyethylene shrink film and the wood pallets used for its palletisation. Raw material production (A1) also has a big contribution to many impact categories (equal or more than 65%, except for PE-Re), the share of resin being more than 99% in all impact categories.

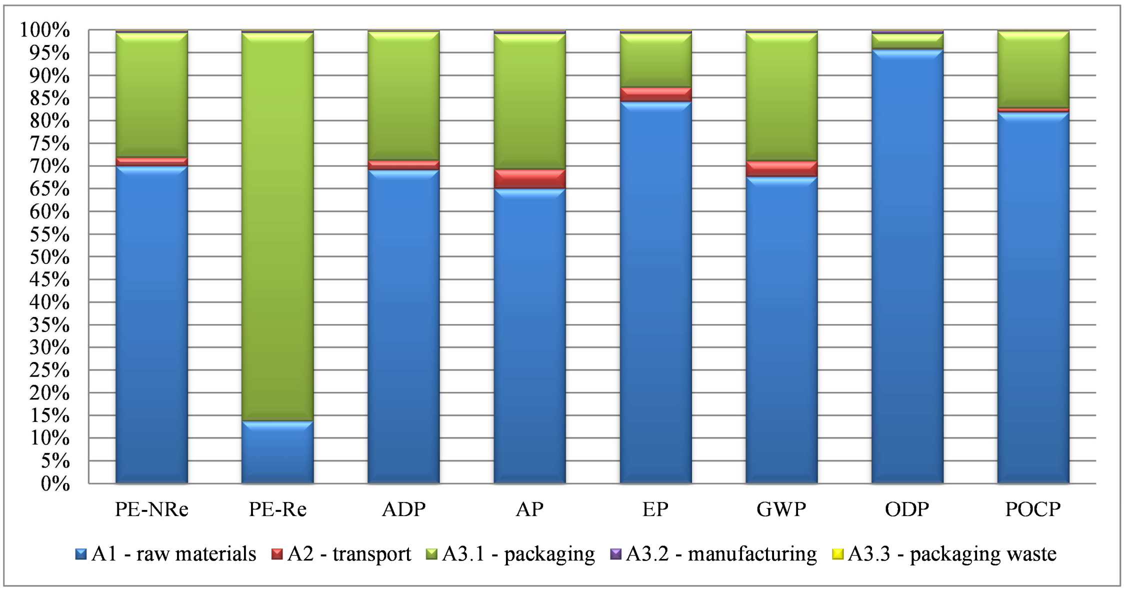

Figure 5.42 – Relative contribution of each sub-stage of the production of one tonne of the resin (comp. B) to environmental impact categories

5.4.3.12. ICS - Gypsum plasterboard

The gypsum plasterboard studied in this thesis is suitable for cladding of internal walls, ceilings and partitions. Cradle to gate LCA results of the production of one square metre of this product are presented in Table 5.26. The relative contribution (in percentage) of sub-stages (from A1 to A3) to the same environmental impact categories is shown in Figure 5.43.

Table 5.26 – LCA results for each sub-stage of the “product stage” (A1-A3) of one square metre of gypsum plasterboard (weight of 7.8 kg/m^2)

Category indicator	Unit	Total per 1 m^2	Life cycle stages				
			A1	A2	A3.1	A3.2	A3.3
PE-NRe	**MJ**	**6.92E+01**	1.29E+01	2.76E+00	7.53E+00	4.58E+01	2.36E-01
PE-Re	**MJ**	**4.45E+00**	3.05E+00	6.56E-02	1.27E+00	-6.84E-03	6.98E-02
ADP	**kg Sb eq**	**3.25E-02**	5.52E-03	1.24E-03	3.15E-03	2.26E-02	7.42E-05
AP	**kg SO_2 eq**	**7.58E-03**	3.13E-03	8.58E-04	9.42E-04	2.61E-03	4.73E-05
EP	**kg PO_4^{3-} eq**	**2.68E-03**	1.60E-03	2.87E-04	2.15E-04	5.60E-04	2.07E-05
GWP	**kg CO_2 eq**	**3.42E+00**	7.50E-01	1.78E-01	2.36E-01	2.25E+00	9.87E-03
ODP	**kg CFC-11 eq**	**4.71E-07**	1.23E-07	4.64E-09	3.58E-09	3.40E-07	6.13E-10
POCP	**kg C_2H_4**	**4.89E-04**	1.54E-04	2.63E-05	4.62E-05	2.61E-04	2.03E-06

Figure 5.43 shows that the environmental profile of gypsum plasterboards is mainly dominated by A3.2 sub-stage (manufacturing). In fact, A3.2 is dominant in five out of eight of

the impact categories, while A1 is dominant only in two of them. Contribution of manufacturing for PE-NRe and ADP is dominated by natural gas spent in stucco slurry preparation and in board drying, while this last process is the main contributor of this sub-stage for GWP. The impact of packaging (A3.1) to PE-Re (29%) results from the use of wood bars (biomass as renewable energy) in palletisation.

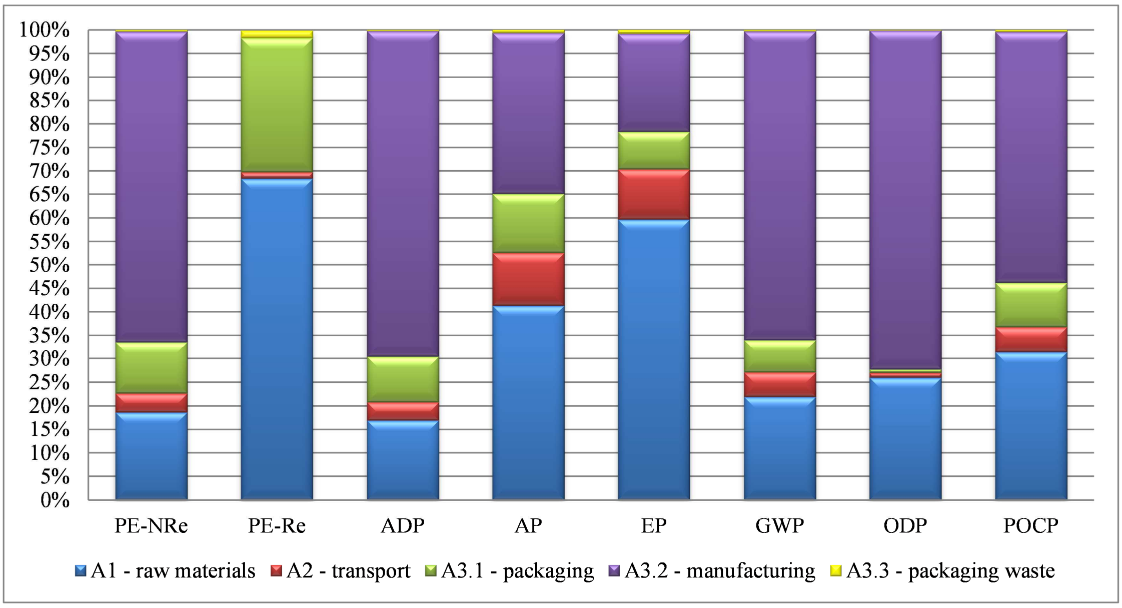

Figure 5.43 – Relative contribution of each sub-stage of the production of one square metre of gypsum plasterboard to environmental impact categories

A more detailed analysis of the individual contributors to stage A1 (and A2) impacts is provided in Table 5.27. In fact, almost all of the burden of each impact category for which the A1 sub-stage (raw material production) has a significant contribution results from the transport of flue-gas desulphurisation (FGD) to the plant (the only process considered in stage A1 of this by-product) and from paper recycling. This table presents, therefore, the relative contribution of both raw materials to each impact category in the A1 and A2 sub-stages (the contribution of the latter sub-stage is lower than 12% in every category).

Table 5.27 – Relative contribution (%) of FGD gypsum and recycled paper to A1 plus A2 sub-stages of the production of gypsum plasterboards

Category indicator	**Relative contribution (%) for A1-A2**	
	FGD gypsum	**Recycled paper**
ADP	14	63
AP	17	59
EP	13	57
GWP	14	56
POCP	12	64

5.5. Conclusion and perspectives

This chapter starts by describing in detail the “Life Cycle Impact Assessment” (LCIA) phase of the “Life Cycle Assessment (LCA) methodology”. This includes LCIA limitations, mandatory elements and optional stages. A detailed description of “Environmental Impact Assessment Methods” (EIAM) functions and available approaches, and also of environmental impact categories, is presented within the mandatory elements section. “Life Cycle Impact interpretation” is the last phase of the global LCA methodology and its procedures are also described in this chapter.

The third main section of this chapter is devoted to LCA tools available in the market. These tools can be classified in one out of three main groups depending on their main characteristics and aim. Each of these groups is characterised in detail, in conjunction with an extensive presentation of available LCI and LCA databases of different industrial sectors. This section finishes with the justified selection of the LCA tool to be used in this thesis based on the analysis previously presented.

The last section of this chapter includes the LCIA of the building products studied in this thesis. It starts with the description of many important presuppositions that have been considered in this stage of LCA studies. These assumptions include the choice of processes for modelling raw material production and background processes (i.e. infrastructure, energy, transportation and waste disposal processes) and the allocation procedures followed. Then, the choice of the most adequate EIAM and environmental categories to be used in this thesis is justified. This chapter ends with the full presentation and analysis in detail of the LCA results of the studies completed on the scope of this thesis. These LCA results are presented per life cycle stage and environmental category, including the relative importance of each stage for each category. Then, the processes that contribute most to each category are identified, namely in the most significant life cycle stage, for some chosen impact categories.

The importance of the selection of the most adequate databases and corresponding processes for modelling the “raw material extraction and processing of secondary material input” (A1) is also highlighted in this chapter. Available LCI and LCA databases are first described, followed by the identification of the processes chosen to model this life cycle stage for each of the products studied in this thesis. The analysis of the "hot spots” of the LCA results achieved for these products proves the significance of this stage for the cradle to gate environmental impacts of most of them, no matter their nature (e.g. cement-based, natural or oil-based) or production process.

The LCA results of the materials studied in this thesis show that some life cycle stages such as transportation of raw materials (A2), packaging and packaging waste (A3.1 and A3.3, respectively), may not be discarded in a cradle to gate study because they can have a significant contribution in some environmental categories and construction products. The results achieved also confirm that the ODP category should continue to be considered in LCA studies (despite their relative low importance - Appendix 5.I), not only because some LCI of background processes are not updated and still consider the use of CFC in industry, but also because HCFC emissions can occur in current manufacturing processes.

This chapter provides a thorough explanation of the LCIA phase, both in theoretical and practical terms. The LCIA of the 12 building products studied was completed using a similar EIAM and environmental categories. The assumptions made in the modelling of these production processes were also consistent, namely the selection of the databases representing background processes for which site-specific data is not available. Thus, the LCA results presented in this chapter can be considered scientifically sound by having been achieved through a consistent methodology that also takes into consideration the most recent European Standards. These results are also innovative and up-to-date LCA data of several products for external walls of buildings in Portugal.

5.6. References - Chapter 5

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6. LIFE CYCLE ASSESSMENT (LCA) DATA SETS OF CONSTRUCTION MATERIALS AND PRODUCTS: SELECTION AND BENCHMARKING

6.1. NATIVELCA methodology

The selection of the LCI or LCA data sets to model the background process of the “production” of a raw material for a given product - or of the “production” of a construction material to be used in a building assembly - is of paramount importance in any LCA study and/or EPD development, as mentioned in Chapter 5. A LCA practitioner must rely on available data sets, or develop a full LCA study himself for each given material. The frequency with which this question arises during a LCA study, and the influence of its answer on the final results of the study, justify the need for a scientifically robust methodology to deal with it. The need of such a methodology grows with the increasing number of LCA data sets available in Europe.

Therefore, the author has developed a methodology for the selection of a coherent Life Cycle Assessment (LCA) data set of construction materials and products to be used as generic data for a national context, namely for the Portuguese situation (Silvestre, J. & Lasvaux, 2012). This methodology is entitled NativeLCA and was developed with the additional scientific supervision of Sébastien Lasvaux (Post-doctoral researcher) during the internship of the author in January-February 2012 in the Environment Division of the “Centre Scientifique et Technique du Bâtiment” (CSTB), in Grenoble, France. This internship intended to provide the author with: data and tools that would be useful in the development of his PhD thesis; and the opportunity to gain practical experience of scientific research in the framework of his studies. The author was allowed to publish the relevant results achieved during this internship in this thesis.

NativeLCA is based on previous research studies completed (Lasvaux, 2010; Lasvaux *et al.*, 2011) and supervised (Hodková & Lasvaux, 2012) by Sébastien Lasvaux with the aim of defining a consistent methodology to derive generic LCA data on building materials for a national context (France in the first case and the Czech Republic in the second case).

6.1.1. Aim

The development of a methodology for the selection of a coherent LCA data set of construction materials and products - NativeLCA - has three main objectives:

- Make a set of LCA data of construction materials and products representative of the European situation available by means of a review of existing EPD or LCA data sets;
- Develop a scientifically robust methodology to assess the quality of available European LCA data to be used in a national context (e.g. the Portuguese context) and identify the sources of variability of these data sets;
- Provide LCA data required by recent European standards (CEN, 2010, 2011) and needed for the calculation of LCA of building assemblies (and/or for EPD development), namely two types of coherent LCA data sets to be used as generic data for a national context:
  - LCA data sets of construction materials, based on an extensive set of data from the existing literature. Some of these data sets will be used as background data (LCA data of raw materials production) for the products studied in this thesis using information from Portuguese producers;
  - LCA data sets of construction products based on an extensive set of data from the existing literature (e.g. European LCA data sets, foreign EPD, or national LCA studies or available EPD). A part of these data sets can serve as benchmark values for the LCA results achieved in this thesis for the same products. The remaining average data sets are used as reference data for all the construction products not studied in this thesis using site specific data.

To fulfil these objectives, it is necessary to start with the review, collection and characterisation of existing LCA data sets of construction materials and products from European LCA databases. These databases can be generic (e.g. Ecoinvent) or based on national Environmental Product Declaration (EPD) programmes (e.g. the French INIES or the German IBU databases). Other databases also include Life Cycle Inventory (LCI) of both LCA and EPD data (e.g. the SLCA database developed at the CSTB). Then, the quality of these data sets is assessed using a scientifically robust methodology, and their sources of variability are identified, analysed and compared. The corresponding results are presented in order to show the variability of LCI flows and Life Cycle Impact Assessment (LCIA) indicators for the same functional unit. Next, the differences are explained based on the available methodological assumptions. Finally, coherent LCA data sets (i.e. NativeLCA) are selected for each construction material and product. NativeLCA is a fundamental tool in improving the reliability of the environmental assessment in building design (namely using a level 2 LCA tool- see Chapter 5), and of the LCA of building assemblies. This type of procedure is proposed but not developed in the European Standards. In fact, a statement from FprEN15978:2011 can be considered a basis for NativeLCA development by referring that (CEN, 2011):

- If no specific EPD in accordance with the requirements of EN 15804 is available for the product which is used in the building, the product stage information modules (A1 to A3) of “available generic (not specific) EPD or a data set” of a similar product may be used and adapted to create a new data set to reflect the actual situation as closely as possible;
- Such a data set shall be “made” only on the basis of suitably reliable and accurate information available for both products;
- In making such adaptations, assumptions shall not simply default to the best case but shall conservatively represent a realistic condition.

In fact, generic, average or EPD data sets on building products do not yet exist in all European countries. However, this information is fundamental for the environmental assessment of buildings or building assemblies. In a national context, foreign generic or non-generic data sets have to be considered. This procedure has to rely on an objective methodology that includes completeness, representativeness, and reliability checks of each available data set (Hodková & Lasvaux, 2012). Even in countries where many EPD from the construction sector are available, NativeLCA is essential for the selection of a coherent LCA data set to be used in the early design stage, while individual EPD can be considered in the following design stages. NativeLCA can also be useful to verify the plausibility of EPD results in the development of these documents and also in their critical review.

6.1.2. Scope

The scope of NativeLCA is limited in this thesis by the construction materials and products used in a building’s external walls, but this methodology can be applied to other building products. Insulation products, elements of the wall structure, and internal and external wall claddings are within this scope (their definition is in Chapter 3). Construction materials within the scope of this thesis are cement, gravel and sand, concrete, reinforcement steel, and gypsum. For concrete, available LCA data sets can be used to provide a value for LCA calculations of finished products, e.g. reinforced concrete and lightweight concrete blocks. Reinforcement steel is also within the scope of this study in order to provide data to perform the LCA of reinforced concrete. The last construction material to be studied is gypsum, which is used in gypsum plasterboards, a cladding material studied in this thesis.

6.1.3. Review of existing LCA databases

There are two main types of LCA data sets: Environmental Product Declaration (EPD) and the “so-called” generic LCA data. The former correspond to Type III environmental declarations (LCA specific data sources) and is more suitable to be used in a detailed design stage (or at on-site assessment or building certification). The latter meets the requirements for the early conceptual design stage (when no detailed information is available for the product). Therefore, data genericness and LCA uncertainty decreases as design detail increases.

An extensive search of LCA data in generic data sets (i.e. Ecoinvent or European Life Cycle Database – ELCD), national and international average data sets, and EPD data sets was made for the materials in the scope of this study. From this search, preliminary trials were made of NativeLCA use and this methodology was validated. Appendix 6.I summarises the main characteristics of the databases chosen to be included in this study, which are all European, in order to comply with a geographical representativeness criterion. EPD databases were described in section 2.2.1.3 and databases containing environmental information of construction products were referred to in section 2.2.2.1, while LCI and LCA (generic and average) data sets are presented in detail in section 5.3.1.1. "STEPWISE EPD" of ready-mixed concrete and the experimental EPD programme of the ceramic industrial sector are identified in Table 6.2, Table 6.3, Appendixes 6.I and 6.II as "Portuguese EPD" and "Portuguese average LCA data set", respectively.

In addition to the generic LCA databases, several country specific or European average LCA data sets have been established. These include the French ATILH (*Association Technique de l'Industrie des Liants Hydrauliques* – see Appendix 6.I) data sets and the European average (CEMBUREAU) for the production of cement or PU-Europe data sets for polyurethane, which are all characterised in Appendix 6.I.

There are therefore three levels of increasing genericness that can be defined in order to evaluate the possibility of using data sets as generic for a national context (Figure 6.1): site specific (e.g. individual EPD), average data sets (e.g. average EPD by producer, by use or by country, or European or country specific average LCA data sets) and generic data (e.g. generic data from Ecoinvent) (adapted from (Hodková & Lasvaux, 2012)). Average LCA data sets belong to the "average" group but are often considered generic (Figure 6.1), namely when the identification of the plants and/or companies included in the study are omitted in the meta data.

6.1.3.1. Syntheses of EPD programmes

Each EPD is usually determined according to "Product Category Rules" developed specifically for each family of products (e.g. wood, cement-based or ceramic products – see

Appendix 6.I). Therefore, each EPD database has unique characteristics, namely background data, methodology, and data origin that may result in significant differences in the LCA results for each construction product. The publicly available EPD documentation is also very often incomplete concerning the data origin and the methodology of calculation, increasing the risk of misunderstandings for the final user. Yet, the methodological report, which is kept confidential most of the time, should report all the hypotheses as in any LCA study. As a result, the choice of the data to be used in every national context should be cautious, chiefly if the aim is to use it as national proxy data, by considering all the complementary information included in the EPD (meta data) (Hodkova & Lasvaux, 2012 (July)).

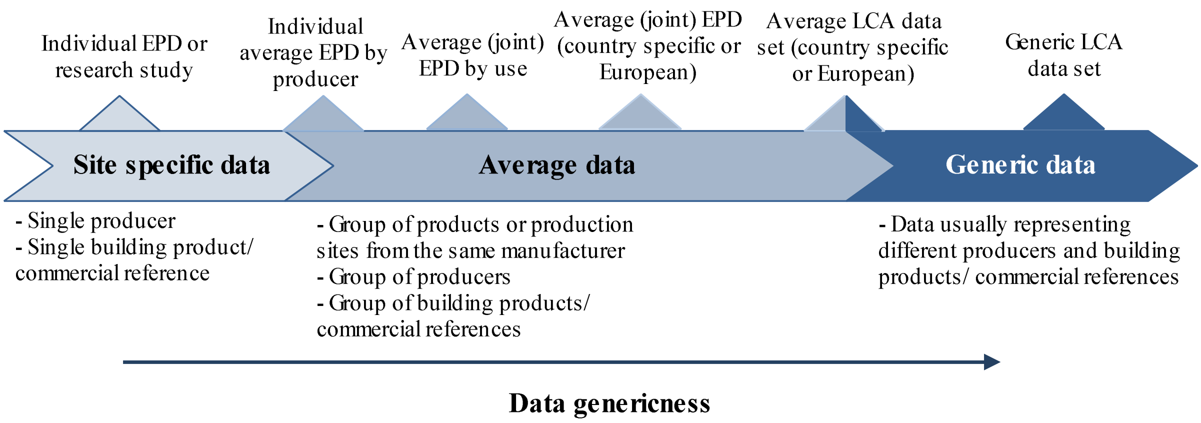


Figure 6.1 – Levels of genericness of LCA data sets (adapted from (Hodková & Lasvaux, 2012) and based on CEN Technical Report TR 15941(CEN, 2010) nomenclature)

Table 6.1 presents a summary of the types of EPD available in the two most representative European EPD programmes (the French, INIES - and the German – IBU, see Appendix 6.I) and compares it with the nomenclature defined in European Standards (CEN, 2010). There is not yet a harmonisation of the names of each type of EPD in each national context. For example, an average LCA data set from different manufacturers can be defined as:

- “Average” data in CEN Technical Report TR 15941(CEN, 2010);
- “Manufacturer group declaration” in the German IBU database;
- “Joint EPD” in the French INIES database.

The two last are identical (except the English translation name). Yet, Table 6.1 and Figure 6.1 show that the “average” term, as defined in the Technical Report TR 15941, also covers the average of different production sites (for the same product or for a branch of products) of the same manufacturer. For these data sets, it is important to register their representativeness in terms of market share, when available.

Table 6.1 – Types of EPD documents and corresponding LCA data nomenclature (for a single or an averaged product)

Data included in the EPD (for the same functional unit)	**LCA data nomenclature**		
	TR 15941:2010 (CEN, 2010)	**EPD Programme**	
		IBU	**INIES**
Data from one manufacturer and site	Site specific	Single manufacturer declaration	Individual EPD
Average data of different production sites of the same manufacturer	Average (from different production sites or manufacturers)		
Average data of different manufacturers		Group of Manufacturers declaration	Joint EPD

Although it is advisable to always follow standardised nomenclature, INIES nomenclature will be followed in this thesis to identify each EPD document in a result of the analysis presented in Table 6.1.

6.1.3.2. Other LCA and EPD databases

Research, with the aim of improving the database of ELODIE (a French tool for LCA of buildings – see section 5.3.3 (ELODIE, 2012)) by calculating generic LCA data for the simplified model of this software, was recently finished at CSTB in France. Generic LCA data was collected in an Excel-based database (database for “simplified” LCA - SLCA) which includes LCI flows and LCIA indicators, for both cradle to gate and cradle to grave data of construction materials, products, and processes. A simplified LCI database was first developed mainly using LCI data from two databases (EPD database INIES and generic LCA database Ecoinvent version 2.01) adding up to around 750 processes (600 LCI data from INIES, 130 from Ecoinvent and some more from IBU and ELCD) with the help of a homogeneous nomenclature and meta data. For the processes from both databases, 168 selected LCI flows (based on French EPD nomenclature) were inventoried in order to make the integration of the French EPD LCI possible within the database. Processes imported from Ecoinvent included transport, energy, waste treatment, water and end-of-life options. Data from INIES corresponds to LCI and LCIA data - cradle to grave - available in each EPD according to the French standard (AFNOR, 2004; Lasvaux *et al.*, 2011).

Based on the selected LCI flows of each of the 750 processes, 20 LCIA indicators were calculated using 15 Environmental Impact Assessment Methods (EIAM). Then, a LCIA of each process was divided according to the building life cycle stages given in French and European Standards (AFNOR, 2004; CEN, 2012): production, transportation to the building site, on-site implementation, use phase and end-of-life (Table 4.2). Next, analyses on life cycle stage contributions were made for the production of each construction material and product. Finally, the most documented families of products (i.e. glass wool, rock wool, gypsum plasterboards, concrete and steel) were studied in detail within each environmental impact category in order to access the suitability of LCA data to the French context. This study included the comparison of the results from each database and the identification and explanation of the differences found (Lasvaux et al., 2011). The construction of SLCA enabled the use of a unified database in the environmental assessment of buildings. The calculation of generic LCA data adapted to the French context (using mainly averaging of national EPD values) allows the use of LCA in the first conceptual stage, after which it is possible to consider the results of individual EPD in the following design stages.

Data from French EPD considered in this study (and identified in Appendix 6.II by construction material and life-cycle stage) was provided by SLCA. Despite having been built based on the assumptions described, SLCA is in fact the only database that provides updated data from French EPD disaggregated by life cycle stage, namely from cradle to gate.

6.1.3.3. LCI flows and LCIA indicators available in each database

Generic LCA databases such as Ecoinvent or ELCD can present more than 1,000 LCI flows for each process. On the other hand, an EPD developed within a national programme can present only a final balance of from 3-4 to 168 LCI flows (depending on the EPD programme), plus five or more LCIA figures. Therefore, when the aim is to compare results for the same products but coming from both types of sources (generic and EPD, and also from national and European average LCA data sets), a first step must be completed to define the LCI and LCIA indicators to be considered. Table 6.2 summarises the LCI flows included in each EPD programme (and also in SLCA database and national and European average LCA data sets) and Table 6.3 includes a balance of the EIAM (see section 5.1.2) used in each of these data sets to calculate each LCIA indicator (see section 5.4.2).

The most recent European Standards (EN 15804:2012 and prEN 15978:2011 (CEN, 2011, 2012)) that support the Environmental assessment of buildings also outline the LCI and LCIA indicators that should be included in an EPD. In what refers to LCI flows, the following are referenced (CEN, 2012):

- Resource use: Renewable primary energy consumption (excluding renewable primary energy resources used as raw materials), use of renewable primary energy resources used as raw materials, total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials), use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials, use of non-renewable primary energy resources used as raw materials, total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials), use of secondary material, use of renewable secondary fuels, use of non-renewable secondary fuels, use of fresh water;

- Waste categories: hazardous, non-hazardous, and radioactive waste disposed;
- Output flows: components for re-use, materials for recycling, materials for energy recovery and exported energy.

In terms of LCIA indicators, European Standards chose seven to be taken into account in future European harmonised EPD ((CEN, 2012), as described in section 5.4.2): global warming, ozone depletion, acidification of soil and water, eutrophication, photochemical ozone creation, and depletion of abiotic resources (elements and fossil, separately, but the latter may be used and explained only if such values are known). The EIAM defined in European Standard EN 15804:2012 to calculate each LCIA indicator has been presented in section 5.4.2.

6.1.3.4. Life cycle stages available in each database

Appendix 6.II summarises the information available in generic data sets, EPD, and National and European average LCA data sets for the construction materials and products selected for this study. These tables include, for each material, the life cycle stages covered based on European Standards nomenclature (Table 4.1 and Table 4.2) and on the disaggregation described in Chapter 5 (i.e. the manufacturing and the transport to the factory of the packaging material that leaves the factory gate with the product considered in sub-stage A3.1 and the remaining impacts from manufacturing included in the A3.2-A3.3 aggregated sub-stage). From the analysis of Appendix 6.II, it is concluded that both generic and non-generic data sets cover the product stage (cradle to gate: A1-A3), but only the latter includes, most of the times, the impacts from the construction process stage (A4-A5) and, rarely, from the use stage (B1-B7). In addition, most EPD include aggregated data either from the production to the end-of-life of the product or within a module (e.g. aggregated value for end-of-life). One of the most significant barriers for inter-comparing LCA data sets (along with the methodological choices) is the different level of aggregation of the data in relation to the sub-modules defined by the European Standards (CEN, 2011, 2012).

Table 6.2 – LCI flows included in each non-generic data set

Non-generic data set	**LCI flows**									
	Water consumption	**Waste**				**Electric energy consumption**	**CO_2 emissions**			**Dust**
		Hazardous	**Non-Hazardous**	**Radioactive**	**Inert**		**Land transformation**	**Biomass**	**Fossil**	
ATILH	X	X	X	X	X			X	X	X
BRE	X	Human toxicity and ecotoxicity to land and freshwater (CML 2000)		Nuclear (higher level)	Total waste disposal					
CEMBUREAU	X	X	X			X	X			
DAPc	According to European Standards									
Environdec	X	X*	X*			X	X*			X*
IBU	X	X (inc. radioactive)	X		X					
INIES	168 (inc. water and electric energy consumption, hazardous, non-hazardous, radioactive and inert waste production, recycled waste, and emissions to the air – including dust – and water)									
Norwegian EPD Foundation	X	X	Reuse/recycling, energy production, to landfill*			X	Total			X
Portuguese EPD		X	X		Recycled waste					
Portuguese average LCA data set	X*	X	X		Recycled waste	X*				
PU-Europe		X	X	X						
SLCA	X	X	X	X	X	X (Partial)		X	X	X

Note: * - Not supplied for all products

Table 6.3 – EIAM used in each non-generic data set to calculate each LCIA indicator

Non-generic data set	**EIAM used to calculate each LCIA indicator**							
	Resources with energy content		**GWP**	**ODP**	**AP**	**ADP**	**EP**	**POCP**
	Renewable	**Non- renewable**						
ATILH	NF P01-010		NF P01-010 (based on CML 2001 for mid-point indicators)				-	NF P01-010 (based on CML 2001 for mid-point indicators)
BRE	-	-	CML 2000			Minerals Resource Extraction (ton); Fossil fuel depletion (MJ)	CML 2000	
CEMBUREAU	X	X	IPCC 2001 - 100 years	Nordic Guidelines on LCA 1992*	CML 1999	CML 2001 v. 2.05	CML 1999; Heijungs et al. 1992	Nordic Guidelines on LCA 1992; Environmental Assessment of Products - Denmark 1992; CML, 1999
DAPc	According to European Standards							
Environdec	X	X	IPCC 2001 - 100 years	Nordic Guidelines on LCA 1992*	CML 1999	-	CML 1999; Heijungs et al. 1992	Nordic Guidelines on LCA 1992; Environmental Assessment of Products - Denmark 1992; CML, 1999
IBU	X	X	CML 2001					
INIES[*2]	NF P01-010		NF P01-010 (based on CML 2001 for mid-point indicators)				NF P01-010*	NF P01-010
Norwegian EPD Foundation	X (kWh)	X (kWh)	IPCC (last version)	CML 2001		-	CML 2001	
Portuguese EPD	X	X	IPCC 2001 - 100 years	Nordic Guidelines on LCA 1992*	CML 1999	-	CML 1999; Heijungs et al. 1992	Nordic Guidelines on LCA 1992; Environmental Assessment of Products - Denmark 1992; CML, 1999
Portuguese average LCA data set	-	X	CML 2001					
PU-Europe	According to the European standard EN 15804:2012					-	According to the European standard EN 15804:2012	
SLCA[*2]	X	X	IPCC (last version)	-	CML 2001			NF P01-010; CML 2001

Note: * - Not supplied for all products. [*2]- plus air pollution.

Generic and non-generic data sets provide also some data concerning the end-of-life stage (C1-C4) for materials used in a building's external walls. However, information from the "Benefits and loads beyond the system boundary" (D) is more rare (Figure 6.2 and Figure 6.3). This conclusion was reached from an extensive review that was made to confirm whether the available information concerning the environmental performance of construction materials for external walls of buildings uniformly covers these life cycle stages ((Silvestre, J. & Lasvaux, 2012), with a summary presented in Appendix 6.II).

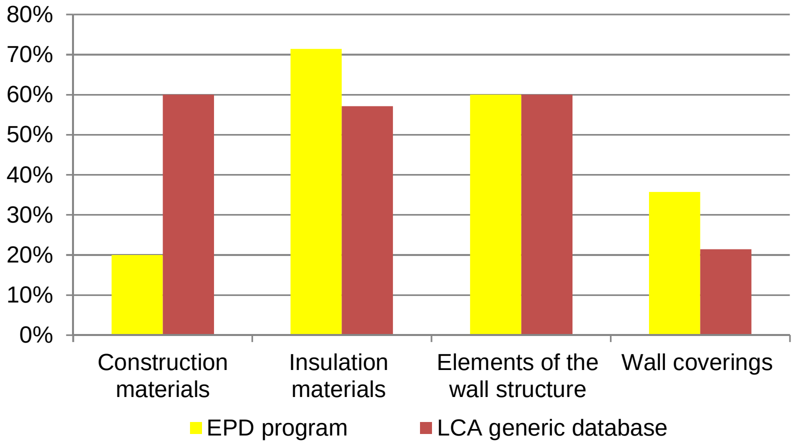


Figure 6.2 – Percentage of products for which data is available in generic LCA databases and EPD programmes concerning the end-of-life stage (C1-C4) (Silvestre, J. D. *et al.*, 2012)

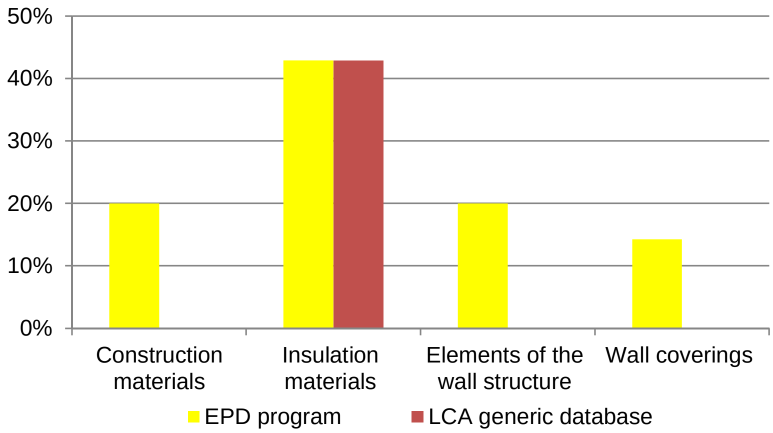


Figure 6.3 - Percentage of products for which data is available in generic LCA databases and EPD programmes concerning module D (Benefits and loads beyond the system boundary) (Silvestre, J. D. *et al.*, 2012)

A shared excel-based database of LCA data sets (generic, EPD, and National and European average) for the construction materials and products selected for this study was developed during the internship of the author at CSTB. It includes the meta data of all data sets identified and the corresponding relevant LCI and LCIA indicators necessary for NativeLCA application. This database is being permanently updated by the author and by Sébastien Lasvaux in order to consider LCA data sets that are continuously being released by different institutions.

6.1.4. Selection of LCA data sets to be used as generic in a given region

To determine generic LCA data sets for a national context in the construction sector, the most accurate method is to accomplish a complete study for each construction material and product (Hodková & Lasvaux, 2012). However, in some cases, e.g. the Portuguese context, only a small portion of construction products have already site specific LCA data (see Chapter 2), and this number will not increase much in the short-term. Therefore, alternative approaches must be put into practice in the selection of LCA data sets based on existing databases, along with a qualification method of the quality of the data available in each source assessed: generic, average or EPD data sets (Hodková & Lasvaux, 2012).

A recent study, described in section 6.1.3.2, developed a data analysis tool for the French context by grouping Ecoinvent and INIES data of construction materials and products in an Excel-based database (SLCA) using harmonised LCI and LCIA indicators (Lasvaux, 2010; Lasvaux *et al.*, 2011). LCA data from both databases were compared and differences between them (i.e. EPD from INIES and generic data from Ecoinvent) were found. This research work is still on-going to define a consistent methodology to derive generic data for the French context. To that purpose, the SLCA database is used as a "case study LCI/LCIA database" to show the applicability of the global methodology. A first contribution of the methodology for the selection of LCA data sets on building materials (e.g. Czech Republic, Portugal, France) has been proposed (Hodková & Lasvaux, 2012). This last reference will be used as a starting point in the development of NativeLCA, namely by the adaptation and the updates of the following principles proposed by (Hodková & Lasvaux, 2012):

- Calculation of mean values from LCA data sets for the same declared unit, when significant documents (both individual and joint EPD and also country specific or European average LCA data sets) are available;
- Quantification and analysis of the variability of the mean values of a given product;
- Comparison of mean values with generic data to benchmark the results and identify and analyse the differences found.

A contextualisation of the Ecoinvent European LCA database is currently being made in Quebec, Canada (for "contextualisation" see 6.1.5.10), which includes all type of industrial processes but does not consider other generic or EPD databases. Despite being scientifically-based, the methodology used is time and resources demanding (and therefore not prone to be applied by every practitioner) and the geographical representativeness criterion (see 6.1.5.4) is not complied with from the beginning (Bourgault *et al.*, 2010). The same issues affect a similar research work completed recently in New Zealand, based on European country-specific (Germany) industry data (Nebel *et al.*, 2011). The data sets of the 13 building materials that were adapted in order to be in accordance with New Zealand reality (and to fulfil the geographical representativeness criteria) are included in the German GaBi LCA software. The methodology used is described in detail in a report and is mainly based on the analysis of environmental hot spots and contextualisation of background processes (Nebel *et al.*, 2011).

At the European level, the need of a LCA data set to be used as generic has already been identified and an LCA database is being built. However, the European SUstainable COnstruction database (ESUCO) is only based on the extrapolation to a European level of German EPD of construction materials, despite that production technology of core materials is based on average European industry data and background data is adapted to European average countries (DGNB, 2011). This database in available only to the auditors of the German system of building energy certification (Deutsche Gesellschaft für Nachhaltiges Bauen - DGNB e.V.) and the methodology used for its development is not publicly available. Nevertheless, DGNB states the need for country-specific LCA data sets in order to take into account the production practices, material diversity and electric mix of each country (DGNB, 2011). This need is also highlighted in the European Project EeBGuide that is still on-course (EeBGuide, 2012).

Another research study was also completed in Germany to develop a systematic procedure to generate country-specific environmental profiles (complete inventories, and not only LCA results) from existing LCA data sets (Colodel *et al.*, 2010). This contextualisation procedure can be applied to processes from any industry sector and is based on available generic and statistical data from the target country. The adaptation of a German LCI dataset for cement production for USA and Japan exemplifies this procedure.

Also in Europe, a LCA database of building materials specifically adapted for the Italian situation has been developed (Barozzi *et al.*, 2009). The development of this database included the regionalisation of existing European LCA data sets for traditional building materials. Apart from the fact that the choice of each data set was based on pre-defined data quality indicators, information concerning the methodology used is not publicly available.

6.1.5. Methodology for the selection of a coherent LCA data set of construction materials and products to be used as generic data for a national context: NativeLCA

Used at the building scale, both generic and average LCA data sets and EPD enable the assessment of the global environmental impacts of a building using LCIA indicators. LCA software for buildings (see section 5.3) has been developed and already uses this data (Peuportier *et al.*, 2009). However, the multiplicity of LCA databases (generic, average LCA data sets and EPD schemes) leads to heterogeneity regarding the data used in the tools for buildings. When several databases are used, the parameters do not necessarily match (different LCI or LCIA indicators considered) and furthermore different results for the same parameter can be achieved depending on the database chosen ((Peuportier & Putzeys, 2005) cited by (Lasvaux *et al.*, 2011)). In addition, the quality of generic data sets is not equivalent and therefore it is always essential to understand how they influence the precision and validity of the results (CEN, 2010). However, this type of analysis is normally impossible for a typical user of software for LCA of buildings because of its workload and lack of advanced skills in LCA. These discrepancies may make the tool users conclude that the LCA approach is not sufficiently robust, leading them to disregard it (Lasvaux *et al.*, 2011).

When the number of EPD of a product (or family of products) is insufficient, its representativeness can be poor and can lead to the use of a unified generic database. For example, the Ecoinvent database uses data from different sources adjusted with a harmonised methodology (Hodková & Lasvaux, 2012). When quantity and/or quality of available EPD is not as good as expected, or if this kind of data is absent, more studies are needed in order to develop a proper approach to select and determine the most appropriate generic LCA data for a national context (Hodková & Lasvaux, 2012).

In order to provide a coherent approach to the LCA of buildings in a national context, one option is to use default values for LCA of construction materials and products. However, this approach is almost an “ideal” as it requires that all the actors of the construction sector of a country agree on LCA results for default compositions of building assemblies (Peuportier *et al.*, 2011). A more robust approach is to select LCA data sets for each construction material and product to be used as generic data for a national context (referred hereafter only as “selection of LCA data sets” in order to simplify the text) based on a coherent methodology. A methodology with this aim and characteristics is described afterwards and was proposed to be entitled NativeLCA (Silvestre, J. & Lasvaux, 2012). Some methodologies with the same aim had been described in 0, but none of them provides the wide-ranging scope (namely in terms of considering all European LCA data sets), straight-forward approach, and single focus (the selection of a LCA data set to be directly used by the practitioner, avoiding inventory analysis and modification) of NativeLCA. The most recent standards and draft standards developed by the Technical Committee (TC) 350 - “Sustainable construction” - of the European Committee for Standardization (CEN/TC 350) (CEN, 2010, 2011) were taken into account in the development of this methodology. In fact, several data sets are needed for the calculation of LCA of building assemblies according to these standards. However, and despite giving a framework for the assessment of LCA data, they do not provide consistent guidelines on the choice of existing LCA to be used in each national context and each design stage, not even included in the CEN Technical Report TR 15941- “Sustainability of construction works - Environmental product declarations - Methodology for selection and use of generic data” (CEN, 2010). Therefore, NativeLCA tries to fill this gap, also taking profit from the experience of the author in being responsible (along with other national experts) for the translation of this Technical Report in its national technical committee.

Figure 6.4 presents the flowchart of NativeLCA implementation. Figure 6.6 includes a table that summarises the information that should be collected and the decisions that must be made in each of the steps of this methodology according to the description presented in the next sections of this Chapter. The most relevant results of NativeLCA development are included in a paper that has been submitted for publication in a journal included in ISI-Journal of Citation Reports ((Lasvaux *et al.*, 2012), which is presented in its present form in Appendix 6.III).

6.1.5.1. Aim and scope of LCA study

In spite of not corresponding to a detailed LCA study, the selection of LCA data sets of construction materials and products should start with the description of its aim and scope. Although the aim may be implicit, the scope definitions should include:

- The functional unit of the study;
- The characterisation of each construction material and product that will be the object of the study, namely their intended composition/formula and physical and chemical characteristics;
- The LCI flows and LCIA parameters (and corresponding EIAM) that will be considered and that are considered to be relevant in a national context;

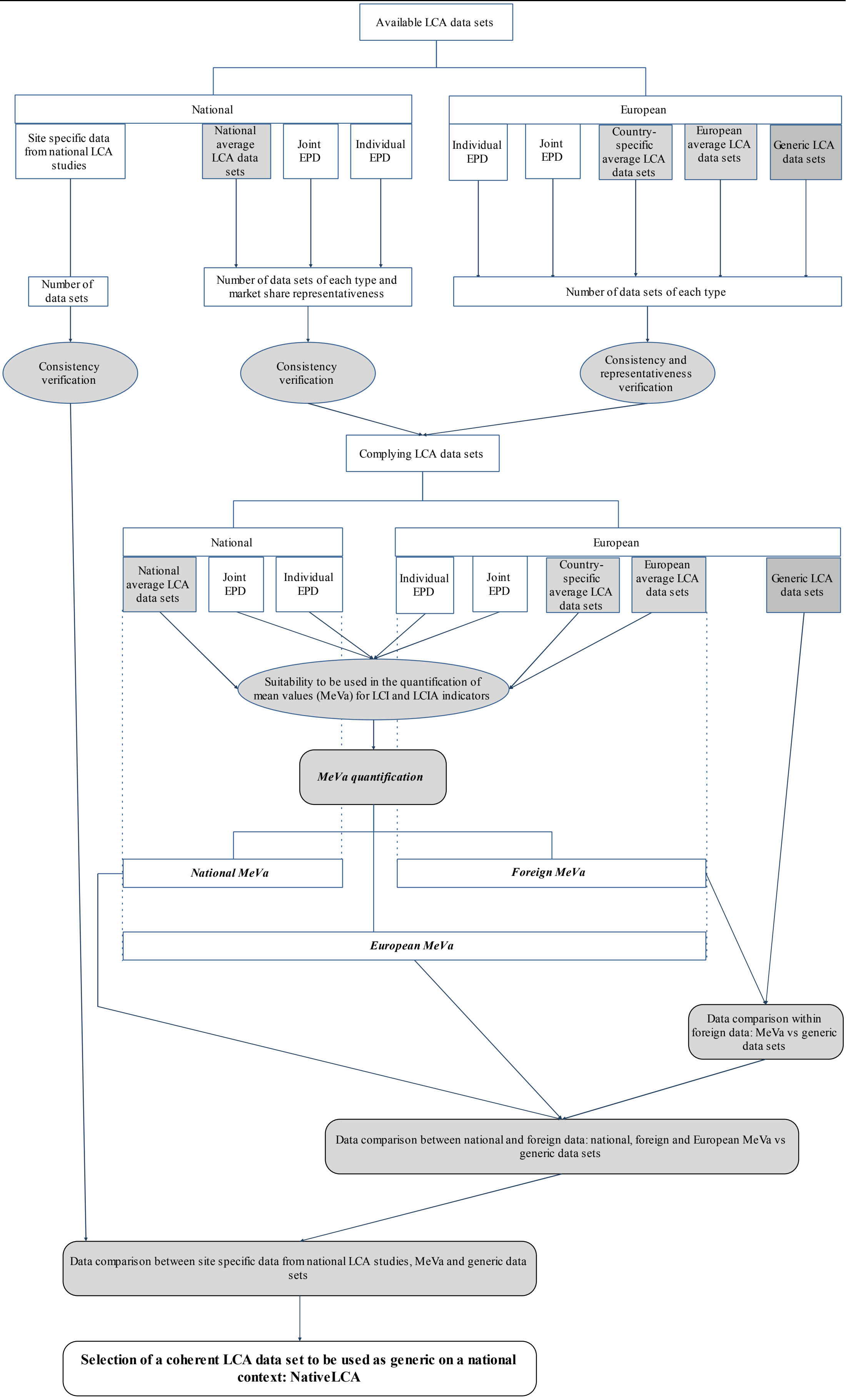


Figure 6.4 – Flowchart of NativeLCA implementation

Product	**LCA data sets**							**National and foreign data verification**	**Suitability to be used in the quantification of mean values (MeVa) for LCI and LCIA indicators and MeVa quantification (EPD and average data sets)**	**Data comparison within foreign data: MeVa vs generic data sets**	**Data comparison between national and foreign data: MeVa vs generic data sets**	**Data comparison between site specific data from national LCA studies, MeVa and generic data sets**	**Selection of a coherent LCA data set to be used as generic on a national context: NativeLCA**
	National			**European**									
	Site specific data from national LCA studies/ *individual EPD*	**Joint EPD (* - representative of all the market share)**	**National average LCA data sets**	**Individual EPD**	**Joint EPD**	**Country-specific or European average LCA data sets**	**Generic LCA data set**	**Consistency (all data sets) and representativeness (foreign data sets)**					
	Yes	Joint (number)	Number of data sets	Number	Joint (number)	Country (number of data sets)	Number of data sets	Identify eliminated data sets	European MeVa	Foreign MeVa discarded	European MeVa discarded	Benchmark	Site specific data from national LCA studies
	Number	Joint* (number)	Number of data sets*			European (number of data sets)			Foreign MeVa	Foreign average data sets discarded	Foreign MeVa discarded	Check the plausibility of site specific data from national LCA studies	National individual EPD
									National MeVa	Generic data sets discarded	National MeVa discarded	Site specific data from national LCA studies not available	European MeVa or average data sets
											National average data sets discarded		Foreign MeVa or average data sets
											Foreign average data sets discarded		National MeVa or average data sets
											Generic data sets discarded		Generic LCA data set (only changing background data, e.g. electricity mix, transport distances)
													A set of LCA data to be used/chosen for the early design stage and other one for the detailed design stage

Figure 6.5 – Decision-making table of NativeLCA

- Similarly, the life cycle stages that will be considered should also be described and justified in detail in order to define a precise life cycle boundary (e.g. cradle to gate) (Hodková & Lasvaux, 2012).

6.1.5.2. Data set identification and description

The first step of the NativeLCA methodology corresponds to the identification and quantification of available LCA data sets, mainly at a national and at the European level, for a chosen building product. At a national level, available data sets for a given building product can be divided into site specific data from national LCA studies, individual and joint EPD and national average LCA data sets. For the last three data sets, it is also important to register their representativeness in terms of market share, when available. At an international level, generic data can also be found and considered, along with individual and joint EPD, and country specific and European average LCA data sets (Hodková & Lasvaux, 2012). Thereafter, a wise choice of the meta data that should be used in the characterisation of each data set should be made, identical to that in Table 6.2, Table 6.3 and Appendix 6.I (in this case, only the databases that include building products in the scope of the study were fully characterised), and each field should be filled for each data set.

6.1.5.3. Choice of LCI and LCIA indicators, life cycle stages and meta data

After the description of the databases (data collection stage), and the comparison of the parameters that describe each one, made in section 6.1.3 (stage I in Figure 6.6), this section includes the definition of the parameters that will be used in the present study to characterise LCA data collected of construction materials and products (stage II in Figure 6.6). These parameters include LCI flows and LCIA categories, life cycle stages and meta data. This choice of parameters provides a harmonised basis to make the results from each database comparable and allow for the analysis of the results and differences found (stage II in Figure 6.6).

Considering the review presented of LCI flows and LCIA indicators included in each EPD programme and foreseen in the European Standards for Environmental assessment of buildings (see Section 6.1.3.3), LCI flows that were chosen for this study are presented in Table 6.4. Chosen LCIA indicators and corresponding EIAM are the same as those selected for the LCA studies completed within the scope of this thesis described in Chapter 5.

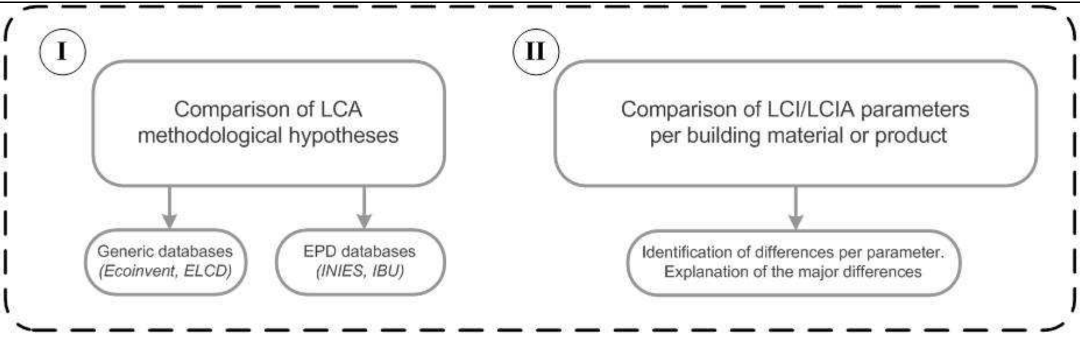


Figure 6.6 – Comparison of LCA data of construction materials and products: the methodology presented in this section was developed after the completion of stage I in order to ease stage II development

Table 6.4 – LCI flows selected

LCI flows			
Group		**Name**	**Unit**
Water		Fresh water consumption	l
Waste		Hazardous waste	kg
		Non-hazardous waste	
		Radioactive waste	
		Inert waste	
		Recycled waste	
Energy consumption		Electric	kWh
Air emissions	**CO_2 emissions**	Carbon dioxide, biomass	g
		Carbon dioxide, fossil	
	Dust		g

Some LCI flows included in the databases and presented in Table 6.2 were not chosen because they are available in only two or less databases (i.e. “carbon dioxide, land transformation” and “materials to landfill” – whose environmental impact is included in most of the databases). There are several other LCI flows already included in European Standards (CEN, 2012) that were not included in this study because available databases do not provide such a disaggregation of results (i.e. components for re-use, materials for energy recovery and exported energy).

As described for LCI flows, European Standards (CEN, 2012) also include different LCIA indicators that are not provided by available databases and therefore were not chosen in the scope of this study (i.e. renewable primary energy consumption - excluding renewable primary energy resources used as raw materials, use of renewable primary energy resources used as raw materials, total use of renewable primary energy resources - primary energy and primary energy resources used as raw materials, use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials, use of non-renewable primary energy resources used as raw materials, total use of non-renewable primary energy resources - primary energy and primary energy resources used as raw materials, use of secondary material, use of renewable secondary fuels, use of non-renewable secondary fuels, depletion of abiotic resources - elements/non fossil resources - and depletion of abiotic resources - fossil).

The next step corresponds to the analysis of LCA data from aggregated production stage (A1-A3) available in the databases for each construction material and product selected (following the summary of the information available in each LCA database for the construction materials and products - Appendix 6.II - and the description and analysis of the content of each database life cycle module - see section 6.1.3.4). This will correspond to a cradle to gate approach. Thereafter, the following life cycle stages for which there is data available will also be assessed, namely to allow for a cradle to grave (A-C) or for a cradle to cradle approach (A-D). Whenever possible, transportation to the building site, installation, use stage and end-of-life LCA data will be analysed in detail for each construction material and product according with their disaggregated or aggregated presentation.

LCA meta data includes all relevant information that aids in the selection of appropriate and qualified data for each context, namely the information necessary to determine the data source and what it represents. According to CEN/TR 15941:2010 requirements, LCA meta data should include (CEN, 2010):

- The origin of the data;
- Geographical and temporal coverage;
- A registry of the transformations that have been made to the data (e.g. averaging);
- Representativeness in all possible dimensions.

However, neither INIES nor Ecoinvent fulfil all the requirements of LCA meta data, but the former is often in better condition to be used in a national (i.e. French) context than the latter because (EC-JRC, 2011; Hodková & Lasvaux, 2012): it represents an actual and realistic situation; it has an appropriate time-related coverage (recent data, not older than 6 years); it has appropriate technological (average national technology) and geographical representativeness; and it is a reliable and unified data set (one unique source: EPD from INIES). In spite of this, EPD meta data does not include the percentage of market share or production volumes (see Appendix 6.I) of each product or producer (for instance this information is not mandatory in the Product Category Rules - PCR - of the French EPD) and therefore its representativeness is concluded *a priori* or when complemented by other sources of data.

Taking into account that this study includes the consultation of data from several sources, it is fundamental that relevant meta data be kept along with each quantitative data set (related with a given database and a specific construction material or product). In this way, LCA figures should be associated with the approach that lead to their calculation, leading to a better understanding of its significance. Then, meta data can also be cross-referenced between databases that present contradictory indicators in order to aid in the search for an explanation of the major differences found. Meta data used to characterise all the LCA data collected in this study is presented in Table 6.5, mostly following the approach of SLCA creation (Lasvaux et al., 2011). The fields chosen do not fulfil all requirements of European Standards because the aim is only to provide sufficient information to allow data comparison.

6.1.5.4. Consistency and representativeness verification

The second step of NativeLCA methodology includes the verification of the consistency and representativeness of each data set in order to, respectively, confirm whether they have sufficient quality to be used in a national context. The first criterion should be verified by all data sets; while the second one is to be verified only by foreign data sets (see Figure 6.4).

The verification of consistency includes the checking of the following characteristics of each data set (CEN, 2010):

- PCR or standard followed during LCA study and corresponding characteristics (see Appendix 6.I);
- LCA study hypothesis, namely system boundaries, cut-off and allocation rules;
- Consistency in the assumptions, methods, models and data, namely in the definition of parameters of the LCI and LCIA procedures, and accordance with the goal and scope of the LCA study;
- Type of internal/external/third party verification (see Appendix 6.I).

The verification of consistency provides a qualification of each data set using the requirements already summarised. A more detailed verification can always be implemented if other dimensions of LCA data sets are analysed, namely (CEN, 2010): plausibility (e.g. including cross-check for selected elementary, mass and energy balances and comparison with other existing data), completeness (e.g. downstream processes should be modelled "to the elementary flows"); and uncertainty (e.g. reliability of the source, differences with other available sources and sensitivity analysis of the final results). However, considering the aim of this methodology these complementary verifications are not required.

A representativeness criterion is only applied to foreign data sets in order to evaluate their suitability to be used as generic data for a national context by checking their accordance with national practices. Therefore, the features of each data set that should be verified are (CEN, 2010):

- Geographical coverage;
- Production technological hypothesis (technological coverage);
- Composition/formula and physical and chemical characteristics of the product represented by the data set (e.g. for cement, CEMBUREAU European average LCA data set presents the results for a median cement, but the cement that is being studied can have a different composition or compressive strength);
- Background data used in LCA calculation (e.g. electric grid mix, manufacturing of raw materials, transportation modes and distances);
- Data sets used to model downstream processes (e.g. transportation modes and distances, maintenance and end-of-life practices).
- Age of the data (e.g. it should have been verified within the last ten years);
- The possibility to modify background data in order to provide “contextualisation”.

International LCA data sets were restricted in this study to the European geographical area because data sets from outside Europe do not comply from the beginning with the representativeness criteria in terms of geographical coverage and their technological hypothesis is more liable to differ from European practices.

The British EPD database (BRE – see Appendix 6.I) was included in this study but is not considered in NativeLCA application because:

- It presents LCA data aggregated from cradle to grave, including the end-of-life stage (system boundaries correspond to a 60-year service life cradle to grave LCA without data about the assumptions), without the possibility of disaggregation;
- End-of-life practices differ a lot all around Europe and therefore it is not correct to use this aggregated data even in comparison with other sources;
- Only national data is prone to be used in an aggregated form;
- Most of the environmental profiles are of construction assemblies without disaggregation in their components, despite the fact that some are for individual materials (only insulation materials, including one for a PUR board).

At the end of this step, the pool of data sets that do not comply either with consistency and/or with representativeness criteria should be identified.

Table 6.5 - Meta data selected to characterise each data set (based on (Lasvaux et al., 2011))

Type of meta data	Description	Examples
Designation of the database / *EPD Programme*	Designation included in the generic data/EPD database that describes the type of construction material or product	Concrete, steel
Function	Describe the function according to SLCA	*Façades, Procède fin de vie (end of life)*
Functional unit	Describe the functional unit of the data	1 kg; 1 m^2
Characteristics	Describe physical characteristics or others	Density, use of primary and secondary raw materials
Organisation responsible for the data/*Manager of the EPD Programme*	Describe the data provider	EMPA; French trade unions
Geographical representativeness	Provide the geographical validity of the data	France
Temporal representativeness	Provide the year of data collection	2006; 2005-2011
Technological representativeness	Provide the technological level of manufacturing processes	Usual technology (most of the cases); advanced technology
Type of LCA data set	Describe the type of LCA data set	Generic, product-specific (EPD) or average
Sampling procedure	Describe the gate-to-gate data collection	Europe, country, producer, or plant data; Based on literature (partly the case of Ecoinvent); based on data collection in the manufacturer’s plant (always the case in French EPD); production volume, percentage of market share or number of companies
System boundaries	Describe the system boundaries of the data	Cradle to gate (A1-A3), cradle to grave (A-B-C), cradle to cradle (A-B-C-D), etc.
Energy and transport processes LCA data	Describe the energy and transport LCA data used	French FDP01-015 LCA data on electric mix and fuel; Ecoinvent ones
Cut-off rules	Describe the cut-off rules	French EPD should comply with 98 % in mass whereas Ecoinvent does not provide such a rule
Allocation of by-products	Describe the allocation of by-products in the plant	Mass, economic, energy
Packaging	Describe the characteristics of the packaging considered in the study	Thermo-retractable PVC film, PE film, wood pallet, adhesive labels
Infrastructures	Describes if the infrastructures of production (e.g. cement plant) are included within the system boundary	Included, not included
EPD programme, number and state	Identify the EPD programme, the number of the document and its state, including the date of expiration	INIES; Expired, on line, stored, expires three year after the date of declaration
Generic LCA databases	Identify the Generic LCA database	Ecoinvent, ELCD
Critical review/verification	Describe if a critical review / third party verification has been conducted	Internal critical review, third-party verification
Year of release of the data	Describe the year of the release of the data	2007 (Ecoinvent 2.0)

6.1.5.5. Suitability test for the quantification of mean values (MeVa) of LCI and LCIA indicators

The third step of the NativeLCA methodology includes, for the pool of data sets that comply with the consistency and representativeness criteria, the confirmation of their suitability to be used in the quantification of mean values (MeVa) for LCI and LCIA indicators.

Generic databases are not included in this verification because they normally include only one life cycle stage represented in each process (see Appendix 6.II) and, when available through a LCA software, all LCI flows and LCIA parameters (using adequate EIAM) are liable to be calculated. Existing or on-going site specific data from national LCA studies (e.g. the LCA studies completed within the scope of this PhD thesis) will not be also subjected to this checking either because: they will not be used in MeVa calculation; they will only be compared with the remaining data sets in the penultimate step of this methodology.

This step includes the assessment of the LCI flows or LCIA parameters included in the results of individual EPD, joint EPD and average LCA data sets, both national (e.g. Portugal, France) and from other European countries (defined as “foreign”). For the LCIA parameters, the EIAM used should also be checked, including the corresponding version and/or issue year. In this step, the level of aggregation per life cycle stages and building material of LCI flows and LCIA indicators in each data set will also be analysed. As a conclusion, this step will not provide a list of data sets to be discarded, but the identification of the data sets that can be used in the quantification of MeVa of each LCI and LCIA indicators and corresponding life cycle stages. In fact, since the definition of the scope of the study is prior to the data selection, only the data sets that are within the scope defined in at least one indicator (LCI or LCIA, for a given material, EIAM and life cycle stage) will be considered.

6.1.5.6. Quantification of national, foreign and European mean values (MeVa) of LCI and LCIA indicators

A quantification of national, foreign and European mean values (MeVa) for LCI and LCIA indicators is accomplished in the fourth step of NativeLCA methodology. These values result from the combination of site-specific and/ or average data related with the manufacturing of the same product but representing different “technologies, sites, countries and/or time” (EC-JRC, 2011). As NativeLCA will mainly be applied to building products, MeVa corresponds therefore to systems averaging (EC-JRC, 2011). MeVa calculation should however register (or avoid, when the goal is a given technology) averaging of processes representing two or more very different technologies for the manufacturing of the same product (EC-JRC, 2011).

European Standards distinguish average (mean values) from generic data sets by referring that the former correspond to “data combined from different manufacturers or production sites for the same declared unit (which also corresponds to a joint declaration in the French EPD system (AFNOR, 2004) – see Table 6.1)” and the latter are “surrogate data used if no system specific data is available”. Nevertheless, both types of data sets have the aim of representing a specified geographic region and time, and generic data sets can also result from site-specific or average LCA studies with the aim of representing a typical variant of a process (CEN, 2010; EC-JRC, 2011).

This step evolves through several sub-steps that are described next:

- Consideration of individual and joint EPD and average data sets (national, country specific or European) available in the country, abroad or both, which have been considered suitable to be used in MeVa quantification;
- For each environmental parameter (LCI flow or LCIA indicator, in each life cycle stage), quantification of the variability per type of material. Then, analysis of the dispersion by means of appropriate scatter plots and bars for the same declared unit. The analysis of the variability of the figures and, mainly, of their mean value, allows for the explanation of the differences found and can also support the decision to maintain or exclude some data sets (Hodková & Lasvaux, 2012);
- Explanation of the LCI and LCIA result dispersion;
- Exclusion of some data sets based on statistical criteria.

For the analysis of the variability of LCI and LCIA indicators, it is important to bear in mind that within each industry branch (e.g. steel or polyethylene industries) there are differences from plant to plant, even when the same technology is used. These variations result from different ages and sizes of plants, levels of maintenance and throughputs, but emission levels can also depend on local pollution regulations. These variations can be as significant as 15%, taking into account a survey of a large amount of similar plants ((Boustead, 2004) cited by (Blengini, 2006)).

All these sub-steps precede national, foreign and European MeVa calculation. MeVa allows for the weakening of the variability that exists in all the figures considered and their quantification is accomplished by means of:

- Calculation of national, foreign and European MeVa based on the remaining data sets:

- National MeVa should preferably be a weighted mean according to the production volumes, for each environmental indicator and for the same declared unit, of individual and joint EPD and average data sets (as recommended in European Standards (CEN, 2010)); when production volumes are not declared, MeVa can be a weighted mean according to the market shares;
- Foreign and European MeVa should be calculated as a weighted mean of declared production volumes, for each environmental indicator and for the same declared unit, of individual and joint EPD and average data sets (as recommended in European Standards (CEN, 2010));
- An arithmetic mean according to the number of companies included in each data set, for each environmental indicator and for the same declared unit, of individual and joint EPD and average data sets (at a national, foreign and European level), will be the last option for the data sets that neither declare market shares nor production volumes;
- National average LCA data sets that do not include information concerning market shares, production volumes or number of companies considered, and foreign average LCA data sets that do not include information concerning the two last figures, should not be treated as an individual EPD to be used in MeVa, but it should be possible to choose this data set to be used as generic in the national context;
- National and foreign (mainly European) average LCA data sets that are considered for MeVa quantification should also be considered as an individual data set in the comparisons in order to be chosen to be used as generic in the national context.

MeVa calculation corresponds to an innovative approach to generating “new” LCA data sets that can be used as generic in a national context, based on available ones for a given product. MeVa, generated using NativeLCA methodology, are data sets calculated for the first time within this thesis and therefore not yet presented. It is expected that MeVa will represent the majority of the market share of each construction product in the medium-term as the number of European producers having EPD approaches 100%. In fact, NativeLCA can be used in the progressive update of national LCA databases, also reflecting advances in manufacturing and processing technologies, using data from new data sets. Data management is in fact an enormous task and needs to be unified and systematically assembled (LeVan, 1995).

MeVa calculation may include preliminary sub-steps such as (Hodková & Lasvaux, 2012):

- The calculation of average EPD figures, by producer, based on the producer’s available individual EPD;

- The calculation of national, foreign or European MeVa by application by grouping EPD or average data sets of products with the same application, based on the rules for MeVa calculation already defined, when all the applications considered are within the scope of the study.

6.1.5.7. Comparison within foreign data: MeVa vs generic data sets

The goal of this step is to compare these data sets - foreign MeVa, foreign average and generic - for each harmonised LCI flow and LCIA parameter, and for each life cycle stage. It has to be decided whether any of these data sets should be discarded at this time. This step also allows the verification of the validity of foreign MeVa when compared to generic and foreign average data sets. Meta data information can be used to explain the differences found between data sets and, in the end, exclusion criteria, based on a statistical criterion, can be defined.

6.1.5.8. Comparison between national and foreign data: MeVa vs generic data sets

Similar to the previous step, this one intends to provide a comparison between data sets at a European level – national, foreign and European MeVa, national and foreign average and generic - for each harmonised LCI flow and LCIA parameter, and for each life cycle stage (Hodková & Lasvaux, 2012). This step also allows the verification of the validity of national MeVa when compared to foreign and European MeVa, to national and foreign average, and generic data sets. Therefore, a decision can be made about the exclusion of some data sets according to an adequate criterion. Meta data information can also be used to explain the differences found between data sets. In fact, the consideration of meta data in this comparison, by using an adequate data analysis tool (Lasvaux et al., 2011) or data quality assessment methodologies, allows the choice of a robust generic data set that is consistent in terms of LCA methodology and technological, temporal and geographical representativeness (Hodková & Lasvaux, 2012). For example, an EPD from INIES is often better to be used in a national (i.e. French) context than Ecoinvent data sets because of the reasons referred to in section 6.1.5.3.

6.1.5.9. Comparison between site specific data from national LCA studies, MeVa and generic data sets

This step of NativeLCA methodology allows the benchmarking of national LCA studies (for each LCI flow and LCIA parameter, and for each life cycle stage) with national average and MeVa and foreign LCA data sets (foreign and European MeVa and average, and generic data sets). Benchmarking with foreign figures is extremely important to verify the validity and check the plausibility of national LCA studies when compared to national MeVa and average, foreign and European MeVa and average, and generic data sets. This is especially true when national MeVa do not exist. When site specific data from national LCA studies are not available, this step is ignored.

This specific step of NativeLCA can also be used by the practitioner or by the critical reviewer in the verification of the plausibility of EPD results.

6.1.5.10. Selection of a coherent LCA data set to be used as generic data for a national context: NativeLCA

The last step of the NativeLCA methodology deals with the selection of a coherent LCA data set within the ones available at this time. Available data sets can be site specific data from national LCA studies, national, foreign or European MeVa, national or foreign average, or generic. At the end of this step, data from this pool (or, in some cases, a combination within) are chosen to be used as generic data for a national context. To achieve this goal, the most adequate option is to create a Data Quality Indicator (DQI – adapted from the criteria given in European Standards (CEN, 2010)) to be assessed for each of these data sets. DQI considers all the information compiled in the previous steps of this methodology, mainly the results of the assessment of consistency and representativeness (CEN, 2010). This procedure also provides complete information for the practitioner concerning the data set that is chosen to be used as generic for a national context, e.g., the indication that the criteria "geographical coverage" is not fulfilled should be attached to every international data set in order to inform the final user (Hodková & Lasvaux, 2012). "Technological representativeness" can also be an important criterion for the selection between available data sets but its verification requires the collection of information related with national production practices of the material being studied. Using DQI, it will be possible to create a quantitative classification and corresponding ranking of available data sets in order to ease the choice of the ones that can be considered by NativeLCA.

Another option can be to choose a combination of LCA data sets to be used as generic data for a national context. Using this approach, one of them can be used during the early design stage (in principle, the most "generic"), and the other one (the most "specific") should be used in the detailed design stage.

When foreign data sets are chosen, mainly because of a lack of national data, preference should go to data sets that allow modifications of their background data (e.g. electricity production mix, technological parameters, transportation modelling and distances, origin of raw materials and waste treatment processes) in an approach known as “contextualisation” (Peuportier et al., 2011). Contextualisation may include in some cases a detailed analysis and change of individual input or output flows of a generic data set, namely based on the differences of industrial statistical information of initial and target regions (Colodel *et al.*, 2010). Generic data sets are usually the only ones that allow for “contextualisation”, and this is an advantage for them because it can improve their representativeness (and is even more advantageous if technological representativeness is fulfilled). “Contextualisation” is also fundamental when the only data set available for a given material is generic and does not fulfil some representativeness criterion. “Contextualisation” is not supposed to include the modification of the process of raw material production, but this is not problematic because technology for primary material production is very similar all over the world and it is therefore reasonable to assume that the technology used, e.g., in the petrochemical or the metals extraction industries is analogous in all countries (Blengini, 2006).

6.2. Application of NativeLCA to “Product stage” (A1-A3)

Following the presentation of the NativeLCA methodology developed in the scope of this thesis, this section presents the first examples of its application. It is divided into four parts according to each “family” of building products. Construction materials are added to the three groups of elements of external walls presented in previous chapters (elements of the wall structure, insulations and claddings).

An additional subdivision is then presented in each “family” of building products by identifying the ones for which a LCA study was completed within the scope of this thesis. NativeLCA is in fact applied in its full form in this section only to the materials not studied in detail in this thesis, while a “simplified” version of this methodology is used in the remaining cases. NativeLCA is used in the first case in the selection of a coherent LCA data set of construction materials and products to be used as generic data for the Portuguese context. For the second case, the aim is to verify the plausibility of the results achieved in the European scope. Each of these data sets can then be used for the LCA of building assemblies (namely external walls) or buildings in the Portuguese context.

6.2.1. Construction materials

Concerning the construction materials group (Appendix 6.II) different sources of LCA data are available for the production stage of cement. On the other hand, gypsum and reinforcement steel are only included in Ecoinvent. Concrete LCA data is supplied in different databases and includes the production, construction and end-of-life stages, and even the benefits and loads beyond the system boundary. The production of gravel and sand and their end-of-life stages are also included in several databases.

Section 6.2.1.1 exemplifies the application of NativeLCA in the choice of a LCA data set of cement to be used as generic data for the Portuguese context. This application is not presented for the other construction materials because: gypsum and reinforcement steel are only included in Ecoinvent and are not used in any building product or assembly in the scope of this thesis; concrete is also not analysed due to the latter reason; the data set to be used in the modelling of sand extraction was described in Chapter 5.

6.2.1.1. Cement (data from previous studies)

Different types of cement with various strength classes and compositions are available on the market. Therefore, NativeLCA should provide a LCA data set for each type of cement to be used as background data (LCA data of raw materials production) for all the products studied in this thesis that use cement as raw material (e.g. one-coat mortar and stabilised mortar).

The selection of a coherent LCA data set of cement – to be used, in this case, in the Portuguese context – should start with the description of its aim and scope. The aim has been described and the scope is defined by:

- The functional unit of the study: the production of one tonne of cement;
- The characterisation of the construction material that will be the object of this study: all different types of cements available in the European market;
- The LCI flows and LCIA parameters (and corresponding EIAM) that will be considered: a database was built in order to compile the information from LCA data sets for each cement type, following the indicators already selected in section 6.1.5.3. Then, the most used data set in the European context – the Ecoinvent generic database – was used to provide a first overview of the impacts in the six environmental categories selected;
- To identify the key LCIA to study in the first step, a normalisation of LCIA impacts was conducted for Ecoinvent data. Figure 6.7 presents the environmental impacts after normalisation (using CML 2001 v. 2.05 and West Europe - 1995 as a reference for normalisation) of the six types of cement available in this database. From this figure, it is concluded that Global Warming Potential (GWP) is the most important environmental impact of cement production in a European context. Therefore, in the first step, GWP, along with non-renewable energy consumption (PE-NRe, using CED method – see Chapter 5), are used as a reference to apply

NativeLCA methodology. PE-NRe is chosen because it is available in all data sets (Table 6.3), it contributes significantly to ADP in most of the building materials, and the second most significant indicator identified (ADP) is not available in all data sets;

- In this study, only the product stage (A1 to A3) is considered, but without taking into account the packaging of the cement because only one data set includes information about the environmental impact of its production and use.

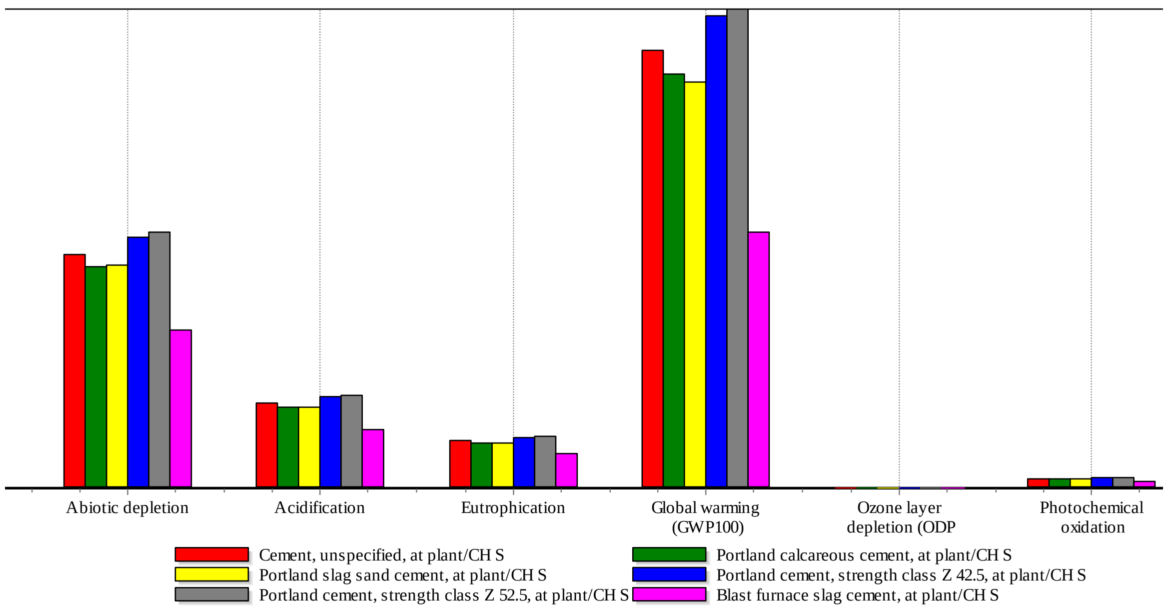


Figure 6.7 – Environmental impacts after normalisation (CML 2001 v. 2.05 and West Europe - 1995) of the six types of cement available in the Ecoinvent generic database

6.2.1.1.1. Data set identification and description

Table 6.6 identifies and quantifies available LCA data sets for cement production both at the national and at the European level. A data set is available at a national level for different types of cements and was described in Chapter 2 ((Blengini, 2006) - see section 2.4.2). Seven individual EPD (from the *International EPD system*), ten (one European and nine from France) average LCA and six generic data sets are available at the European level for cement production.

Table 6.6 – Available data sets for cement production

Product	LCA data sets						
	National (Portugal)			European			
	Site specific data from national LCA studies/ *individual EPD*	Joint EPD	National average LCA data sets	Individual EPD	Joint EPD	Country specific or European average LCA data sets	Generic LCA data set
Cement	1	0	0	7	0	European (1); France (9)	6

It is also important to characterise each of the foreign data sets via meta data (using the fields chosen in section 6.1.5.4 and the information already included in Appendix 6.I). Therefore, Table 6.7 presents the meta data for the data sets identified.

Table 6.7 – Meta data of each data set that provides LCA of cement production

Acronym	**ATILH**	**CEMBUREAU**	**Ecoinvent**	**Environdec**
Designation of the database / *EPD Programme*	*Inventaires de Cycle de vie*	CEMBUREAU	Ecoinvent version 2.2	*International EPD System*
Country	France	Europe	Switzerland	Italy
Type of LCA data set	Country specific average (9 types of cement)	European average	Generic (6 types of cement)	Individual EPD (7 types of cement)
Sampling procedure	Aggregation of French cement plants' data (from four companies), weighted according to production	Aggregation of representative plant data weighted according to production	Aggregation of data measured by all the Swiss cement plants	Site specific

6.2.1.1.2. Consistency and representativeness verification

The second step of NativeLCA methodology includes the verification of the consistency and representativeness of each data set. This verification is made only for foreign data sets, while site specific data from national LCA studies only has to be verified in terms of its consistency. This study followed ISO standards (ISO, 2006a, 2006b) and also the "PCR 2004:1 for preparing an EPD for Product Group "Cement" (from Environdec)". It is a cradle to gate LCA study (A1-A3, without including the packaging material) completed in the scope of a PhD thesis, the data having been collected in 2003 from the major Portuguese cement producer (Cimpor, with 58% of market share in 2004) (Blengini, 2006).

Table 6.8 presents the meta data from each foreign data set that is necessary for both verifications.

From Table 6.8 it can be concluded that:

- Each data set was achieved using different PCR, except CEMBUREAU data set and EPD from *International EPD System* that were both based on Environdec PCR for Cement (version of 2004);
- All data sets have similar system boundaries, except CEMBUREAU that does not include the complete assessment of the processes of stage A1 (raw material extraction and processing, processing of secondary material input) because the corresponding LCA study did not take into account the "explosive, grinding media and alternative fuels" processes in this stage. Therefore, this limitation will be taken into account in the comparison between data set figures;

- The CEMBUREAU data set and EPD from *International EPD System* were achieved using the same cut-off and allocation rules (because they were both based on the same PCR);
- The Ecoinvent database does not provide a quantified procedure to be applied for cut-off (the database however follows the environmental relevance criterion as stated in ISO 14044). Ecoinvent uses the cut-off approach considering that no impact is allocated to waste reused in the subsequent process. For example, the blast furnace slag (co-product from the steel industry) will have the impact of its treatment only when used in the manufacturing of the blast furnace slag cement. This approach is similar to the NF P01-010 and for the ATILH data;
- The ATILH data set was achieved based on a French standard that defines a wider set of processes that cannot be considered in the inventory (until 2% in mass) and followed the international standard for dealing with allocation (ISO, 2006b). Specific allocation rules defined in the NF P01-010 standard for wastes reused in a subsequent process are in line with Ecoinvent (Lasvaux, 2010).

Table 6.8 – Meta data of each data set (for cement) that enables consistency verification

Characteristics	ATILH	CEMBUREAU	Ecoinvent	Environdec
Methodology/*PCR followed*	French standard NF P01-010	Based on ISO 14020:2005, ISO 14025:2006, ISO 14040:2006, ISO 14044:2006 *PCR 2004:1 for preparing an EPD for Product Group “Cement” (Environdec)*	Ecoinvent methodology	*PCR 2004:1 for preparing an EPD for Product Group “Cement” (Environdec)*
System boundaries	A1-A3, without including the packaging material	A1(partial); A2-A3 A1-A3, without including the packaging material	A1-A3, without including the packaging material	A1-A3, without including the packaging material
Cut-off rules	NF P01-010 (< 2% mass)	PCR 2004:1 - Cement (< 1% mass or environmental impact)	Not defined by the database management	PCR 2004:1 - Cement (< 1% mass or environmental impact)
Allocation rules	ISO 14044:2006 and NF P01-010 for the by-product (no system expansion is allowed)	PCR 2004:1 - Cement (mass)	ISO 14044:2006 and cut-off rules for the wastes (no system expansion is accounted for in the database)	PCR 2004:1 - Cement (mass)
Critical review/verification	External critical review	External critical review	Internal critical review	External review and approval by an accredited certification body
Market share of average LCA data (%)	85 % of the French market (but 100 % of national production)	Not documented	100% of the national production	Not declared

Therefore, all data sets are consistent with respect to the assumptions, methods, models and data used for their calculation. The LCI flows and LCIA parameters provided in each data set (Table 6.2 and Table 6.3) are consistent within but not similar in different data sets. Nevertheless, they are all in accordance with the goal and scope of this study (namely in terms of functional unit, of being cements available in the European market, including the non-renewable energy consumption in the process and GWP, and including the production stage, despite the fact that the CEMBUREAU data set does not include the complete assessment of the processes of stage A1). In terms of verification of the data sets, ATILH, CEMBUREAU data sets and EPD *from International EPD System* were externally verified, while Ecoinvent data sets were only reviewed internally.

A representativeness check should be made to foreign data sets (from a Portuguese point of view) in order to evaluate their suitability to be used as generic data for a national context. Therefore, all the data sets considered in this case study should be evaluated on the parameters summarised in Table 6.9.

Analysing Table 6.9, the following conclusions can be reached:

- Only the CEMBUREAU data set has European coverage, while the remaining data sets are only country specific;
- The production technology can be considered as “classic” in the European context for all data sets, despite the potential use of different rates of “waste fuels” in each country;
- These data sets cover several compositions and therefore the interest on separating the data sets per type of cement will be evaluated in the comparison of results;
- Only in the EPD from *International EPD System* the background data used is not documented, while in the remaining data sets it corresponds mainly to European data;
- The Ecoinvent data set is the oldest one (the inventory was made in 2004) while the remaining resulted from studies done in the last five years;
- The Ecoinvent data set is the only one that offers the possibility of modifying background data in order to provide “contextualisation”.

Therefore, a “contextualisation” was made to the six Ecoinvent data sets (namely by changing the electricity production mix, from the Swiss to the present Portuguese context – see Chapter 5, and changing the transportation processes from the Swiss to the European average process) and only the “contextualised” values will be considered in the remaining sections of this study.

At the end of this step, all data sets were considered valid in terms of consistency and representativeness, even though some of them do not comply with some of the criteria defined. The criteria that were not complied with by each data set are shaded in grey in Table 6.8 and Table 6.9.

Table 6.9 - Meta data of each data set (for cement) that enables representativeness verification

Characteristics	**ATILH**	**CEMBUREAU**	**Ecoinvent**	**Environdec**
Designation of the database / *EPD Programme*	*Inventaires de Cycle de vie*	CEMBUREAU	Ecoinvent version 2.2	*International EPD System*
Geographic coverage	France (30 plants) representing 85 % of French consumption	Plants which are representative of CEMBUREAU European member countries	Switzerland (8 plants)	One plant in Italy
Technological representativeness	Current technology used in France including the 4 types of ovens (dry, half-dry, half-moist, moist); the dry process is the most used to date in France; caloric substitution from secondary fuels - 30% on average	CEMBUREAU members technology mix for clinker burning (dry process, semi-dry/semi-wet process, wet process) (Europe); secondary non-renewable raw materials without energy content - 3% on mass; secondary non-renewable raw materials with energy content - 16% on net caloric value	Typical technology for Swiss production; Caloric substitution from secondary fuels - 36% (42% in mass)	11.8% of secondary raw materials on mass (in average cement, with 68% of 32.5 R); caloric substitution from secondary fuels - 4.5 %; Italian practice
Characteristics of the product (according to EN 197-1 Cement – Part 1: Composition, specifications and conformity criteria)	CEM I (52.5), II/B-L (32.5), II/B-M (32.5; 42.5), III/B (32.5; 42.5), II/A-V (32.5; 42.5), II/A-L(32.5; 42,5; 52.5), III/A (42.5; 52.5), II/A-S (52.5), V/A (32.5; 42.5)	CEM I	Average (mix of different types of cement, based on CH statistics: 2% blast furnace slag cement, 50% Portland calcareous cement, 40% Portland cement, resistance class Z 42.5, 6% Portland cement, resistance class Z 52.5, 2% Portland slag sand cement); 42.5; 52.5; blast furnace slag cement; Portland calcareous cement; Portland slag sand cement; I (42.5); I (52.5); II/A-S(42.5); II/A-L(32.5); III/B (32.5)	CEM IV A 32.5 R CEM II B/P 32.5 R, II BLL 32.5 R, II /A-LL 42.5 R, II BLL 42.5 R, I 52.5 R
Energy and transport processes LCA data	Ecoinvent and DEAM combined using the TEAM(R) LCA software	Specific electricity mix based on the electricity mix of CEMBUREAU member countries (ELCD data) in proportion to their relative cement production; transports, energy carriers and raw materials – ELCD; GaBi database 2006 was used when ELCD data was not available. Data combined using the GaBi® LCA software	For some exchanges RER-modules have been used as proxy	Not documented
Temporal representativeness	2008	2006	2004	2006
Possibility of background data "contextualisation"	No (aggregated data set)	No (aggregated data set)	Yes (unit process data set)	No (aggregated data set)

6.2.1.1.3. Suitability test for the quantification of mean values (MeVa) of LCI and LCIA indicators

GWP and non-renewable energy (PE-NRe) consumption have been chosen to be used as reference to apply NativeLCA methodology. From Table 6.3 it is possible to conclude that all non-generic data sets include these LCIA indicators and therefore they are all suitable to be used in the quantification of mean values (MeVa) for these parameters.

The level of aggregation of data per life cycle stage in each data set is not equal in all data sets: the *International EPD System* and CEMBUREAU present the environmental impacts disaggregated in stages A1-A2 (raw material extraction and processing, processing of secondary material input plus transport to the manufacturer) and stage A3 (cement manufacturing) while all other data sets (except Ecoinvent) present the result in stages A1-A3 for this LCIA indicator. The scope of this research study includes the product stage (from A1 to A3) and therefore all available data sets can be considered suitable to be used in the quantification of MeVa of GWP and PE-NRe.

6.2.1.1.4. Quantification of European mean values (MeVa) for non-renewable energy consumption (PE-NRe) and GWP

A quantification of European mean value (MeVa) for PE-NRe and GWP is made in this step (which in this case could be equally named “foreign” MeVa). In the previous steps, the seven individual EPDs and the ten average data sets (country specific - nine from France - and one European) have been considered suitable to be used in MeVa quantification. However, it was found that CEMBUREAU - European average data set - does not include data concerning production volumes or number of companies considered, and therefore will not be considered for MeVa calculation (however, it will be considered in the following comparisons). Therefore, only individual EPD (*International EPD system*) and country specific average (the French one from ATILH) were considered for European MeVa calculation. A first overview of the values of each of these data sets for non-renewable energy consumption and GWP for the production of one ton of cement is presented in Figure 6.8 and Figure 6.9.

Considering the various types of cements in the sample (and the NativeLCA procedures – that consider the calculation of MeVa by application), it was decided to calculate four types of European MeVa (for PE-NRe and GWP): a European MeVa considering all the values in this sample, and European MeVa for CEM I, CEM II and CEM III. Each European MeVa was calculated as an arithmetic mean according to the number of companies included in each data set, for each environmental indicator and for the same declared unit, of individual EPD (*International EPD system*) and country specific average (French one from ATILH, which includes four companies) because not all of these data sets declare production volumes. European MeVa, that was calculated considering all the values in this sample, and European MeVa for CEM I, CEM II and CEM III, are presented in Figure 6.10 and Figure 6.11 for PE-NRe and GWP, respectively. These charts also include the standard deviation of each group of data sets. Analysing this variability, it was concluded that it is directly dependent on the number of data sets in each group, except for CEM III. However, as this group only includes two data sets, it was decided not to exclude any of them at this stage of the methodology.

Taking into account that four types of European MeVa were calculated and that there is one Portuguese data set available, the French average LCA data set (from ATILH) will not continue to be considered as an individual data set in the next comparisons.

6.2.1.1.5. <u>Comparison within foreign data: MeVa vs generic data sets</u>

This step provides a comparison between European MeVa calculated in the previous step and generic data sets (including in this last group the CEMBUREAU average data set, as decided in the last step). This comparison is presented in Figure 6.12 and Figure 6.13, where Ecoinvent data sets “contextualised” for the Portuguese context are identified by the abbreviation “EI”.

Figure 6.12 and Figure 6.13 also include three more types of European MeVa (for PE-NRe and GWP, respectively) depending on cement strength classes. However, these figures were not considered as relevant as European MeVa per cement type (CEM I, II and II) and will not be considered in the following steps of the methodology.

Comparing the four European MeVa (average and per cement type - Figure 6.12 and Figure 6.13) with the generic and European average LCA data sets, their validity is verified for GWP, but not for PE-NRe. The values for this last LCIA are not consistent between MeVa and Ecoinvent data sets “contextualised” for the Portuguese context. In fact, Ecoinvent data sets “contextualised” for the Portuguese context (and even more the original Ecoinvent data sets from the Swiss context) presented lower values for PE-NRe than European MeVa for each cement type, despite their concordance in terms of GWP. This fact can be explained by:

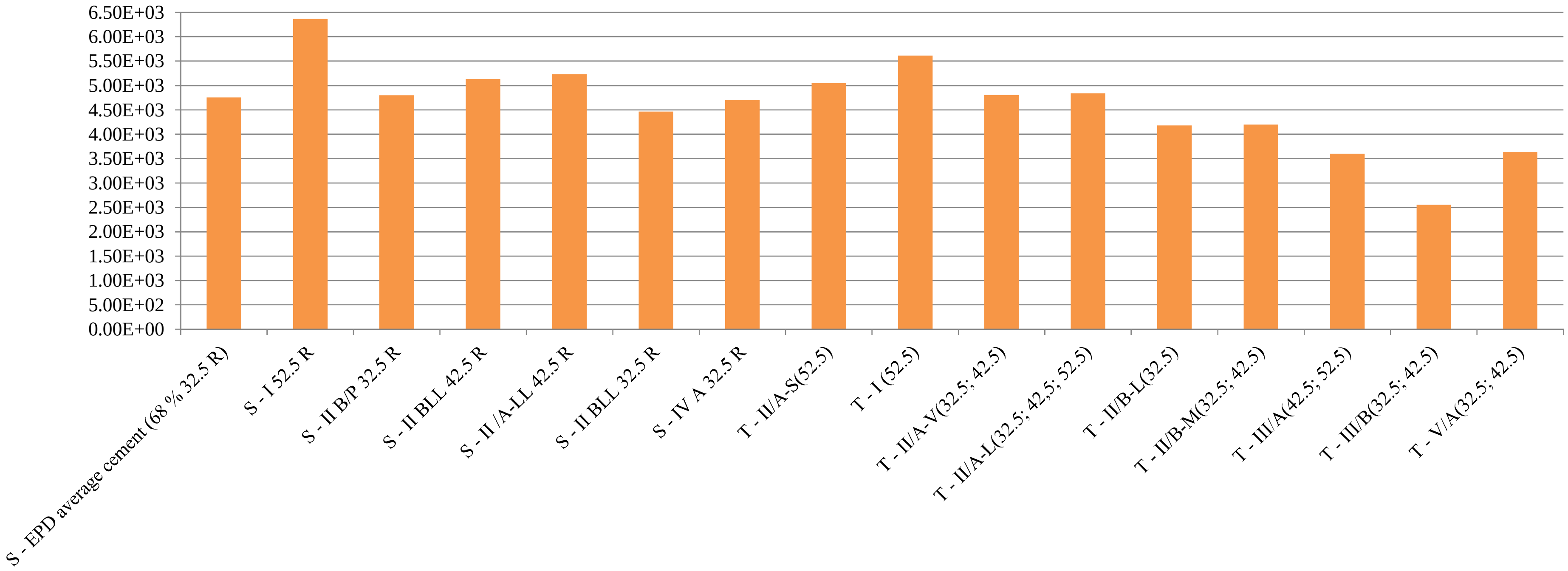


Figure 6.8 - Consumption of PE-NRe (MJ) in the production of one ton of cement from individual (S - *International EPD system*) and joint EPD identified by the type of cement (T - French one from ATILH) identified by the type of cement

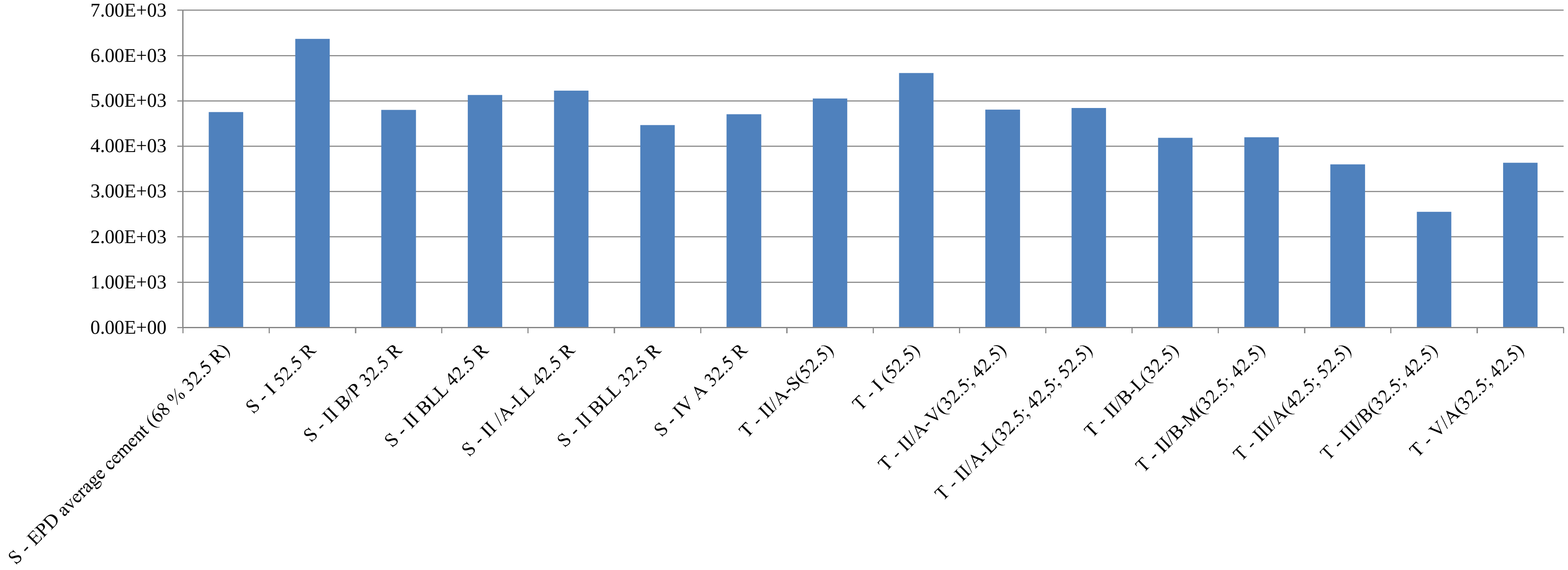


Figure 6.9 - GWP (kg CO_2 eq) in the production of one ton of cement from individual (S - International EPD system) and joint EPD (T - French one from ATILH) identified by the type of cement

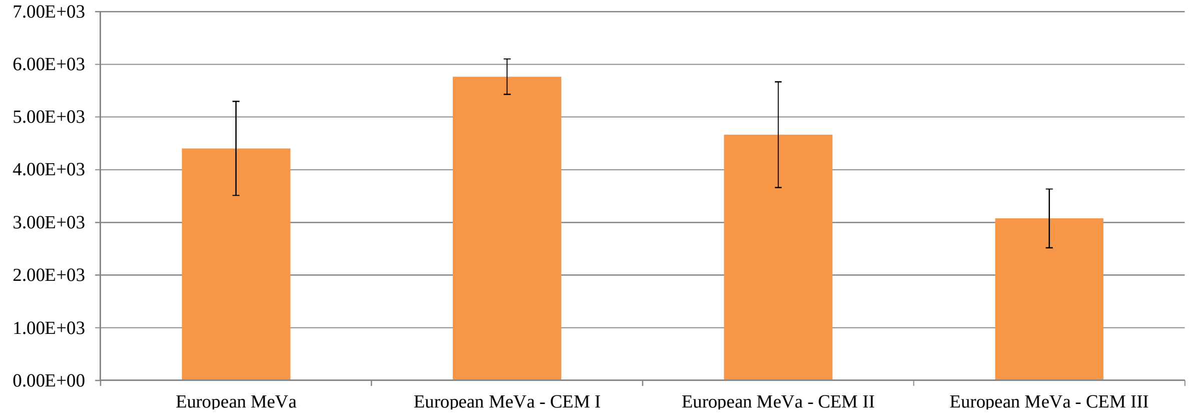


Figure 6.10 - European MeVa considering all the values in this sample and for CEM I, CEM II and CEM III for PE-NRe (MJ) in the production of one ton of cement

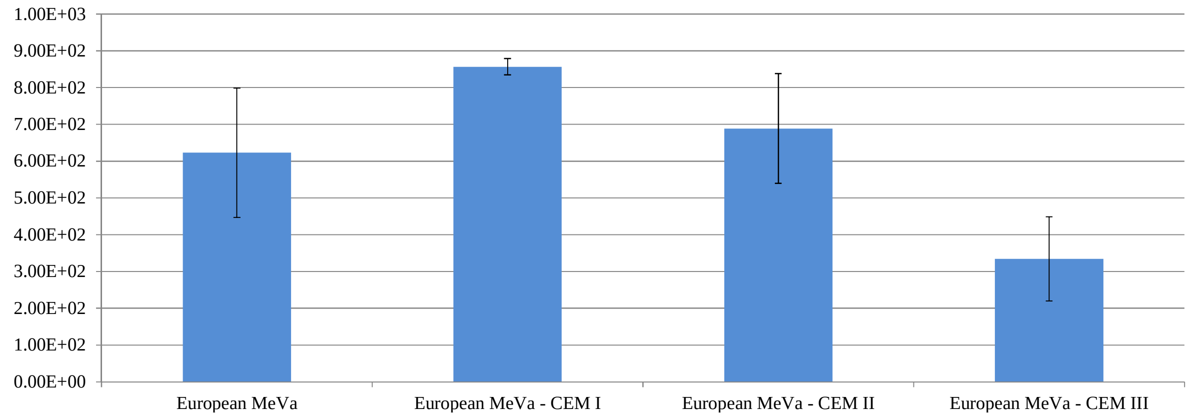


Figure 6.11 - European MeVa considering all the values in this sample and for CEM I, CEM II and CEM III for GWP (kg CO_2 eq) in the production of one ton of cement

- The connection between GWP and the CO_2 release during clinker production, which should be similar in a European context for each cement type;
- The inverse relation between PE-NRe and the share of secondary fuels used as input in the process under analysis.

In fact, from Table 6.9 it is possible to confirm an inverse relationship between the share of secondary non-renewable raw materials with energy content used in clinker production and PE-NRe figures presented in Figure 6.13. Ecoinvent data sets present the lowest values for PE-NRe and are based on an average caloric substitution from secondary fuels of 36%. This share is 16% for the CEMBUREAU (European average) data set, which also has the second lowest figures for PE-NRe. European MeVa (which corresponds to an average between individual EPD of *International EPD system* and country specific average - the French one, from ATILH) can be considered to have an average of 25% of caloric substitution from secondary fuels (taking into account that a higher number of data sets were considered from ATILH) and its value is higher than Ecoinvent ones and similar to CEMBUREAU.

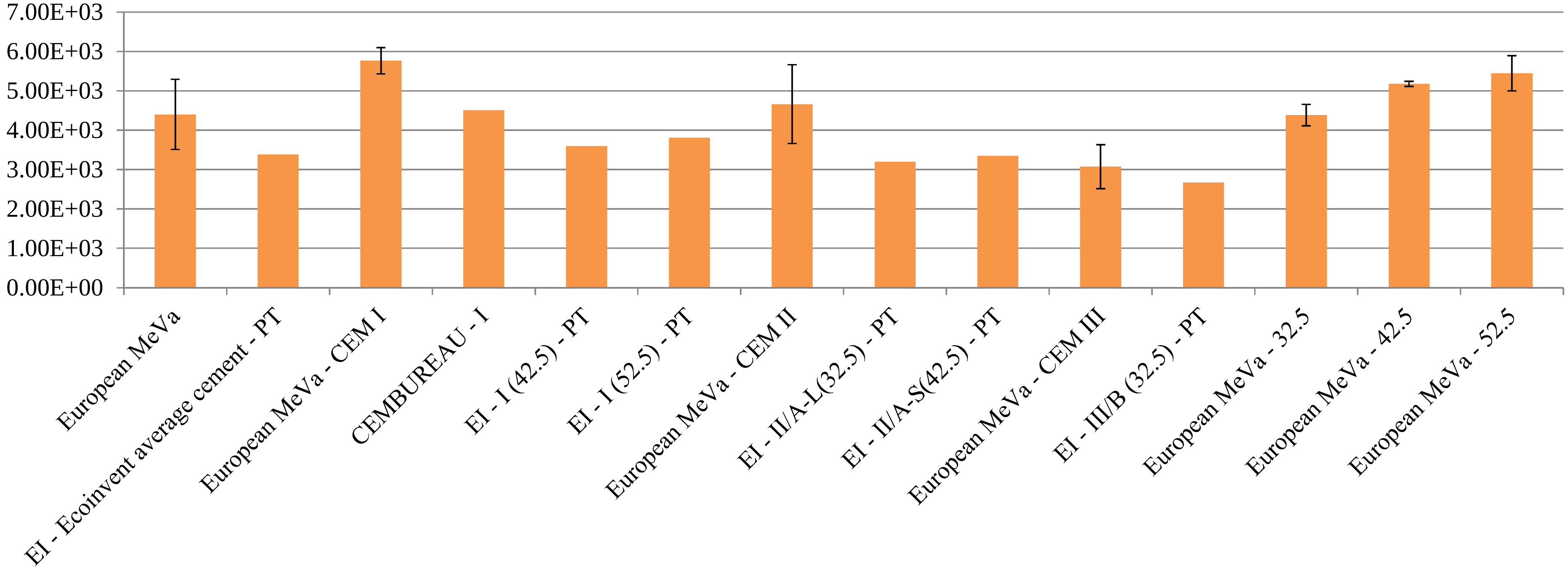


Figure 6.12 - Consumption of PE-NRe (MJ) in the production of one ton of cement for overall European MeVa, CEM I, CEM II and CEM III European MeVa and generic data sets

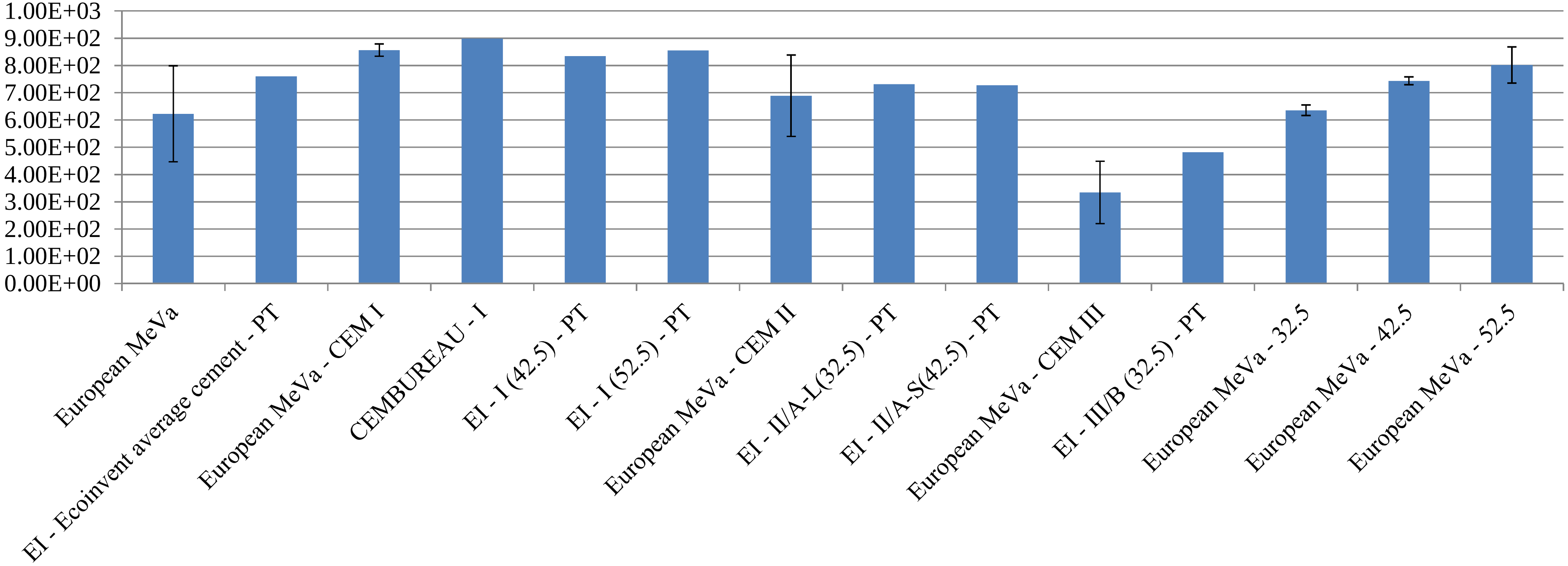


Figure 6.13 - GWP (kg CO_2 eq) in the production of one ton of cement for overall European MeVa, CEM I, CEM II and CEM III European MeVa and generic data sets

6.2.1.1.6. Comparison between site specific data from national LCA studies, MeVa and generic data sets

This step of NativeLCA methodology allows, in this case study, for the benchmarking of national LCA studies (for each LCI flow and LCIA parameter, and for each life cycle stage) with foreign LCA data sets (foreign and European MeVa and average, and generic data sets). National LCA study includes different types of cements, but only "average cement", CEM I (42.5 and 52.5) and CEM II (A-L/42.5) are considered thereafter, this data set being identified as "Blengini" (Blengini, 2006). If the validity of this data set is verified, it can be considered plausible to be used as generic in the Portuguese context, mainly because of its higher representativeness when compared to foreign data sets (and due to the non-significant market of imported cement in Portugal), and also because average data sets (or third-party reviewed LCA results) for cement production do not exist at a national level yet.

Before making the comparison between "Blengini", MeVa and generic data sets, the percentage of caloric substitution from secondary fuels of the national study must be confirmed in order to select only a foreign data set with similar production practices for this comparison. This percentage was 7.5% on average (in 2003, at the Alhandra plant). Taking into account the dissimilar Swiss practices (36%), the Ecoinvent data set is not considered in this step.

The comparison between "Blengini", MeVa, and the CEMBUREAU (European average) data set is presented in Figure 6.14 and Figure 6.15, and the following conclusions can be drawn from the analysis of these charts:

- For PE-NRe, the validity of "Blengini" is proved for all types of cement, despite "Blengini" figures being placed in the higher extreme of the interval of variability of European MeVa ("Blengini" average cement, CEM I 52.5 and CEM II/A-L 42.5). This result is expected due to the lower share of caloric substitution from secondary fuels of the national study;
- For GWP, the validity of "Blengini" is proved for average cement and for CEM II (with both values in the highest extreme of the interval of variability of European MeVa), but not for CEM I. However, this is the European MeVa with lower standard deviation and "Blengini" figures show a difference between 3% (CEM I 42.5) and 5% (CEM I 52.5) from the CEMBUREAU data set, which can be considered to have a higher geographical representativeness than European MeVa. Figure 6.16 presents the environmental impacts after normalisation (using CML 2001 v. 2.05 and West Europe - 1995 as a reference for normalisation) of the CEMBUREAU and "Blengini" CEM I data sets. From this figure, it is possible to confirm the difference already known in the ADP category (due to dissimi-

lar PE-NRe), the analogous significance of GWP and a different composition of air emissions (“Blengini” ones more related with AP and CEMBUREAU ones more linked to POCP).

Therefore, it was considered that the “Blengini” data set is plausible to be used as generic for the Portuguese context, namely for cement types and corresponding strength classes used in the construction products studied in this thesis (see Chapter 5).

6.2.1.1.7. Selection of a coherent LCA data set to be used as generic data for a national context: NativeLCA

Based on the conclusions taken from the last section, site specific data from a national study has been chosen to be used as generic for the Portuguese context for two cement types and corresponding strength classes (CEM I - 42.5 and 52.5 - and CEM II A-L/42.5) (Blengini, 2006). Table 6.10 summarises the decisions that have been made in each of the steps of the application of NativeLCA methodology to cement production.

Table 6.10 – Summary of decisions made in each of the steps of the application of NativeLCA methodology to cement production

National and foreign data verification **Consistency (all data sets) and representativeness (foreign data sets)**	**Suitability to be used in the quantification of mean values (MeVa) for LCI and LCIA indicators and MeVa quantification (EPD and average data sets)**	**Data comparison within foreign data: MeVa vs generic data sets**	**Data comparison between site specific data from national LCA studies, MeVa and generic data sets**	**Selection of a coherent LCA data set to be used as generic for a national context: NativeLCA**
No eliminated data sets	Calculation of European MeVa and European MeVa CEM I, II and III	Generic (Ecoinvent data sets “contextualised” for the Portuguese context) data set discarded (in the next step) because of lack of technological representativeness	Plausibility of site specific data from national LCA studies confirmed	Site specific data from national LCA studies

The confirmation of the Portuguese practice in terms of clinker production was paramount for this choice, namely the use of secondary fuels in clinker production (more according to European average or Italian than Swiss practice). Generic data sets (i.e. Ecoinvent) have the advantage of allowing “contextualisation” that improves their representativeness, but in this case their technological representativeness was not fulfilled and therefore they cannot be chosen. The final choice was also based on the information compiled in previous steps of this methodology, mainly in the results of the assessment of consistency and representativeness (CEN, 2010).

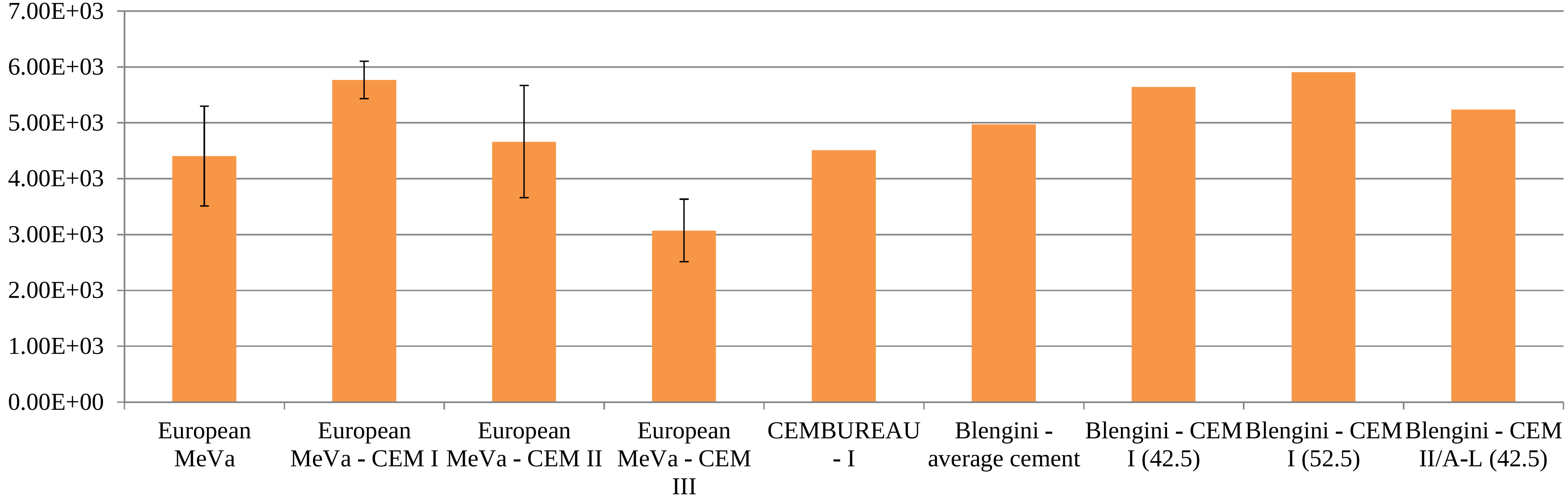


Figure 6.14 - Consumption of PE-NRe (MJ) in the production of one ton of cement for overall European MeVa, CEM I, CEM II and CEM III European MeVa, CEMBUREAU and “Blengini” data sets

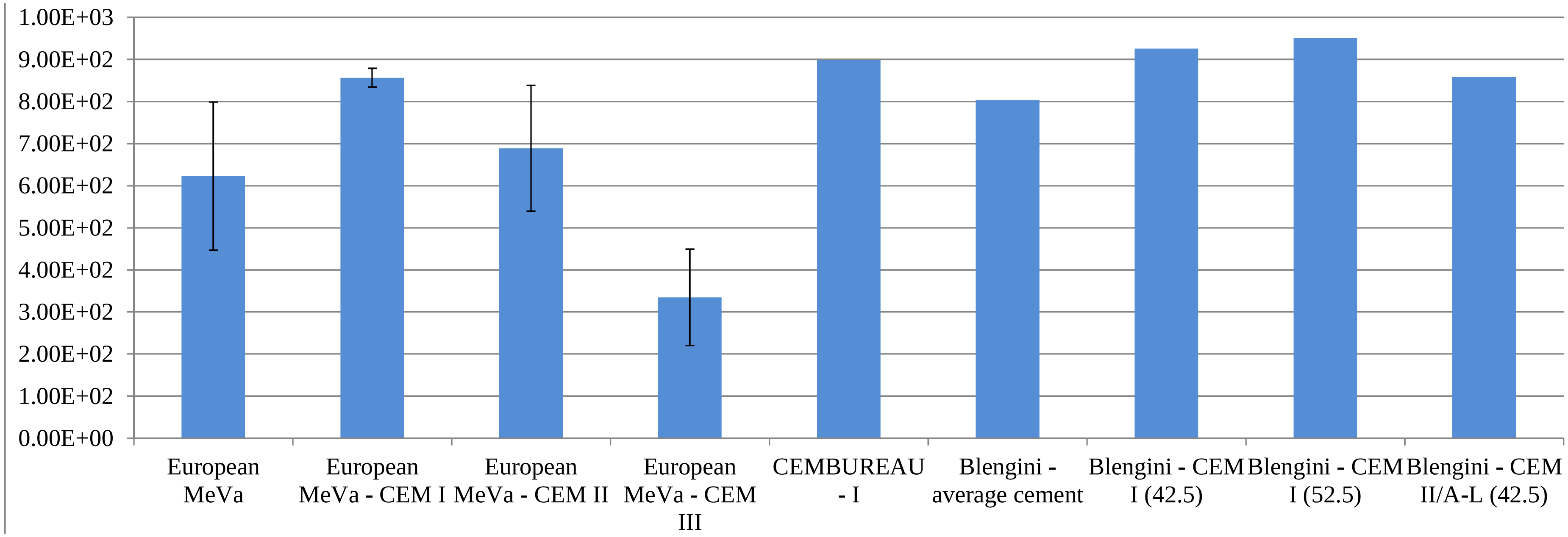


Figure 6.15 - GWP (kg CO_2 eq) in the production of one ton of cement for European MeVa, CEM I, CEM II and CEM III European MeVa, CEM-BUREAU and “Blengini” data sets

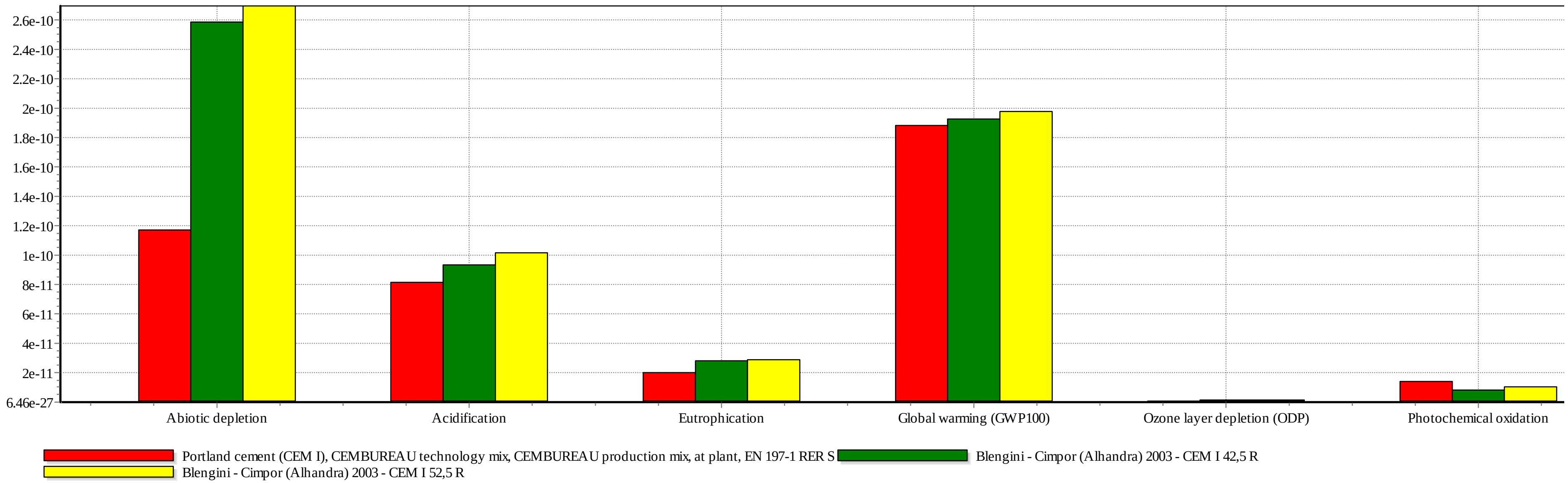


Figure 6.16 - Environmental impacts after normalisation (CML 2001 v. 2.05 and West Europe - 1995) of the CEMBUREAU and “Blengini” CEM I data sets

6.2.2. Elements of the wall structure (EWS)

Three elements of the wall structure have data available (Appendix 6.II) in more than one of the selected LCA sources for production, construction, use and end-of-life: lightweight concrete blocks (with LECA as lightweight element) and hollow fired-clay blocks (along with masonry mortar). By contrast, reinforced concrete does not satisfy this condition, not even for the production stage. This construction product is also not used in any building product or assembly in the scope of this thesis. The remaining element of the wall structure - GFRC precast panels – is included in two databases for the production, construction and use, but in only one database for the end-of-life stage. However, none of these data sets are of similar products but of reinforced concrete or fibre cement panels (see 6.2.2.3).

Section 6.2.2.1 exemplifies the application of NativeLCA in the choice of a LCA data set of hollow fired-clay bricks to be used as generic data for the Portuguese context. The next sub-sections include the application of a “simplified” version of NativeLCA in the verification of the plausibility of the LCA studies completed in the scope of this thesis for lightweight concrete blocks, GFRC precast panels and stabilised masonry mortar.

6.2.2.1. <u>EWS - Hollow fired-clay bricks (data from previous studies)</u>

NativeLCA provides a LCA data set for hollow fired-clay bricks used in external walls of buildings in Portugal. This data set can be used as generic for the Portuguese context. The aim of this methodology has been described, and the scope is, in this case, defined by:

- The functional unit of the study: the production of one kilogram of hollow fired-clay bricks, including the packaging material (because not all data sets declare the thermal conductivity of the bricks; because generic data sets also use this functional unit in order to be used to model bricks of any density or thickness; and because all data sets include the packaging material);
- The characterisation of the construction material that will be the object of this study: different types of non-structural hollow fired-clay bricks available on the European market;
- The LCI flows and LCIA parameters (and corresponding EIAM) that will be considered: in a procedure similar to previous case studies, a normalisation of LCIA impacts was conducted for Ecoinvent data to provide a first overview of the environmental impacts. Figure 6.17 presents the environmental impacts (after normalisation) of the brick production process available in this database. From this figure it is concluded that ADP is the most important environmental impact of clay brick production in a European context, followed by

GWP and AP. Therefore, PE-NRe, GWP and AP are used as a reference to apply NativeLCA methodology. PE-NRe is chosen instead of ADP for the reason described in cement case study;

- In this study, only the product stage (A1 to A3.1) is considered.

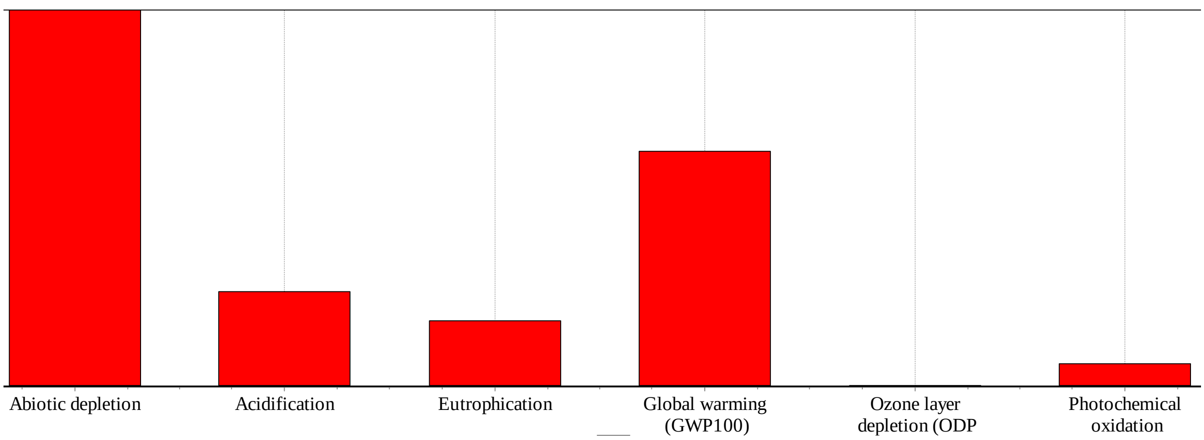


Figure 6.17 – Environmental impacts after normalisation (CML 2001 v. 2.05 and West Europe - 1995) of the brick process available in the Ecoinvent generic database (the highest value of the chart is $7.94x10^{-14}$)

The scope of this study considers only non-structural solutions but most of the data sets declare that the corresponding bricks can be used both in non-structural and in structural applications. However, this potential structural use is implicit in the apparent density and in the geometry of these blocks, and is also dependent on additional elements added on-site to the wall assembly. Therefore, no data set was excluded in this step.

Table 6.11 identifies and quantifies available LCA data sets for hollow fired-clay brick production both at the national and at the European level. An average data set is available at a national level for this construction product, which is identified in Table 6.2, Table 6.3, Appendixes 6.I and 6.II as “Portuguese average LCA data set” (Almeida *et al.*, 2010). Three individual (two French and one from the *International EPD system*) and one (French) joint EPD, and one generic data set are available at the European level for hollow fired-clay brick production. Table 6.12 presents the meta data for these data sets.

To provide the verification of the consistency and representativeness of foreign data sets, Table 6.13 presents meta data for both verifications, except the fields presented in Table 6.8 for Ecoinvent and for the *International EPD system* and in Table 6.18 for INIES.

Table 6.11 – Available data sets for hollow fired-clay brick production

Product	LCA data sets						
	National (Portugal)			European			
	Site specific data from national LCA studies/ ***individual EPD***	Joint EPD	National average LCA data sets	Individual EPD	Joint EPD	Country specific or European average LCA data sets	Generic LCA data set
Cement	0	0	1	3	1	0	1

Table 6.12 – Meta data of each data set that provides LCA of hollow fired-clay brick production

Acronym	Ecoinvent	Environdec	INIES
Designation of the database/*EPD Programme*	Ecoinvent version 2.2	*International EPD System*	*Programme de Déclaration Environnementale et Sanitaire pour les produits de construction*
Country	Switzerland	Italy	France
Type of LCA data set	Generic	Individual EPD	Two individual and one joint (of three different companies) EPD
Sampling procedure	Aggregation of data measured in 12 brick production plants in Germany, Austria and Switzerland	Site specific	Individual EPD: one based on three plants, and the other based on five plants, in France, each from the same producer; joint EPD: aggregated data from three different companies

Table 6.13 – Meta data of each foreign data set of hollow fired-clay bricks that enables consistency verification

Characteristics	Ecoinvent	Environdec	INIES
Functional unit/apparent density (kg/m^3)	1 kg; 1500	1 ton; 793.5 (average for the different types of bricks included)	1 m^2 and thickness of 20, 30 (individual EPD) or 37.5 cm (joint EPD), including masonry mortar; 615, 868 (individual EPD); 894.5 (joint EPD)
System boundaries	A1-A3.3		
Critical review/verification	Internal critical verification	External review and approval by an accredited certification body	External critical review (one individual, and the joint, EPD)
Market share of average LCA data (%)	-	-	-

From Table 6.13 it can be concluded that:

- All data sets have similar functional units and system boundaries, except INIES data sets which include the production of the masonry mortar in the inventory of the brick production. This difference will therefore be taken into account in the comparison between data set figures;
- Only EPD from the *International EPD system* and from INIES (partially) were subjected to external review while the Ecoinvent data set was only reviewed internally.

All data sets were considered consistent in what concerns assumptions, methods, models and data used for their calculation. The LCI flows and LCIA parameters provided in each data set (Table 6.2 and Table 6.3) are consistent within but not similar in different data sets. Nevertheless, they are all in accordance with the goal and scope of this study (namely in terms of functional unit, of being clay bricks available on the European market, of including the PE-NRe, GWP, and AP, and of including the production stage and the brick packaging, despite that French EPD also include the production of the masonry mortar).

This verification is made only for foreign data sets, while the national average LCA data set only has to be verified in terms of its consistency. The development of this data set followed ISO standards (ISO, 2006a, 2006b) and also PCR developed for this specific study. It is a cradle to gate LCA study (A1-A3.3) completed in 2008 from five national companies (Almeida *et al.*, 2010). The clay blocks included in this study have an estimated thermal conductivity between 0.36 and 0.42 W/ (m. ºC) and an average apparent density of 672.3 kg/m^3.

A representativeness check should also be made of foreign data sets (from a Portuguese point of view) in order to evaluate their suitability to be used as generic data for a national context. Analysing Table 6.14 and Table 6.9 (which contains the parameters necessary for this verification), the following conclusions can be reached:

- Only the Ecoinvent data set has a broader European coverage, while the remaining data sets are only country specific;
- The production technology can be considered as "classic" in the European context for all data sets;
- The thermal conductivity of the clay bricks represented by this data is lower than the one of the bricks studied for the Portuguese average data set, except Ecoinvent that does not declare this characteristic. Ecoinvent is also the only data set whose bricks' apparent density is not similar to the Portuguese one (Table 6.13);
- The Ecoinvent data set is the oldest one (the inventory between 1992 and 2002) while the remaining resulted from studies done in the last eight years;
- The Ecoinvent data set is the only one that offers the possibility of modifying background data in order to provide "contextualisation".

Therefore, a "contextualisation" was made to the Ecoinvent data set (namely by changing the electricity production mix, from the Swiss to the Portuguese context) and only the "contextualised" values will be considered in the remaining sections of this study.

At the end of this step, all data sets were considered valid in terms of consistency and representativeness, despite the fact that some of them do not comply with some of the criteria defined (shaded in grey in Table 6.13 and Table 6.14).

PE-NRe, GWP and AP have been chosen to be used as reference to apply NativeLCA methodology. From Table 6.3 it is possible to conclude that all non-generic data sets include these LCIA indicators and therefore they are all suitable to be used in the quantification of mean values (MeVa) for these parameters. The level of aggregation of data per life cycle stage in each data set is equal (from A1 to A3.3) and therefore all available data sets can be considered suitable to be used in the quantification of MeVa of PE-NRe, GWP and AP.

Table 6.14 - Meta data of each data set (for hollow fired-clay bricks) that enables representativeness verification

Characteristics	Ecoinvent	Environdec	INIES
Geographic coverage	Plants in Germany, Austria and Switzerland	One plant in Italy	Plants in France
Technological representativeness	Mix of different technologies (different firing fuels, except hard coal coke) from the three countries	Single extrusion line brickyard with a traditional dryer / tunnel kiln assembly; rendering fat is directly used for firing	Standard technologies; fuels: natural gas, biogas or biomass
Thermal conductivity (W/(m.ºC)) (for density see Table 6.13)	Not declared	0,12-0,28	0.151-0.256 and 0.115 (individual EPD); 0.125-0.128 (joint EPD)
Energy and transport processes LCA data	Ecoinvent Hypotheses	Defined on PCR 2004:9 - Clay Construction products	AFNOR FD P01-015 Document
Temporal representativeness	1992-2002	2004	2011 (one individual EPD) and 2008 (remaining EPD)
Possibility of background data "contextualisation"	Yes (unit process data set)	No (aggregated data set)	No (aggregated data set)

Despite the variety of thicknesses and thermal conductivity values of the bricks available on the European market (and the NativeLCA procedures - that consider the calculation of MeVa by application), MeVa calculations by use, thickness or density were not done (e.g. for bricks of improved thermal performance) because of the low number of data sets in the sample.

The quantification of MeVa for PE-NRe, GWP and AP was done in this step for five figures (Figure 6.18):

- European MeVa, considering the three individual (two from INIES and the one from the *International EPD system*) and one joint (from INIES – called "INIES_19" in Figure 6.18) EPD and the Portuguese average data set; European MeVa is the arithmetic mean for each environmental indicator (based on the number of companies included in each data set) and for the same declared unit, because none of these data sets declare production volumes (only Ecoinvent does);
- Foreign MeVa, considering the same data sets but the Portuguese average data set and following the same procedure;

- Foreign MeVa for the data sets that do not include masonry mortar ("wtt mortar"), which in this case corresponds only to the EPD from the *International EPD system* (ENV8 in Figure 6.18);
- European (or Foreign) MeVa for the data sets that include masonry mortar ("inc. mortar"), considering two individual and one joint (all from INIES) EPD and following the same procedure;
- European MeVa for the data sets that do not include masonry mortar ("wtt mortar"), considering the individual EPD from the *International EPD system* and the Portuguese average data set, and following the same procedure.

An overview of the values of each of these data sets for PE-NRe, GWP and for the production of one kg of hollow fired-clay bricks is presented in Figure 6.18, including the standard deviation of each MeVa. Analysing this variability, it was concluded that it is not directly dependent on the number of data sets in each group.

Comparing the "contextualised" Ecoinvent data set with Foreign MeVa (Figure 6.18), a similarity is found in terms of PE-NRe, but GWP and AP present lower values for the former data set. The difference for GWP stays within the "standard deviation" interval, but the Ecoinvent value for AP is less than half of the one from Foreign MeVa. Foreign MeVa includes data sets with masonry mortar, but those have less impact in AP than the remaining ones and therefore do not provoke this difference of the Ecoinvent figures.

Comparing "contextualised" Ecoinvent (EI-PT) and Foreign MeVa also with European MeVa (full, with, or without masonry mortar) and the Portuguese average data set (PTAv1 - Figure 6.18), some conclusions can be drawn:

- As expected, European MeVa with masonry mortar presents higher values than the same data set without this additional material (European MeVa – wtt mortar), and "Foreign MeVa - wtt mortar", in all categories but AP. Therefore it was considered that these three MeVa should be discarded in this step because their significance was not proven;
- European MeVa has a higher similarity with Ecoinvent than Foreign MeVa in all impact categories, despite the difference in AP still being significant;
- European MeVa also has a higher similarity with PTAv1 than Foreign MeVa, presenting the same value for PE-NRe, and the values of GWP and AP staying within the "standard deviation" interval of European MeVa (despite the latter including data sets with masonry mortar). PTAv1 presents values within the "standard deviation" interval of Foreign MeVa in all impact categories, even though GWP corresponds to the lower extreme of this interval;

- PTAv1 is similar to EI-PT in terms of PE-NRe, but presents a lower value for GWP and a higher value (almost double) for AP.

The comparison of the Portuguese average data set with EI-PT, and with European and mainly with Foreign MeVa, allowed the verification of its plausibility in the European context, despite the diversity in terms of apparent density of these data sets (Table 6.13). The comparison with European MeVa may not be fair because PTAv1 is considered in the calculation of this parameter, but the comparison with Foreign MeVa proved its validity for the impact categories analysed (despite that Foreign MeVa considers individual EPD from INIES that include masonry mortar and whose bricks have a thermal conductivity lower than the one of the bricks studied for the Portuguese average data set). Therefore, it was considered that the PTAv1 data set is plausible and can be chosen to be used as generic for the Portuguese context for the production of one kilogram of hollow fired-clay bricks, including the packaging material. Despite the adequate geographical representativeness of this data set and its third-party verification, it was considered adequate to make the application of NativeLCA to hollow fired-clay brick production because of their importance in the range of solutions used in Portugal for external walls of buildings. It was also considered that it is not yet possible to choose a data set to be used as generic to represent hollow fired-clay bricks and the corresponding masonry mortar together (mainly due to the low quantity of available data sets). Table 6.15 summarises the decisions that have been made in each of the steps of the application of NativeLCA methodology to hollow fired-clay brick production.

6.2.2.2. EWS - Lightweight concrete blocks

NativeLCA can also be used by the practitioner (or by the critical reviewer) in the verification of the plausibility of EPD (or LCA study) results. This application corresponds to a “simplified” version of NativeLCA for the comparison between site specific data from national LCA studies, MeVa and generic data sets (and the importance of this benchmarking exercise was referred to in 6.2.1.1.6). The aim is not, in this case, to provide a data set to be used as generic for a national context. The objective is to verify the plausibility of the results achieved (via a methodology that is a priori consistent) in the European scope, in order to allow their use in LCA of building assemblies (namely external walls) or buildings. This application has some similarities with the cement case-study (see 6.2.1.1) however this “simplified” alternative is to be used when the practitioner (or the author, in this case) has a better knowledge of the methodology used in the LCA study and of its consistency.

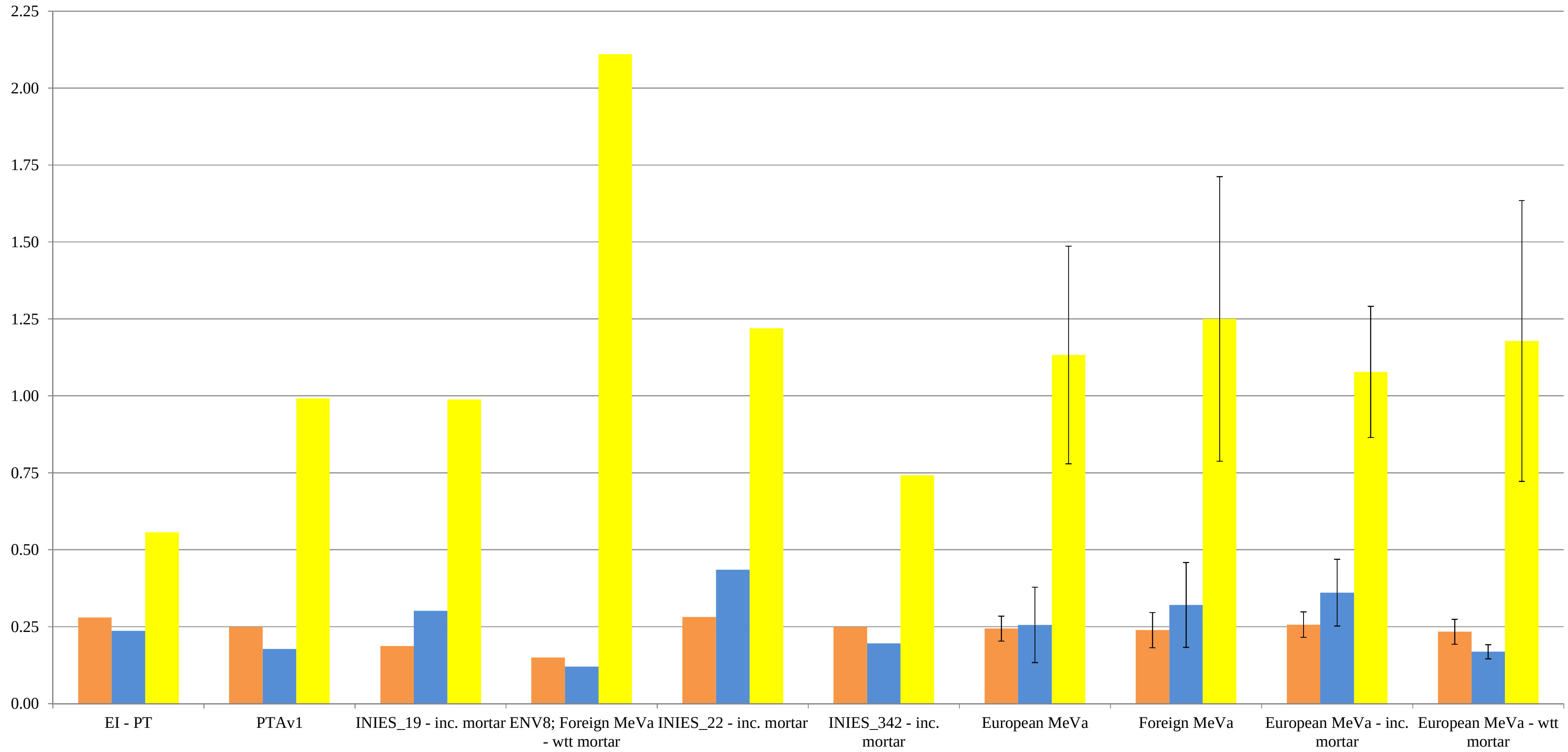


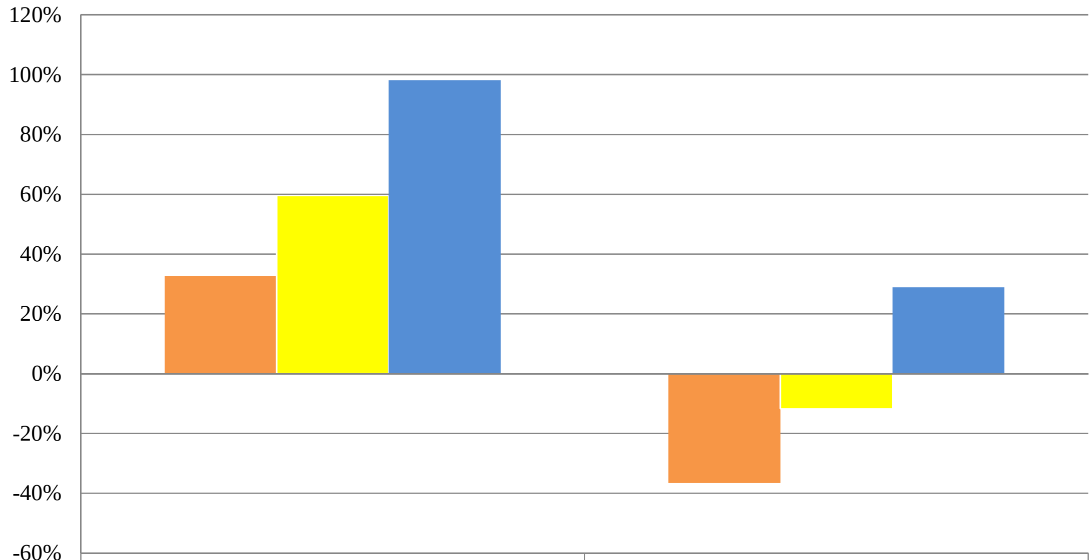
Figure 6.18 - PE-NRe (in orange, x10MJ), GWP (in blue, kg CO_2 eq), and AP (in yellow, $x10^{-3}$kg SO_2 eq) in the production of one kilogram of hollow fired-clay bricks from generic (Ecoinvent – EI) and average (average national – PTAv1) data sets, and joint (INIES_19) and individual EPD (ENV8 from the *International EPD system*, and INIES_22 and INIES_342)

Table 6.15 – Summary of decisions made in each of the steps of the application of NativeLCA methodology to hollow fired-clay brick production

National and foreign data verification **Consistency (all data sets) and representativeness (foreign data sets)**	**Suitability to be used in the quantification of mean values (MeVa) for LCI and LCIA indicators and MeVa quantification (EPD and average data sets)**	**Data comparison within foreign data: MeVa vs generic data sets**	**Data comparison between national and foreign data: MeVa vs generic data sets**	**Selection of a coherent LCA data set to be used as generic for a national context: NativeLCA**
No eliminated data sets	Calculation of European and Foreign MeVa: for all data sets, for data sets that include masonry mortar (in this case European is equal to Foreign MeVa) and for data sets that do not include it	Generic (Ecoinvent data sets "contextualised" for the Portuguese context) data sets discarded because of lack of temporal representativeness, and AP figures and average apparent density not concordant with European and Foreign MeVa	European and Foreign MeVa for data sets that do not include masonry mortar and European MeVa for data sets that include it, were discarded due to their lack of significance and due to the low quantity of data sets in each group; plausibility of national average data set confirmed (mainly when compared with foreign MeVa)	National average LCA data set - PTAv1 for the production of one kilogram of hollow fired-clay bricks (A1 to A3.1)

To apply this “simplified” version of NativeLCA, it is necessary to complete the step “Comparison between site specific data from national LCA studies, MeVa and generic data sets” of this methodology. Prior to this step, the identification of available LCA data sets, at a national and at the European level for building products very similar to the one studied, has to be made.

NativeLCA is used in this case only for the comparison between LCA results for lightweight concrete block production (A1-A3.3) of a Portuguese company (site specific data from a national LCA study, presented in Chapter 5) and two generic data sets: Ecoinvent and ELCD. The relative differences found between the national results and foreign data sets (for the three most important impact categories after normalisation - see Appendix 5.I) are presented in Figure 6.19.



	ECO11	ELCD8
NRe	33%	-37%
AP	60%	-12%
GWP	98%	29%

Figure 6.19 - Differences in PE-NRe (in orange), AP (in yellow) and GWP (in blue) in the production of one kilogram of lightweight concrete blocks (A1-A3.3) between generic data sets (Ecoinvent and ELCD) and national site specific data

The comparison with Ecoinvent results (ECO11 in Figure 6.19) shows that this data set has higher results than the national study in all environmental categories (between 33% and 98%). Despite the fact that the Ecoinvent data set refers to “lightweight concrete block, expanded clay, at plant”, it was found that this process considers a block with a composition of 90% of LECA and 10% of cement, in weight, without any other type of aggregates. The lightweight concrete block studied in Portugal has a composition of 35% of LECA and 12.5% of cement, in weight, the remaining weight being composed of natural aggregates.

Taking into account that the environmental impacts in raw material production come mainly from cement and LECA (see Chapter 5 – e.g. 98% of AP and 97% of GWP, the contribution of LECA being 77% and 40%, respectively), the replacement of the share of natural aggregates (around 52%) by LECA can lead to a significant increase of the impact in all categories. This result is expressed in the Ecoinvent process and can explain the differences found between the figures of this data set and national results. It is also important to refer that the Ecoinvent process was modelled based on literature and has a temporal representativeness between 1995-2000, this last fact being important to analyse and justify the differences found in GWP (in fact, a significant improvement of production technology in different sectors has been made in order to reduce greenhouse gases between 1995 and 2012).

Meta data of the ELCD data set also reveals that its temporal and geographical representativeness are not coincident with the national study. The data acquisition for composition of the blocks was conducted in 2007 based on a survey with manufacturers, cement data was collected in 2004 within an industrial project, and the production process is based on a research project developed in 2000, but the geographical area of each of these studies or the process used to model LECA is not referred to. Meta data also refers to a steam supply during production, which may be used to accelerate the curing (heat curing) of the blocks.

ELCD has environmental impacts lower than the LCA study developed in Portugal for PE-NRe (-37%) and AP (-12%), and higher for GWP (29%; ELCD8 in Figure 6.19). ELCD has a steam supply that can lead to an increase of some environmental impacts (namely in GWP, depending on the technology used), while in the latter the curing conditions are controlled using a ventilation and moist air exhaust system that provides the permanent regulation of temperature and humidity conditions. The ELCD data set considers a composition of 42% of LECA and 10% of cement (in weight). Considering the environmental profile achieved in the national LCA study, this higher quantity of LECA can lead to higher environmental impacts in GWP (8% more, despite having a higher significance in NRe and in AP - 15% more). One additional cause can explain the differences found in NRe and in GWP: the use of an updated Portuguese electric mix (of 2011 – see Chapter 5) in the LCA of lightweight concrete blocks studied in Portugal (and also in LCA of LECA used in these blocks, in which electric energy consumption during manufacturing is significant – see Chapter 5) resulted in a reduction of 25% of the GWP (and 50% in AP) figures, and in an increase of 92% in NRe of the electric energy consumption. Taking into account the lack of data concerning the databases used for modelling cement and LECA production in the ELCD data set, and the low number of data sets available for this type of construction product, it is not possible to make more inferences concerning the causes of the differences found in LCA results.

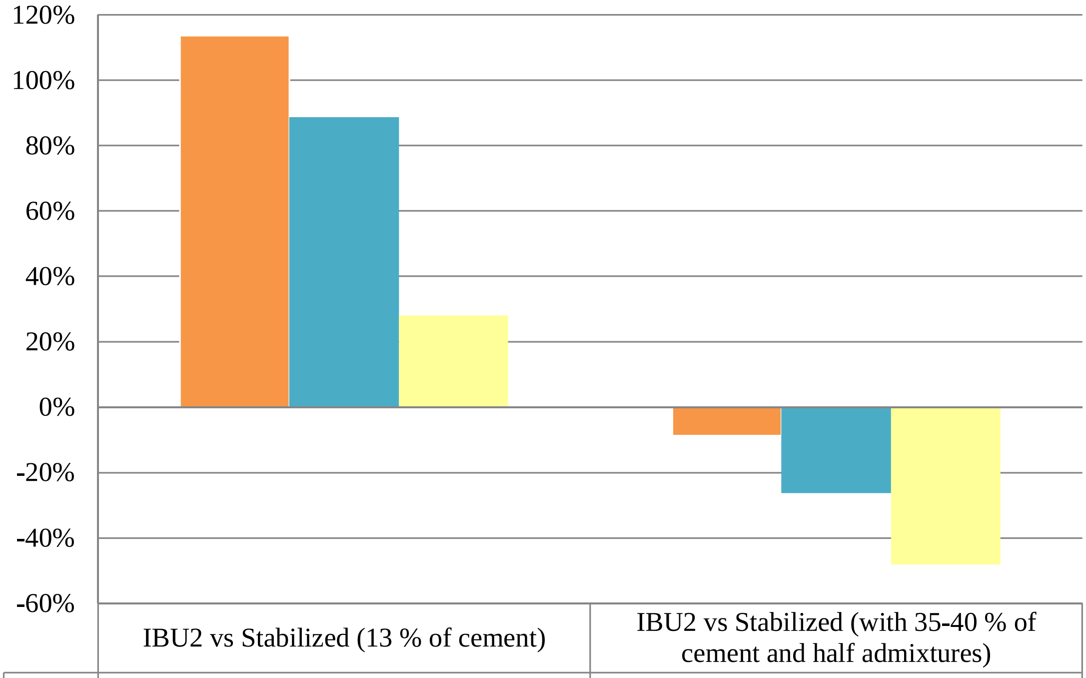
6.2.2.3. EWS - GFRC precast panels

The Glass Fibre Reinforced Concrete (GFRC) precast panels studied in this thesis are not produced on a daily-basis but on request. These panels have improved thermal characteristics due to the placement of EPS boards filling the voids between frontal and posterior GFRC layers, and can either be considered as an element of the wall structure or as a cladding. Due to these particular characteristics, no LCA data set was identified at the European level (not even in reference literature) for very similar (nor even for similar) products. In fact, only data sets for reinforced concrete or fiber cement panels were found in LCA databases. The LCA results presented in Chapter 5 can therefore be considered original at an international level. Thus, the option was not to apply, in this case, the “simplified” version of NativeLCA but to consider the LCA results of the GFRC precast panels for the LCA of building assemblies or buildings in the Portuguese context. Nevertheless, the NativeLCA methodology was applied in this chapter to two important components of GFRC panels: cement (see 6.2.1.1) and EPS boards (see 6.2.3.4).

6.2.2.4. EWS - Stabilised masonry mortar

NativeLCA is used in this case only for the comparison between LCA results for stabilised masonry mortar production (A1-A3.3) of a Portuguese company (site specific data from a national LCA study, already presented in Chapter 5) and MeVa and generic data sets. In this case, only a joint EPD (from the German system) is available for products with characteristics similar to the one studied (namely with a thermal conductivity of 1 W/ (m.ºC) while the national mortar has 0.85 W/ (m.ºC)). This EPD corresponds to an average LCA data set that includes more than 20 types of dry and wet (stabilised) masonry mortars from different companies belonging to a German manufacturing association. This document does not mention the share of each type of product but, for the dry mortars, the packaging is also considered (metallic containers are also considered as packaging material of the stabilised mortar studied in this thesis but its environmental impact is not significant – see Chapter 5).

The results achieved in this thesis for the Product stage (A1-A3.3 see Chapter 5) of stabilised masonry mortar were compared with the ones included in the EPD, and the relative differences found for the three most important impact categories after normalisation (see Appendix 5.I) are presented in Figure 6.20. This comparison was made per kilogram of product. The analysis of the significant differences found between the LCA results of both data sets (between 28% - in AP - and 114% - in NRe) required the comparison between their compositions. The national one has 13% of cement while the German one has 35-40% of this component (in weight). A trial was therefore made with a “virtual” modification in the composition of the stabilised mortar studied in Portugal: 35-40% of cement and a half of the admixtures. This “virtual” mixture tries to reproduce the composition of the average product (between a wet and a dry mortar, with 35-40% of cement and with admixtures mainly in the first product) considered in the German EPD. Figure 6.20 also includes the differences found between this EPD and the “virtual” product described.



	IBU2 vs Stabilized (13 % of cement)	IBU2 vs Stabilized (with 35-40 % of cement and half admixtures)
NRe	114%	-9%
GWP	89%	-26%
AP	28%	-48%

Figure 6.20 - Differences in PE-NRe (in orange), GWP (in blue) and AP (in yellow) in the production of one kilogram of stabilised mortar (A1-A3.3) between a joint EPD (IBU2) and national site specific data (from a stabilised mortar with a real composition and with a modified composition)

The trial described had the intention of verifying if the major differences found between the German EPD (IBU2) and the national LCA results are directly related to the amount of cement in both products. The results achieved (IBU2 vs Stabilised (with 35-40% of cement and half admixtures) in Figure 6.20) show that the differences between data sets diminished in GWP and in NRe, becoming equal or less than 26% (now with a lesser impact of German EPD). The difference in NRe can be justified by the higher share of secondary fuels in clinker production for the cement considered in the German EPD (14%, being 6% higher than the national one - see 6.1.5.9). The differences found in GWP and AP (lesser impact of 48% in German EPD) can result from the similar differences observed in the same environmental categories between the LCA data set chosen to model cement in the building products studied in this thesis and European MeVa and CEMBUREAU data sets (see 6.1.5.9). However, this explanation requires the assumption that the environmental profile chosen to model cement in the German EPD is in accordance with European average figures. Therefore, it can be concluded that results are similar between data sets for the most important categories after normalisation if an analogous "virtual" composition is considered for the stabilised mortar produced in Portugal. Thus the plausibility of the national LCA study is confirmed, despite the limitations found in the available LCA data set of a similar product.

6.2.3. Insulation materials (IM)

Concerning the insulation materials group (Appendix 6.II) all the materials chosen are available in, at least, two LCA databases, except ICB. For the remaining insulation materials, in all cases LCA data comprises not only the production stage but also the end-of-life.

Section 6.2.3.1 exemplifies the application of NativeLCA to stone wool in order to select a LCA data set to be used as generic data for the Portuguese context. The next subsections include the application of a "simplified" version of NativeLCA in the verification of the plausibility of the LCA studies completed in the scope of this thesis for LECA, XPS, EPS, PUR/PIR and ICB.

6.2.3.1. IM - Stone Wool (SW) (data from previous studies)

Different types of stone wool boards with a variety of densities, thicknesses and thermal conductivity values are available on the European market. The national practice is summarised in a LNEC publication (Santos & Matias, 2006) that describes the following solutions for the insulation of the external walls of buildings using SW (both with a thickness between 30 mm and 80 mm):

- Boards with a density between 35 and 100 kg/m^3 and a thermal conductivity of 0.04 W/(m.ºC) for use in VRF, inside cavity walls and over the inner face of external walls;
- Boards with a density between 100 and 180 kg/m^3 and a thermal conductivity of 0.042 W/ (m.ºC) for use in ETICS and in VRF.

NativeLCA should provide a LCA data set for each group of densities (or for both groups) to be used as generic in the Portuguese context. The first step of this methodology is the description of its aim and scope. The application of NativeLCA to SW (and to the subsequent products) follows the same steps as the cement case-study, although no formal division is made between them. The aim has been described and the scope is defined by:

- The functional unit of the study: the production of one kilogram of SW boards (because not all data sets declare the thermal conductivity of the board and because generic data sets also use this functional unit in order to be used to model a board of any density);
- The characterisation of the construction material that will be the object of this study: different types of SW boards available in the European market, uncoated and produced using a synthetic binder (the most common type of SW boards available in the Portuguese market);
- The LCI flows and LCIA parameters (and corresponding EIAM) that will be considered: in a procedure similar to the one used in the cement case study (see section 6.2.1.1), a normalization of LCIA impacts was conducted for Ecoinvent and ELCD data to provide a first overview of the impacts in the six environmental categories selected. Figure 6.21 presents, therefore, the environmental impacts after normalisation of the two types of SW boards available in these databases. From this figure, it is concluded that ADP is the most important environmental impact of SW production in a European context, followed by AP and GWP in equal terms. Therefore, PE-NRe, AP and GWP are used as a reference to apply NativeLCA methodology. PE-NRe is chosen instead of ADP for the reason described in section 6.2.1.1;
- In this study, only the product stage (A1 to A3) is considered, taking into account the packaging of the SW because four data sets include information about the environmental impact of its production and use.

Table 6.16 identifies and quantifies available LCA data sets for SW production at the European level. A data set is available at a national level – a French EPD from a Portuguese company – however this data set was not considered because the board analysed is coated on the surface (due to its preferred use in roof insulation). This company also produces different types of uncoated SW boards (also produced using a synthetic binder) adequate to be used in the insulation of walls, but no EPD has yet been developed for this group of boards. Therefore, the aim of this application is to provide an LCA data set for this last type of SW boards. Along with this French EPD, four more were not considered because they correspond to coated boards, two German EPD were not considered because they correspond to boards produced with a vegetable binder, and a Norwegian EPD was not considered from this point because of the aggregated nature - from cradle to grave - of its results (that avoids their use in MeVa calculation or their comparison with the remaining data sets – see Appendix 6.II). Ten individual EPD (one Spanish, seven French and two German), and three generic data sets (two from Ecoinvent and one from ELCD) are therefore considered to represent this type of SW board production at the European level.

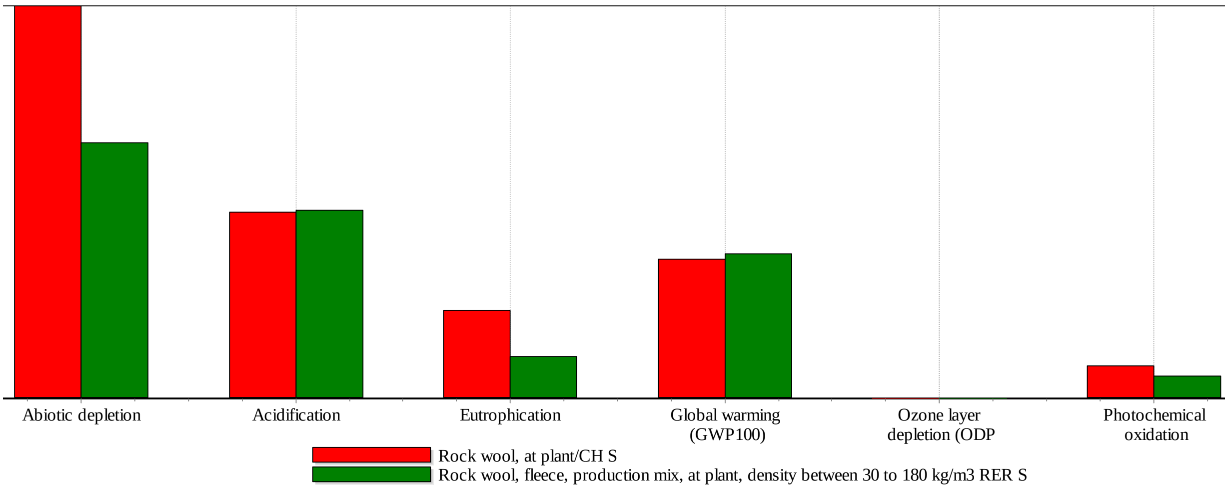


Figure 6.21 – Environmental impacts after normalisation (CML 2001 v. 2.05 and West Europe - 1995) of the SW production processes available in Ecoinvent (“rock wool, at plant”) and ELCD (“Rock wool”) generic databases (the highest value of the chart is 6.7x10^{-13})

Table 6.16 – Available data sets for SW production

Product	LCA data sets						
	National (Portugal)			European			
	Site specific data from national LCA studies/ ***individual EPD***	Joint EPD	National average LCA data sets	Individu-al EPD	Joint EPD	Country specific or European average LCA data sets	Generic LCA data set
Cement	0	0	0	10	0	0	3

It is also important to characterise each of these data sets via meta data, which is presented in Table 6.17.

To provide the verification of the consistency and representativeness of each data set, Table 6.18 presents the meta data from each foreign data set that is necessary for both verifications, except for Ecoinvent data sets (meta data for these data sets is similar to the one presented in Table 6.8, but the market share is not declared in this case; the functional unit is also 1 kg of product, the weighted density of the mix of the boards being 59.49 kg/m^3).

From Table 6.18 it can be concluded that:

- Each data set was achieved using different PCR;
- All data sets have similar system boundaries (A1-A3 or A1-A3.3), except DAPc that does not include the complete assessment of the processes of stage A1 (raw material extraction and processing, processing of secondary material input) because the corresponding LCA study did not take into account one of the components of the board (the oil, due to lack of

production data). Therefore, this limitation will be taken into account in the comparison between data set figures;

- Each data set was achieved using different cut-off and allocation rules;
- Only the DAPc and INIES (partially) data set was subjected to external review while the ELCD and IBU data sets were only reviewed internally.

Table 6.17 – Meta data of each data set that provides LCA of SW production

Acronym	**DAPc**	**Ecoinvent**	**ELCD**	**IBU**	**INIES**
Designation of the data-base / *EPD Programme*	*Declaración Ambiental de Producto (DAPc)*	Ecoinvent version 2.2	European Life Cycle Database version 2.0	*Umwelt-Deklarationen (EPD)*	*Programme de Déclaration Environnementale et Sani-taire pour les produits de construction*
Country	Spain	Switzerland	European Union	Germany	France
Type of LCA data set	Individual EPD	Generic (2 types of SW – packed and unpacked)	Generic (average of several SW products, such as boards, felts and mats)	Two individual EPD (2 types of SW, one packed and one unpacked)	Seven individual EPD (7 types of SW, one packed and six unpacked)
Sampling procedure	One plant in Spain	One company in Switzerland	European plants	One (packed SW) and three (unpacked SW) plants in Germany	One company in France

Table 6.18 – Meta data of each data set (for SW) that enables consistency verification

Characteristics	**DAPc**	**ELCD**	**IBU**	**INIES**
Methodology/*PCR followed*	EN 15804:2012; *National-based development for each group of materials*	ISO 14040:2006, ISO 14044:2006	*National-based development for each group of materials*	*French standard NF P01-010*
Functional unit/density (kg/m^3)	1 m^2 and 50 mm thickness; 30	1 kg; 140-162 (from 180 to 60 mm)	Packed SW (1 kg; 25-200) and unpacked SW (1 kg; 25-180)	1 m^2; 30, 35, 50, 70 (packed), 130, 140 (two)
System boundaries	A1 (partial) - A3.3	A1-A3 (without including the pack-aging material)	A1-A3 (without including the packaging material) and A1-A3.3	A1-A3 (six EPD, without including the packaging material) and A1-A3.3 (one EPD)
Cut-off rules	(< 5% mass and energy)	Coverage of at least 95 % of mass and energy of the input and output flows, and 98 % of their environmental relevance	Input side - all material flows greater than 1% of their total mass or contribute more than 1% of primary energy demand were taken into account; Output side - environmental impact greater than 1% of total effects of the category	Mass criterion (max. 2% of the reference flow) according to the French standard (NF P01-010)
Allocation rules	Not described	Exergetic content, net calorific value or mass, depending on the process	Packed SW (not made) and unpacked SW (based on mass)	Partitioning (ener-gy, mass, econom-ic)
Critical review / verifi-cation	External critical review	Internal critical review	Advisory board	External critical review (three out of seven)
Market share of average LCA data (%)	-	Not documented	-	-

Therefore, all data sets are consistent in what concerns assumptions, methods, models and data used in their calculation. The LCI flows and LCIA parameters provided in each data set (Table 6.2 and Table 6.3) are consistent within each but not similar between different data sets. Nevertheless, they are all in accordance with the goal and scope of this study (namely in terms of functional unit, SW boards being available on the European market, including the PE-NRe, AP and GWP, and including the production stage, despite the fact that DAPc data set does not include the complete assessment of the processes of stage A1).

A representativeness check has also been made according to the parameters summarised in Table 6.19. The following conclusions can be reached from this procedure:

- Only the ELCD data set has a European coverage, while the remaining data sets are only country specific;
- The production technology can be considered as “classic” in the European context for all data sets;
- The thermal conductivity of SW boards represented by this data are lower or equal to the figures defined in the scope;
- Only in the DAPc and ELCD, the background data used corresponds to European data;
- The Ecoinvent data set is the oldest one (the inventory between 1994 and 1997) while the remaining resulted from studies done in the last seven years;
- The Ecoinvent data set is the only one that offers the possibility of modifying background data in order to provide “contextualisation”.

Therefore, a “contextualisation” was made to both Ecoinvent data sets (namely by changing the electricity production mix, from the Swiss to the Portuguese context) and only the “contextualised” values will be considered in the remaining sections of this study.

After this step, all data sets were considered valid in terms of consistency and representativeness, even though some of them do not comply with some of the criteria defined. The criteria that were not complied with by each data set are shaded in grey in Table 6.18 and Table 6.19.

PE-NRe, AP and GWP have been chosen to be used as reference to apply NativeLCA methodology. From Table 6.3 it is possible to conclude that all non-generic data sets include these LCIA indicators and therefore they are all suitable to be used in the quantification of mean values (MeVa) for these parameters.

The level of aggregation of data per life cycle stage in each data set is similar (A1-A3 or A1-A3.3 - Table 6.18). The scope of this research study includes the product stage (from A1 to A3) and therefore all available data sets can be considered suitable to be used in the quantification of MeVa of PE-NRe, AP and GWP.

Table 6.19 - Meta data of each data set (for SW) that enables representativeness verification

Characteristics	DAPc	Ecoinvent	ELCD	IBU	INIES
Geographic coverage	One plant in Spain	One company in Switzer-land	European plants	One (packed SW) and three (unpacked SW) plants in Germany	One company in France
Technological representative-ness	Typical technology for Spanish produc-tion	Typical technology of the company	Typical European technology	Typical technology for German production (packed SW) and typical technology of the company (un-packed SW)	Typical technology for that production site
Thermal conductivity (W/(m.ºC)) (for density see Table 6.18)	0.037	0.036 (weighted)	Not declared	Between 0.035 and 0.041 (packed SW) and between 0.035 and 0.040 (unpacked SW)	0.035 (three, one packed), 0.037, 0.039 (two), 0.04
Energy and transport processes LCA data	ELCD	Ecoinvent Hypotheses	ELCD	GaBi 4	AFNOR FD P01-015 Document
Temporal representativeness	2008	2000-2002 (data collec-tion - 1994-1997)	2006	2006 (packed SW) and 2003 (un-packed SW)	2005
Possibility of background data “contextualisation”	No (aggregated data set)	Yes (unit process data set)	No (aggregated data set)	No (aggregated data set)	No (aggregated data set)

Considering the different types of SW in the sample and the corresponding applications (and the NativeLCA procedures - that consider the calculation of MeVa by application), a trial was made to calculate two MeVa according to the density of the boards (one for the data sets in the interval 35-100 kg/m^3 and another one for the data sets in the interval 100-180 kg/m^3). However, it was found that the standard deviation of these figures is higher than the one of European MeVa considering all data sets for all impact categories considered (PE-NRe, AP and GWP) and this option was therefore not taken into account.

Another trial was made to calculate a European MeVa only for data sets that consider the SW packaging (A1-A3.3 – signed “packed” in Figure 6.22). However, it was found that the standard deviation of this figure is higher than the one of European MeVa considering all data sets for two of the impact categories considered (PE-NRe and AP) and that the figures of these data sets are lower than the remaining data sets (and not higher, which is not expected because of the environmental impact of the packaging), and this option was therefore not taken into account. In fact, despite the fact that these data sets appear in Figure 6.22, they were not considered in European MeVa calculation (for PE-NRe and GWP), because of their low quantity and figures, higher variability, and because European MeVa should be consistent in terms of boundaries (and therefore consider in this case only the modules A1-A3, without considering the packaging material).

The quantification of European mean value (MeVa) for PE-NRe, AP and GWP was made in this step (which in this case could be equally named “foreign” MeVa) considering only the seven individual EPDs (from IBU and INIES, which do not include SW packaging) and being an arithmetic mean for each environmental indicator and for the same declared unit, because none of these data sets declare production volumes. A first overview of all data sets (including European MeVa and its standard deviation, and Ecoinvent data sets “contextualised” for the Portuguese context - identified by the abbreviation “EI”) is presented in Figure 6.22 for PE-NRe, AP and GWP for the production of one kg of SW board.

The comparison between European MeVa calculated in the previous step and generic data sets (Ecoinvent and ELCD) is already included in Figure 6.22. Comparing the European MeVa with the generic LCA data sets, their validity is only verified for PE-NRe (and only for Ecoinvent), but not for the remaining categories. The validity of two individual EPD (DAPc and IBU – not packed) is also questioned because of their low figures. Therefore, charts that express the relation between the impacts in each category and the density of the boards in each data set were built, but considering the same thermal performance (considering the thickness of each board necessary to achieve a thermal resistance of the layer of 1 (m^2.ºC)/W, taking into account the corresponding density and thermal conductivity presented in Table 6.18 and Table 6.19).

This analysis is also justified by the significant interval of densities of available datasets (30-180 kg/m^3). These charts are presented in Figure 6.23 and Figure 6.24 and include all data sets included in Figure 6.22, except ELCD that does not provide its thermal conductivity (two INIES data sets are represented by only one plot because they have similar values). European MeVa is represented by “89.64” which corresponds to the average density – in kg/m^3 – of the seven individual EPDs considered in its calculation, the average thermal conductivity being 0.04 W/(m.ºC).

These charts show that there is an almost “linear” relationship between PE-NRe, GWP, and AP for a given thermal performance and the density of the boards (even for “INIES_350” data set with a density of 35 kg/m^3, which is considered more adequate to acoustic insulation). However, this relation is not completely expressed for Ecoinvent for GWP and AP (the values are lower than expected), despite its fulfilment being confirmed for PE-NRe (Ecoinvent data sets correspond to the “59.49” values). The DAPc data set (corresponding to the “30” value with lower PE-NRe) expresses the stated relation for all impact categories, and the low values observed in Figure 6.22 seem to be related with its low density. The IBU unpacked data set (corresponding to the “102.5” value) continues to show lower values than expected in all impact categories (while the IBU packed data set, corresponding to the “112.5”, only presents a low value for AP which is in accordance with Figure 6.22). It is, however, considered adequate to maintain the IBU unpacked data set in European MeVa calculation in order to provide a significant geographical representativeness to this figure.

Considering the conclusions drawn from the analysis made, European MeVa has been chosen to be used as generic for the Portuguese context for uncoated SW boards produced using a synthetic binder and with a density between 35 and 180 kg/m^3. The Ecoinvent data set was not chosen, neither its “contextualised” version. In fact, the environmental profile of this data set is not in accordance with available EPD, corresponds to a single Swiss plant, and is quite old (1994-1997). The ELCD data set is not represented in Figure 6.23 and Figure 6.24, but using a “hypothetical” value of 0.041 W/ (m.ºC) for the corresponding thermal conductivity and its average value of density, its relative position is not in accordance with the “linear” relationship found for the majority of data sets. The environmental impacts of this data set were therefore considered low, which can be caused by its high “genericness” and wide scope (average of several SW products, such as boards, felts, mats and other products, with a density between 30 m^3 and 180 m^3).

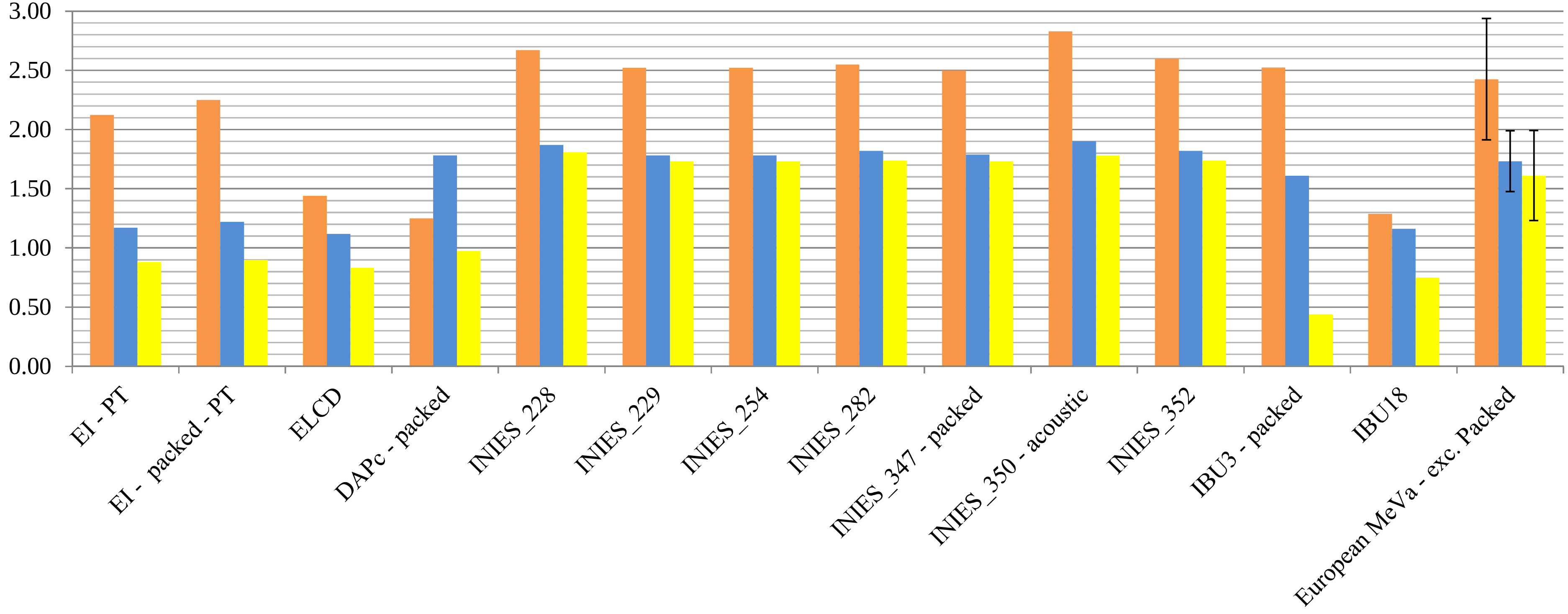


Figure 6.22 - PE-NRe (in orange, x10MJ), GWP (in blue, kg CO_2 eq), and AP (in yellow, x10^{-2}kg SO_2 eq) in the production of one kilogram of SW board from generic (Ecoinvent – EI, and ELCD) and individual EPD (DAPc, INIES and IBU) data sets

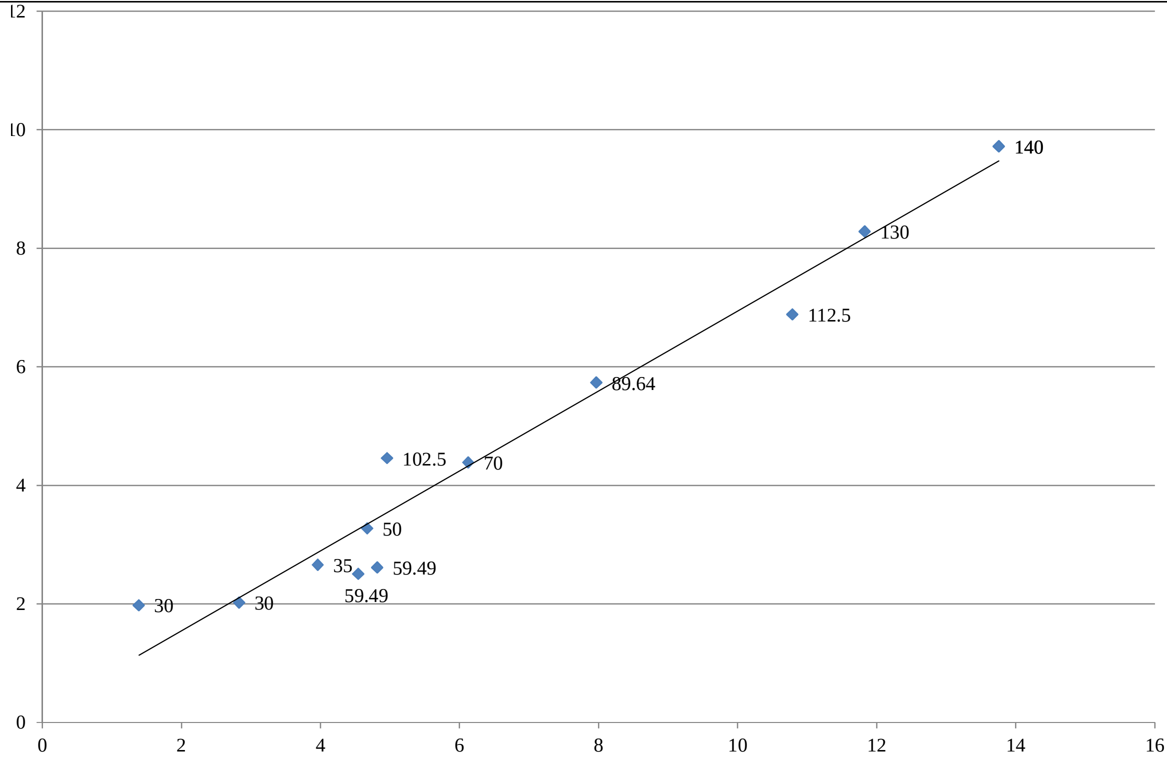


Figure 6.23 - PE-NRe (in abscissas, x10MJ) and GWP (in ordinates, kg CO_2 eq) in the production of SW boards with the same thermal performance, where each point is represented by the corresponding density (kg/m^3)

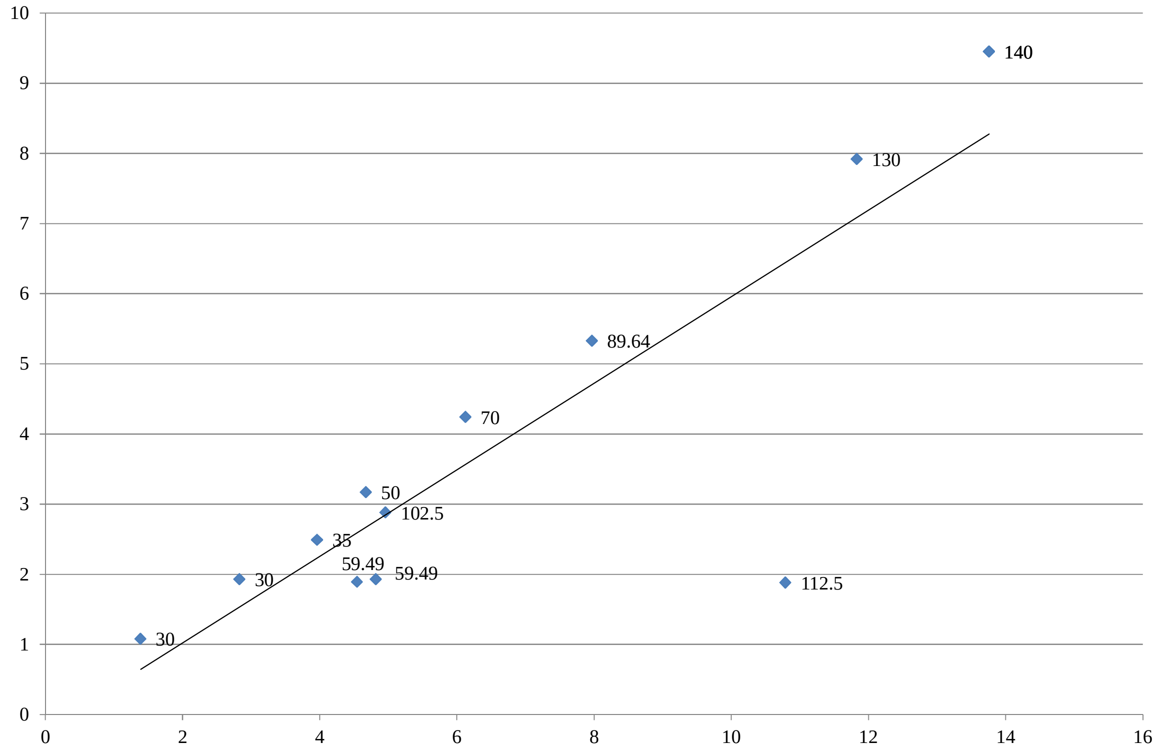


Figure 6.24 - PE-NRe (in abscissas, x10MJ) and AP (in ordinates, $x10^{-2}$kg SO_2 eq) in the production of SW boards with the same thermal performance, where each point is represented by the corresponding density (kg/m^3)

Table 6.20 summarises the decisions that have been made in each of the steps of the application of NativeLCA methodology to SW production.

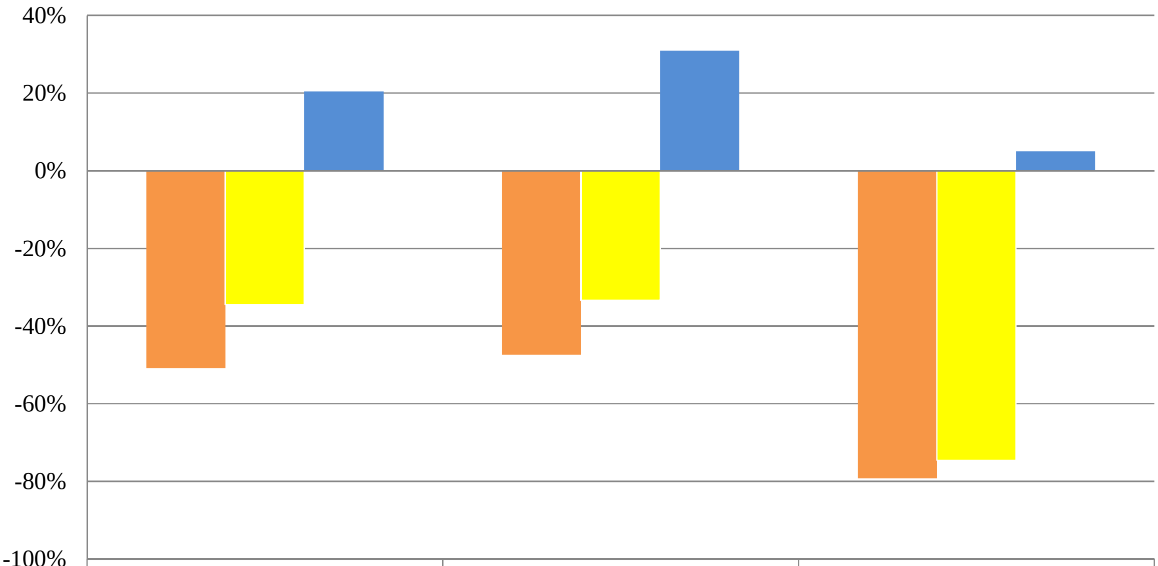
Table 6.20 – Summary of decisions made in each of the steps of the application of NativeLCA methodology to SW production

Foreign data verification	**Suitability to be used in the quantification of mean values (MeVa) for LCI and LCIA indicators and MeVa quantification (EPD and average data sets)**	**Data comparison within foreign data: MeVa vs generic data sets**	**Selection of a coherent LCA data set to be used as generic for a national context: NativeLCA**
Consistency and representativeness			
Eliminated data sets: SW coated boards (French and German EPD) and boards produced with a vegetable binder (German EPD), EPD from cradle to grave (Norwegian)	Calculation of European MeVa for packed and unpacked SW boards, and for densities of 35-100 kg/m^3 and 100-180 kg/m^3; only European MeVa for unpacked SW boards was considered	Generic data sets discarded because of lack of geographical and temporal representativeness (Ecoinvent data sets were “contextualised” for the Portuguese context but represents only one Swiss plant) and due to high “genericness” and wide scope (ELCD)	European MeVa (with an average density of 89.64 kg/m^3 and an average thermal conductivity of 0.04 W/(m.ºC)) for uncoated SW boards produced using a synthetic binder and boards with a density between 35 and 180 kg/m^3 (A1-A3)

6.2.3.2. IM - Light Expanded Clay Aggregate (LECA)

NativeLCA is used in this case only for the comparison between LCA results for LECA (A1-A3.3) of a Portuguese company (site specific data from a national LCA study, presented in Chapter 5) and one individual EPD (from the Norwegian system) and a generic data set (from Ecoinvent). The relative differences found between the national results (with a bulk density of 297 kg/m^3 for 8-16 size) and foreign data sets (for the three most important impact categories after normalisation - see Appendix 5.I, taking into account that the LCA results of these data sets are provided by kilogram) are presented in Figure 6.25.

The Norwegian EPD is based on a study (completed in 2007) of the production process of LECA in bulk of a Norwegian company. The figures of this data set are only very similar to the national study in GWP (only has 5% more impact), while being much lower in the remaining environmental categories (between 75% in AP and 79% in PE-NRe). The national plant does not yet use secondary fuels in the oven, but it was found that the Norwegian one already uses them. Considering the amount of secondary fuels used by the latter, 10% of the difference in NRe can be explained. Taking into account the significant contribution of coke production to AP and NRe in the national case study (see Chapter 5), it is of paramount importance to know the characteristics and amount of fuels used in the oven in the Norwegian company to explain the differences found in both categories. However, this information is not provided in the corresponding EPD. Taking into account this absence of data, it is not possible to make more inferences concerning the causes of the differences found in NRe. However, the analysis of the remaining environmental impact categories shows that the Norwegian data set has higher impact in POCP than the national one (57% more). This difference, along with inverse the difference in AP, can be related to the secondary fuels only used in the Norwegian plant that can lead to a different combination of air emissions resulting in a higher impact in POCP and in a lower impact in AP.



	ECO17 vs LECA - palletized PE bags	ECO17 vs LECA - PP bags	NEPD4 - bulk
NRe	-51%	-47%	-79%
AP	-34%	-33%	-75%
GWP	20%	31%	5%

Figure 6.25 - Differences in PE-NRe (in orange), AP (in yellow) and GWP (in blue) in the production of one kilogram of LECA between national site specific data and generic data set (Ecoinvent, represented by ECO17) and individual EPD (NEPD)

The Ecoinvent data set for LECA production (ECO17 in Figure 6.25) includes packaging and therefore the comparison between this data set and the national results considered the two hypotheses of LECA packaging presented in Chapter 5 (palletised Polyethylene (PE) bags and Polypropylene (PP) bags). The Ecoinvent data set has higher results than the national study only in GWP (between 20% and 31%) and lower in the remaining environmental categories (between around 34% in AP and between 47% and 51% in PE-NRe). This data set is based on literature and on data from the period between 1995 and 2000.

Along with these limitations of representativeness, it was found that the LECA production process uses around half of the electricity and less 25% of fuels (and only heavy fuel oil, without considering petroleum coke) compared with the national case-study. Therefore, a trial was made with a "virtual" modification in the manufacturing of the LECA studied in Portugal: the same quantity of electricity and heavy fuel of the Ecoinvent process. This "virtual" LECA tries to reproduce the latter, maintaining the other characteristics of the product studied in this thesis (and also the air emissions from the Portuguese plant). Figure 6.26 shows the differences found between Ecoinvent and the “virtual” product described. It was confirmed that most of the differences in NRe and AP stemmed from the assumptions related to the lower quantity of fossil fuels and electric energy consumption of the Ecoinvent process. The “virtual” product indeed shows a lower difference to Ecoinvent in these two categories (from 34% to around 21% in AP and from around 50% to equal or less than 22% in NRe). However Ecoinvent has, in this case, an even higher difference in GWP, which can again be justified by the significant improvements of production technology in different sectors that have been made in order to reduce greenhouse gases between 1995 and 2012 (which can be confirmed by GWP figures of the Norwegian EPD and of the national case study).

Benchmarking of national results for LECA production confirmed that these results are plausible and can be used in LCA of building assemblies in the Portuguese context, despite the lack of detailed data concerning the technology for LECA production in the Norwegian EPD and a poor temporal and geographical representativeness of the Ecoinvent data set.

6.2.3.3. IM - Extruded Polystyrene (XPS)

The comparison between LCA results for XPS production (A1-A3.3) of a Portuguese company (presented in Chapter 5) and MeVa and generic data sets is shown in this section. In this case, one individual (from the *International* EPD system, from an Italian company) and two joint (one from five companies all over Europe and another one from five companies that sell to the German market, both available in the German system) EPD are available for XPS boards with characteristics similar to the ones studied. A European MeVa was also calculated via an arithmetic mean according to the number of companies included in each data set. All these data sets correspond to the set of blowing agents used in the national plants for thicknesses equal or lower than 80 mm (dimethyl ether and carbon dioxide). For the other set of blowing agents (difluoroethane and ethanol, for thicknesses equal or higher than 80 mm), the only data set available is Ecoinvent (with four different data sets, depending on the set of blowing agents used). However, all Ecoinvent processes for XPS production consider Polystyrene expandable (expandable beads) as raw material, which is not correct. This raw material is not used at XPS plants, but in EPS ones. Instead, XPS production uses polystyrene pellets (General-Purpose Polystyrene – GPPS). Therefore, these generic data sets are not taken into account in this comparison. Thus, this comparison is only valid for XPS boards with thicknesses equal or lower than 80 mm, because there are no data sets available for the other set of blowing agents (difluoroethane and ethanol).

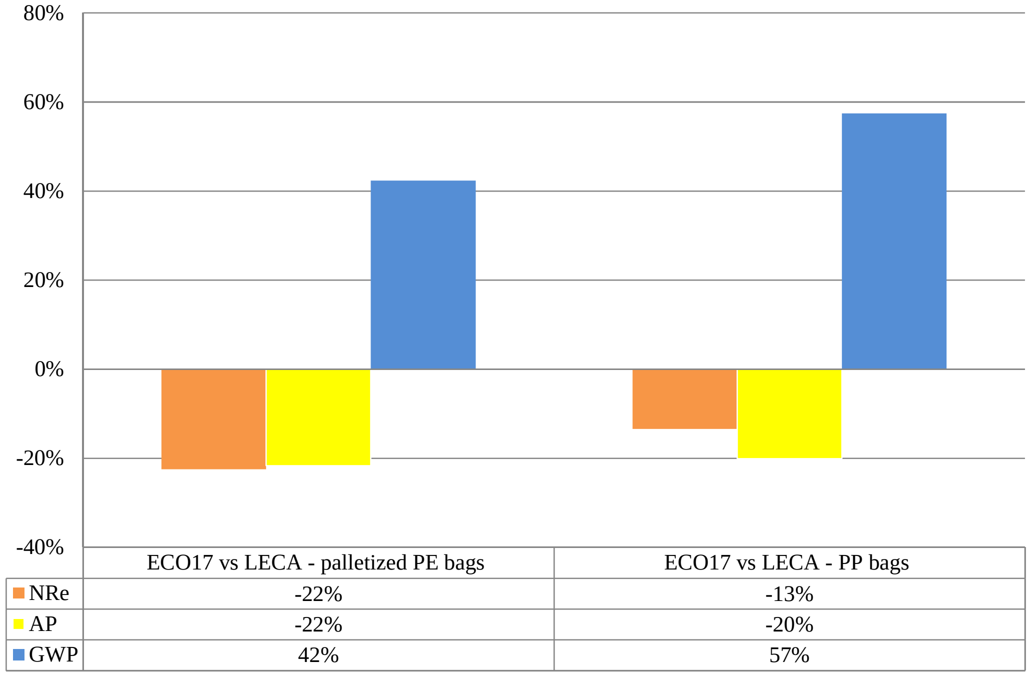
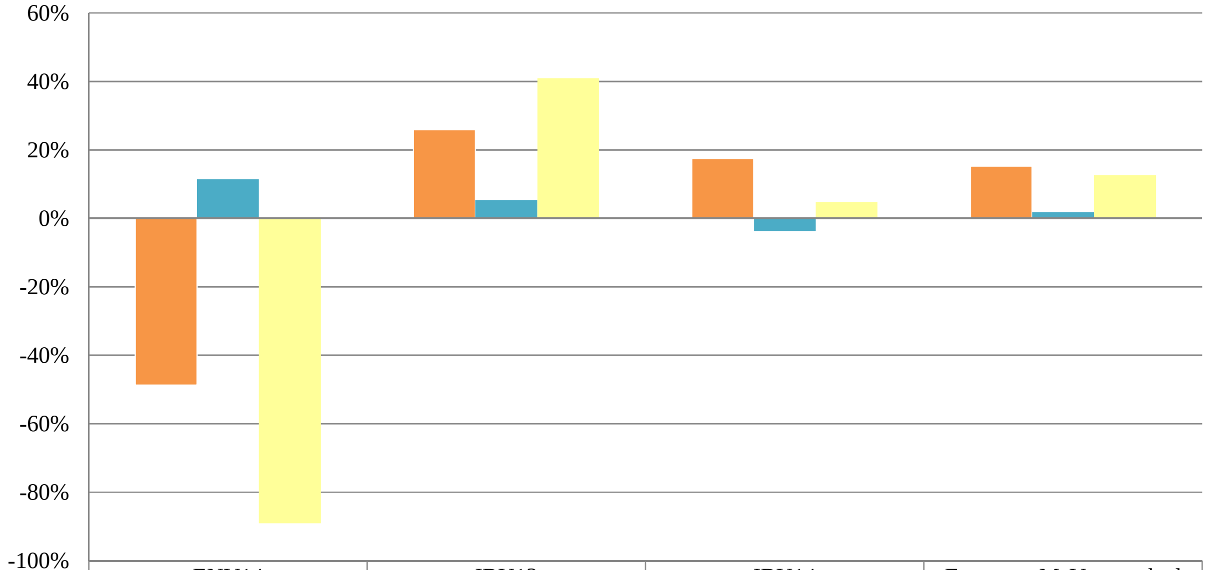


Figure 6.26 - Differences in PE-NRe (in orange), AP (in yellow) and GWP (in blue) in the production of one kilogram of LECA (A1-A3.3) between national site specific data and generic data set (Ecoinvent, represented by ECO17) (from LECA with a modified manufacturing process)

The results achieved in this thesis for the Product stage (A1-A3.3 see Chapter 5) of XPS boards were compared with the ones included in the three EPD and with the European MeVa, and the relative differences found for the three most important impact categories after normalisation (see Appendix 5.I) are presented in Figure 6.27. This comparison was made considering the same thermal performance for the XPS boards represented by each data set (considering the thickness of each board necessary to achieve a thermal resistance of the layer of 1 (m^2.ºC)/W, taking into account the corresponding density and thermal conductivity).

The main difference found in the comparison between national results and German joint EPD (IBU13 and IBU14 in Figure 6.27) is in POCP (between 5% and 41% higher in the EPD). POCP are, in the national study, mainly caused (94%) by the air emissions during manufacturing, namely due to the release of dimethyl ether during the extrusion process (A3.2 – see Chapter 5). Due to the lack of site specific data concerning the percentage of this blowing agent that is released during this stage, it was considered that 25% of the quantity of this compound initially included in the mixture is freely released to the atmosphere during the gate-to-gate stage (and, for the same reason, a percentage of 20% of difluoroethane emissions was considered for boards with thicknesses equal or higher than 80 mm). This value was based on the Ecoinvent process for XPS because EPD do not quantify this percentage, despite referring to it. Therefore, it is probable that EPD consider a higher percentage of this blowing agent released during the manufacturing stage.



	ENV14	IBU13	IBU14	European MeVa - packed
NRe	-49%	26%	18%	15%
GWP	12%	5%	-4%	2%
POCP	-89%	41%	5%	13%

Figure 6.27 – Differences in PE-NRe (in orange), GWP (in blue), and POCP (in light yellow) in the production of XPS boards (A1-A3.3, with thickness ≤ 80 mm) with the same thermal performance between national site-specific data and European MeVa and individual (ENV) and joint (IBU) EPD

Joint EPD and national results are very similar in GWP (differences equal or lower than 5%) and are similar in NRe (difference between 18% and 26%). It is also important to highlight the higher similitude of the national figures with the joint EPD based on data from a higher number of plants (IBU14 in Figure 6.27, from 18 plants, while IBU13 is based on data from 5 plants) and with European MeVa (corresponding to an average result of 24 plants), than with IBU13 or with the individual EPD. In fact, the individual EPD presents very different results from the other data sets in NRe and POCP (49% and 89% lower than national results, respectively, and even lower than joint EPD), despite having similar composition and physical characteristics. In terms of GWP, the difference is only 12%. Looking at the meta data of this EPD, the background database used to model polystyrene pellets is not declared. This raw material has a high contribution to NRe and the use of a different background process to model its production can explain the differences found in this impact category (because the national case study and the joint EPD used the same background process). Concerning the differences found in POCP, the difference found has to rely on a much lower quantity of hazardous air emissions during manufacturing accounted for in the individual EPD. Even though this individual EPD was critically reviewed externally, its validity is not verified in this comparison, namely for some of the most significant environmental categories.

The plausibility of the national LCA study of XPS production was checked through a benchmarking with European EPD. Despite the assumptions made concerning the release of the blowing agent during manufacturing, it can be considered that the results achieved for the Portuguese case study are plausible and can be used in LCA of building assemblies in the Portuguese context. It was also found that this type of methodology can be extremely useful in the critical review of EPD.

6.2.3.4. IM - Expanded Polystyrene (EPS)

NativeLCA is used in this case only for the comparison between LCA results for EPS production (A1-A3.3) of a Portuguese company (site specific data from a national LCA study, presented in Chapter 5) and MeVa and generic data sets. In this case, only two individual (from the French and *International* EPD systems) and one joint (a joint declaration from 24 European companies, available in the German system) EPD are available for EPS boards with characteristics similar to the one studied. A European MeVa was not calculated because it would be similar to the joint EPD that contributes with a share of 92% (24 out of 26 companies).

The results achieved in this thesis for the Product stage (A1-A3.3 see Chapter 5) of EPS boards were compared with the ones included in the three EPD, and the relative differences found for the three most important impact categories after normalisation are presented in Figure 6.28. This comparison was made considering the same thermal performance for the EPS boards represented by each data set (considering the thickness of each board necessary to achieve a thermal resistance of the layer of 1 (m^2.ºC)/W, taking into account the corresponding density and thermal conductivity). Concerning PE-NRe and GWP, it was found that EPD present figures between 14% and 53% lower than national results. Two causes can justify this difference:

- Raw material production (A1) has a share of more than 65% in both categories in the national results and this life cycle stage was modelled using the ELCD database (the most recent data set for this process – see Chapter 5). If other databases were used to model this process in the EPD, this may have caused the differences found (EPD do not declare the database used, except joint EPD that refers that raw material production was based on the literature);

- The manufacturing sub-stage (A3.2) has a share between 18% (in PE-NRe) and 25% (in GWP) in these categories. In the national case, these impacts are mainly due to the burning of naphtha in the boiler (e.g. 87% in GWP) to generate steam for the foaming process, which can be considered an "old" technology taking into account the age of this plant and of the equipment used in this process. Although no data is available in EPD concerning the fuels or the processes used to generate steam for foaming, it is probable that a more recent technology can have an improved efficiency both in terms of naphtha (or other non-renewable fuel) consumption and in terms of greenhouse gas emissions.

Concerning POCP, it was found that EPD present figures between 59% and 187% higher than national results. POCP are, in the national study, mainly (90%) caused by pentane and isopentane release during manufacturing (A3.2 – see Chapter 5). Due to the lack of site specific data concerning the percentage of the blowing agents that are released during this stage, it was considered that 30% of the quantity of these compounds initially included in polystyrene expandable granulate is freely released to the atmosphere during the gate-to-gate stage. This value was based on the Ecoinvent process for EPS (which was not included in this comparison because it corresponds to a board with twice the density of the one produced in Portugal) because EPD do not quantify this percentage, despite referring to it. Therefore, it is probable that EPD consider a higher percentage of blowing agents released during manufacturing stage.

Benchmarking of national results for EPS production was extremely important to verify the validity and check the plausibility of this LCA study. Despite the lack of detailed data concerning the technology for EPS production represented in each EPD, and the assumptions made concerning the release of the blowing agent during this stage, it can be considered that the results achieved for the Portuguese case study are plausible and can be used in LCA of building assemblies in the Portuguese context.

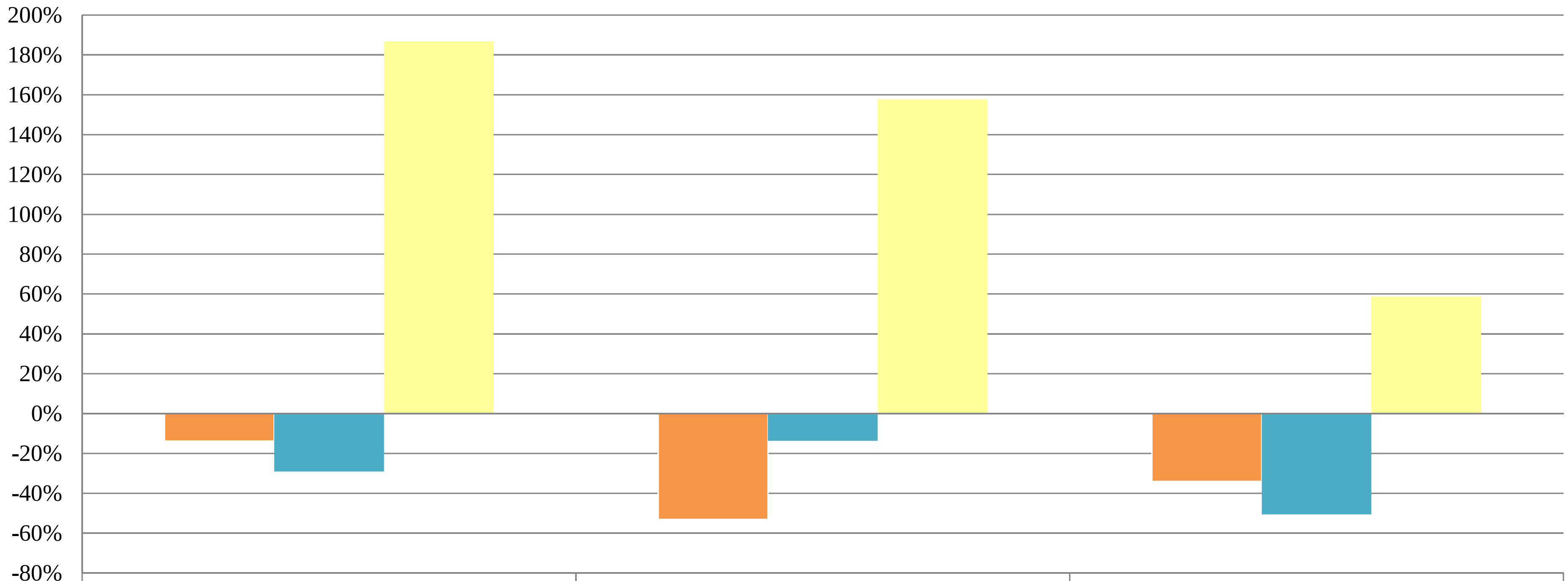
6.2.3.5. IM - Polyurethane/Polyisocyanurate (PUR/PIR)

This section presents the benchmarking of LCA results for PUR/PIR production of a Portuguese company (presented in Chapter 5) with generic and average data sets and individual EPD. In this case, one joint EPD (from the German system, including 8 companies), one European average (from PU-Europe – see Appendix 6.I) and two generic (one from Ecoinvent and another one from Plastics Europe - see Appendix 6.I, both not including the packaging of the boards) data sets are available for PUR/PIR boards with characteristics similar to the ones studied. A European MeVa was not calculated because the European average data set does not refer to the number of companies included in the corresponding LCA study.

The results from this thesis for the Product stage (A1-A3, not including the packaging material - see Chapter 5) of PUR/PIR boards were compared with the ones included in the referred data sets, and the relative differences found for the three most important impact categories after normalisation (see Appendix 5.I) are presented in Figure 6.29. Figure 6.30 shows a similar comparison, but only including the European average data set and the joint EPD because generic data sets do not refer to the density or the thermal conductivity of the boards studied. This comparison was made considering the same thermal performance for the PUR/PIR boards represented by each data set (considering the thickness of each board necessary to achieve a thermal resistance of the layer of 1 (m^2.ºC)/W, taking into account the corresponding density and thermal conductivity).

The results from this thesis (see Chapter 5) are very similar to generic data sets in NRe and in GWP (1-4% differences). However, the difference is higher in AP, generic data sets presenting an impact around 14% higher than national results. This difference can be explained by the higher content of isocyanate in the products considered in generic data sets (4% more, on average, when compared with Portuguese boards). In fact, this component has a contribution of 78% to AP within raw materials (see Chapter 5), but lower for GWP (66%) and for NRE (62%).

Concerning the European average data set and the joint EPD (PUE and IBU in Figure 6.29 and Figure 6.30, respectively), differences are not significant in the production of one kilogram of PUR/PIR boards for any environmental category when compared with national results (between 7% and 18%). These differences are even lower for NRe and AP when the comparison relies on the quantity of material necessary to achieve the same thermal performance (between 1 and 2%, which can be considered residual). This difference increases however in this second comparison for GWP, PUE and IBU presenting an impact 11% and 21% higher (respectively) than national production. This increase is mainly explained by the better thermal performance (thermal conductivity 30% lower) of the PUR/PIR boards produced in Portugal.



	INIES_192	ENV11	IBU5
NRe	-14%	-53%	-34%
GWP	-29%	-14%	-51%
POCP	187%	158%	59%

Figure 6.28 – Differences in PE-NRe (in orange), GWP (in blue), and POCP (in light yellow) in the production of EPS boards (A1-A3.3) with the same thermal performance between individual (INIES and ENV) and joint (IBU) EPD and national site specific data

There is a higher similitude of the national figures with the European average data sets, which are based on the production of a higher number of companies than the other data sets and have a higher geographical representativeness. The plausibility of the national LCA study of the production of PUR/PIR boards was verified through a benchmarking with European data sets of similar products. Given the low significance of the differences found, it can be considered that the results achieved for the Portuguese case study are plausible and can be used in LCA of building assemblies in the Portuguese context.

6.2.3.6. IM - Agglomerate of Expanded Cork (ICB)

Agglomerate of Expanded Cork (Insulation Cork Board - ICB) boards is an insulation material that is produced in Portugal and some other countries around the world. Portugal is, however, the world's largest producer and exporter of cork-based materials. There is yet no complete LCA study available worldwide concerning this insulation material apart from the one presented in this thesis, neither any environmental declaration. The LCA results presented in this thesis (see Chapter 5) are therefore original at an international level, in that no LCA data set was identified for very similar (nor similar) products (not even a generic one – see next paragraph). Thus, the option was to not apply the "simplified" version of NativeLCA in this case, but to consider the LCA results of the ICB boards for the LCA of building assemblies or buildings in the Portuguese context.

The extraction of the only raw material of ICB - "falca" - was modelled in this thesis using a process from Ecoinvent (Raw cork, at forest road/kg/RER, as referred in Chapter 5) that is based on data from Germany and Portugal extrapolated for Europe. This process is used in Ecoinvent to model the production of a "cork slab" that is "used as underlay for floating floorings or as insulation material". Data for the production of this cork slab was collected from a "major producer in Portugal", but it must be referred that cork "underlays" and ICB are produced in different plants using different raw materials. While the former use cork waste from cork wine stopper production agglomerated with resins, the latter use "falca" (the waste wood that results from periodical paring and pruning operations of cork oak trees (Sofalca, 2012)) and no additional admixtures or artificial resins. Therefore, the "cork slab" process of Ecoinvent corresponds to a mixture of production processes from different plants, their disaggregation being impossible to a practitioner without having access to the complete information concerning the data collection.

6.2.4. Claddings (ICS or ECS)

Two of the wall claddings chosen do not have LCA data available from any source (stabilised cement mortars and wood-plastic composite boards – see Appendix 6.II). The remaining wall claddings (ceramic tiles along with their adhesive, gypsum plasterboards, one-coat mortars and paints) are included in more than one database which express their environmental performance in production, construction, use stages and the benefits and loads beyond the system boundary.

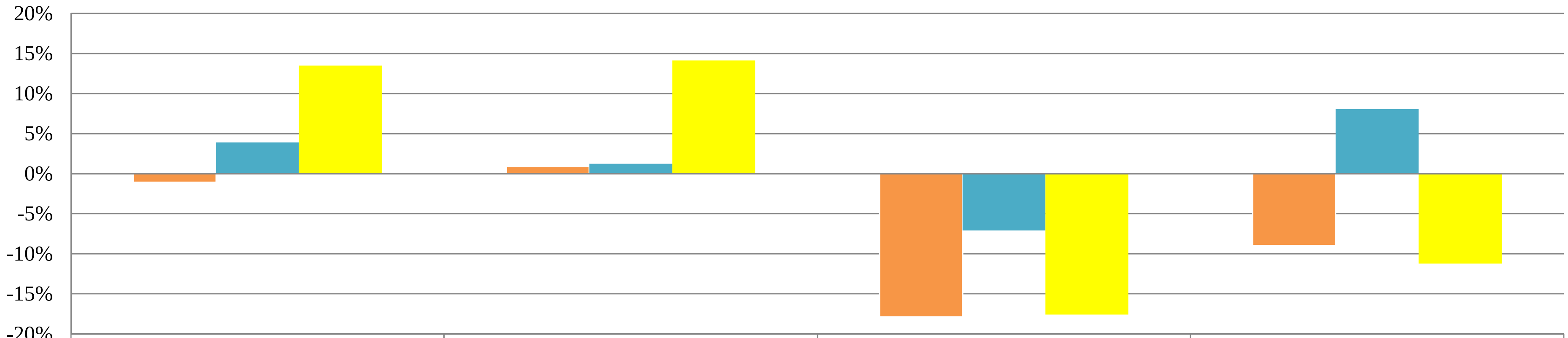
Section 6.2.4.1 exemplifies the application of NativeLCA in the choice of a LCA data set of paints to be used as generic data for the Portuguese context, namely for water-based and solvent-based for application as internal and/or external coating of walls. The next subsections include the application of a "simplified" version of NativeLCA in the verification of the plausibility of the LCA studies completed in the scope of this thesis for one-coat mortar, wood-plastic extruded boards, stabilised mortar, two-component adhesive and gypsum plasterboard.

6.2.4.1. Paints (data from previous studies)

Several types of paints are available on the European market. Paints are composed of mineral fillers, pigments, a binder or vehicle (e.g. oil or resin) and a volatile vehicle (e.g. water in water-based paints, solvent or diluent) and can be used as finishing layers of the inner or of the outer faces of external walls (Eusébio, 2003).

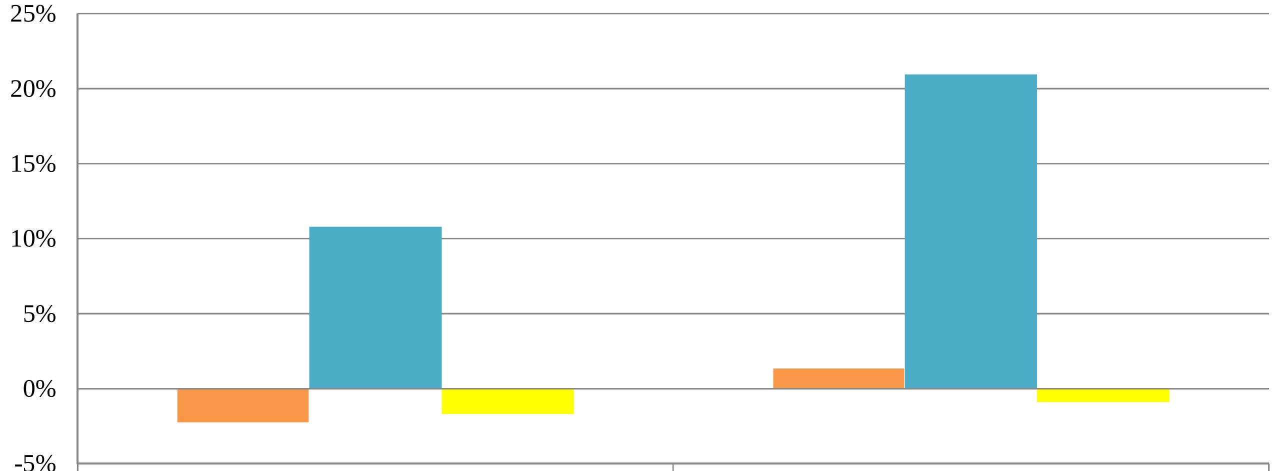
NativeLCA application should allow the selection of a LCA data set for each group of paints, namely water-based and solvent-based, for internal and/or external use. The first step of this methodology is the description of its aim and scope. The aim has been described and the scope is defined by:

- The functional unit of the study: the production of one kilogram of paint (because not all data sets declare the consumption per square metre and because generic data sets also use this functional unit in order to be used to model any type of paint);
- The characterisation of the construction material that will be the object of this study: different types of paints available in the European market, namely water-based and solvent-based for topcoat (finishing layer), for internal and/or external use;



	Eco_99	PE1	PUE1	IBU21
NRe	-1%	1%	-18%	-9%
GWP	4%	1%	-7%	8%
AP	13%	14%	-18%	-11%

Figure 6.29 – Differences in PE-NRe (in orange), GWP (in blue), and AP (in yellow) in the production of one kilogram of PUR/PIR boards (A1-A3, without including the packaging material) between national site specific data and generic (Eco and PE) and European average (PUE) data sets and joint EPD (IBU)



	PUE1	IBU21
NRe	-2%	1%
GWP	11%	21%
AP	-2%	-1%

Figure 6.30 – Differences in PE-NRe (in orange), GWP (in blue), and AP (in yellow) in the production of PUR/PIR boards (A1-A3, without including the packaging material) with the same thermal performance between national site specific data and a European average data set (PUE) and a joint EPD (IBU)

- The LCI flows and LCIA parameters (and corresponding EIAM) that will be considered: a normalization of LCIA impacts was conducted for Ecoinvent data to provide a first overview of the impacts in the six environmental categories selected. Figure 6.31 presents the environmental impacts after normalisation of the two types of paints available in this database. From this figure, it is concluded that ADP is the most important environmental impact of paint production in a European context, followed by AP and GWP. Therefore, PE-NRe, AP and GWP are used as a reference to apply NativeLCA methodology. PE-NRe is chosen instead of ADP for the reason stated in section 6.2.1.1;
- In this study, only the product stage (A1 to A3.1) is considered, taking into account the packaging of the paint because all data sets except Ecoinvent include information about the environmental impact of its production and use.

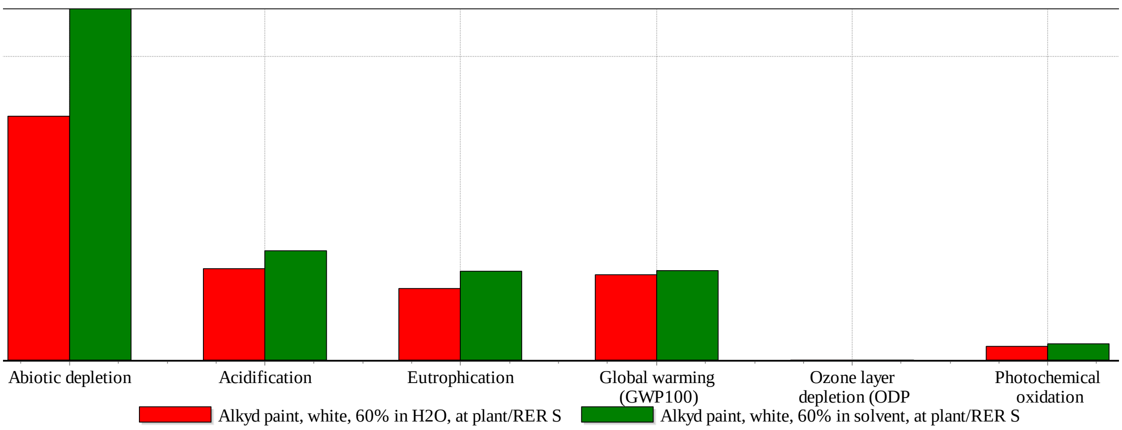


Figure 6.31 – Environmental impacts after normalisation (CML 2001 v. 2.05 and West Europe - 1995) of both paint production processes available in Ecoinvent (alkyd paints, water and solvent-based) generic database (the highest value of the chart is $2.31x10^{-12}$)

Table 6.21 identifies and quantifies available LCA data sets for paint production at the European level. Two French EPD were not considered because they correspond to an undercoat for inner walls and to one restoration paint for façades. Six individual and one joint EPD (all French) and two generic data sets (from Ecoinvent) are therefore considered to represent paint production at the European level. It is also important to characterise each of these data sets via meta data, which is presented in Table 6.22.

Table 6.21 – Available data sets for paint production

Product	LCA data sets						
	National (Portugal)			European			
	Site specific data from national LCA studies/ *individual EPD*	Joint EPD	National average LCA data sets	Individ-ual EPD	Joint EPD	Country specific or European average LCA data sets	Generic LCA data set
Cement	0	0	0	6	1	0	2

Table 6.22 – Meta data of each data set that provides LCA of paint production

Acronym	Ecoinvent	INIES
Designation of the database/*EPD Programme*	Ecoinvent version 2.2	*Programme de Déclaration Environnementale et Sanitaire pour les produits de construction*
Country	Switzerland	France
Type of LCA data set	Generic (2 types of paints – water-based and solvent-based)	Six individual and one joint EPD
Sampling procedure	Reference literature from Europe (solvent-based); one plant in Western Europe (consumption of energy) and reference literature from Europe (water-based)	One company in France (individual EPD); 25 French manufacturers (joint EDP, but not including the company from which individual EPD belong to)

Table 6.23 presents the meta data that are necessary to provide consistency verification of each data set, for both verifications, except for Ecoinvent ones (meta data for this data set is similar to the one presented in Table 6.8, but the market share is not declared in this case; the functional unit is also 1 kg of product but the consumption per square metre is not declared).

Table 6.23 – Meta data of each data set (for paints) that enables consistency verification

Characteristics	INIES
Methodology/*PCR followed*	*French standard NF P01-010*
Functional unit/consumption (kg/m^2)	1 m^2; 0.22 (two EPD), 0.25, 0.29, 0.36, 0.41 (individual EPD), 0.38 (joint EPD)
System boundaries	A1-A3.3
Cut-off rules	Mass criterion (max. 2% of the reference flow) according to the French standard (NF P01-010)
Allocation rules	Partitioning (energy, mass, economic)
Critical review/verification	No
Market share of average LCA data (%)	Not declared

From Table 6.23 it is concluded that:

- System boundaries from French EPD is not equal to Ecoinvent ones, because the latter do not consider packaging. Therefore, this limitation will be taken into account in the comparison between data set figures;
- The INIES data set was not subjected to external review.

Therefore, all data sets are consistent in what concerns assumptions, methods, models and data used for their calculation. The LCI flows and LCIA parameters provided in each data set (Table 6.2 and Table 6.3) are consistent within but not similar between data sets. Nevertheless, they are all in accordance with the goal and scope of this study (namely in terms of functional unit, of being paints available in the European market, of including the PE-NRe, AP and GWP, and of including the production stage, despite that the Ecoinvent data set does not include the packaging material).

A representativeness check has also been made according to the parameters summarized on Table 6.24. The following conclusions can be reached from this procedure:

- The Ecoinvent data set has European coverage, while INIES data sets are country specific;

- The production technology can be considered as “classic” in the European context for all data sets;
- The Ecoinvent data set is the oldest one (the inventory between 1995 and 2001) while INIES data sets resulted from studies made in the last five years;
- The Ecoinvent data set offers the possibility of modifying background data in order to provide “contextualization”.

Table 6.24 - Meta data of each data set (for paints) that enables representativeness verification

Characteristics	Ecoinvent	INIES
Geographic coverage	Reference literature from Europe (solvent-based); one plant in Western Europe (consumption of energy) and reference literature from Europe (water-based)	France
Technological representativeness	Common technology	Classic production processes of each plant
Energy and transport processes LCA data	Ecoinvent Hypotheses	AFNOR FD P01-015 Document
Temporal representativeness	1995-2001	2007-2008 (individual EPD); 2009 (joint EPD)
Possibility of background data “contextualization”	Yes (unit process data set)	No (aggregated data set)

Therefore, a “contextualization” was made to both Ecoinvent data sets (namely by changing the electricity production mix, from the Swiss to the Portuguese context) and only the “contextualized” values will be considered in the remaining sections of this study. After this step, all data sets were considered valid in terms of consistency and representativeness, even though some of them do not comply with some of the criteria defined. The criteria that were not complied with by each data set are shaded in grey in Table 6.23 and Table 6.24.

PE-NRe, AP and GWP have been chosen to be used as reference to apply NativeLCA methodology. From Table 6.3 it is concluded that INIES data sets include these LCIA indicators and are therefore suitable to be used in the quantification of mean values (MeVa) for these parameters.

The level of aggregation of data per life cycle stage in INIES data sets is similar (A1-A3.3 – see Table 6.23) and, therefore, they can be considered suitable to be used in the quantification of MeVa of PE-NRe, AP and GWP.

Considering the different types of paints in the sample and the corresponding applications (and the NativeLCA procedures - that consider the calculation of MeVa by application), four European (or foreign) MeVa were considered: two for solvent-based paints (inner and external) and two for water-based paints (inner and external). However, it was found that:

- All available non-generic data sets correspond to water-based paints, and therefore the only available data set for solvent-based paints is generic (Ecoinvent) and cannot be used in MeVa calculation (and it is not possible to calculate any MeVa for solvent-based paints);

- All available non-generic data sets are French, and therefore any European MeVa corresponds to a country-specific (French) MeVa;
- All individual EPD correspond to inner paints, and therefore only the joint EPD includes external paints (along with inner paints) - and corresponds to the European MeVa for water-based paints for external use.

Only European MeVa for water-based paints for inner use was calculated for PE-NRe, AP and GWP but in two steps: firstly, without considering the joint EPD (because it represents 25 companies, while individual EPD correspond to the same company), in order to have a preliminary overview of the average of individual EPD figures (European MeVa_int_wtt_SIPEV in Figure 6.32); then, the calculation was repeated taking into account all EPD, namely the joint one (corresponding to European MeVa_int in Figure 6.32), via an arithmetic mean according to the number of companies included in each data set (25 for the joint EPD and 1/6 for each individual EPD, as they all belong to the same producer) for each environmental indicator and for the same declared unit, because none of these data sets declare production volumes. A first overview of all data sets (including European MeVa_int_wtt_SIPEV and European MeVa_int and their standard deviations, Ecoinvent data sets “contextualized” for the Portuguese context - identified by the abbreviation “EI”, and joint EPD - SIPEV1_int_ext) is presented in Figure 6.32 for PE-NRe, AP and GWP for the production of one kilogram of paint.

The comparison between European MeVa for inner water-based paints (European MeVa_int) calculated in the previous step and generic data sets (Ecoinvent) is included in Figure 6.32. European MeVa has a small standard deviation because the joint EPD do not provide this parameter and the only source of variability is the difference between this document (with a weight of 25) and the six individual EPD (with a weight of one, as a whole). This was the main reason that led to the calculation of the average of individual EPD figures (European MeVa_int_wtt_SIPEV): the assessment of the variability of individual EPD and the comparison of its average with joint EPD figures (it was found from this comparison that joint EPD present values within the standard variation range of European MeVa_int_wtt_SIPEV).

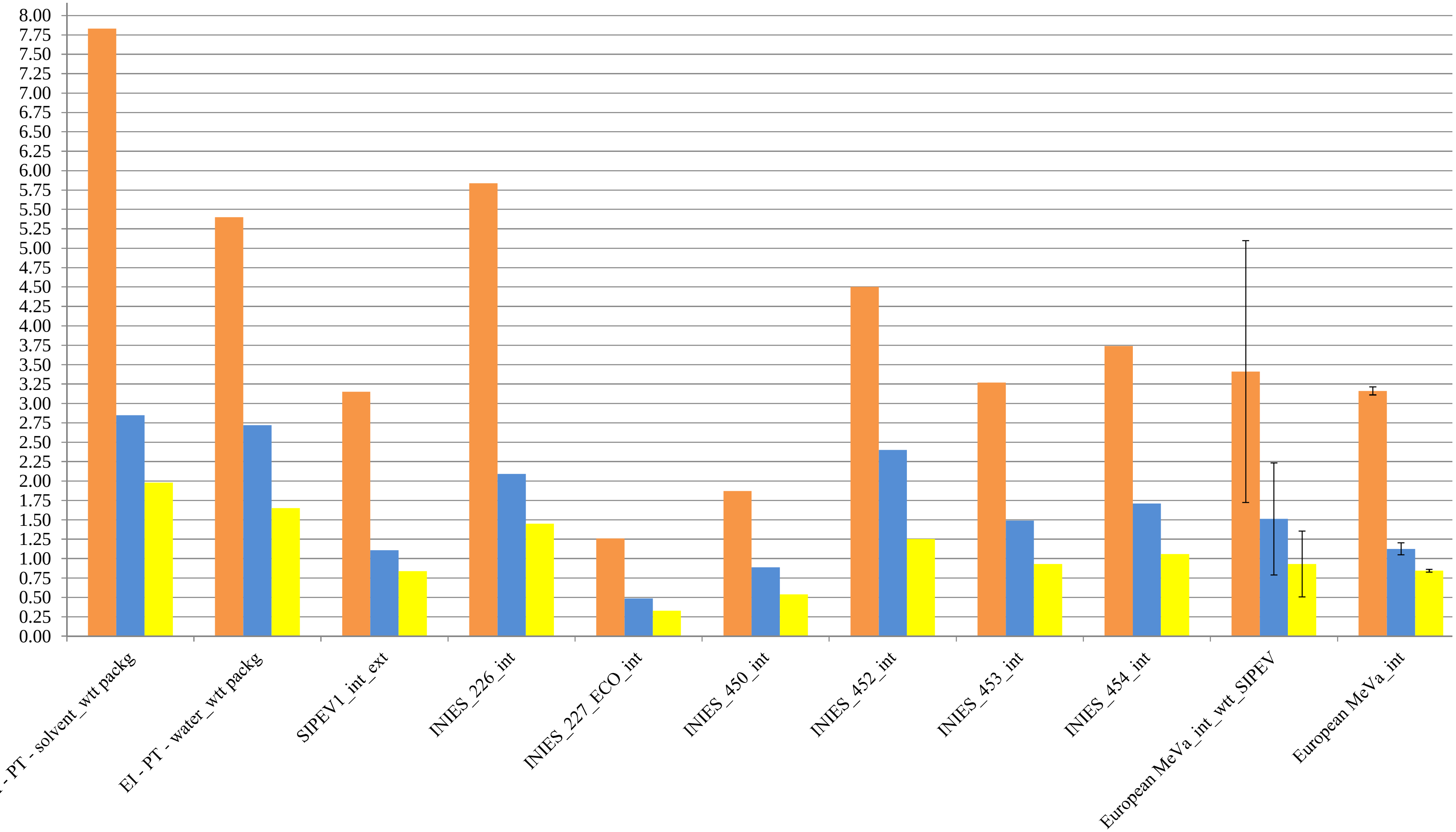


Figure 6.32 - PE-NRe (in orange, x10MJ), GWP (in blue, kg CO_2 eq), and AP (in yellow, $x10^{-2}$kg SO_2 eq) in the production of one kilogram of water-based paint from generic data sets (Ecoinvent – EI, which include the only data set for solvent-based paints: EI – PT - solvent), individual EPD (INIES), and joint EPD (SIPEV1)

Comparing European MeVa_int with the Ecoinvent data set for water-based paints (EI - PT - water), it is found that the latter has more than twice the impact of the former in GWP and AP, and almost twice in PE-NRe, despite not including packaging material. Ecoinvent data set figures are indeed higher than any non-generic data set in all impact categories, except one value of PE-NRe of an individual EPD (INIES_226_int). It is not possible to analyse these values per square metre of paint applied on the wall because Ecoinvent does not declare the consumption per square metre. Considering that the validity of this Ecoinvent data set (EI - PT - water) was not proven, and its lack of geographical and temporal representativeness (Table 6.24), it was decided to discard it at this step (but it still comes up in Figure 6.33 in order to demonstrate the relation between the impact categories chosen).

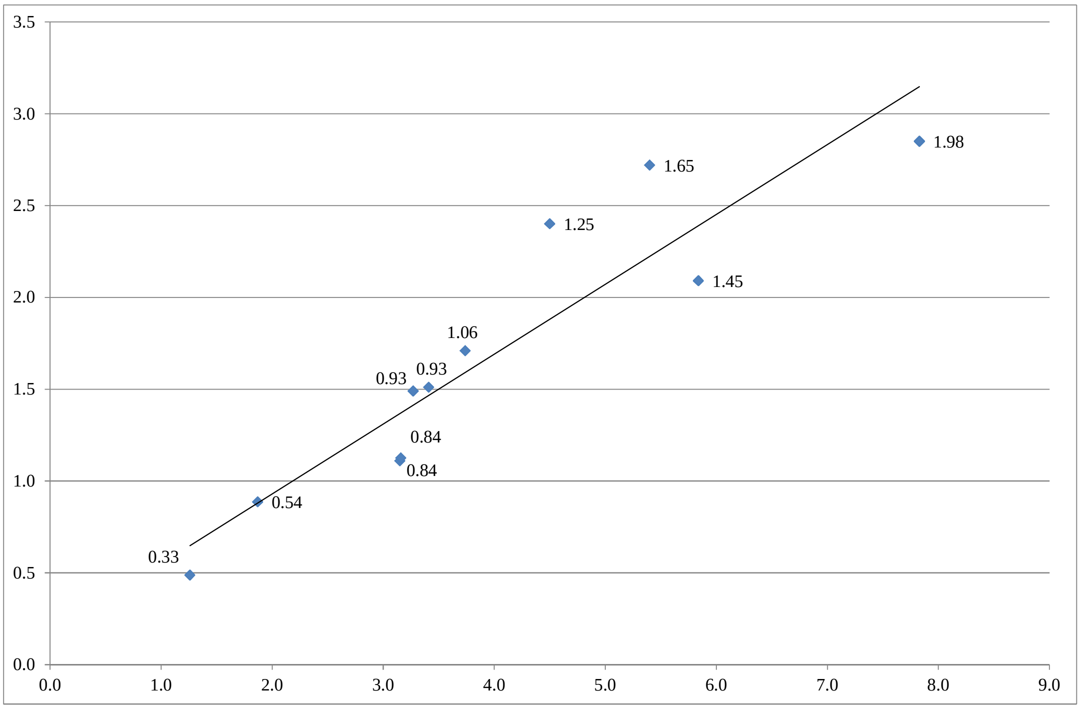


Figure 6.33 - PE-NRe (in abscissas, x10MJ) and GWP (in ordinates, kg CO_2 eq) in the production of one kilogram of paint, where each point is represented by the corresponding AP figures ($x10^{-2}$kg SO_2 eq)

The validity of some individual EPD - namely INIES_227 - is also put into question because of their low figures, despite that this specific paint is named "Eco". Therefore, a chart that expresses the relation between the impacts in each category was built. This chart is presented in Figure 6.33 and includes all data sets of Figure 6.32. This chart shows that there is an almost "linear" relationship between PE-NRe, GWP and AP in the production of one kilogram of each of the paints. This relationship can be expressed by the impacts from some "artificial" raw materials whose incorporation rate directly affects the environmental profiles of paints in all these impact categories. This relation is even expressed for Ecoinvent "contextualised" data sets for water-based and solvent-based paints (which correspond to the

"1.65" and "1.98" values, respectively). "INIES_227" (corresponding to the "0.33" value with lower AP) also expresses the enunciated relationship for all impact categories and it was considered adequate to maintain this data set in European MeVa because it was developed following the same procedures as the remaining EPD.

Considering the conclusions taken from the analysis made, European MeVa_int (which corresponds indeed to a French MeVa) has been chosen to be used as generic for the Portuguese context for the production of one kilogram of inner water-based paint (A1 to A3.1) for topcoat (finishing layer) with an average consumption of 0.38 (kg/m^2). A joint EPD has been chosen to be used as generic for the Portuguese context for the production of one kilogram of external water-based paint (A1 to A3.1) for topcoat (finishing layer) with an average consumption of 0.38 (kg/m^2) because it is the only data set available at a European level for this type of product. The "Contextualised" version of the Ecoinvent data set for solvent-based paints was chosen to be used as generic for the Portuguese context for the production of one kilogram of inner and external solvent-based paints (A1 to A3, without declared consumption per square metre) for topcoat (finishing layer) due to the same reason.

Table 6.25 summarises the decisions that have been made in each of the steps of the application of NativeLCA methodology to paint production.

6.2.4.2. <u>ECS - One-coat mortar</u>

NativeLCA is used in this case only for the comparison between LCA results for one-coat mortar production (A1-A3.3) of a Portuguese company (site specific data from a national LCA study, presented in Chapter 5) and foreign data sets. In this case, only a joint EPD (from the German system) is available for products with characteristics similar to the one studied (namely with similar application thicknesses and a thermal conductivity of 0.405 W/ (m.ºC), while the national mortar has 0.47 W/ (m.ºC)). This EPD corresponds to an average LCA data set that includes more than 20 types of one-coat mortars from four companies.

This document does not refer to the market share of each type of product but includes the packaging for all of them (in plastic and paper bags - similar to the product studied in Portugal, but also transport and delivery on-site into silos of a percentage of the product, the corresponding environmental impact being similar to the bags).

The results from this thesis for the Product stage (A1-A3.3 see Chapter 5) of one-coat mortar were compared with the ones included in the EPD, and the relative differences found for the three most important impact categories after normalisation are presented in Figure 6.34. This comparison was made per kilogram of product and shows that the German data set has lower results than the national study in GWP and AP (26% and 38%, respectively) but very similar in PE-NRe (higher by only 2%). These differences are in line with the ones found for stabilised masonry mortar between national results and also a joint German EPD (see 6.2.2.4, for which the differences for GWP and AP were 26% and 48%, respectively, for a similar composition). In this case, the percentage of cement in both products is very similar (with a difference of only 1% which, along with the similar share of secondary fuels used in clinker production, justifies the similar NRe figures) but the type and percentage of lightweight aggregates to achieve the same thermal performance is not. While the national product includes a mineral expanded aggregate in a very low percentage (and without significant environmental impacts –see Chapter 5), the German one considers 14% of lightweight aggregates from expanded glass, EPS or other materials. However, with the data available in the joint EPD, it is not possible to conclude about the influence of the environmental impacts of these aggregates in the differences found in GWP and AP. Therefore, the differences found in GWP and AP in this comparison can be justified by the similar differences observed in the same environmental categories between the LCA data set chosen to model cement in the building products studied in this thesis and European MeVa and CEMBUREAU data sets (see 6.1.5.9). However, this explanation requires the assumption that the environmental profile chosen to model cement in the German EPD is in accordance with European average figures, as it is done in the application of NativeLCA to the stabilised masonry mortar (see 6.2.2.4).

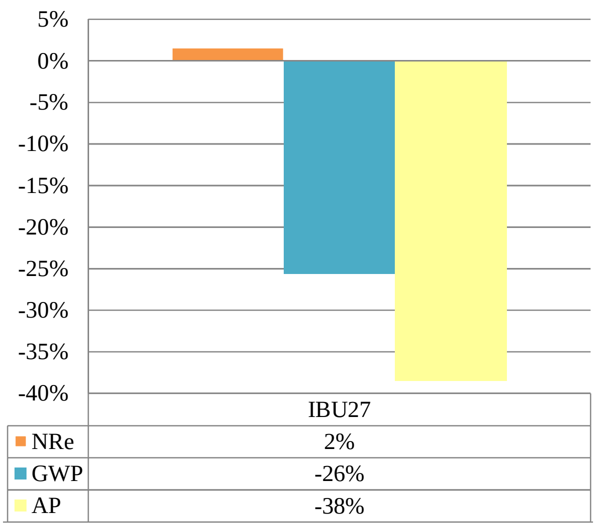


Figure 6.34 - Differences in PE-NRe (in orange), GWP (in blue) and AP (in yellow) in the production of one kilogram of one-coat mortar (A1-A3.3) between a joint EPD (IBU27) and national site-specific data

Table 6.25 – Summary of decisions made in each of the steps of the application of NativeLCA methodology to paint production (for topcoat - finishing layer)

Foreign data verification **Consistency and representativeness**	**Suitability to be used in the quantification of mean values (MeVa) for LCI and LCIA indicators and MeVa quantification (EPD and average data sets)**	**Data comparison within foreign data: MeVa vs generic data sets**	**Selection of a coherent LCA data set to be used as generic for a national context: NativeLCA**
Eliminated data sets: two French EPD were not considered because they correspond to an undercoat for inner walls and to a restoration paint for façades	Calculation of European MeVa for inner water-based paints, including packaging (A1-A3.1)	Generic data set (Ecoinvent data set for water-based paints) was discarded because of lack of geographical and temporal representativeness (Ecoinvent data sets were “contextualised” for the Portuguese context but are based on only one plant in Western Europe and on European reference literature) and because its validity was not proven (LCIA figures not concordant with European MeVa or EPD)	- European MeVa_int (with an average consumption of 0.38 kg/m2) for the production of one kilogram of inner water-based paint (A1 to A3.1) - Joint EPD (with an average consumption of 0.38 kg/m^2) for the production of one kilogram of external water-based paint (A1 to A3.1) - “Contextualised” version of Ecoinvent (without declared consumption per square metre) for the production of one kilogram of inner and external solvent-based paints (A1 to A3)

Therefore, it can be concluded that results are similar between data sets for the most important impact categories after normalisation and the plausibility of the national LCA study for one-coat mortar is confirmed, despite the limitations found in the available LCA data set of a similar product.

6.2.4.3. ECS and ICS - Wood-plastic extruded boards

Wood-plastic extruded boards are suitable for application in internal and external walls, and also in ceilings. At an international level, this type of board is also used in external decking. Cradle to gate LCA results of the production of one tonne of these boards and the relative contribution (in percentage) of sub-stages (A1-A3) for the same environmental impact categories was presented in Chapter 5. This complete LCA study can be considered original at an international level, given that no other has been found in reference literature nor within EPD programmes (for very similar, or similar, products). In fact, a recent study that compares alternatives for decking using LCA methodology, uses site specific LCI data for a wood-based decking, and uses literature data (plus assumptions and estimations, including omissions of some admixtures) for wood-plastic extruded boards, without collection of data at the corresponding manufacturing plants (Bolin & Smith, 2011). Again, the option was not to apply the “simplified” version of NativeLCA but to consider the LCA results of the wood-plastic extruded boards for the LCA of building assemblies or buildings in the Portuguese context.

6.2.4.4. ECS and ICS - Stabilised (wet and ready-to-use) masonry mortar

LCA results for stabilised masonry mortar production (A1-A3.3) of a Portuguese company (site specific data from a national LCA study) were presented in Chapter 5. NativeLCA methodology has been applied to this building product within the “Elements of wall structure” group (see 6.2.2.4), but it can be used further as an external render or internal coating. Therefore, this product is also considered in the claddings group. For the application as masonry mortar, only a joint EPD (from the German system) was found for products with characteristics similar to the one studied (see 6.2.2.4). However, in the case of the application in external render or internal coating, no LCA data set was found for very similar (nor similar) products (not even in reference literature) due to its particular characteristics. The LCA results presented in Chapter 5 can therefore be considered original at an international level for stabilised (wet) mortar applied as external render or internal coating. Thus, the option was not to apply, in this case, the “simplified” version of NativeLCA but to consider the LCA results of this product for the LCA of building assemblies or buildings in the Portuguese context. Nevertheless, NativeLCA methodology was applied in this chapter to cement (see 6.2.1.1), one of the most important components of stabilised mortar, and to the use of this product as masonry mortar (see 6.2.2.4).

6.2.4.5. ECS and ICS - Two-component adhesive

LCA results for two-component adhesive production (A1-A3.3) of a Portuguese company (site specific data from a national LCA study) were presented in Chapter 5. This cement-based adhesive can be used both for fixing all types of ceramic tiles and natural stone to walls, and laying indoor and outdoor paving. Both components of the adhesive - the powder (component A) and the resin (component B) - are sold separately and mixed on-site. Due to the particular characteristics of this product, no LCA data set was identified at the European level (not even in reference literature) for very similar (nor similar) products. The LCA results presented in Chapter 5 can therefore be considered original at an international level. Thus, the option was not to apply, in this case, the “simplified” version of NativeLCA but to consider the LCA results of the two-component adhesive for the LCA of building assemblies or buildings in the Portuguese context. Nevertheless, NativeLCA methodology was applied in this chapter to cement (see 6.2.1.1), one of the most important components of two-component adhesive.

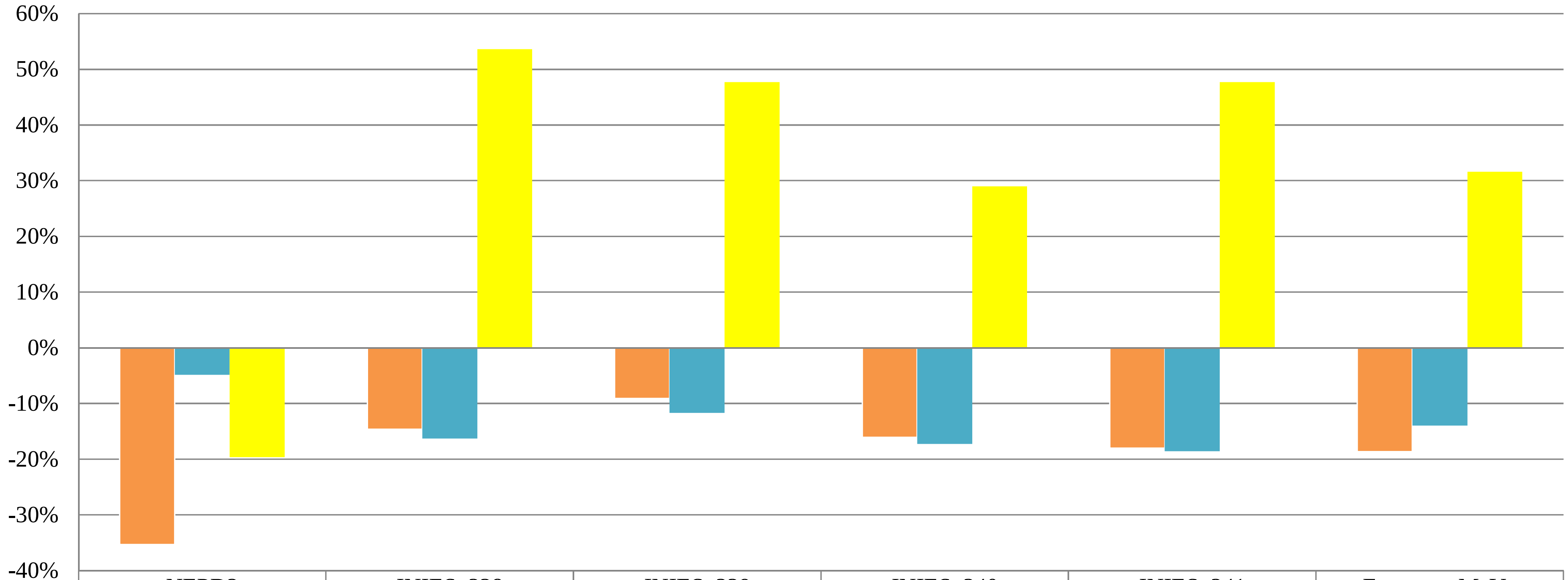
6.2.4.6. ICS - Gypsum plasterboard

This section presents the benchmarking of LCA results for gypsum plasterboard production of a Portuguese company (presented in Chapter 5) with generic and average data sets and individual EPD. In this case, five individual EPD (four from France, and one from the Norwegian systems) are available for gypsum plasterboards with characteristics similar to the ones studied (namely using gypsum as raw material that results exclusively from flue-gas desulphurisation (FGD)). A European MeVa was also calculated via an arithmetic mean according to the number of companies included in each data set.

The results from this thesis for the Product stage (A1-A3.3 see Chapter 5) of gypsum plasterboard (considering one kilogram as functional unit) were compared with the ones included in the five EPD and with European MeVa, and the relative differences found for the three most important impact categories after normalisation (see Appendix 5.I) are presented in Figure 6.35.

The data set that shows a higher difference from national results in PE-NRe in the production of one kilogram of gypsum plasterboard is the Norwegian EPD (- 35%), while European MeVa shows a lower difference in this category (- 19%). In Chapter 5 it was shown that the main contributors to PE-NRe (66%) in the national study are stucco slurry preparation and board drying. A deeper analysis reveals that natural gas consumption has a share of 77%, and electric energy the remaining part (23%), in the environmental impact of these two processes. Two causes can justify this difference: the lower quantity of natural gas spent in these two processes in foreign plants (or the use of other fuel); the use of an updated Portuguese electric mix (of 2011 – see Chapter 5) in the LCA of gypsum plasterboard studied in Portugal, which resulted in an increase of 92% in PE-NRe (and in a reduction of 25% and 50% of the GWP and of the AP figures, respectively) of the electric energy consumption. Meta data, and inventory flows quantified, in each EPD do not clarify if the first cause is plausible, however the second cause seems credible based on AP figures included in Figure 6.35. In fact, the majority of data sets (except NEPD) reveal a higher impact in AP when compared to national results, resulting in a difference of +32% for European MeVa. Again, the reduction in 50% of the AP of the electric energy consumption that resulted from the use of an updated Portuguese electric mix can contribute to this difference, along with the use of different fuels in the two processes already referred to (that contribute 34% to AP). These processes also contribute significantly to GWP (66%), even though the average difference of the data sets to the national figures is not significant in this impact category (-14%).

The plausibility of the national LCA study of gypsum plasterboard production was verified through a benchmarking with European EPD of similar products. Despite the lack of detailed data concerning the technology for gypsum plasterboard production represented in each EPD, the conclusions taken from the comparison made for the three most important impact categories after normalisation showed that the results achieved for the Portuguese case study are plausible and can be used in LCA of building assemblies or buildings in the Portuguese context.



	NEPD2	INIES_338	INIES_339	INIES_340	INIES_341	European MeVa
NRe	-35%	-15%	-9%	-16%	-18%	-19%
GWP	-5%	-16%	-12%	-17%	-19%	-14%
AP	-20%	54%	48%	29%	48%	32%

Figure 6.35 – Differences in PE-NRe (in orange), GWP (in blue), and AP (in yellow) in the production of one kilogram of gypsum plasterboard (A1-A3.3, including the packaging material) between national site specific data and individual EPD (Norwegian – NEPD, and French - INIES) and European MeVa

6.3. Conclusions and perspectives

This chapter proposes an innovative methodology for the selection of a coherent LCA data set of construction materials and products to be used as generic data for a national context: NativeLCA. This methodology is innovative mainly because of being: wide-ranging (none of the approaches identified in the state of the art considers all types of LCA data sets); straightforward in its application (not excessively time and resources demanding); focused on the final output, i.e. the selection of a LCA data set to be directly used by the practitioner, avoiding therefore inventory analysis and modification. This methodology was developed in the course of this thesis with the additional scientific supervision of Sébastien Lasvaux, from CSTB. The scope of NativeLCA was limited in this thesis by the construction materials and products used in a building’s external walls, but this methodology can be applied to other building products.

The application of this methodology to four case studies in its full form, and to eight in its “simplified” form, showed its feasibility, benefits, and limitations, while allowing for the identification of some potential improvements. The following limitations and potential improvements of NativeLCA methodology can be highlighted:

- Data from French EPD considered in this study was provided by SLCA, which is the only database that provides data from these documents disaggregated by life cycle stage. Therefore, the use of this data by other practitioners to apply NativeLCA from cradle to gate implies their access to SLCA;
- The different level of aggregation of LCA results *per* life cycle stages in available data sets can be one of the most significant barriers for their inter-comparison, avoiding therefore NativeLCA application;
- The case studies showed that generic data sets can be some types discarded, and not considered to be used as generic in a national context, because of their lack of geographical, technological or temporal representativeness, or due to their high “genericness” and wide scope;
- Many LCA data sets were not yet subjected to external review and the validity of their methodological procedures cannot be therefore confirmed;
- NativeLCA includes consistency and representativeness verification procedures which verify the meta data of each data set. However, the improvement of this methodology is advisable by creating of a Data Quality Indicator (DQI) to be assessed for each data set. The use of

DQI can provide a quantitative classification and corresponding ranking of available data sets in order to ease the choice of the ones that can be considered in NativeLCA.

Particularly, the application of NativeLCA to four case studies in its full form allowed for the selection of coherent LCA data sets for a construction material (cement) and building products not yet studied in the Portuguese context (or resulting from Portuguese LCA studies of other authors, but not all third-party verified) and revealed the whole potential of this methodology when no national LCA data set is available. In the application of NativeLCA in its “simplified” form, the aim was the verification of the plausibility of the LCA studies completed in the scope of this thesis. The results of these studies can therefore be used in LCA of building assemblies or buildings while external verified LCA databases (e.g. based on EPD) are not available at a national level. In fact, in terms of geographical and technological representativeness, it is preferable to use national LCA results of construction materials and products from traceable, referenced and verifiable sources (and from studies complying with international LCA standards) than foreign EPD or generic LCA data sets (even when the latter are third-party verified).

NativeLCA relies on the selection and/or adaptation of LCA data sets of construction materials and products (generic, average, EPD or site specific) available in the European context to be used as generic for a national context. The aim of achieving generic data adapted to a specific geographic context is to provide robust results that can be used in simplified LCA or early design assessment of buildings, for example, while individual EPD can be considered in the following design stages. NativeLCA can also be used as a research tool to answer some of the questions raised by practitioners concerning the coherency of the LCA data to be used to model a building in a national context, namely when several LCA databases are available for the same material. Thus, most of the pitfalls they find in this activity can be avoided (Lasvaux et al., 2011). This kind of scientifically-based aid to decision-making is also useful to LCA practitioners in EPD development or critical review (to select a data set for background processes in the first case, or to check the plausibility of final results in both cases), as it was proven in the applications of NativeLCA presented in this chapter.

6.4. References - Chapter 6

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7. ENVIRONMENTAL, ENERGY AND ECONOMIC ASSESSMENT OF EXTERNAL WALLS OF BUILDINGS FROM CRADLE TO CRADLE (3E-C2C)

7.1. 3E-C2C method

A building's design process is iterative and involves many decision stages. When a component, namely a construction material or assembly that is closely related to a building's thermal performance, has to be chosen, it is necessary to compare available alternatives by using a method that allows:

- The comparison of alternatives that comply with all the requirements (e.g. legal rules or regulations and the building's geometry) but are not functionally equivalent (e.g. that do not have the same thermal performance), without having to change their characteristics to make them comparable (e.g. changing the insulation thickness);
- The quantification of different aspects (e.g. environmental, economic and energy) of the performance of the alternatives in each stage of their life cycles, and also from cradle to cradle, in accordance with the Life Cycle Assessment (LCA) International Standards and with recent European standards related to the assessment of construction work sustainability;
- The simultaneous comparison of all these aspects of the performance of the alternatives, generally by using suitable weights for each aspect (since the designer usually cannot - or does not know how to - define them).

Such an integrated approach has not yet been developed, and so this thesis proposes an innovative method that satisfies all these requirements and answers the needs of the building's designer. This method provides an assessment of the environmental, energy and economic (3E) life cycle of construction materials or assemblies - closely related to a building's thermal performance - from cradle to cradle (3E-C2C). The 3E *cost*-C2C method enables the definition of appropriate weights for each aspect of the assembly's performance and their quantification, using the same unit. The applications already undertaken in the scope of this thesis of the 3E-C2C method (i.e. case studies of selection of an external wall and corresponding insulation thickness from several alternatives, corresponding to two papers submitted for publication in journals included in ISI-Journal of Citation Reports and presented in their present form in Appendixes 7.I and 7.II (Silvestre, J. D. *et al.*, 2011a; Silvestre, J. D.; de Brito*; et al.*, 2012b)) allowed its validation and calibration, and confirmed its suitability, resulting in the improvement and refinement of each of its modules and steps. However, the 3E-C2C and 3E *cost*-C2C approaches should both be used in the choice of other construction materials or assemblies also closely related to a building's thermal performance to aid in their continuous development.

This section sets out the scope and modules of 3E-C2C and 3E *cost*-C2C, including an appraisal of similar approaches. An example of the method's application and the results are presented afterwards, and the resulting figures are analysed in the discussion section.

7.1.1. 3E assessment

Kloepffer (2008) proposes a life cycle sustainability assessment (LCSA) scheme for products based on the following formula: LCSA = LCA + LCC + SLCA. For this approach the LCA should comply with ISO standards (ISO, 2006c, 2006d), the LCC is an LCA-type ('environmental') life cycle costing assessment and SLCA stands for social LCA, but this paper does not draw conclusions about the weighting of the three pillars of sustainability. Although SLCAs are beyond the scope of this thesis, the approach proposed by Kloepffer (2008) to sum various pillars of sustainability includes some prerequisites that have been taken into account in the method proposed in this chapter (Ciroth & Franze, 2009; Kloepffer, 2008), viz.:

a) The functional unit and system boundaries of each one of the 3E assessments should be identical, or at least consistent; one option is to use the same LCI and establish a similar goal and scope;
b) Each assessment should be life cycle-based and include the whole life cycle (i.e. cradle to grave) to avoid trade-offs between life cycle stages;
c) LCC should avoid any monetarisation of external costs related to potential environmental damage (which should be considered only in LCA) in order to avoid double counting.

In fact, it is important to use LCA for decision-making at the design stage, although it should be supplemented at least by a whole LCC which addresses the economic element of sustainability (Ciroth & Franze, 2009). This is even more important for "green" products and services which usually have a greater acquisition cost but can represent a cheaper solution for the entire life cycle (Kloepffer, 2008). Decision-making that takes these two aspects into account is increasingly important in building design and public procurement (Gervásio, 2010). Even though it is generally agreed that the third aspect of sustainability (which concerns socio-cultural issues such as welfare, health, safety and comfort) should be included so as to provide an overall assessment of a building or of one of its parts, namely because they can lead to choices that contradict the best alternatives in environmental and economic terms. However, there is not yet a similar agreement on the assessment of these issues in construction products due to their fuzzier nature (Gervásio, 2010); this third aspect was therefore not included in the method proposed here.

In Europe, the “Energetic certification of buildings” (EC, 2002) has already had positive consequences, not only in terms of the thermal performance of the buildings. In Portugal, for example, it is already possible to establish a direct relationship between the energy class and the quality of construction. With the minimisation of carbon emissions resulting from the use of buildings, namely due to the progress towards low energy buildings, the relative importance of a building’s life cycle stages is changing ((Blengini & Carlo, 2010) cited by (Peuportier *et al.*, 2012)). Thus, the measures to control and reduce the environmental impacts of the entire production chain of construction have become a priority. For this reason, it is time to begin determining the “carbon invoice” of the production of construction materials and construction of buildings (Machado, 2009). As soon as this determination has credible and statistically significant data, the theoretical “carbon invoice” can become a real environmental tax to be applied to new constructions (and may be an incentive for rehabilitation works).

Even though the European building industry has energy efficiency as its most recent priority, in a desirable future it will be possible to evaluate a building, and make its energetic certification via a balance of the environmental impacts of its materials in its whole life cycle (as it was proposed in Italy (Campioli & Lavagna, 2007) and in Spain (Bribián *et al.*, 2009), and is recommended by the German Government (DGNB, 2011)). To fulfil the ISO 15392 general principle "holistic approach” (ISO, 2008b), the sustainability assessment of a building must represent a part of an assessment of integrated building performance (Ilomäki et al., 2008a, 2008b).

The European standards recently compiled by the Technical Committee (TC) 350 of the European Committee for Standardisation (CEN/TC 350 - Sustainability of Construction Works, described in detail in Chapter 2) for the sustainability assessment of buildings and construction products have been structured along three lines (framework, building, and product) and three columns (environmental, social, and economic), but always taking technical and functional performance characteristics into account. This harmonised European system allows for the assessment of the environmental, economic and social performance of buildings based on a life cycle approach, and its guidelines for environmental and economic assessment were followed when developing the method proposed here. The novel nature of these standards means their applications are not yet significant, even during their development. A detailed review of the LCA results of more than 10 years of international research studies on the external walls of buildings, completed in the scope of this thesis (see Chapter

2 and (Silvestre, J. D. *et al.*, 2010)), found that only 13 (21%) of the studies explicitly mention that they followed the method described in the LCA International Standards, but none of them refer to the use of the approaches set out in the relevant European Standards.

7.1.2. Appraisal of the available methods for 3E assessment of building assemblies

The external walls of a building highly influence the 3E performance of the building envelope (as referred in detail in Chapter 2). The 3E impacts of each external wall solution result directly from the technical and functional characteristics of its components (e.g. initial embodied energy and thermal properties). Therefore, it is of paramount importance for the building's designer to have a method at hand for comparing alternative external wall solutions of a building (or of other main building components) and for choosing the most economically and environmentally (including energy) advantageous one. Methods that partially answer this need are described next, and their main characteristics are summarised in Table 7.1.

Table 7.1 - Impacts and life-cycle stages considered in methods for the environmental, economic and energetic assessment of building assemblies (economic issues are underlined)

Country	Method	Life cycle stages				
		Product stage	Transportation to the building site	Use stage		End-of-life
				Energy use for heating and cooling	Maintenance, repair and replacement	
China	(Gu, L. *et al.*, 2008)	Initial economic and carbon cost		Economic and carbon costs	Economic and carbon replacement costs	-
European Union	Recast EPBD	Construction and energy costs			-	
France	(Peuportier *et al.*, 2012)	LCA		Operational energy	LCA	
Lithuania	3 E factor	Energy consumption, environmental pollution (CO_2 emissions) and expenses			Energy consumption and expenses	-
New Zealand	NZ calculator	LCA and initial cost		Thermal performance	LCA	-
Portugal	(Monteiro, 2010)	LCA				-
Spain	Simplified LCA	EPD (total primary energy and CO_2 emissions)	-	Total primary energy and CO_2 emissions	-	
United Kingdom	Project 'Butterfly'	Life cycle cost, and operational energy and embodied carbon cost				-
USA	(Pierquet *et al.*, 1998)	Embodied energy	-	Thermal performance	-	

In Spain, a simplified LCA method has been proposed for inclusion in the energy certification of buildings. It uses the Environmental Product Declarations (EPDs) of construction materials that are already available (Bribián *et al.*, 2009) for the product stage, and also considers the operational energy use (for heating, cooling and hot water). The final results give the total primary energy and CO_2 emissions of these two stages.

Project ‘Butterfly’ in the United Kingdom involved consulting companies and Universities to create a software tool to calculate life cycle cost and maintenance, operational energy and embodied carbon cost (http://www.blpinsurance.com/sustainability/butterfly/) that will be marketed by the end of 2012. The life cycle cost method follows ISO 15686-5 (ISO, 2004a) and energy and carbon costs are calculated as described in the CEN/TC 350 group of standards. Operational energy and embodied carbon (including the product and use stages) costs are estimated using a given carbon value. The aim is not to compare the different options in building design element by element but to reach conclusions on the impact of these options on the economic and energy performance of the whole building.

An optimisation method (3E - energy, economic and ecological - factor) to minimise the energy costs, environmental pollution (i.e. CO_2 emissions) and expenses during the life cycle of a single-family house was developed in Lithuania. It was used to optimise the thermal insulation, using the same weight for all three aspects. The energy used and the cost of production of the insulation material and its transportation to the construction site, the cost of building construction, renovation, and heating (comparing alternative technologies) were taken into account, along with the cost associated with all these activities and products. The ecological performance includes the CO_2 emissions (taken from literature and without describing the type of insulation material) during the production of the insulation material and arising from heating the building, but the authors state that “in an ideal case the emissions of all pollutants should be taken into account” (Rogoža *et al.*, 2006).

A combined evaluation of thermal performance and LCA was completed in France for two attached single-family houses. This evaluation compares a reference design with a “passive house”-compliant design, and it also compares two types of occupants’ behaviours (economical or spendthrift) for each design alternative. LCA included the product stage, the transport to site, and the corresponding application of the materials to build the whole house, using generic data sets from Ecoinvent partially contextualized for the French context. This assessment considered several environmental impact categories and also included the maintenance of the building (during 50 or 100 years) and its end-of-life impacts. However, the latter life cycle stage was modelled in a simplified manner by assuming landfill as the destiny of all demolition waste. A final comparison is provided between the energy required for product, maintenance and end-of-life stages, and the operational energy for air and water heating, ventilation and other appliances (Peuportier *et al.*, 2012).

In Portugal, the LCA of a house was calculated for seven alternative exterior wall solutions with similar thermal transmittance, and seven heating systems. This study included the production phase and the heating energy and maintenance requirements for 50 years (Monteiro, 2010).

A methodology to identify optimal performance levels of building elements that only covers construction and energy cost optimisation is proposed in the Recast of the European Energy Performance of Buildings Directive (EPBD) of 2010 (EC, 2010). This approach is insufficient since it disregards environmental aspects of the building element in the life cycle analysis that leads to a “cost-optimal level” (Silvestre, J. D. *et al.*, 2011a).

In the USA, a research study included the calculation of the embodied energy and thermal performance (for 30 years) of twelve external wall solutions for a building in a cold climate region (Pierquet *et al.*, 1998). In China, five façade solutions for an office building were compared in terms of their operational energy consumption (cost and carbon dioxide emissions for 50 years), life cycle environmental load (carbon cost), life cycle cost, green payback time and general payback time (Gu, L. *et al.*, 2008; Gu, L. J. *et al.*, 2007).

A calculator of the thermal resistance and environmental impact of external walls (only for low-weight wood solutions) was developed in New Zealand (Kellenberger, 2008, 2010). The LCA study of the walls used the Ecoinvent database, considering the same thermal resistance for a 50-year service life, but excluding the construction and the demolition of the building and the operational energy. The final user of this tool can find the environmental impact of alternative solutions for external walls for buildings, along with their initial cost.

This review shows that some of the methods only consider the environmental performance (two out of nine (Monteiro, 2010; Pierquet *et al.*, 1998)) and one only considers the economic performance (EC, 2010). There are three methods that only consider carbon emissions (or related costs) within the environmental impacts, along with the LCC ((Gu, L. *et al.*, 2008; Gu, L. J. *et al.*, 2007; Rogoža *et al.*, 2006) and Project Butterfly). The method developed in New Zealand (Kellenberger, 2008, 2010) covers both the LCA of the production and maintenance stages and the initial cost of each assembly. Therefore, none of these methods quantifies the performance of the alternatives, in all three aspects (i.e. environmental, economic and energetic), in all stages of their life cycles, either from cradle to cradle or from cradle to grave (despite one that includes the end-of-life stage but only for LCA

(Peuportier *et al.*, 2012), see Table 7.1). To fill this gap, the 3E-C2C approach is proposed in this thesis which is therefore innovative at an international level and allows the appraisal and comparison of construction materials and assemblies that are closely related to a building’s thermal performance. It considers their whole life cycle (C2C) by assessing the 3E’s (environment, energy and economy) impacts and taking into account all the factors that could affect them, such as the performance of the assembly in the use phase of the building, and its service life and recycling potential (Table 7.2).

Table 7.2 - Impacts and life-cycle stages (see section 7.1.3) of an assembly in each module of the 3E-C2C approach

3E-C2C module - assembly performance	Product stage (A1-A3)	Transport to the building site (A4)	Installation in the building (A5)	Use stage		End-of-life stage - transport, processing and disposal (C2-C4), and reuse, recovery and/or recycling potential (D)
				Maintenance, repair and replacement (B2-B4)	Energy use for heating and cooling (B6)	
Environmental	LCA					
Economic	Initial cost			Costs	-	Costs
Energy	-				Costs	-

7.1.3. Scope - system boundaries

The boundaries of an LCA study of a building material or assembly can be defined either from cradle to gate (including the extraction and processing of raw materials and the production), from cradle to grave (including also the transportation, distribution and assembly, use, maintenance and final disposal), or from cradle to cradle (C2C) (also including the reuse, recovery and/or recycling - 3R - potential) (Table 7.3, which summarises Tables 4.1 and 4.2) (Ferrão, 2009; Ortiz *et al.*, 2009).

The detailed review of the LCA results of a building’s external walls completed in the scope of this thesis has shown that all the studies include the production of the construction materials and the majority of them (63%) evaluate the embodied energy of each external wall. However, only a third include the end-of-life of the building assembly and just 42% include the construction, operation and maintenance stages (see Chapter 2 and (Silvestre, J. D. *et al.*, 2010)). Therefore, the end-of-life stage has to be studied in detail, namely its environmental impacts and the 3R potentials of reusable and recyclable products (see 7.1.5.5 and Appendix 7.III). Even though the avoided impacts at this stage are very uncertain, their quantification allows efforts towards “design for dismantling” to be rewarded (Peuportier *et al.*, 2011). The application of the C2C perspective in LCA of construction materials is also necessary to create cyclic metabolisms (Braungart & McDonough, 2009; Farrall, 2010). These conclusions motivated the selection of a C2C approach for the 3E-C2C method.

Table 7.3 - Detailed life cycle stages of building materials classification based on European standards (adapted from (CEN, 2012; Silvestre, J. & Lasvaux, 2012); modules included in 3E-C2C are underlined)

LCA boundaries			**Life cycle stages / *LCA information modules***	**Life cycle stage designation and description**	
Cradle to cradle	**Cradle to grave**	**Cradle to gate**	Product stage (A1-A3)	A1	Raw material extraction and processing, processing of secondary material input
				A2	Transportation to the manufacturer
				A3	Manufacturing
		Gate to grave	Construction process stage (A4-A5)	A4	Transportation to the building site
				A5	Installation in the building
			Use stage - information modules related to the building fabric (B1-B5)	B1	Use or application of the installed product
				B2	Maintenance
				B3	Repair
				B4	Replacement
				B5	Refurbishment
			Use stage - information modules related to the operation of the building (B6-B7)	B6	Operational energy use
				B7	Operational water use
			End-of-life stage (C1-C4)	C1	De-construction, demolition
				C2	Transportation to waste processing
				C3	Waste processing for reuse, recovery and/or recycling (3R)
				C4	Disposal
			Benefits and loads beyond the system boundary (D)	D	Reuse, recovery and/or recycling (3R) potentials

The boundaries of the 3E-C2C method include the life cycle stages and/or processes affected by the external walls (i.e. material production and transport, heating and cooling, and maintenance operations - see Table 7.2), but do not include the 3E impacts of activities during the use stage that are not affected by the exterior wall solution. In fact, the 3E impacts of electricity consumption by the technical building systems for heating and cooling are considered in the operational energy use stage (B6), but consumption by electric appliances, lighting, cooking, and domestic hot water (CEN, 2012) is not considered.

7.1.4. Scope - functional or declared unit

The stricter application of the LCA approach to building assemblies is difficult because of the amount of data in its processes. This makes the definition of a functional unit (which is a service as well as a product), the boundary of the assessment and the databases to be used (see Chapter 6) even more important, since they lessen the sensitivity and errors of the results (Erlandsson & Borg, 2003; Ozik, 2006).

The functional unit is usually directly linked with the functions or performance characteristics of the products and is defined in a way that it provides a reference that enables a construction product's LCA results to be expressed with a common basis (CEN, 2012). Therefore, the functional unit for an LCA of a building's external wall can be defined as 'a square metre of external wall for 50 years’, given that this is the service life considered for a building at the design stage. However, a functional equivalent must be established at the design stage so that the alternatives can be compared, with particular reference to the external walls of a building. This concept is defined as “the quantified functional requirements and/or technical requirements for an assembled system for use as a basis for comparison” (CEN, 2012; ISO, 2010). Following this definition, LCA studies usually use “a square metre of external wall with a given heat transfer coefficient for 50 years” as the functional equivalent for the comparison of alternatives for the external walls of a building (Monteiro & Freire, 2012). This creates a serious limitation for the designer because each solution has to be adapted to have the same heat transfer coefficient, usually by changing the thermal insulation thickness, to make them comparable. This approach also results in the rejection of innovative or less-often used alternatives such as precast concrete with rigid insulation foam placed in the core (e.g. sandwich panels - see Figure 3.8), or ceramic or lightweight concrete blocks of high thickness and void content (see Figure 3.27), which sometimes do not need an insulation panel in the external wall. This limitation was circumvented by means of an approach that allows the comparison of two or more assemblies with selection of the best alternative, even if they are not functionally equivalent. This is possible by just taking ‘a square metre of external wall for 50 years’ as the declared unit for the comparison, do not considering a functional unit, and taking into account the use and end-of-life stages and the reference service life of each alternative. It is possible to compare external wall solutions with different heat transfer coefficients using this approach because the environmental impacts of their relative thermal performance for 50 years (the chosen study period) is also considered in the LCA study, along with the production impacts related to the choice of the corresponding relative thermal insulation thickness.

7.1.5. Environmental performance

The environmental performance quantification from cradle to cradle of the 3E-C2C method follows the LCA standardised method (based on ISO 14040:2006 and ISO 14044:2006 International Standards (ISO, 2006c, 2006d)) and most of the principles already included in the draft standards FprEN 15643-2:2010 (CEN, 2010a) and FprEN 15978:2011 (CEN, 2011a) “Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method”, such as the following ones:

- The assessment of the environmental performance shall apply the LCA approach in accordance with the guidelines and requirements of ISO 14040:2006 (ISO, 2006d);

- The results of the assessments shall be organized in three main groups (Table 7.3): impacts specific to building fabric and site (results from the product stage and from the construction process stage - A1-A4), impacts and aspects specific to the building in operation (maintenance, repair and replacement, and energy use for heating and cooling - B2-B4, and B6) and results from the end-of-life stage of the building (C2-C4 and D);
- The quantification of the impacts of operational energy (B6 sub-stage) is a direct result of the calculation of the energy used during the use stage of the building according to the EPBD (EC, 2002) and shall be derived from different energy carriers or LCA databases;
- The impacts and aspects related with benefits and loads beyond the building life cycle, e.g. those that result from further reuse, recycling potential and energy recovery and other recovery operations, are also included as supplementary information (D stage). They are essential in promoting and allowing a C2C approach in the life cycle of the buildings and corresponding assemblies;
- The default value for the reference study period shall be the required service life of the building and the estimated service life of the assemblies shall take into account rules and guidance included in the standards ISO 15686-1,-2,-7 and -8 (ISO, 2000, 2001, 2006a, 2006b).

The use of a standardised procedure in environmental assessment allows for LCA results from different studies to be compared and be used to make meaningful choices (Ekvall, 2005; Krigsvoll et al., 2007).

The LCA results of the “Product stage” (A1-A3) of each construction product were presented in Chapters 5 and 6. The remaining stages of their life cycles are characterised, assessed and evaluated in this chapter based on scenarios, according to the procedures described in Chapter 4 (and taking into account the “Main environmental impacts in each phase of the life cycle of building products” summarised in section 4.2.2). In fact, in LCA of construction products, the information related to all the stages after the production (B, C or D) shall be based on scenarios. These scenarios, according to European Standards, have to be built and assessed using generic LCA data “as realistic as possible and properly documented (covering the present or anticipated situation), rather than idealistic or “carefully selected” (CEN, 2010b). The assumptions made in each stage must be inter-related, because, for example, construction process scenarios are important not only for the construction stage, but also for the use and end-of-life stages. Scenarios describing the end-of-life stage (downstream processes) must reflect the existing technology, current regulations, today's average practice and a mix of different end-of-life treatments available at the national or regional level (CEN, 2010b).

7.1.5.1. Product stage (A1-A3)

The LCA of the production of each construction material or product (cradle to gate approach that corresponds to the “Product stage” (A1-A3)) result either from the studies completed in national plants in the scope of this thesis (see Chapters 4 and 5, the description of the manufacturing of each product being presented in Section 4.3 and the corresponding LCA results shown in section 5.4.3) or from the application of NativeLCA in the selection of coherent LCA data sets to be used as generic data in the Portuguese context (see Chapter 6).

7.1.5.2. Construction process stage (A4-A5)

The construction stage includes the transport from factory gate to the construction site (A4), the on-site storage of products, the wastage of construction products (CW in Figure 7.1), and the processing of product packaging and product waste (A4-A5). The installation of the product in the building includes the manufacture and transportation of ancillary materials and any energy or water required for installation or operation of the construction site (A5) (CEN, 2012). The 3E-C2C method considers the environmental impacts of all these activities, except any energy or water required for installation or operation of the construction site due to their variable and unpredictable nature.

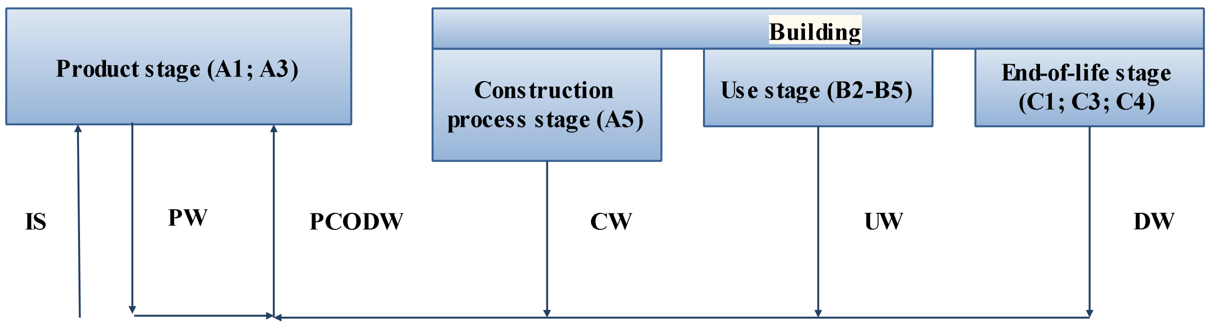

Figure 7.1 - Construction and demolition waste input and output flows (IS – Industrial Symbiosis) (Silvestre, J. D.; de Brito*; et al.*, 2012a)

7.1.5.3. Use stage - maintenance, repair and replacement (B2-B4)

This stage concerns the quantification of the environmental impacts of the materials used in maintenance, repair and replacement operations over the life cycle of the assembly (in the year that they occur, according to Appendix 7.IV), including the corresponding waste flows (UW in Figure 7.1). However, this module does not include other impacts from these operations (i.e. water for cleaning or energy for equipment operation) due to their variable and unpredictable nature, particularly in terms of frequency (but also concerning waste flows and replacement materials). The frequency of the maintenance work considered in the environmental and economic module (see section 7.1.6.2) is identical, but there is more information about the cost of this work than there is about its environmental impacts.

The estimated service life of each building product takes into account the rules and guidance in ISO 15686-1,-2,-7 and -8 (ISO, 2000, 2001, 2006a, 2006b), as referred. The relationship between the durability and the environmental performance of these products - that are complex and have long life-cycles - must be analysed in detail. In fact, the construction of buildings differs from other industrial processes by yielding a product that: incorporates a high quantity of products and processes; has a long life-cycle; contains components that have different service lives; has a dynamic that differentiates it from other standard industrial products, in particular during the execution, use and end-of-life phases (Blok *et al.*, 2007; Chevalier & LeTeno, 1996; Kibert, 2002).

ISO 15686-6 (ISO, 2004b) and FprEN 15804:2011 (CEN, 2012) establish the interface between LCA and service life planning, and describe how to consider the service life of construction materials and buildings in LCA studies. These documents particularly stress that the use phase should be included and that LCA results will be significantly dependent on scenarios and assumptions about the duration and the processes involved in the use phase (CEN, 2012). Realistic scenarios require the incorporation of information obtained from service life prediction studies (SLP). The reference service life of a product can be based on empirical, probabilistic, statistical, deemed to satisfy or research (scientific) data, and must always take into account the intended use (description of use) (CEN, 2012).

The relationship between the durability and LCA of building materials shall be analysed through the use of stochastic data from SLP studies. However, SLP uncertainty is not yet considered in LCA, thus resulting in unsound decisions at the design stage. In fact, a deterministic service life cycle is considered for the building materials included in the external walls studied in this chapter using the 3E-C2C method. To answer this need, the author developed an interdisciplinary research study of SLP and LCA in the scope of this thesis, in collaboration with two experts in SLP (one of which is the scientific supervisor of this thesis). The aim of this study was to: model the uncertainty of SLP using advanced statistical methods; apply these results in the estimation of service life and corresponding number of replacements of claddings (renderings and stone claddings) of external walls of buildings; complete an interdisciplinary study of SLP and LCA to apply in the stochastic comparison of the LCA of claddings. The methodology developed in this study aids in the choice of the cladding alternative with the best environmental performance right at the design stage, via the comparison of their standard, deterministic and stochastic (using reference values for SLP and Monte-Carlo analysis) LCA results from cradle to cradle. This ranking provides a basis for decision-making under (modelled) uncertainty. The most relevant results of this interdisciplinary study are included in a paper that has been accepted for publication in a journal included in ISI-Journal of Citation Reports ((Silvestre, J. D.; Silva*; et al.*, 2012), which is presented in its present form in Appendix 7.V). The author also collaborated in the development of two proposals for research projects on the same subject submitted for funding by the National Research Agency (FCT - Foundation for Science and Technology) (de Brito - Coord., 2011, 2012).

This interdisciplinary study found that the service life considered for each element of buildings can have a bigger influence on LCA results than the characteristics of their components. Construction, disposal and deconstruction are processes that can be generally traced and described to calculate environmental impacts, whereas the building’s use, maintenance and management are characterised by the utmost variability. These stages involve other variables that are totally unpredictable and hard to define because they depend on decisions about building operation and maintenance scheduling, thus creating limitations to the actual reliability of LCA studies. Therefore, only a thorough interdisciplinary study of the interrelation between the SLP and LCA of buildings or building elements allows the characterisation of the dependence between their durability and environmental impacts along the entire life cycle (Silvestre, J. D.; Silva*; et al.*, 2012). The importance of this interrelation is increasing, largely because of several research studies that compare different options based on their service life or environmental performance (Nunen, 2010).

7.1.5.4. Use stage - energy performance (B6)

The 3E-C2C approach determines energy performance from the estimation of the needs of energy for heating and cooling during a building’s operation. These are the only operational impacts and costs that the façade influences (electric appliances, lighting, cooking, or domestic hot water uses are similar for all the external wall solutions evaluated). These energy needs are calculated according to the national regulations for Energy and indoor air quality certification in buildings (RCCTE, 2006), which transposes the EPBD (EC, 2002). This certification system forces the construction, sale or rental of a building or house to be followed by the corresponding certification of its energetic performance. For residential buildings, this regulation stipulates maximum nominal annual heating (Nic, in winter) and cooling (Nvc, in summer) needs per square metre of net floor area of the flat (kWh/m^2*year), and also limits the energy for heating sanitary waters and the primary energy consumption (Ferreira & Pinheiro, 2011). For a detailed explanation of the determination of these limit values see section 3.2.1 - Thermal performance.

The heating and cooling needs of a given flat in each year of the study period correspond to: $0.1 \times (\frac{Nic}{\eta_i} + \frac{Nvc}{\eta_v}) \times Aap$, in kWh and calculated as described in section 7.1.6.3. These needs are, in the 3E-C2C method, divided by the total area of the external wall under evaluation (in square metres) to give a value related to the declared unit used, and allow the estimation of their environmental impacts. This value (in kWh), times the number of years of the study period, is then introduced in the LCA software (e.g. SimaPro) and the environmental impacts are estimated considering a process to model the residential consumption for heating or cooling at the use stage which represents an updated Portuguese electricity mix (data from 2011, according to the detailed analysis presented in section 5.4.1.3) (ERSE, 2012). The use of a national electricity mix expressing the present reality is very important for the estimation of the environmental impacts of energy intensive activities, such as domestic heating and cooling, and also to their comparison with the impacts from remaining life cycle stages.

It is essential that operational impacts, namely resulting from energy consumption for heating and cooling, be included in the environmental balance of buildings due to their long life span when compared to most industrial products ((Adalberth, 1997) cited by (Peuportier *et al.*, 2012)). It is also relevant to link thermal simulation and LCA in order to: assess, and potentially improve, the integrated performance of building assemblies; balance embodied and operational energy when choosing for example insulation material and thickness. Insulation materials are essential in improving the thermal performance of external walls, but adequate masonry blocks can also reduce heating and cooling needs (Peuportier *et al.*, 2012).

7.1.5.5. End-of-life stage (C) and "Benefits and loads beyond the system boundary" (D)

End-of-life is probably one of the more complex stages to model, due to the large uncertainty of processes that will occur in buildings in a far future (Peuportier *et al.*, 2011). Moreover, more studies are required in Portugal to evaluate the potential for improving the recycling and reuse of CDW, particularly through industrial symbioses, because the end-of-life phase can have a positive contribution to the environmental performance of construction materials (Silvestre, J. D. *et al.*, 2011b). LCA of stage C or module D can also be an important source of data for decision-making between alternatives for the end-of-life of construction products. Taking this need into account, the author developed a research study in the scope of this thesis to evaluate the LCA contribution to “close the loop” in the life cycle of these products (Silvestre, J. D.; de Brito*; et al.*, 2012c). The most relevant results of this study are included in a paper that has been submitted for publication in a journal included in ISI-Journal of Citation Reports ((Silvestre, J. D.; de Brito*; et al.*, 2012a), which is presented in its present form in Appendix 7.III). This study provides a framework for the environmental assessment of the waste flows in the life cycle of building materials. This framework follows the most recent European standards (CEN, 2012) and is structured in four main parts (Silvestre, J. D.; de Brito*; et al.*, 2012a):

- Summary of the information available in LCA databases concerning the end-of-life and related processes (see section 6.1.3.4 and Appendix 6.II);
- Identification of the waste flows that can be generated or used along the life cycle of building materials - Figure 7.1 (at product stage: production waste (PW - see section 5.4.1.5), or secondary material inputs - recycled content - from the construction industry (PCODW) or from other industries (Industrial Symbiosis - IS); at the construction (CW), use (UW), and end-of-life (DW) stages - CDW outputs);
- Description, detailed analysis, visual presentation and interpretation of the standardised calculation rules for the evaluation of the environmental impacts and benefits of these flows (CEN, 2012), including the correlation of these rules with the “European Waste Framework Directive” and a simplified comparison with other allocation procedures of reuse, recycling and recovery (see 7.1.5.5.1);
- Analysis of selected case studies to provide an overview of the contribution of LCA methodology to “close the loop” in the life cycle of building materials (see Appendix 7.III).

This study demonstrated that the application of the framework proposed can be very important for decision-making between different alternatives at the end-of-life of building materials, namely to “close the loop” in the life cycle of these products and to confirm whether the minimisation of waste flows, the maximisation of their reuse or recycling operations, or the increase of the recycled content maximises their C2C environmental performance.

7.1.5.5.1. Stage C and module D - LCA calculation rules

Standardised procedures for LCIA of waste disposal during the manufacturing stage (A3) are described in detail in section 5.4.1.5. This section is devoted to explaining the standardised calculation rules for the LCA of waste streams generated at stage C (DW in Figure 7.1).

When a construction product is replaced, dismantled or deconstructed from the building, it reaches the end-of-life stage. All outputs of this stage are at first considered to be waste, but they can cease to be waste and gain a status of product (or a secondary raw material) if they reach the “end-of-waste” state (CEN, 2012). According to the “European Waste Framework Directive” (EP, 2008), the latter state is achieved when the following conditions are cumulatively verified: it is commonly used for specific purposes; a market or demand exists for such material; it fulfils the technical requirements for the specific purposes and meets the existing legislation and standards; the use of the substance or object will not lead to overall adverse environmental or human health impacts.

Waste processing for reuse, recovery and/or recycling (C3 sub-stage) is usually within the product system under study. Processes (e.g. collection and transport) before the “end-of-waste” state for materials leaving the system as secondary materials are, as a rule, part of the C3 sub-stage (system boundary 2 in the common practice and in the alternative in Figure 7.2). Further necessary processing (e.g. in order to replace primary material input in another product system) after having reached the “end-of-waste” state are considered to be beyond the system boundary and have to be included in module D (system boundary 1 of the alternative in Figure 7.2) (CEN, 2012).

It is important to clarify that waste processing (e.g. collection and transport, but sometimes also recovery or recycling) during any stage of the product system up to the system boundary (i.e. production, construction, use, or end-of-life stages) is included in the corresponding stage, and only waste processing after reaching the “end-of-waste” state (during any stage of the product system, i.e. during A, B or C stages) is part of module D, similarly to the approach described for the C3 sub-stage and represented in Figure 7.2 (CEN, 2012). Thus, not all environmental impacts from waste processing operations are included in stage C and module D because they can be accounted for in the remaining life cycle stages when they occur before the “end-of-waste” state.

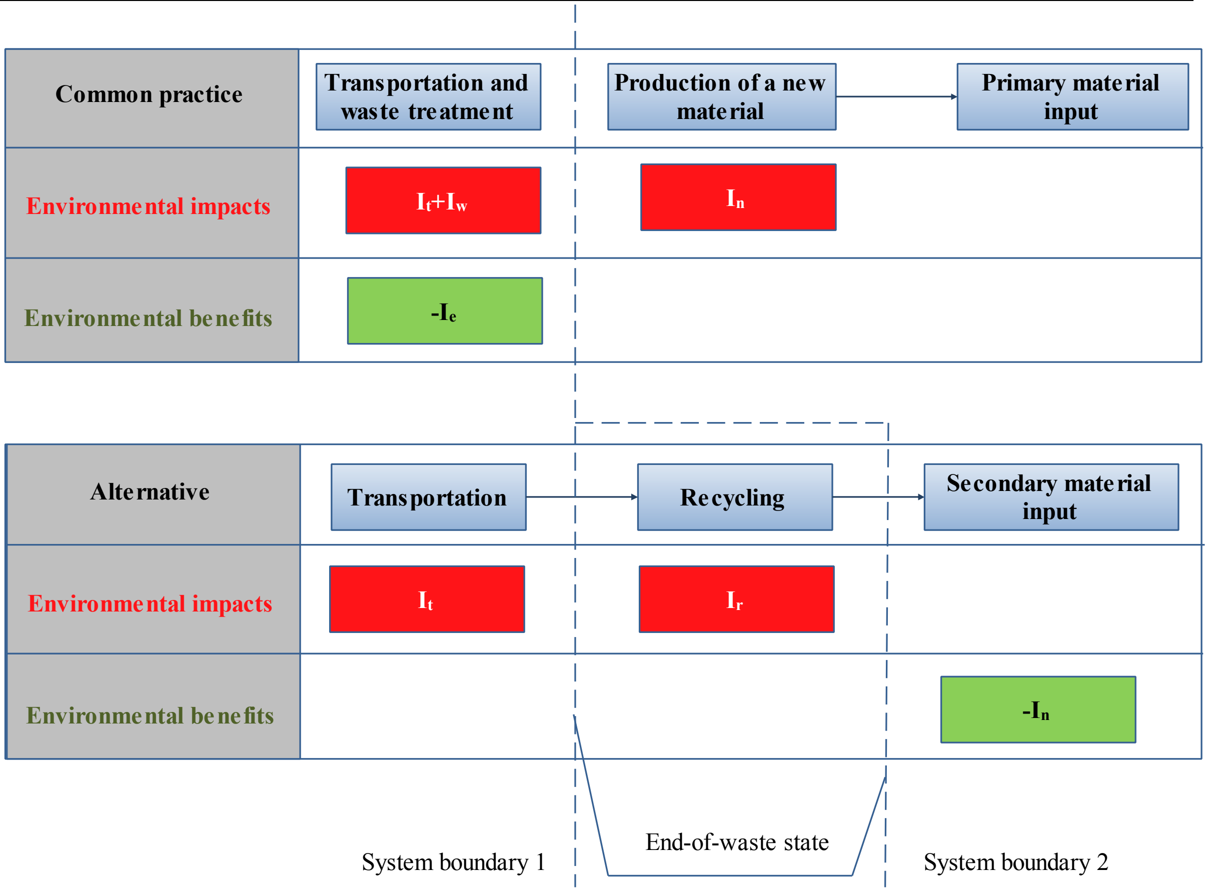

Figure 7.2 - Comparison between common practice in construction materials production (use of primary raw materials), with its alternative (use of recycled materials), including the two possible ways to define the LCA system boundary in accordance with European standards (CEN, 2012; Silvestre, J. D.; de Brito*; et al.*, 2012a)

To clarify the concept of “end-of-waste” state, the European Commission is preparing a set of “end-of-waste” criteria for priority waste streams, namely for CDW (EC, 2012; EP, 2008). However, these criteria are only available for certain types of scrap metal (iron, steel and aluminium scrap) (as referred in section 5.4.1.5). This type of waste only reaches the “end-of-waste” state after a sequence of treatment processes (e.g. cutting or shredding) that prepares it to be used as a direct input into the next product system (EU, 2011). Thus, no waste processing after the “end-of-waste” state is reached has yet been defined for any waste type, so as a result there are no environmental loads to be quantified beyond the system boundary and assigned to module D (and therefore system boundary 2, in the common practice and in the alternative in Figure 7.2, has to be followed - see Figure 7.3) (CEN, 2012).

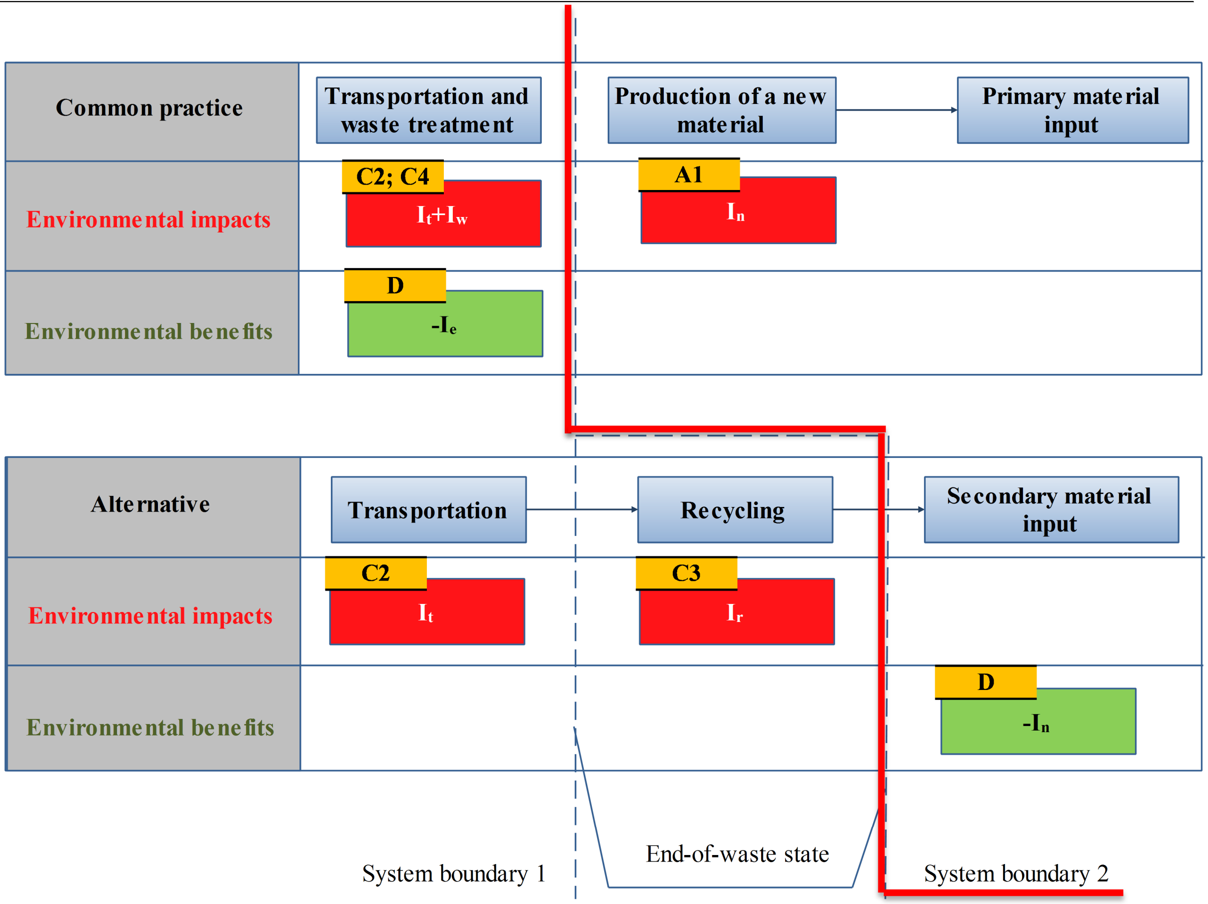

Figure 7.3 - Assignment of environmental impacts and benefits to end-of-life stage (C) and to module D, taking only system boundary 2 into account (CEN, 2012)

Figure 7.3 shows the assignment of environmental impacts and benefits to end-of-life stage (C) and to module D, taking only system boundary 2 into account. Potential benefits from the use in the next product system of energy (i.e. heat and power - I_e in Figure 7.3) generated at sub-stage C4 (waste disposal) from waste incineration or landfill should be considered in module D, while the loads (e.g. emissions - I_w in Figure 7.3) from waste disposal in this sub-stage are part of the product system under study, according to the "polluter pays principle", and should be considered at sub-stage C4 - see (CEN, 2012).

European standards define a specific "allocation procedure of reuse, recycling and recovery" - 3R. In fact, LCA information module D can award the "design for 3R" of buildings and building products by considering the potential benefits of avoiding the use of primary materials, and also the loads from the recycling and recovery processes (CEN, 2012). The calculation of the net impacts from this stage includes the following steps (CEN, 2012):

- Calculation of the net output flows of secondary material from the product system: adding all output flows and subtracting all input flows of this type from each sub-stage (e.g. B1-B5, C1-C4, etc.), then from the stages (e.g. B, C), and finally from the total product system;

- Calculation of the potential impacts and benefits of processing the net output flows calculated in the previous step: adding the impacts from recycling and recovery processes from beyond the system boundary (after the “end-of-waste” state) until the point of functional equivalent (“where the secondary material or energy substitutes primary production”), and subtracting the impacts from “the substituted production of the product or substituted generation of energy from primary sources”;
- Application of a justified value-correction factor (in order to reflect the difference in functional equivalence when the output flow “does not reach the functional equivalence of the substituting process”).

From these calculation rules, it is important to highlight that the substitution effects are calculated only in module D for the net output flows, while the amount of secondary material output “that is able to replace one to one the input of secondary material as closed loop” is allocated to the product system under study (sub-stage A1) (CEN, 2012).

The environmental impact from waste recycling (and from the eventual transport) can be represented as: $I_r + I_t$ (and assigned to C3 and C2 sub-stages, respectively - see Figure 7.3). This operation avoids the impacts from the production of a similar new product (potential benefit of I_n in module D, see alternative in Figure 7.3) and the impacts from waste treatment (I_w - common practice in Figure 7.3). Therefore, recycling should be promoted only if $(I_r + I_t) < (I_n + I_w)$, because it will avoid an impact that corresponds to: $(I_n + I_w - I_r - I_t)$ (Peuportier et al., 2011). The environmental impacts represented by I_r and I_t should be included in module D only if they occur after the “end-of-waste” state (system boundary 1 of the alternative in Figure 7.2; otherwise it should be considered in the stage of the product system where the flow occurs - see alternative in Figure 7.3). If the option is not to recycle, I_w should be included in sub-stage C4 (common practice in Figure 7.3). The methodology used for this calculation should avoid double counting of the benefit of recycling (Peuportier et al., 2011).

If recycling rates are defined as r_p and r_e, respectively at production and end-of-life stages, and net output flows are represented by N_f, the “allocation procedure of 3R” defined in the European Standard (CEN, 2012) can correspond to an environmental impact reduction that can be represented by three individual amounts (this is an approach similar to the stock flow method - for the first amount, and to the one proposed by the steel industry - all amounts (adapted from (Peuportier et al., 2011)):

- $[r_p.(I_n–I_r)]$ at sub-stage A1 (that includes processing of secondary material input, such as recycling processes – see Table 7.3 and common practice in Figure 7.4), where only the impact from I_r is considered for the amount of secondary material used;

- [$r_e.(I_w-I_t)$] expressed by a reduced environmental impact ($r_e.I_t$ instead of $r_e.I_w$) at the stage of the product system where the waste flow occurs;
- [(I_n-I_r) for N_f], this impact reduction being entirely considered as impacts and benefits in module D when recycling occurs after the "end-of-waste" state. When recycling occurs before the "end-of-waste" state, the benefit is considered in module D (I_n for N_f) and the impact from I_r is considered at the stage of the product system where recycling occurs but for the entire end-of-life flow (r_e), and not only for net output flows (N_f). This results in double counting of the impacts of the recycling process for the output flows that are used as input of secondary material in the same system process (sub-stage A1) as closed loop (as represented in the alternative in Figure 7.4).

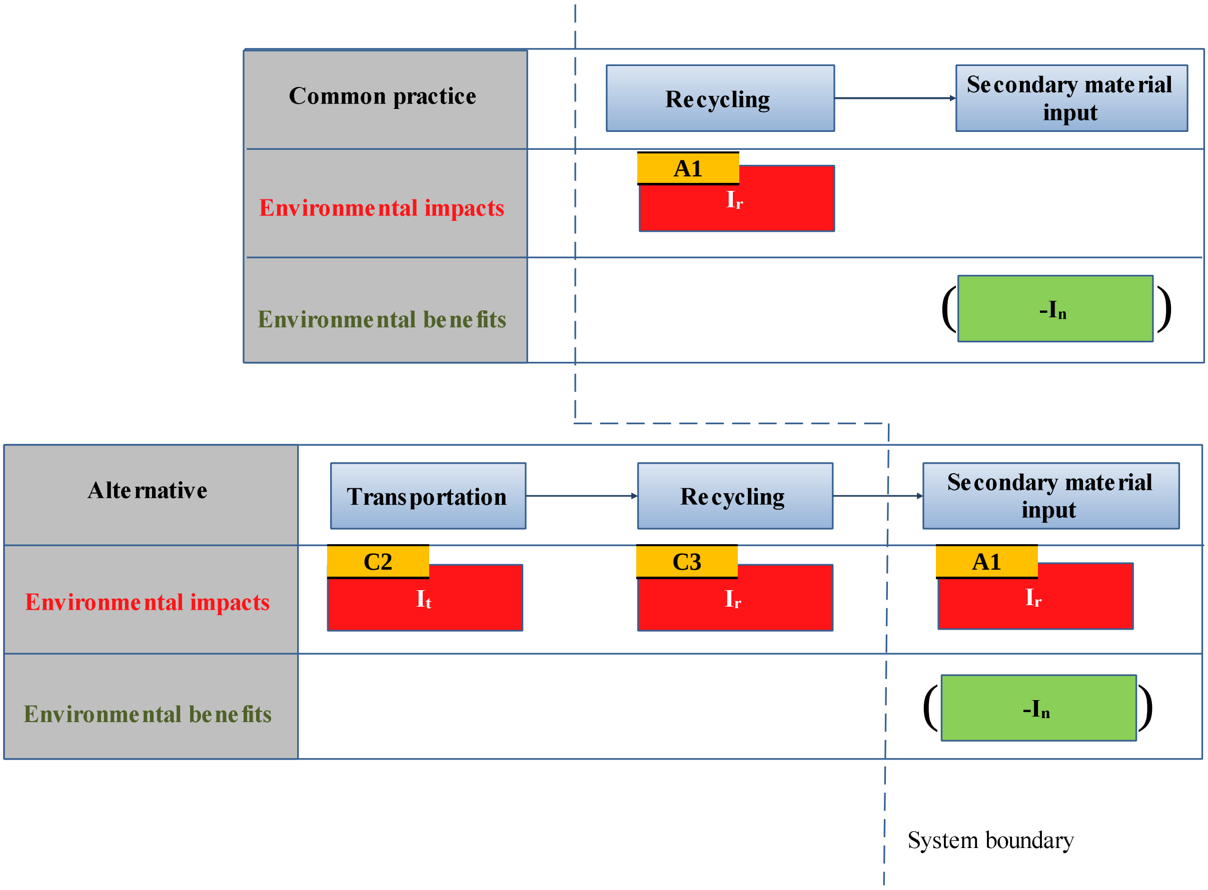

Figure 7.4 - Assignment of the environmental impacts from recycling operations before the "end-of-waste" state: secondary material input from other system processes (common practice) and output flows that are used as input of secondary material in the same system process as closed loop (alternative) (CEN, 2012)

In conclusion, it was found that three important criteria defined in reference literature (Peuportier *et al.*, 2011) were considered in the standardised LCA calculation rules (CEN, 2012) described:

- Reward of the use of recycled products at the construction phase (by considering only the recycling process, instead of the production of a new product, at stage A1);
- Reward of the sorting of waste and recycling at the end-of-life (by considering: disposal scenarios with less impacts or higher benefits from sorted CDW; the potential benefits of avoiding the use of primary materials; the loads from the recycling and recovery processes);
- Avoidance of double counting of the benefit of recycling (by calculating substitution effects in module D only for the net output flows).

However, it was also found that standardised LCA calculation rules (CEN, 2012) result in double counting of the impacts of the recycling process for the output flows that are used as input of secondary material in the same system process as closed loop, but only when recycling occurs before the "end-of-waste" state (as represented in the alternative in Figure 7.4).

7.1.5.5.2. Stage C and module D - assumptions and data used in the application of the 3E-C2C method

The LCA of the end-of-life stage should be supported by realistic and representative scenarios (CEN, 2012) and a precautionary approach leads to the consideration of the same waste treatment processes as today (or, at least, the current average technology or practice (CEN, 2012)). However, an alternative can be the use of a probabilistic range of scenarios (Peuportier et al., 2011).

Selective demolition (or deconstruction) is considered in the 3E-C2C method to estimate the environmental (and economic) impacts of transporting and disposing of "Construction and Demolition Waste" (CDW) in suitable sites, and also the corresponding benefits and loads beyond the system boundary (3R potential of construction and demolition waste (CDW) and of other waste flows). This technique is increasingly being used in Portugal for environmental (allowing the maximisation of CDW reuse/recycling potential) and economic reasons (Coelho & de Brito, 2011). Deconstruction eases the reuse of building materials and components by promoting their split-up by type from the beginning, and allows a "cradle to cradle" viewpoint in the life cycle of these products, thus preventing matter and energy losses (Santos, A. L. d. & de Brito, 2007).

However, for external wall solutions in which some components cannot be physically separated, it is considered that they are mixed after demolition and therefore have to be considered as undifferentiated CDW (waste code 17 09 04 - mixed construction and demolition wastes (EC, 2000)) and sent to landfill. The environmental impacts (and economic costs) of demolition (sub-stage C1 - deconstruction, including dismantling or demolition, of the product from the building, including initial on-site sorting of the materials) were not considered as they are similar for all the alternatives under assessment. This sub-stage, plus C2, account for (on average) 10% of the amount of energy consumed in construction materials from "cradle to grave" ((Berge, 1999) cited by (Mendonça, 2005)). Therefore, environmental impacts from stage C correspond in the 3E-C2C method to:

- The transportation of the discarded product as part of the waste processing (C2, e.g. to a recycling site) and transportation of waste (C2, e.g. to final disposal);
- The waste processing (C3, e.g. collection of waste fractions from the deconstruction and waste processing of material flows intended for reuse, recycling and energy recovery);
- The waste disposal, including physical pre-treatment and management of the disposal site (C4).

The environmental impacts (and the cost) of transporting and disposing of the CDW generated by each external wall solution are based on Portuguese case studies which used data from waste operators and market prices. Therefore, the most probable disposal site (CDW management and Portuguese recycling plants in the study area) and final destination (e.g. landfill, reuse or recycling) are considered for each type of CDW (Coelho & de Brito, 2011). Following the same approach chosen for the product stage (see section 5.4.1.5.1), waste treatment processes from Ecoinvent database are used to model the referred disposal of each waste stream generated at stage C of each external wall alternative. Disposal alternatives and corresponding environmental loads are described in detail in section 5.4.1.5.1. The procedure used for the choice of the type of lorry for the transportation of each waste stream was described in section 5.4.1.4.1.

7.1.6. Economic performance

Whole-Life Cost (WLC) is defined as 'all significant and relevant initial and future costs and benefits of an asset, throughout its life cycle, while fulfilling the performance requirements' (ISO, 2008a), as described in Chapter 3. The economic module of the 3E-C2C approach is based on the WLC method (ISO, 2008a) and follows most of the principles in the draft standard FprEN 15643-4:2011: "Sustainability of construction works - Sustainability assessment of buildings - Part 4: Framework for the assessment of economic performance" (CEN, 2011b), such as:

- Only the cost value was considered to express the economic performance over the life cycle, which means that the “lowest life cycle cost” building is the most economic one;
- To link the results from environmental, economic and energy performance assessments requires that the functional equivalent (a square metre of external wall) is one and the same for all assessments.

The economic performance (WLC) from “cradle to cradle” of the building assemblies under analysis have to be estimated taking into account these principles and considering current national practices. To facilitate the choice between the competing alternatives, the net present value (NPV) method was used. The NPV of an alternative is the sum of all costs incurred during the period of study of the life cycle of the solution under analysis (Figure 7.5), converted to their present value (using a discount rate). This makes the NPV of all solutions comparable in the year 0 - the present moment - which corresponds to the design phase (Real, 2010). In order to use WLC to choose among competing design alternatives, the maximum benefit is achieved at an early design stage when most, if not all, options are open to consideration. The ability to influence cost is also maximum at this stage and lowers continually to 20% or less by the time construction starts (Kishk et al., 2003).

The NPV of the declared unit of each alternative is calculated for the study period using equation (7.1), assuming constant prices (ISO, 2008a):

$$NPV = \sum_{n=0}^{50} \frac{C_n}{(1+d)^n} \quad (€/m^2) \tag{7.1}$$

Where

C_n cost of the external wall in year n ($€/m^2$) - see section 7.1.7;

d real discount rate (without considering risk) applied (3%).

7.1.6.1. Product and construction process stages (A1-A5)

The economic cost in year n per square metre of external wall - Cec_n - includes, before the use stage, the market acquisition cost in year 0 (which aggregates the cost of manufacturing and transporting products to the site and the cost of the construction process, without VAT). This cost was mainly provided by the companies involved in the LCA studies completed in the scope of this thesis, but obtained also through market surveys, construction firms and building materials suppliers (Real, 2010), and based on reference national documents (Manso *et al.*, 2010).

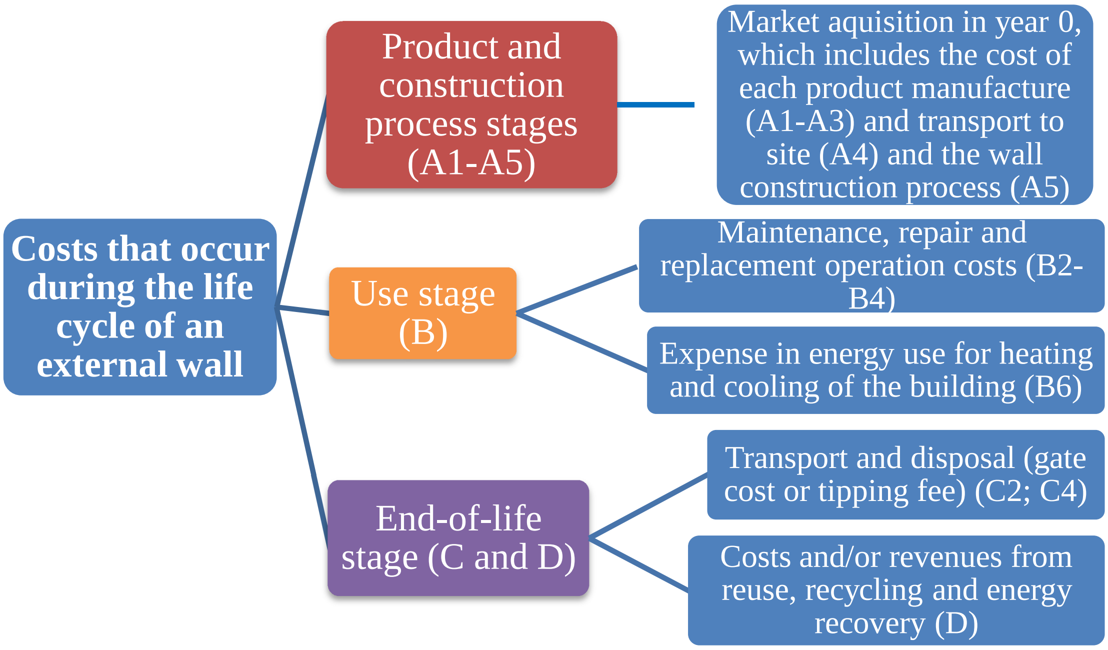

Figure 7.5 - Costs that occur in each stage of the life cycle of an external wall of a building

7.1.6.2. Use stage - maintenance, repair and replacement cost (B2-B4)

The economic cost in year n per square metre of external wall - Cec_n - includes the costs of the maintenance, repair and replacement operations incurred in that year. These costs were also provided by the companies involved in the LCA studies completed in the scope of this thesis, but also obtained through market surveys, construction firms and building materials suppliers (Real, 2010). The maintenance, repair and replacement operations defined in this thesis for each element of the external wall are described in Appendix 7.IV.

7.1.6.3. Use stage - energy cost (B6)

The energy cost in year n per square metre of external wall - Ceg_n - corresponds to the energy use expenditure in heating and cooling, calculated by the method described in the national regulations (see 7.1.5.3) and shown in equation (7.2) (Mateus & Bragança, 2011; RCCTE, 2006):

$$Ceg_n = 0.1 \times T \times (\frac{Nic}{\eta_i} + \frac{Nvc}{\eta_v}) \times \frac{Aap}{Aew} \quad \text{(€/year*m}^2 \text{ of external wall)} \qquad (7.2)$$

Where

T cost of 1 kWh of electricity in Portugal for household consumers, without VAT or standing charges (€/kWh) (0.139 €/kWh considering an installation of more than 2.3 kVA (EDP, 2012));

Nic nominal annual heating needs per square metre of net floor area of the flat (kWh/m^2*year);

η_i nominal efficiency of the heating equipment (1, considering the reference value (RCCTE, 2006));

Nvc nominal annual cooling needs per square metre of net floor area of the flat (kWh/m^2*year);

η_v nominal efficiency of the cooling equipment (3, considering the reference value (RCCTE, 2006));

Aap net floor area of the flat under assessment;

Aew total area of the external wall being assessed.

7.1.6.4. End-of-life stage (C2-C4 and D)

The economic costs in year 50 per square metre of external wall (Cec_{50}), i.e. end-of-life costs, only include those for transport and disposal (gate cost or tipping fee) of the building assemblies and expenses and/or revenues from reuse, recycling, and energy recovery (Coelho & de Brito, 2011), using the approach described in section 7.1.5.5.2. The economic costs of demolition were not considered in this approach as they are similar for all external wall solutions being assessed.

7.1.7. 3E cost-C2C assessment

Companies have been able to consume resources or pollute air, water or land, with little efforts to internalize the corresponding consequences, and with costs that are normally tolerated by the general public despite being unsustainable and ethically unacceptable. The most difficult issue when dealing with this abuse is to determine the actual cost of such damage to nature. But there are already examples of quantifications of “natural capital”, as the “Canadian Boreal Initiative” that calculated the value of the ecological services of a valley in order to “tax” industries that destroy it. Transferring the cost of harm to the company that does the damage (e.g.: the carbon market related with the cost of CO_2 emissions of the production of goods) would create strong fiscal incentives to find ways of doing business that will reduce costs. But it is a huge challenge to regulate these issues at a global scale, namely making the richest countries pay for the environmental effects that they cause in neighbouring countries (Goleman, 2010, pp. 233-235). A recent report of “The Economics of Ecosystems and Biodiversity” (TEEB) refers that the invisibility of many of nature’s services to the economy results in widespread neglect of natural capital, leading to decisions that degrade ecosystem services and biodiversity (TEEB, 2010). However, it is only by establishing a universal economic value of natural elements and services that the excessive consumption of natural resources can be avoided (Buchanan, 2010).

The 3E *cost*-C2C approach includes an EIAM with a weighting step that converts the results of most of the LCA impact categories (except PE-NRe and PE-Re within the ones chosen to be used in this thesis) into an economic unit. This enables the potential cost of the environmental impacts to be added to the economic and energy whole-life cost, resulting in an overall single score (3E *cost*-C2C) for each alternative being assessed.

It is true that a single score should never be used in public comparisons of LCA results (ISO, 2006c) and the interpretation and evaluation of the results of the assessment are not within the scope of LCA International Standards (ISO, 2006c, 2006d) (for weighting see section 5.1.4). However, this has led to research studies (e.g. (Monteiro & Freire, 2012)) that only analyse the results of each alternative for each individual environmental category but do not provide final answers about the best alternative in environmental terms. There are, however, LCA studies that use an EIAM with a single indicator which weights the results of each impact category to express them in the same unit: a damage-oriented indicator (e.g. Eco-indicator 99 whose unit is Points, as described in Chapter 5); a single issue indicator (e.g. Cumulative Energy Demand, having MJ as its reference unit - see Chapter 5); a prevention based indicator (e.g. *Eco-costs* 2007, whose economic unit is the euro). All of them are suitable for different types of analysis, but *Eco-costs* give the most satisfactory results for C2C calculations. *Eco-costs* express a prevention based single indicator for environmental burdens that is based on the concept of marginal prevention costs (e.g. costs required to bring the environmental burden to a sustainable level, by either end-of-pipe measures or process integrated solutions). Marginal prevention costs include the *Eco-costs* of toxic emissions, material depletion and energy. One substance can cause damage in different impact categories but it only has one prevention cost. Therefore, it should be counted in only one impact category, and accordingly the *Eco-costs* model considers it only in the most relevant (most expensive) impact category. This EIAM was built based on the Dutch reality by the Delft University of Technology but it can be applied to other western European countries (TUDelft, 2011), namely with adjustments to each specific geographic or scientific context.

Table 7.4 presents a comparison between selected environmental impact categories of CML 2001 baseline (the EIAM with a mid-point approach and corresponding categories chosen to be used in the LCA studies completed in the scope of this thesis - see Chapter 5) and all the *Eco-costs* impact categories (the ones used in the single indicator calculus), where the related categories are placed on the same line. The weighting factor used in the 3E *cost*-C2C approach (and defined in *Eco-costs*) for each environmental impact category is also presented in Table 7.4.

Table 7.4 - Comparison between selected impact categories of the EIAM CML 2001 baseline and all Eco-costs impact categories

CML 2001 baseline category	**Unit**	***Eco-costs* category**	**Unit**	**Weighting factor in 3E *cost*-C2C**
Abiotic depletion potential (ADP)	kg Sb eq	Metals depletion	Euro	1
		Oil & Gas depletion excl. energy	kg oil eq	0.7
		Depletion of natural forests	Euro	1
Acidification potential (AP)	kg SO_2 eq	Acidification	kg SO_2 eq	7.55
Eutrophication potential (EP)	kg PO_4^{3-} eq	Eutrophication	kg PO_4^{3-} eq	3.6
Fresh water and marine aquatic ecotoxicity	*kg 1.4-DB eq*	Aquatic ecotoxicity	kg TEG eq	-
Global Warming potential (GWP)	kg CO_2 eq	Global Warming potential - IPPC	kg CO_2 eq	0.135
Human toxicity	*kg 1.4-DB eq*	Fine dust (PM 2.5)	kg PM 2.5 eq	-
		Carcinogens	kg C_2H_3Cl eq	-
Ozone layer depletion potential (ODP)	kg CFC-11 eq	-		
Photochemical ozone creation potential (POCP)	kg C_2H_4 eq	Summer smog	kg C_2H_4 eq	8.9
-	-	Waste	MJ	-

Table 7.4 shows that *Eco-costs* include environmental categories that are similar to those most often used in the environmental assessment of construction materials and assemblies. The characterisation tables of *Eco-costs* for acidification, eutrophication and summer smog (photochemical oxidation) are even equal to those from CML 2001. *Eco-costs* includes toxicity impact categories (i.e. aquatic ecotoxicity, fine dust (PM 2.5) and carcinogens) which, despite also being included in CML 2001 and presented in italics in Table 7.4, are not usually used in LCA studies because of their high uncertainty and lack of scientific robustness ((Nemry *et al.*, 2008) cited by (Monteiro & Freire, 2012)). Due to this fact, these impact categories were not considered in the 3E *cost*-C2C approach. The ozone layer depletion category is not considered in *Eco-costs* because HCFCs are already banned in Europe and in the USA (TUDelft, 2011). Nevertheless, these gases are considered in the global warming potential characterisation tables of this EIAM. As for the waste produced in the system process under study, *Eco-costs* gives economic credits to recyclable or combustible waste and considers the cost of disposing inert or mixed waste (i.e. non-recyclable and non-combustible). This impact category is not considered in the 3E *cost*-C2C approach to avoid double counting. In fact, since all assemblies are modelled in detail from C2C using LCA

software, an appropriate end-of-life (e.g. recycling or landfill) is attributed to each waste flow during its life cycle, according to the Portuguese situation, and the emissions and avoided burdens of these waste flows are duly quantified and assigned to the corresponding module (e.g. to Module D - Benefits and loads beyond the system boundary).

Although it is important to analyse the results of each module of 3E-C2C separately, only the application of weights for the environmental, economic and energy results enables a sound choice to be made between alternatives, based on a justifiable criterion. Therefore, 3E *cost*-C2C provides a common subjectivity-free unit to compare different alternatives for the design of a building. For each alternative, the cost in year n (e.g. per square metre of external wall - see equation (7.3)) is the sum of the environmental (*Cev*), economic (*Cec*, see 7.1.6) and energy (*Ceg*, see 7.1.6.3) cost:

$$C_n = Cev_n + Cec_n + Ceg_n \text{ (€/declared unit)} \tag{7.3}$$

Cev (potential environmental cost, which is referenced as “environmental cost” hereafter) corresponds to the application of the EIAM *Eco-costs* to the LCA results for each life cycle stage (see 7.1.5). The NPV of each alternative is found by applying equation (7.1).

7.2. Application of 3E-C2C method in an external wall’s selection

This section illustrates the use of the 3E-C2C method in the selection of an external wall of a building in Portugal. The most common external wall solutions in Portugal (see Chapter 3 and Appendix 3.I), and the construction products for which a LCA study was completed within the scope of this thesis or to which NativeLCA methodology was applied (see Chapter 5 and Chapter 6, except the two-component adhesive that was not considered in any alternative), have conditioned the range of alternatives considered in this selection process.

The 3E-C2C method (described in detail in section 7.1) was used to evaluate the 3E performance of the alternatives considered in this case study. The data on the life cycle stages of the external walls included in each module of this method were summarised in Table 7.2.

The LCA results for the external wall solutions under evaluation - C2C (without weighting or aggregation) - are presented in section 0. Section 7.2.3 presents the NPV of the economic (*Cec*, see 7.1.6) and energy (*Ceg*, see 7.1.6.3) costs (without weighting or aggregation) for the external wall solutions under evaluation. Section 7.2.4 sets out the environmental performance results expressed by a single economic indicator and their combination with economic and energy performance results, using the 3E *cost*-C2C approach.

7.2.1. Scope of the study

The 3E-C2C method was applied to a process of selecting the external walls of a model building called Hexa (developed under LiderA, a Portuguese building environmental certification system - see Chapter 2). The building has five residential floors (the ground floor is to be used for commerce) (Real, 2010) and represents the most common building and architectural practices in Portugal, but has not been built yet (Ferreira & Pinheiro, 2011). The Hexa design drawing can be seen in Figure 7.6 (the building faces south), and the subject of the study is the flat on the right (with a net floor area of 129.96 m^2) located on a middle floor without a building adjacent to the east façade.

Figure 7.6 - Hexa design drawing of a middle floor: the subject of the study is the flat on the right, with no adjacent building on the east façade (Ferreira & Pinheiro, 2011)

The external walls to be chosen are on the north and south façades of the flat (with a total area of 40.27 m^2) and the declared unit is 'a square metre of external wall for 50 years' (the east façade is considered to be the same - with a heat transfer coefficient (U-value) of 0.47 W/(m^2.ºC) - for all alternatives).

A summarised characterisation of the 60 outer wall alternatives considered in this study are shown in Table 7.5 to Table 7.9, while their composition, dimensions and thermal performance (U-value) are included in Appendix 7.IV. This appendix also includes the maintenance, repair and replacement operations considered for each external cladding and internal coating over the life cycle of the external walls (according to the procedures described in 7.1.5.3, and based on confidential LNEC reports and in-field information provided by the producer of each construction material).

The calculation of the heat transfer coefficient (U-value) of each solution was made according to equation (3.1) and considering the thermal conductivity declared by the producer of each material (see Chapter 5 and Chapter 6) or the LNEC publication used as reference in the energetic certification system (Santos, C. Pina & Matias, 2006). All these alternatives have U-values lower than reference values included in RCCTE for climatic regions I1 and I2, and only four solutions (W37-W40) have a U-value slightly higher than the reference value for region I3 (RCCTE, 2006), which is in accordance with the present national practice (see section 3.2.1).

The default location for Hexa in this study is Lisbon (namely for the A4 sub-stage - transport from factory gate to the construction site), because of being the national metropolitan area with the highest density of buildings in the country. However, the discussion section (see 7.3) presents a sensitivity analysis of the best alternatives for external walls of this building considering three additional locations: Porto, Bragança and Évora.

Table 7.5 - Single-leaf walls - External insulation

External wall	External cladding	Internal coating	Insulation		Elements of the wall structure [Thickness (m)]
			Material	Thickness (mm)	
W1	ECS3 - Adherent [0.02 m render, adhesive, (insulation), glass fiber mesh, 0.01 m render and water-based paint] within an ETICS	ICS1 - Adherent (0.02 m render and water-based paint)	SW	80	CHB (0.22, plus stabilised masonry mortar)
W2			EPS		
W3			ICB		
W4			PUR	60	
W5			XPS	80	
W6		ICS2 - Adherent to the wall structure (adhesive, gypsum plasterboards and water-based paint)	SW		
W7			EPS		
W8			ICB		
W9			PUR	60	
W10			XPS	80	
W11	ECS4 - Fastened to a supporting structure - VRF (0.02 m render in the outer surface of the CHB, and WPC structure and boards creating a ventilated cavity)	ICS1	SW		
W12			EPS		
W13			ICB		
W14			PUR	60	
W15			XPS	80	
W16		ICS2	SW		
W17			EPS		
W18			ICB		
W19			PUR	60	
W20			XPS	80	
W21	ECS5 - GFRC precast panels with 12 cm EPS boards as void formers (can also be considered an element of the wall structure)	ICS1	-		CHB (0.15, plus stabilised masonry mortar)
W22		ICS2			

Table 7.6 - Single-leaf walls - No insulation (and LCB with 0.38 m of thickness as the element of the wall structure, plus stabilised masonry mortar)

External wall	External cladding	Internal coating
W23	ECS1 - Adherent (0.02 m render and water-based paint)	ICS1
W24		ICS2
W25	ECS2 - One-coat mortar	ICS1
W26		ICS2

Table 7.7 - Single-leaf walls - Internal insulation

External wall	External cladding	Internal coating	Insulation		Elements of the wall structure [Thickness (m)]
			Material	Thickness (mm)	
W27	ECS1	ICS3 - Adherent to the insulation material [adhesive, (insulation), gypsum plasterboards and water-based paint]	SW	80	CHB (0.22, plus stabilised masonry mortar)
W28			EPS		
W29			ICB		
W30			PUR	60	
W31			XPS	80	
W32	ECS2		SW		
W33			EPS		
W34			ICB		
W35			PUR	60	
W36			XPS	80	

Table 7.8 - Cavity walls - Thermal insulation completely filling the cavity

External wall	External cladding	Internal coating	Insulation		Elements of the wall structure [Thickness (m)]
			Material	Thickness (mm)	
W37	ECS1	ICS1	LECA	80	CHB (cavity wall - 0.15+0.11, plus stabilised masonry mortar and internal 0.02 m render)
W38		ICS2			
W39	ECS2	ICS1			
W40		ICS2			

Table 7.9 - Cavity walls - Thermal insulation partially filling the cavity (cavity wall with 0.15+0.11 m CHB, plus stabilised masonry mortar and internal 0.02 m render)

External wall	External cladding	Internal coating	Insulation material (60 mm thickness)
W41	ECS1	ICS1	SW
W42			EPS
W43			ICB
W44			PUR
W45			XPS
W46		ICS2	SW
W47			EPS
W48			ICB
W49			PUR
W50			XPS
W51	ECS2	ICS1	SW
W52			EPS
W53			ICB
W54			PUR
W55			XPS
W56		ICS2	SW
W57			EPS
W58			ICB
W59			PUR
W60			XPS

Notes to Table 7.5 - Table 7.9:

- External cladding systems (ECS) - ETICS (External Thermal Insulation Composite System), GFRC (Glass Fibre Reinforced Concrete), VRF (Ventilated Rainscreen Façades) and WPC (Wood-plastic composite);
- Internal cladding systems (ICS);
- Insulation materials - EPS (Expanded Polystyrene), ICB (Insulation Cork Board), LECA (Light Expanded Clay Aggregate), PUR (Polyurethane), SW (Stone wool) and XPS (Extruded Polystyrene);
- Elements of the wall structure - CHB (Hollow fired-clay bricks, horizontally perforated) and LCB (Lightweight - with LECA - concrete blocks, vertically perforated).

7.2.2. Environmental performance C2C

The LCA results C2C (without weighting or aggregation) in six environmental categories (using CML 2001 baseline - version 2.05) are presented in Table 7.10, Table 7.11, and Table 7.12 for the 60 external wall solutions being evaluated, including the difference in percentage for alternative W1. These results do not include B6 sub-stage (energy use for heating and cooling), because it is directly related with the U-value of each alternative and therefore stems directly from the energy needs of the flat and do not help as a standalone criterion in the choice of the best environmental performance solution (Silvestre, J. D.; de Brito*; et al.*, 2012b). However, the relation between the U-value and the energy use for heating and cooling of each alternative is not similar for each group of alternatives. In fact, the heating (Nic) and cooling (Nvc) needs of the flat being studied (see equation (7.2)) are directly related with the U-value of each external wall, but only within each group. This means that if three walls with the same U-value are chosen (one wall from each group), the one with external insulation has the lowest heating and cooling needs, while the needs of a cavity wall with an insulation in the cavity (or a wall with a lightweight concrete block) can be between 6% and 8% higher, and the needs of a wall with an internal insulation can be between 11% and 13% higher (depending on the region of Portugal where the flat is located). These differences result from the linear thermal bridges that were identified along the area of external wall of this flat and from the presuppositions included in the national regulation (RCCTE, 2006). This regulation considers that walls with external insulation, cavity walls with an insulation in the cavity or walls with “distributed insulation”, and walls with an internal insulation, avoid with decreasing efficiency the heating losses during winter along these linear thermal bridges. Although, this regulation considers a similar thermal inertia of the building for all alternatives (because many other elements - that are equal for all alternatives – other than the external wall also influence this parameter).

7.2.2.1. Single leaf walls with external insulation

Concerning the environmental performance (LCA without energy for heating and cooling) of the single leaf walls with external insulation (Table 7.10) it was found that the alternatives with GFRC panels (with EPS boards as void formers) as external cladding (W21 and W22) present the worst performance in five out of six categories. It is however important to highlight that these two alternatives are within the ones with the best thermal performance (see Appendix 7.IV), and are also the ones with the lowest heating and cooling needs due to the external position of the insulation (see 0). EP is the only category for which other solutions - the ones with wood-plastic extruded (WPC) boards as external cladding (W11 to W20) - present a worse performance than W21 and W22.

The solutions with the best environmental performance are mainly the ones with an ETICS system as external cladding (W1 to W10). Within those, the one with gypsum plasterboard as internal cladding and an EPS board within the ETICS (W7) has the lowest value in AP. The solutions with painted cement render as internal cladding and an ETICS system have the best performance in the remaining impact categories: in ADP and GWP, with an ICB board (W3); in EP and POCP, with a PUR board (W4); and in ODP, with a XPS board (W5).

7.2.2.2. Single leaf walls with internal, and without (W23-W26), insulation

Table 7.11 shows the environmental performance (LCA without energy for heating and cooling) of the single leaf walls with internal, and without (W23-W26), insulation. The solutions with the worst environmental performance are mainly the ones without insulation material and with a lightweight concrete block as an element of the wall structure (W23-W26), except in EP and POCP. The solution with a one-coat mortar as external cladding, and an ICB board covered by gypsum plasterboard in the inner surface of the clay brick (W34), has the worst performance in EP. The worst performance in POCP corresponds to a similar solution but with XPS as insulation material (W36). The solutions with the best environmental performance are the ones with a painted cement render as external cladding and gypsum plasterboard glued over the internal insulation (W28 to W31), namely in: ADP and GWP (W29, with an ICB board); AP (W28, with an EPS board); EP and POCP (W30, with a PUR board); ODP (W31, with a XPS board).

7.2.2.3. Cavity walls with insulation within the cavity

Concerning the environmental performance (LCA without energy for heating and cooling) of cavity walls with insulation within the cavity (Table 7.12) it was found that the alternative with one-coat mortar as external cladding, gypsum plasterboard as internal cladding, and a SW board in the cavity (W56) present the worst performance in three out of six categories: ADP, GWP and ODP. A similar solution but with an ICB board in the cavity (W58) has the highest value in EP, while another one with an EPS board in the cavity has the worst performance in POCP (W60). W53, similar to the latter ones but with a painted cement render as internal coating and an ICB board in the cavity, has the worst performance in AP.

Table 7.10 - LCA results for single leaf walls with external insulation - C2C of each alternative (A1-A5; B2-B4; C2-C4 and D)

External wall solution	ADP		AP		EP		GWP		ODP		POCP	
	kg Sb eq	Difference from W1 (%)	kg SO_2 eq	Diff. from W1 (%)	kg PO_4^{3-} eq	Diff. from W1 (%)	kg CO_2 eq	Diff. from W1 (%)	kg CFC-11 eq	Diff. from W1 (%)	kg C_2H_4 eq	Diff. from W1 (%)
W1	4.16E-01	0%	3.01E-01	0%	5.02E-02	0%	7.75E+01	0%	8.67E-06	0%	3.64E-03	0%
W2	2.31E-01	-44%	2.65E-01	-12%	3.82E-02	-24%	5.72E+01	-26%	5.11E-06	-41%	1.27E-02	248%
W3	1.81E-01	-56%	3.20E-01	6%	8.70E-02	73%	5.38E+01	-31%	5.17E-06	-40%	5.43E-03	49%
W4	2.55E-01	-39%	2.77E-01	-8%	3.30E-02	-34%	5.95E+01	-23%	5.14E-06	-41%	3.05E-03	-16%
W5	2.71E-01	-35%	2.92E-01	-3%	4.78E-02	-5%	6.69E+01	-14%	5.01E-06	-42%	2.70E-02	641%
W6	4.41E-01	6%	2.96E-01	-2%	5.12E-02	2%	7.79E+01	1%	8.73E-06	1%	3.83E-03	5%
W7	2.56E-01	-38%	2.60E-01	-14%	3.92E-02	-22%	5.75E+01	-26%	5.17E-06	-40%	1.29E-02	253%
W8	2.06E-01	-50%	3.14E-01	4%	8.81E-02	76%	5.42E+01	-30%	5.23E-06	-40%	5.62E-03	54%
W9	2.80E-01	-33%	2.72E-01	-10%	3.41E-02	-32%	5.99E+01	-23%	5.20E-06	-40%	3.23E-03	-11%
W10	2.96E-01	-29%	2.87E-01	-5%	4.88E-02	-3%	6.73E+01	-13%	5.07E-06	-41%	2.72E-02	647%
W11	5.15E-01	24%	3.73E-01	24%	3.32E-01	563%	8.98E+01	16%	8.83E-06	2%	1.13E-02	210%
W12	3.30E-01	-21%	3.36E-01	12%	3.20E-01	539%	6.95E+01	-10%	5.26E-06	-39%	2.03E-02	458%
W13	2.80E-01	-33%	3.91E-01	30%	3.69E-01	636%	6.61E+01	-15%	5.33E-06	-39%	1.31E-02	259%
W14	3.54E-01	-15%	3.48E-01	16%	3.15E-01	529%	7.18E+01	-7%	5.30E-06	-39%	1.07E-02	194%
W15	3.70E-01	-11%	3.63E-01	21%	3.30E-01	558%	7.92E+01	2%	5.17E-06	-40%	3.46E-02	851%
W16	5.39E-01	30%	3.68E-01	22%	3.34E-01	565%	9.02E+01	16%	8.89E-06	3%	1.15E-02	215%
W17	3.55E-01	-15%	3.31E-01	10%	3.22E-01	541%	6.98E+01	-10%	5.33E-06	-39%	2.05E-02	463%
W18	3.05E-01	-27%	3.86E-01	28%	3.70E-01	638%	6.65E+01	-14%	5.39E-06	-38%	1.33E-02	264%
W19	3.79E-01	-9%	3.43E-01	14%	3.16E-01	531%	7.22E+01	-7%	5.36E-06	-38%	1.09E-02	199%
W20	3.95E-01	-5%	3.58E-01	19%	3.31E-01	560%	7.96E+01	3%	5.23E-06	-40%	3.48E-02	856%
W21	7.94E-01	91%	5.55E-01	84%	1.20E-01	139%	1.38E+02	79%	1.06E-05	23%	4.47E-02	1129%
W22	8.19E-01	97%	5.50E-01	82%	1.21E-01	141%	1.39E+02	79%	1.07E-05	23%	4.49E-02	1134%

Table 7.11 - LCA results for single leaf walls with internal, and without (W23-W26), insulation - C2C of each alternative (A1-A5; B2-B4; C2-C4 and D)

External wall solution	ADP		AP		EP		GWP		ODP		POCP	
	kg Sb eq	Difference from W1 (%)	kg SO_2 eq	Diff. from W1 (%)	kg PO_4^{3-} eq	Diff. from W1 (%)	kg CO_2 eq	Diff. from W1 (%)	kg CFC-11 eq	Diff. from W1 (%)	kg C_2H_4 eq	Diff. from W1 (%)
W23	6.08E-01	46%	4.93E-01	64%	5.21E-02	4%	7.71E+01	0%	1.06E-05	22%	1.52E-02	319%
W24	6.33E-01	52%	4.88E-01	62%	5.32E-02	6%	7.75E+01	0%	1.06E-05	23%	1.54E-02	324%
W25	6.22E-01	50%	5.06E-01	68%	5.56E-02	11%	7.94E+01	2%	1.12E-05	29%	1.61E-02	341%
W26	6.47E-01	56%	5.00E-01	66%	5.67E-02	13%	7.98E+01	3%	1.13E-05	30%	1.62E-02	346%
W27	4.06E-01	-2%	2.77E-01	-8%	4.67E-02	-7%	7.23E+01	-7%	8.14E-06	-6%	3.02E-03	-17%
W28	2.22E-01	-47%	2.40E-01	-20%	3.47E-02	-31%	5.19E+01	-33%	4.58E-06	-47%	1.21E-02	231%
W29	1.72E-01	-59%	2.95E-01	-2%	8.35E-02	66%	4.86E+01	-37%	4.64E-06	-46%	4.81E-03	32%
W30	2.45E-01	-41%	2.52E-01	-16%	2.95E-02	-41%	5.43E+01	-30%	4.61E-06	-47%	2.42E-03	-33%
W31	2.62E-01	-37%	2.67E-01	-11%	4.43E-02	-12%	6.16E+01	-20%	4.48E-06	-48%	2.64E-02	624%
W32	4.20E-01	1%	2.89E-01	-4%	5.02E-02	0%	7.45E+01	-4%	8.77E-06	1%	3.83E-03	5%
W33	2.36E-01	-43%	2.53E-01	-16%	3.82E-02	-24%	5.42E+01	-30%	5.21E-06	-40%	1.29E-02	254%
W34	1.86E-01	-55%	3.08E-01	2%	8.70E-02	73%	5.09E+01	-34%	5.27E-06	-39%	5.62E-03	55%
W35	2.60E-01	-38%	2.65E-01	-12%	3.30E-02	-34%	5.65E+01	-27%	5.24E-06	-40%	3.24E-03	-11%
W36	2.76E-01	-34%	2.80E-01	-7%	4.78E-02	-5%	6.39E+01	-18%	5.11E-06	-41%	2.72E-02	647%

Table 7.12 - LCA results for cavity walls - C2C of each alternative (A1-A5; B2-B4; C2-C4 and D)

External wall solution	ADP		AP		EP		GWP		ODP		POCP	
	kg Sb eq	Difference from W1 (%)	kg SO_2 eq	Diff. from W1 (%)	kg PO_4^{3-} eq	Diff. from W1 (%)	kg CO_2 eq	Diff. from W1 (%)	kg CFC-11 eq	Diff. from W1 (%)	kg C_2H_4 eq	Diff. from W1 (%)
W37	1.44E-01	-65%	2.56E-01	-15%	2.83E-02	-44%	5.36E+01	-31%	5.15E-06	-41%	-7.17E-04	-120%
W38	1.69E-01	-59%	2.50E-01	-17%	2.93E-02	-41%	5.40E+01	-30%	5.22E-06	-40%	-5.31E-04	-115%
W39	1.58E-01	-62%	2.68E-01	-11%	3.18E-02	-37%	5.58E+01	-28%	5.79E-06	-33%	9.88E-05	-97%
W40	1.83E-01	-56%	2.63E-01	-13%	3.28E-02	-35%	5.62E+01	-27%	5.85E-06	-33%	2.85E-04	-92%
W41	3.38E-01	-19%	3.00E-01	0%	4.41E-02	-12%	7.39E+01	-5%	7.98E-06	-8%	2.20E-03	-39%
W42	2.01E-01	-52%	2.73E-01	-9%	3.01E-02	-40%	5.86E+01	-24%	5.30E-06	-39%	8.97E-03	146%
W43	1.62E-01	-61%	3.13E-01	4%	5.43E-02	8%	5.57E+01	-28%	5.32E-06	-39%	3.32E-03	-9%
W44	2.44E-01	-41%	2.91E-01	-3%	3.23E-02	-36%	6.29E+01	-19%	5.39E-06	-38%	2.60E-03	-28%
W45	2.31E-01	-45%	2.85E-01	-5%	3.13E-02	-38%	6.31E+01	-19%	5.23E-06	-40%	2.35E-02	545%
W46	3.63E-01	-13%	2.95E-01	-2%	4.52E-02	-10%	7.43E+01	-4%	8.05E-06	-7%	2.39E-03	-34%
W47	2.26E-01	-46%	2.68E-01	-11%	3.12E-02	-38%	5.90E+01	-24%	5.37E-06	-38%	9.16E-03	152%
W48	1.87E-01	-55%	3.08E-01	2%	5.54E-02	10%	5.61E+01	-28%	5.38E-06	-38%	3.50E-03	-4%
W49	2.69E-01	-35%	2.86E-01	-5%	3.34E-02	-33%	6.33E+01	-18%	5.45E-06	-37%	2.79E-03	-23%
W50	2.55E-01	-39%	2.80E-01	-7%	3.24E-02	-35%	6.35E+01	-18%	5.29E-06	-39%	2.37E-02	550%
W51	3.53E-01	-15%	3.13E-01	4%	4.76E-02	-5%	7.61E+01	-2%	8.62E-06	-1%	3.02E-03	-17%
W52	2.15E-01	-48%	2.85E-01	-5%	3.36E-02	-33%	6.09E+01	-21%	5.94E-06	-32%	9.79E-03	169%
W53	1.76E-01	-58%	3.25E-01	8%	5.78E-02	15%	5.80E+01	-25%	5.95E-06	-31%	4.13E-03	14%
W54	2.58E-01	-38%	3.03E-01	1%	3.58E-02	-29%	6.51E+01	-16%	6.02E-06	-31%	3.42E-03	-6%
W55	2.45E-01	-41%	2.98E-01	-1%	3.48E-02	-31%	6.54E+01	-16%	5.86E-06	-32%	2.43E-02	568%
W56	3.77E-01	-9%	3.07E-01	2%	4.87E-02	-3%	7.65E+01	-1%	8.68E-06	0%	3.21E-03	-12%
W57	2.40E-01	-42%	2.80E-01	-7%	3.47E-02	-31%	6.13E+01	-21%	6.00E-06	-31%	9.97E-03	174%
W58	2.01E-01	-52%	3.20E-01	6%	5.89E-02	17%	5.84E+01	-25%	6.02E-06	-31%	4.32E-03	19%
W59	2.83E-01	-32%	2.98E-01	-1%	3.69E-02	-26%	6.55E+01	-15%	6.08E-06	-30%	3.61E-03	-1%
W60	2.70E-01	-35%	2.93E-01	-3%	3.59E-02	-28%	6.57E+01	-15%	5.93E-06	-32%	2.45E-02	573%

W37 is the solution with the best environmental performance in five out of six environmental categories. It includes a painted cement render as external and internal cladding and LECA filling the whole cavity. In the remaining category, AP, the best performance is achieved by a similar solution but with gypsum plasterboard as internal cladding (W38). It is however important to highlight that these two alternatives (along with W39 and W40) are the ones with the worst thermal performance of the 60 being evaluated (see Appendix 7.IV) and the ones with the highest heating and cooling needs.

7.2.2.4. Environmental performance C2C – overview of the 60 alternatives

An overview of the LCA of the 60 alternatives allows the conclusion that single leaf walls with GFRC panels as external cladding (W21 and W22) present the worst performance in five out of six categories (except EP), despite having the best thermal performance and the lowest heating and cooling needs within the alternatives being evaluated (see Appendix 7.IV). In EP, the worst performance corresponds to single leaf walls with wood-plastic extruded boards as external cladding (W11 to W20), namely W18. The best overall environmental performance is achieved in three categories (ADP, EP and POCP) by the cavity wall with a painted cement render as external and internal cladding and LECA filling the whole cavity (W37). This better performance is however offset by the worst thermal performance of this solution (along with W38, W39 and W40) in comparison with the remaining alternatives evaluated (see Appendix 7.IV). The best performance in the remaining categories corresponds to the single leaf walls with a painted cement render as external cladding and gypsum plasterboard glued over the internal insulation (W28 to W31), namely in: AP (W28, with an EPS board); GWP (W29, with an ICB board); and in ODP (W31, with a XPS board).

7.2.3. Economic performance C2C and energy performance

The NPV of the economic (*Cec*, see 7.1.6) and energy (*Ceg*, see 7.1.6.3) costs (without weighting or aggregation) for the external wall solutions under evaluation are presented in Figure 7.7, Figure 7.8 and Figure 7.9.

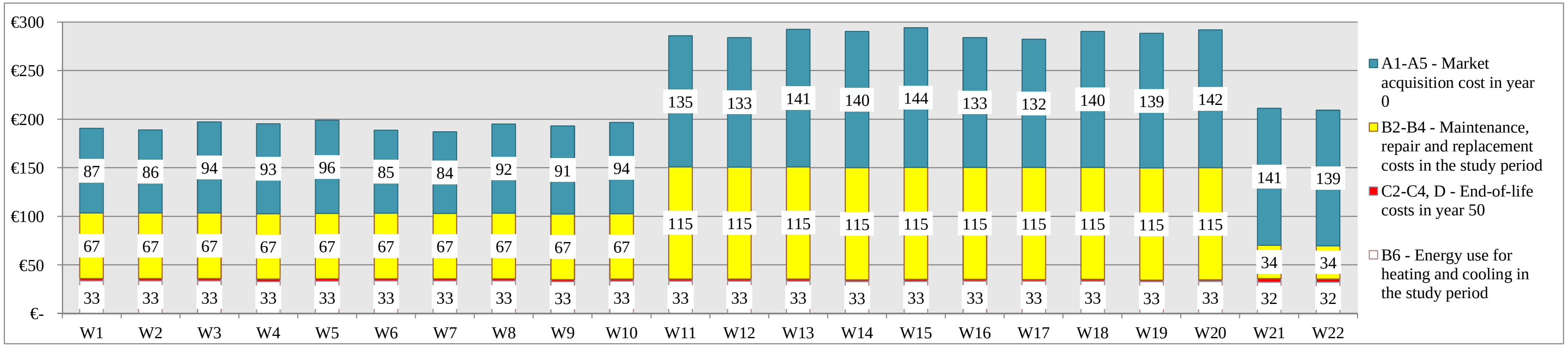

Figure 7.7 - NPV of the economic (*Cec*: A1-A5, B2-B4 and C2-C4 and D stages) and energy (*Ceg* -B6 sub-stage) costs of single leaf walls with external insulation

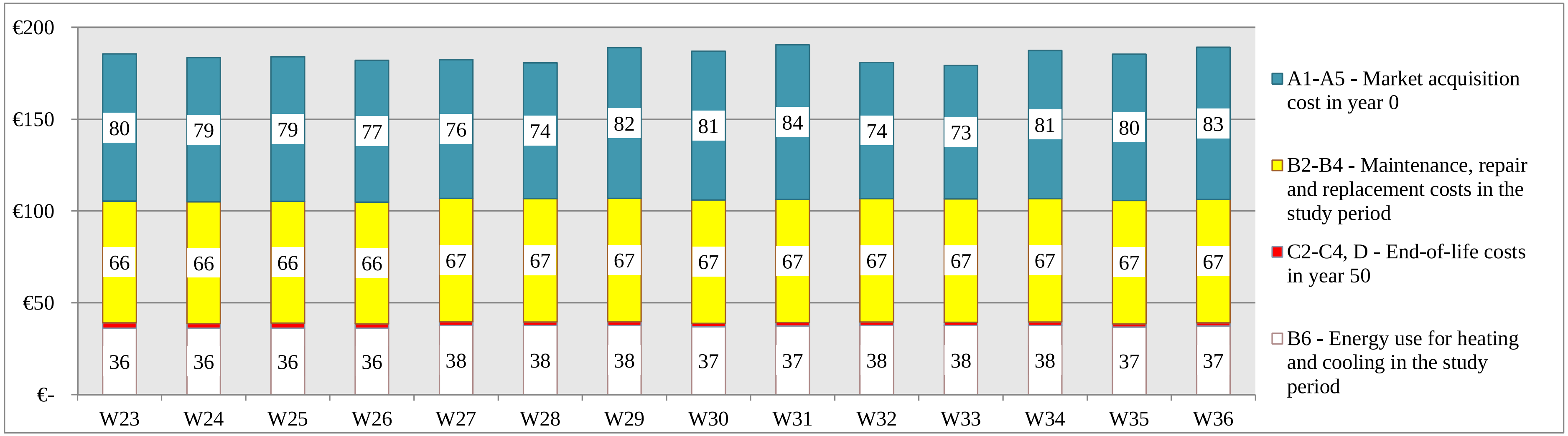

Figure 7.8 - NPV of the economic (*Cec*: A1-A5, B2-B4 and C2-C4 and D stages) and energy (*Ceg* -B6 sub-stage) costs of single leaf walls with internal, and without (W23-W26), insulation

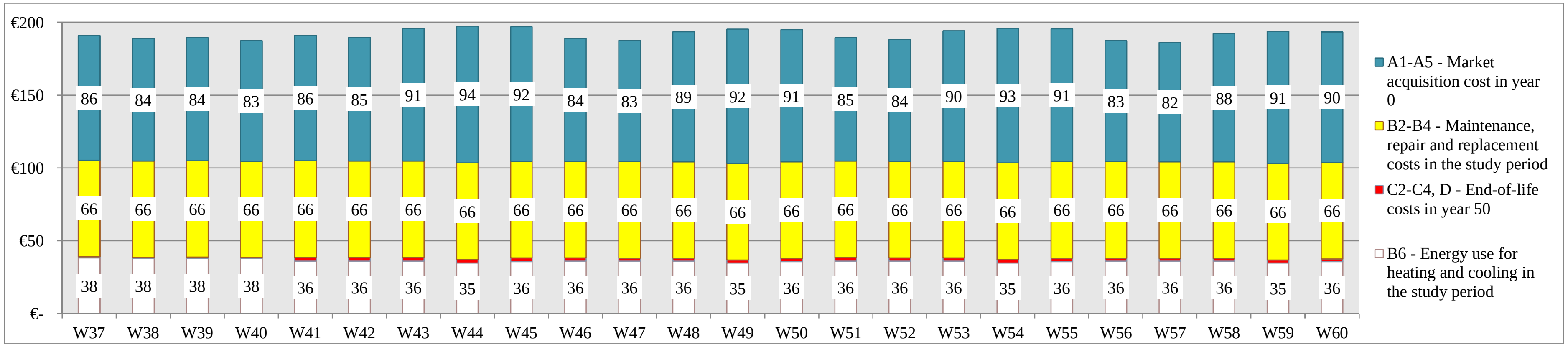

Figure 7.9 - NPV of the economic (*Cec*: A1-A5, B2-B4 and C2-C4 and D stages) and energy (*Ceg* -B6 sub-stage) costs of cavity walls

7.2.3.1. Single leaf walls with external insulation

Concerning the economic performance of the single leaf walls with external insulation (Figure 7.7), the cheapest solution in terms of initial cost is W7, corresponding to an ETICS system with an EPS board as external cladding and a gypsum plasterboard as internal cladding.

The most expensive one is W15, which includes wood-plastic extruded boards with XPS boards in the corresponding VRF system and a painted cement render as internal coating. The solutions with this external cladding (W11 to W20) present the highest maintenance costs, while the ones with GFRC panels as external cladding (W21 and W22) present the lowest ones. This dissimilarity is highly influenced by the differentiated service life and maintenance needs of these external cladding solutions. Concerning the NPV of the end-of-life costs, W21 is the most expensive due to the cost of transportation and disposal in landfill of its heavy claddings (GFRC panels and painted cement render). The cheapest alternative in this life cycle stage is W19, due to the lower volume of insulation material (0.06 m^3 of PUR) that is transported to landfill in this alternative in comparison with the other ones with wood-plastic extruded boards as external cladding and gypsum plasterboard as internal cladding (W16 to W20).

7.2.3.2. Single leaf walls with internal, and without (W23-W26), insulation

Figure 7.8 shows the economic performance of single leaf walls with internal, and without (W23-W26), insulation. The cheapest solution in terms of initial cost is W33, which corresponds to a one-coat mortar as external cladding and an EPS board covered by gypsum plasterboard in the inner surface of the clay brick. W31 is the most expensive one and is composed of a painted cement render as external cladding and gypsum plasterboard glued over a XPS board. The range of solutions with the lowest maintenance costs (W23 to W26) include a painted cement render or one-coat mortar as external cladding and a painted cement render or a painted gypsum plasterboard as internal cladding. The remaining solutions (W27 to W36) present a slightly higher maintenance cost due to the increasing repair cost of the internal cladding of gypsum plasterboard glued to an insulation board. W23 is the most expensive solution in terms of NPV of the end-of-life costs due to the cost of transport and disposal in landfill of its heavier claddings (painted cement render as internal and external cladding). W35 is the cheapest solution in this life cycle stage due to the lower volume of insulation material (0.06 m^3 of PUR) that is transported to landfill in this alternative within the ones with one-coat mortar as external cladding and gypsum plasterboard as internal cladding.

7.2.3.3. Cavity walls with insulation within the cavity

Concerning the economic performance of cavity walls with insulation within the cavity (Figure 7.9), it was found that the cheapest solution in terms of initial cost is W57, which has a one-coat mortar as external cladding, gypsum plasterboard as internal cladding, and an EPS board in the cavity. W44 is the most expensive solution of this group due to the painted cement render as internal and external cladding and to the PUR board placed in the cavity. All the solutions in this group have similar maintenance costs due to the equal maintenance plan defined for the external and internal claddings considered. Concerning the NPV of the end-of-life costs, W41 is the most expensive because SW boards were the only insulation material that was considered to be sent to landfill (and not reused on-site, as LECA, or recycled like the remaining insulation materials) at end-of-life. The cheapest solution in this life cycle stage is W40 due to the reuse on-site of LECA and to sending a lower weight of demolition waste from claddings to landfill.

7.2.3.4. Economic performance C2C and energy performance – overview of the 60 alternatives

An overview of the economic performance of the 60 alternatives allows the conclusion that W33, single leaf walls with internal insulation of EPS board covered by gypsum plasterboard and one-coat mortar as external cladding, is the cheapest solution in terms of initial cost. The most expensive one is W15, mainly due to the use of wood-plastic extruded boards in the corresponding VRF system in this single leaf wall with external insulation, which makes the range of solutions where it is used (W11 to W20) the most expensive ones. Single leaf walls with external insulation also include the solutions with the lowest (W21 and W22, with GFRC panels as external cladding) and the highest (W11 to W20, with wood-plastic extruded boards as external cladding) maintenance costs due to the differences referenced. Concerning the NPV of the end-of-life costs, W21 is the most expensive alternative within the 60 being evaluated due to the cost of transport and disposal in landfill of the heavy claddings (GFRC panels and painted cement render) of this single leaf wall. The cheapest solution in this life cycle stage is a cavity wall - W40 - mainly due to the reuse on-site of LECA.

Concerning the energy costs, it was confirmed that the differences between the alternatives are directly related with their U-values and with the position of the insulation (see 0). It was also found that, for each group of walls (Figure 7.7, Figure 7.8 and Figure 7.9), the alternatives with the highest and lowest initial cost (A1-A5) are also the ones with extreme values both for the aggregated assessment of the NPV of the economic (*Cec*: A1-A5, B2-B4 and C2-C4 and D stages) costs, and for the aggregated assessment of the NPV of the *Cec* and energy (*Ceg* -B6 sub-stage) costs, except in the case of the lower values of the cavity walls group. In this case, W57 is the cheapest solution in terms of the aggregated assessment of the NPV of the *Cec* and *Ceg* costs, but not when only the NPV of the *Cec* is analysed. In the latter case, W40 is the cheapest solution mainly due to its lower NPV of the end-of-life costs that results from the reuse on-site of LECA.

7.2.4.3E cost-C2C results

The potential environmental cost (*Cev*, referenced as "environmental cost" hereafter) corresponds to the application of the EIAM *Eco-costs* to the LCA results for each life cycle stage (see 7.1.5 and 0). The NPV of the *Cev* of each alternative is found by applying equation (7.1). In one of the applications already undertaken in the scope of this thesis of the 3E-C2C method (Silvestre, J. D.; de Brito*; et al.*, 2012b), the author compared the results of the maintenance, energy use and end-of-life environmental costs of five external wall alternatives with (NPV of the *Cev*) and without a discount rate. These results are presented in Figure 7.10 and Figure 7.11, respectively, just to draw conclusions from the comparison of these approaches.

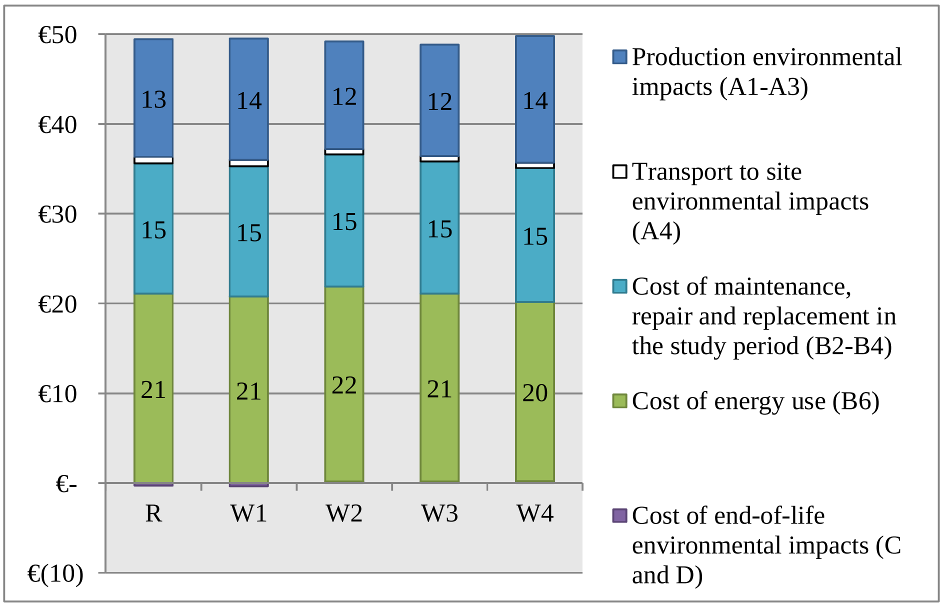

Figure 7.10 - NPV of the environmental (*Cev*) cost of five external wall alternatives (Silvestre, J. D.; de Brito*; et al.*, 2012b)

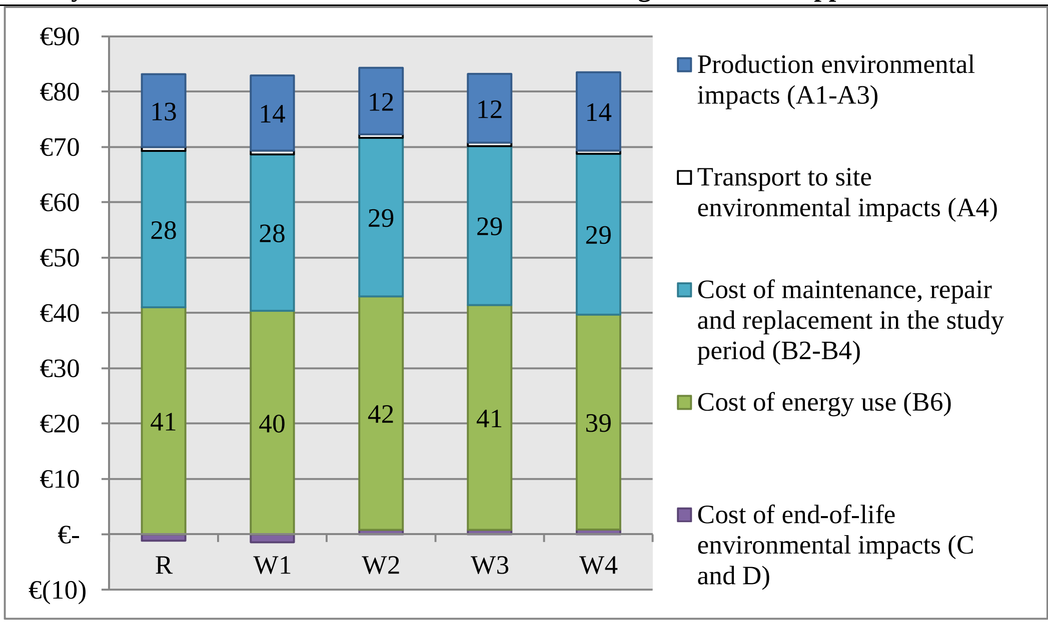

Figure 7.11 - Environmental (*Cev*) cost without discount rate of five external wall alternatives (Silvestre, J. D.; de Brito*; et al.*, 2012b)

When marginal prevention costs from life-cycle stages after stage A are considered at their present value and not discounted (Figure 7.11), even a solution that does not have the lowest environmental impacts in either the product (A1-A3) or the energy use (B6) stages can have a lower overall *Cev* thanks to lower maintenance and end-of-life costs (i.e. W1 in Figure 7.11). When marginal prevention costs from life-cycle stages after stage A are discounted (Figure 7.10), these costs become less relevant and the alternatives with less environmental impacts in the product stage (A1-A3) are always more prone to having a lower overall *Cev*, even when they have the highest environmental costs for energy use (i.e. W2 and W3 in Figure 7.10). Nevertheless, *Eco-costs* for future environmental impacts should mainly be based on NPV, because of its meaning and nature (see 7.1.7).

7.2.4.1. NPV of the environmental cost (Cev) C2C of the 60 alternatives

Figure 7.12, Figure 7.13 and Figure 7.14 present the NPV of the environmental cost (*Cev*) C2C of each alternative using the 3E *cost*-C2C approach. The analysis of the contribution of each life cycle stage to these results allowed the following conclusions to be drawn:

- The production (A1-A3) of each wall can represent between 31% and 56% of its discounted C2C environmental cost;
- The environmental cost of the transport to site (A4) varies between 1.1% and 2.2% in the NPV of the *Cev* C2C of the alternatives evaluated;

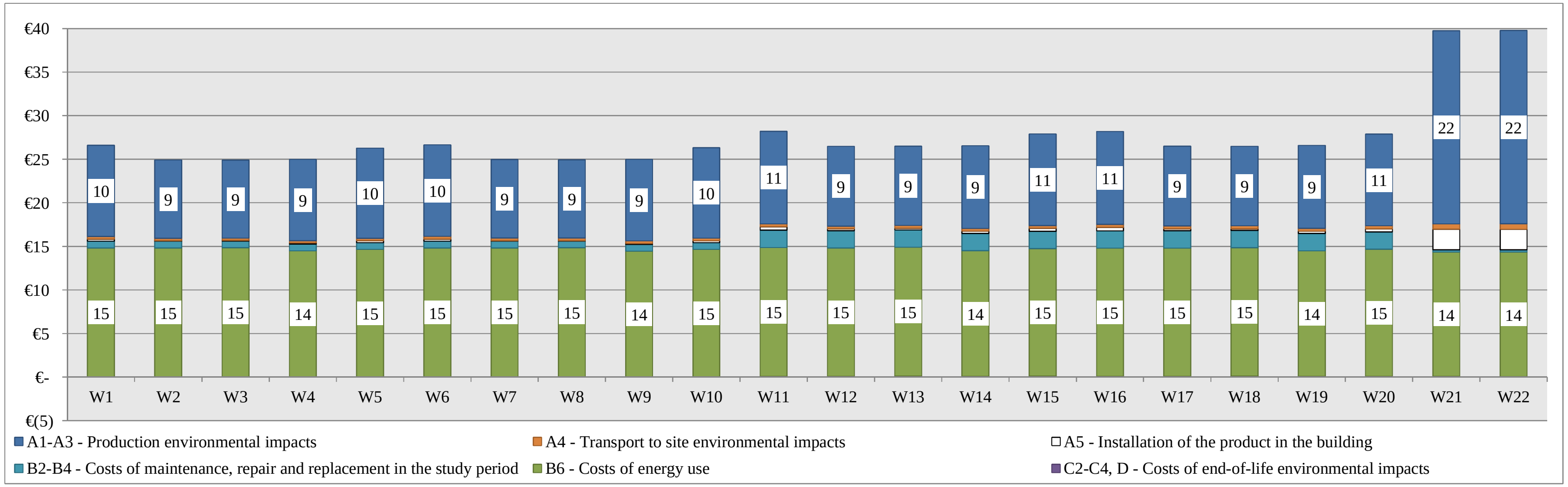

Figure 7.12 - NPV of the environmental (*Cev*) cost of single leaf walls with external insulation

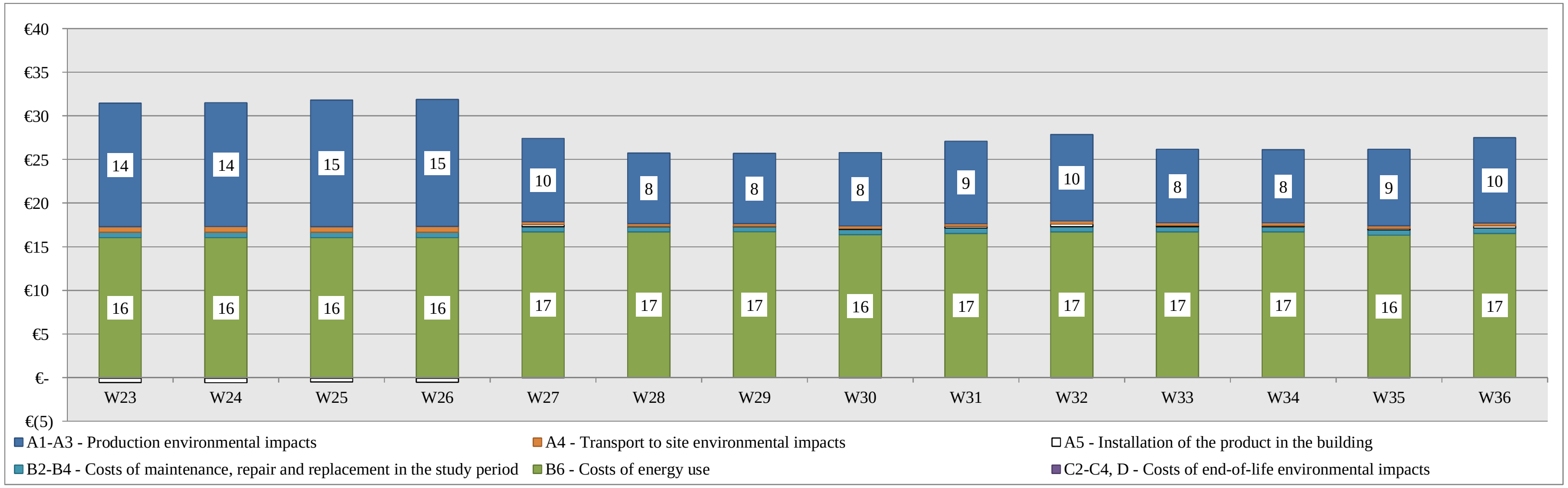

Figure 7.13 - NPV of the environmental (*Cev*) cost of single leaf walls with internal, and without (W23-W26), insulation

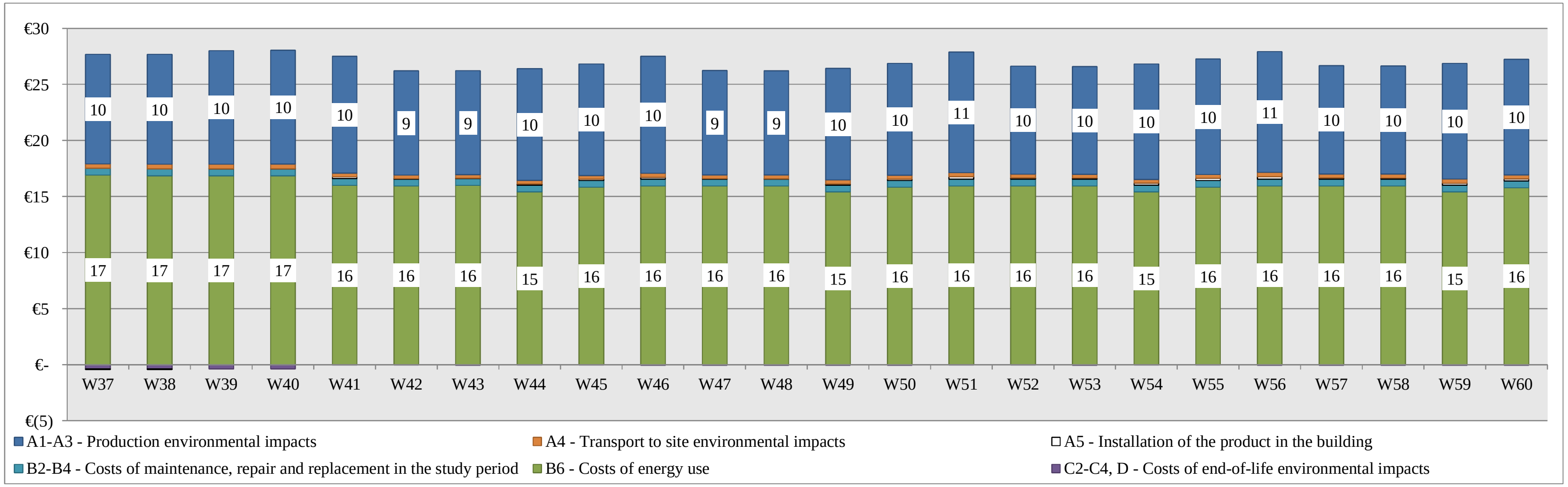

Figure 7.14 - NPV of the environmental (*Cev*) cost of cavity walls

- The process of installation in the building (A5) can represent 5.9% of the C2C environmental cost of an external wall as a maximum, but, on the other hand, can contribute up to -1.6% of the environmental cost (or 1.6% of the environmental benefits) in other alternatives;
- The discounted environmental cost of the maintenance operations (B2-B4) can signify between 0.7% and 7.5% of the C2C impacts of an external wall;
- Concerning the environmental costs of energy use (B6), its discounted value can contribute between 36% and 65% to the C2C impacts of each alternative, and the external walls that present these values are the same with extreme values for the product stage (A1-A3), but in inverse order;
- The discounted end-of-life stage (C2-C4, and D) environmental cost can represent 0.4% of the C2C environmental cost of an external wall as a maximum, but, on the other hand, can contribute up to -1.4% of the environmental cost (or 1.4% of the environmental benefits) in other alternatives;
- The alternatives that present the lowest and the highest percentages of contribution of each life cycle stage for these results are also the ones that have similar extreme absolute values in the same life-cycle stages (see the detailed analysis of absolute values per group of walls in the following paragraphs).

7.2.4.1.1. Single leaf walls with external insulation

Concerning the environmental cost of the production (A1-A3) of single leaf walls with external insulation (Figure 7.12) it was found that the alternatives with GFRC panels as external cladding (W21 and W22) present the worst performance, which is in accordance with the analysis made of the LCA results C2C (see 0). The latter (W22) also presents the highest NPV of the environmental cost (*Cev*) C2C within this group. The solution with the lowest environmental cost at this stage (and also from a C2C perspective) is the one with an ETICS system with an ICB board as external cladding and a painted cement render as internal cladding (W3). This is also the solution with the lowest environmental cost of installation in the building (A5), namely due to the low environmental cost of production and high environmental benefits of disposal (wood recycling) of on-site ICB wastage. W21 and W22 are also the solutions with the highest environmental costs of the transport to site (A4) and installation in the building (A5). The former, related to the high weight of GFRC panels. The latter are due to the manufacture and transportation of ancillary materials (i.e. EPS boards, adhesive mortar, metallic accessories and sealants) required for the installation of this cladding. The solutions with the lowest impact at this stage are the ones with an ETICS system with an ICB board as external cladding and a painted cement render as internal cladding (W2 to W5, W2 being the solution with the lowest environmental cost due to the low weight of EPS boards in comparison with the remaining insulation products) due to the shorter distance to construction site from the place of production of stabilised mortar used as render in these two claddings in comparison with the remaining cladding solutions.

The solutions with the highest (W11 to W20) and lowest (W21 and W22) maintenance costs (see 7.2.3) are also the ones with extreme environmental cost at this stage (B2-B4). W6, W7 and W9 are the solutions with the lowest environmental costs (or highest environmental benefits) at end-of-life stage. This performance is related with the lower environmental impacts of the disposal in landfill (and/or lower weight) of SW, EPS and PUR boards in comparison with the remaining solutions with an ETICS system as external cladding and a gypsum plasterboard as internal cladding. W13 is the solution with the highest environmental cost at this stage due to the high weight of the wood-plastic extruded boards with ICB boards in the corresponding VRF system that are sent to landfill (and corresponding environmental impacts in transport and disposal).

7.2.4.1.2. Single leaf walls with internal, and without (W23-W26), insulation

Figure 7.13 shows the NPV of the environmental cost (*Cev*) C2C of the single leaf walls with internal, and without (W23-W26), insulation. The alternatives with the worst environmental performance C2C in the majority of impact categories (see 0) are also the ones with the highest environmental cost at the product (A1-A3) and transport to site (A4) stages (without insulation material and with a lightweight concrete block as an element of the wall structure - W23-W26, W26 being the solution with the highest environmental cost in these stages and also from a C2C perspective due to the production and transport of claddings - one-coat mortar and gypsum plasterboard - that are produced in a farther place than the stabilised mortar used in painted cement renders). However, these solutions are the ones with the lowest environmental costs (or highest economic benefits) in the installation (A5), namely W23 and W24, due to the lower quantity of construction wastes in comparison with the solutions with insulation boards. This characteristic makes them the solutions that also have the lowest environmental costs at the end-of-life stage (namely W24 and W26, due to the lower weight of the gypsum plasterboard that is sent to landfill in these alternatives in comparison with the painted cement render that is the internal coating of W23 and W25).

The solution with the best environmental performance C2C in two environmental categories (ADP and GWP see 0) is the one with the lowest environmental cost at the product stage and from C2C (W29: painted cement render as external cladding and gypsum plasterboard glued over an ICB board in the inner surface of the clay brick). Two similar alternatives, but with an EPS (W28) and a PUR board (W30), are the ones with the lowest environmental costs of transport to site (A4) due to the lower weight and shorter transportation distances of these insulations products. W32, with a one-coat mortar as external cladding and gypsum plasterboard glued over an SW board in the inner surface of the clay brick, has the highest environmental costs in the installation in the building (A5) due to the high weight of SW wastage that has to be transported to landfill and to the corresponding disposal impacts. All the solutions in this group present equal environmental cost at maintenance stage (B2-B4) due to the similarity of claddings, and corresponding conservation operations, during the study period. W29 is the solution with the highest environmental cost at end-of-life stage due to the high weight of ICB boards that are sent to landfill (and corresponding environmental impacts in transportation and disposal).

7.2.4.1.3. Cavity walls with insulation within the cavity

Concerning the environmental cost of the production (A1-A3) of cavity walls with insulation within the cavity (Figure 7.14) it was found that W56 has the worst performance, namely due to the high environmental impacts of the production of SW boards (since other solutions also have one-coat mortar as external cladding and gypsum plasterboard as internal cladding, but other insulation products). This alternative also presents the highest NPV of the environmental cost (*Cev*) C2C within this group. This classification is in accordance with the analysis of LCA results C2C, because this alternative has the worst performance in three out of six environmental categories (see 0). The solution with the lowest environmental cost within this group from a C2C perspective is W48, which includes an ICB board in the cavity. Nevertheless, the solution with the best performance at production (A1-A3) stage is W43, mainly due to the use of an ICB board in the cavity (but with just a slight difference to W48 due to the different internal coating solutions: gypsum plasterboard in the latter and painted cement render in W43). This alternative is also in the group of the alternatives (W42 to W45) with less environmental cost of transport to site (A4) mainly due to the shorter distance to construction site from the place of production of stabilised mortar used as render in internal and external cladding in comparison with the remaining cladding solutions. On the other hand, W40 is the solution with the highest environmental cost at this stage due to the higher weight and/or longer transportation distances of the corresponding cladding (one-coat mortar and gypsum plasterboard) and insulation (LECA) solutions.

The solution with the highest environmental cost of installation in the building (A5) is W51 due to the high weight of SW wastage that has to be transported to landfill and to the corresponding disposal impacts. The alternatives with the lowest environmental cost at this stage are W37 and W38 (the former with a painted cement render as external and internal cladding and LECA filling the whole cavity, while the latter is similar but has a gypsum plasterboard as internal cladding) due to recycling of stabilised mortar wastage, the inexistence of packaging from this product to be processed and to the reuse on-site of LECA. All the solutions in this group present equal environmental cost at maintenance stage (B2-B4) due to the similarity of claddings, and corresponding conservation operations, during the study period. All these alternatives have environmental benefits at end-of-life stage, W40 (with a one-coat mortar as external cladding, gypsum plasterboard as internal cladding and LECA filling the whole cavity) being the best one in this issue due to the reuse on-site of LECA and to the lower weight of claddings that are transported and disposed of into landfill in this alternative in comparison with the ones with painted cement render. This was also considered the cheapest solution in this life cycle stage (see 7.2.3). The lowest environmental benefits at this stage are achieved by five alternatives (W41, W42, W44, W45 and W51) due to the high weight of claddings (and of SW board in W41 and W51) that are transported and disposed of into landfill, and due to the high quantity and environmental benefits of the ICB board recycling (W43) in comparison with the end-of-life of the remaining insulation materials (recycling of EPS in W42, PUR in W44 and XPS in W45, and SW sent to landfill in W41).

7.2.4.1.4. *<u>Overview of the 60 alternatives</u>*

An overview of the NPV of the environmental cost (*Cev*) C2C of the 60 alternatives allows the conclusion that single leaf walls with GFRC panel as external cladding and gypsum plasterboard as internal cladding (W22) have the highest NPV of the environmental cost (*Cev*) C2C and also the worst performance in the product stage (A1-A3), which is in accordance with the analysis made of the LCA results C2C (see 0). W21 and W22 are also the solutions with the highest environmental costs of installation in the building (A5) due to the manufacture and transportation of ancillary materials (i.e. EPS boards, adhesive mortar, metallic accessories and sealants) required for the installation of GFRC panels. This alternative has, however, the best thermal performance within the alternatives being evaluated (see

Appendix 7.IV). The best performance at this stage is also achieved by single leaf walls but with a painted cement render as external cladding and gypsum plasterboard glued over an ICB board (W29). Nevertheless, the solution with the lowest environmental cost from a C2C perspective is W3, which is a single leaf wall with external insulation, an ETICS system with an ICB board as external cladding, and a painted cement render as internal cladding. Single leaf walls with an ETICS system with an EPS board as external cladding, and a painted cement render as internal cladding (W2), is the alternative with the lowest environmental cost at the transport to site stage (A4). This is due to: the shorter distance to the construction site from the place of production of stabilised mortar used as render in these two claddings in comparison with the remaining cladding solutions; the shorter distance to the construction site and lower weight of EPS boards in comparison with the remaining insulation products. The solution with the highest environmental cost at this stage is W26, which has a lightweight concrete block as an element of the wall structure, due to the production and transport of claddings - one-coat mortar and gypsum plasterboard - that are produced in a farther place than stabilised mortar used in painted cement renders. Similar alternatives but with a painted cement render as external cladding (W23, with the same solution as internal coating, and W24, with gypsum plasterboard as internal coating) have the lowest environmental costs (or highest economic benefits) in the installation stage (A5) due to the lower quantity of construction waste in comparison with the solutions with insulation boards.

Single leaf walls with external insulation with the highest (W11 to W20, with wood-plastic extruded boards as external cladding) and lowest (W21 and W22, with GFRC panels as external cladding) maintenance costs (see 7.2.3) are also the ones with extreme environmental cost at this stage (B2-B4). Another alternative from this group, W13, is the solution with the highest environmental cost at the end-of-life stage due to the high weight of the wood-plastic extruded boards with ICB boards in the corresponding VRF system that are sent to landfill (and corresponding environmental impacts in transport and disposal). The cheapest solution in this life cycle stage (see 7.2.3) is also the one with the highest environmental benefits (W40, a cavity wall with a one-coat mortar as external cladding, gypsum plasterboard as internal cladding and LECA filling the whole cavity) due to the reuse on-site of LECA and to the lower weight of claddings that are transported and disposed of into landfill in this alternative in comparison with the ones with painted cement render.

Concerning the environmental costs of energy use (B6), it was confirmed that the differences between the alternatives are directly related with their U-values and with the position of the insulation (see 0). It was also found that, for each group of walls (Figure

7.12, Figure 7.13 and Figure 7.14), the alternatives with the highest and lowest environmental cost at the product stage (A1-A3) are also the ones with extreme values for the aggregated assessment of the NPV of the environmental costs (*Cev*: A1-A3, A4, A5, B2-B4, B6 and C2-C4 and D stages), except in the case of the solutions with the lowest value in the group of cavity walls. Nevertheless, in this case the two solutions (W43 and W48) with the lowest environmental cost at the product stage (A1-A3) are also the ones with the lowest values for the aggregated assessment of the NPV of the *Cev*, but in an inverse order.

7.2.4.2. NPV of the total environmental, economic and energy cost

Once the results of each 3E-C2C module have been analysed separately, the 3E *cost*-C2C approach can be used to compare the 3E performance of the alternatives, using the same economic unit. For each alternative, the cost in year n (per square metre of external wall) is the sum of the environmental (*Cev*), economic (*Cec*) and energy (*Ceg*) costs, as described in section 7.1.7. The weighted results of the 3E performance based on the *Eco-costs* model are presented in Figure 7.15, Figure 7.16, and Figure 7.17. The 3E *cost*-C2C results show the importance of economic cost, which accounts for between 68% and 81% of the total cost. This fact makes the result of this type of study highly dependent on the inherent uncertainty of market prices for acquisition and on maintenance operations (the first are more important because they occur in year 0). Environmental (*Cev*) costs contribute between 8% and 16% to the total cost, being similar to the energy (*Ceg*) costs contribution (between 10% and 18%).

As referred, the differences between the alternatives in terms of energy (*Ceg*) costs are directly related with their U-values and with the position of the insulation (see 0). The analysis of the aggregated NPV of the economic (*Cec*, see 7.2.3) and environmental (*Cev*, see 7.2.4.1) costs was completed. The weighted results of the 3E performance based on the *Eco-costs* model are therefore analysed per external wall group only in terms of the NPV of the total environmental, economic and energy cost.

7.2.4.2.1. Single leaf walls with external insulation

Concerning the single leaf walls with external insulation (Figure 7.15) it was found that W7 has the best performance from a 3E *cost*-C2C point of view. This is also the cheapest solution in terms of initial cost (see 7.2.3), the alternative with the best environmental performance C2C in terms of AP (see 0), and is within the group of solutions with the lowest environmental costs (or highest environmental benefits) at end-of-life stage. It corresponds to an ETICS system with an EPS board as external cladding and gypsum plasterboard as internal cladding. The worst performance in terms of 3E *cost*-C2C results corresponds to W15, which includes wood-plastic extruded boards with XPS boards in the corresponding VRF system and a painted cement render as internal coating. This alternative is, in opposition to W7, the most expensive of this group and also presents the highest maintenance costs due to the limited service life and maintenance needs of its external cladding.

7.2.4.2.2. Single leaf walls with internal, and without (W23-W26), insulation

Figure 7.16 shows the 3E *cost*-C2C results of single leaf walls with internal, and without (W23-W26), insulation, the difference between the highest and the lowest value being only 6%. W33 shows the best performance from a 3E *cost*-C2C point of view and is also the cheapest solution of this group in terms of initial cost. It corresponds to one-coat mortar as external cladding and an EPS board covered by gypsum plasterboard in the inner surface of the clay brick. The worst 3E *cost*-C2C performance corresponds to W31, which is the most expensive solution within this group but also the one with the best environmental performance C2C in ODP (see 0). This alternative is composed of a painted cement render as external cladding and gypsum plasterboard glued over a XPS board.

7.2.4.2.3. Cavity walls with insulation within the cavity

Concerning the 3E *cost*-C2C performance of cavity walls with insulation within the cavity (Figure 7.17), the difference between the highest and the lowest value is even lower than in the last group (only 5%), W57 showing the best results. This is the cheapest solution in terms of initial cost and is composed of one-coat mortar as external cladding, gypsum plasterboard as internal cladding, and an EPS board in the cavity. W45 has the worst performance from a 3E *cost*-C2C point of view. This alternative is within the group of solutions that the lowest environmental benefits at end-of-life stage due to the high weight of claddings that are transported and disposed of into landfill, and due to the lower benefits of XPS recycling in comparison with the remaining insulation products. However, it is also in the group of alternatives with less environmental cost of transport to site (A4) mainly due to the shorter distance to the construction site from the place of production of stabilised mortar used as render in internal and external cladding in comparison with the remaining cladding solutions.

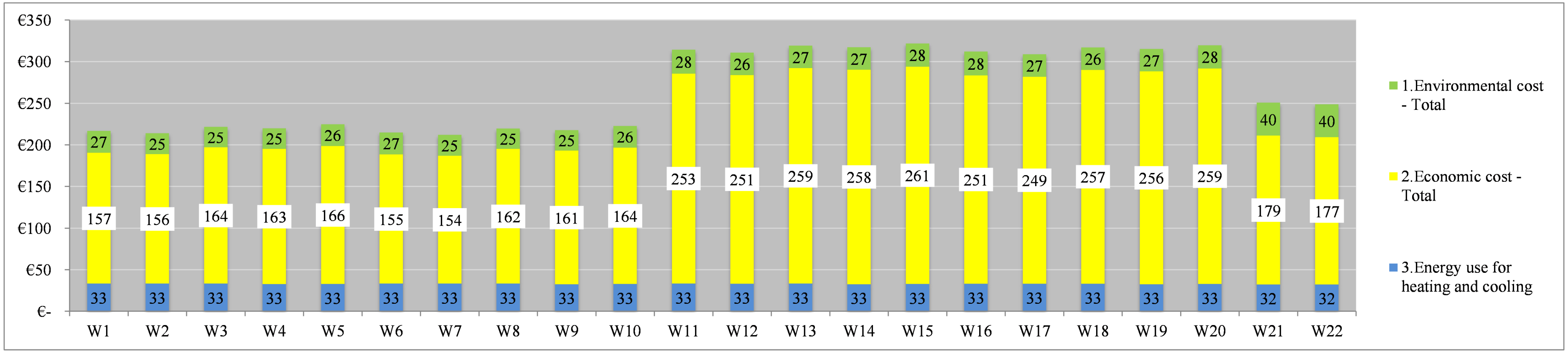

Figure 7.15 - NPV of the total environmental, economic and energy cost of single leaf walls with external insulation

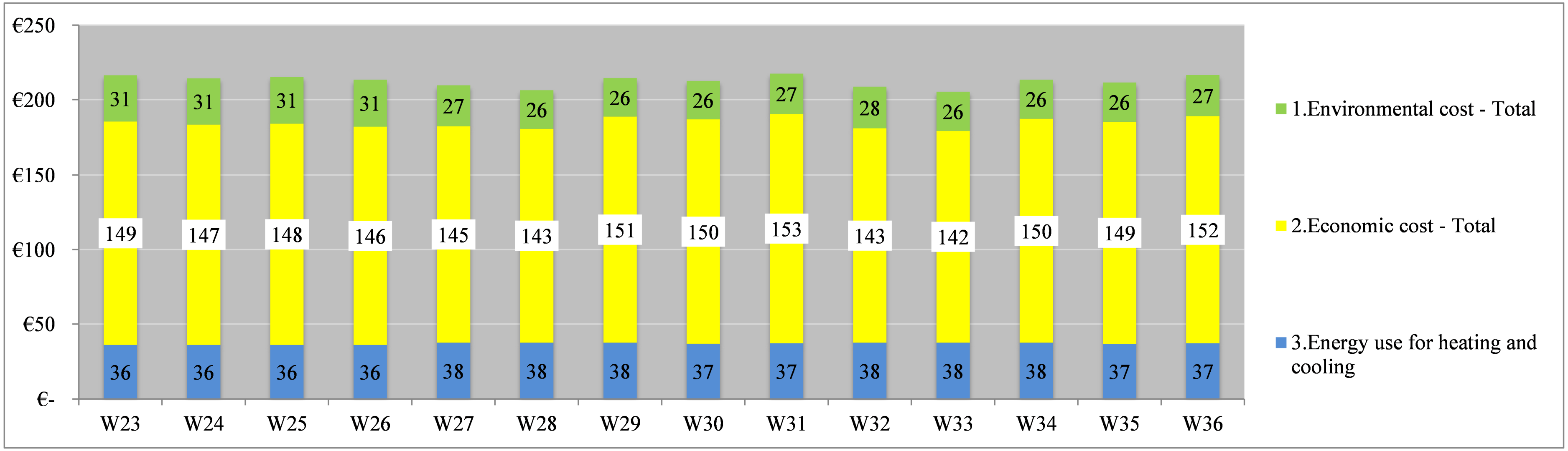

Figure 7.16 - NPV of the total environmental, economic and energy cost of single leaf walls with internal, and without (W23-W26), insulation

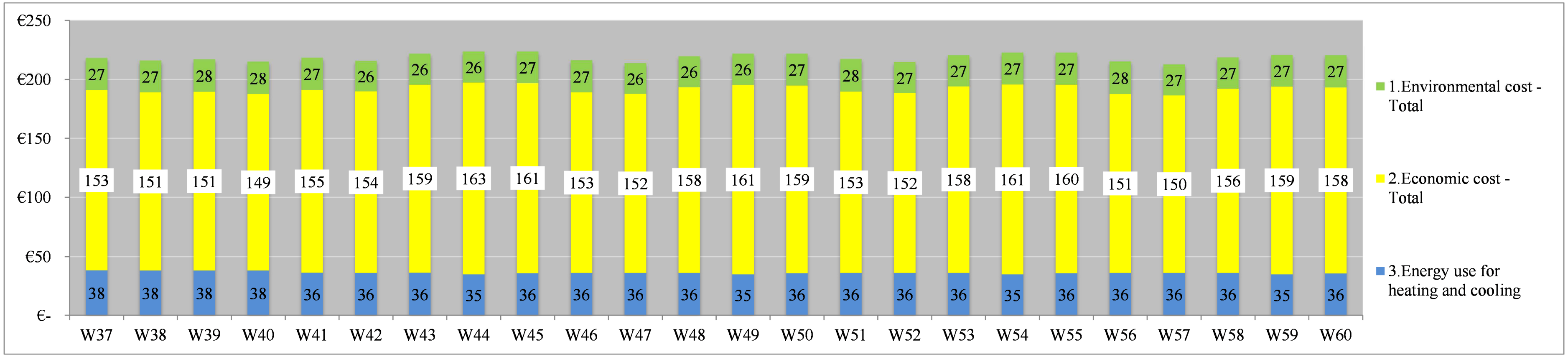

Figure 7.17 - NPV of the total environmental, economic and energy cost of cavity walls

7.2.4.2.4. Overview of the 60 alternatives

An overview of the NPV of the total environmental, economic and energy cost of the 60 alternatives allows the conclusion that W15 has the worst overall performance in terms of 3E *cost*-C2C results. This single leaf wall with external insulation includes wood-plastic extruded boards with XPS boards in the corresponding VRF system and a painted cement render as internal coating. This bad performance is mainly due to its high initial (it is the most expensive alternative in terms of acquisition cost) and maintenance costs. On the other extreme, the cheapest solution in terms of initial cost also shows the best performance from a 3E *cost*-C2C point of view. W33 is a single leaf wall with internal insulation with one-coat mortar as external cladding, and an EPS board covered by gypsum plasterboard in the inner surface of the clay brick.

This analysis confirmed the importance of economic cost in 3E *cost*-C2C results, namely of acquisition costs. In fact, a high influence of this factor was found in defining the alternatives with the best and worst performances in terms of 3E *cost*-C2C results. This relation occurs in all cases except for the alternative with the worst performance in the cavity walls group: W45. In fact, this is the third most expensive alternative of this group beyond W44 and W54, but its considerably higher U-value (0.34 W/(m^2.ºC instead of 0.26 W/(m^2.ºC) - see Appendix 7.IV) results in increased energy costs and environmental costs from energy use. Within each group of walls, and in the overall analysis, the highest price of XPS boards and the lowest one of EPS boards highly contributes to the final ranking of the alternatives.

It was found that the first and the last alternatives ranked in terms of their NPV of the total environmental, economic and energy cost do not change even if the discount rate used for the calculations (3% by default) is defined as 0% or as 7%. However, higher values of discount rate mostly affect the alternatives with higher acquisition cost (Silvestre, J. D. *et al.*, 2011a; Silvestre, J. D.; de Brito*; et al.*, 2012b).

7.3. Discussion

The results presented in section 7.2 provide an overview of the use of the 3E-C2C assessment method in the individual and combined quantification and comparison of various aspects (e.g. environmental, economic and energy) of the performance of building assemblies in each stage of their life cycle, and also from cradle to cradle. But the usefulness of the method proposed in this thesis is better highlighted by summarising the design choice, depending on the method used. In particular, it shows the benefits of providing the results of the 3E *cost*-C2C performance for the alternatives, using the same economic unit to aid the designer's choice. This summary is presented in Table 7.13 and it was concluded that even alternatives that are not functionally equivalent can be compared, and sound choices can be made, if, and only if, an approach such as 3E *cost*-C2C is used. Otherwise:

- Different alternatives are preferable depending on the environmental impact category analysed and the designer usually cannot - or does not know how to - define weights for each of these categories (C2C LCA in Table 7.13);
- The solution offering the best combination of thermal performance and insulation position will be the design choice in terms of energy performance (W21 and W22);
- The combined analysis of more than one performance aspect can lead to contradictory conclusions (W33 for economy and energy, or W3 for environment and energy).

From Table 7.13 it is possible to confirm that W33 has the best performance from a 3E *cost*-C2C point of view. However, if the designer has a constraint at the design stage that limits the external wall thickness (including the claddings), W35 can be an alternative due to its lower thickness (0.32 m instead of 0.34 m of W33), despite having a 3E *cost*-C2C that is 3.0% higher than the one of W33.

Despite the fact that 3E *cost*-C2C indicates wall W33 as the best option, it is important to discuss the coefficient 0.1 included in the calculus of the consumption of energy for heating and cooling (see equation (7.2)) and that has consequences both in the environmental and in the economic performance of the alternatives. In fact, the national regulation (RCCTE, 2006) considers in the primary energy calculation a dimensionless reduction factor of 0.1 - both for heating and cooling- to represent the intermittent domestic use of artificial heating and cooling systems in Portugal (Monteiro & Freire, 2012). However, there are ongoing changes in building occupancy and in the comfort demands of the Portuguese that have led to a higher consumption of energy by this type of equipment (that is also progressively more available in residential buildings). These changes are already expressed in recent national research studies that consider not only the default value (consumption of energy to fulfil 10% of the heating and cooling needs) but also higher values (20% to 50%) to simulate future realistic scenarios for dwellings (Monteiro & Freire, 2012) or multi-familiar residential buildings (Pinto, 2008), despite not considering this dimension of performance for decision-making.

Table 7.13 - External wall solution that offers the best performance, depending on the method used (adapted from (Silvestre, J. D.; de Brito*; et al.*, 2012b))

Approach	EIAM	Results	Life cycle stages considered	Performance aspects	Best performance/design choice	Difference to the second (or to the following) alternative	Total thickness of the external wall alternatives (m)
LCA	CML 2001 baseline	Table 7.10, Table 7.11, and Table 7.12	C2C (A1-A3; A4; A5; B2-B4; C2-C4 and D), without energy use for heating and cooling	Environmental	W28 (AP), W29 (GWP), W31 (ODP) and W37 (ADP, EP and POCP)	1% (W28 and W30 in ODP), 3% (W34 in GWP, W39 in ADP, W30 and W38 in AP and EP) and 5% (W38 in POCP)	0.32 - W30 and W35 0.33 - W9 0.34 - W27 to W29, and W31 to W34 0.35 - W2, W3, W7 and W8 0.37 - W14, W19, W21 and W22 0.38 - W37 to W39 and W57 0.42 - W26
LCA		U-values and position of the insulation in Appendix 7.IV	Energy use for heating and cooling	Energy	W21 and W22	1% (W14 and W19)	
WLC	-	Figure 7.7, Figure 7.8 and Figure 7.9	C2C (A1-A5; B2-B4; B6; C2-C4 and D)	Economic and energy	W33	0.8% (W28)	
NPV of the environmental cost	*Eco-costs*	Figure 7.12, Figure 7.13, and Figure 7.14	C2C (A1-A3; A4; A5; B2-B4; B6; C2-C4 and D)	Environmental and energy	W3	0.1% (W2 and W8) and 0.2% (W7 and W9)	
3E cost-C2C	*Eco-costs*	Figure 7.15, Figure 7.16 and Figure 7.17	C2C (A1-A3; A4; A5; B2-B4; B6; C2-C4 and D)	3E	W33	0.5% (W28), 1.6% (W32), 2.1% (W27), 3.0% (W35), 3.1% (W7), 3.6% (W57 and W30), 3.9% (W26 and W34)	

The method proposed in this thesis complements the 3E *cost*-C2C approach with a sensitivity study in order to account for the variability of real occupancy scenarios. However, it does not require monitoring results in order to be performed during the design phase. Similar methodologies have already been applied in France to show the essential influence of occupants on the overall performance of houses, despite not changing the ranking between the compared alternatives (Peuportier et al., 2012).

Figure 7.18 presents the difference between the NPV of the environmental (*Cev*) cost of single leaf walls with external insulation and the one of W1 considering different consumption patterns for the use stage: 10 (similar to the results presented in Figure 7.12), 30% or 50% of the energetic needs. This chart shows that W9 becomes the solution with the best environmental performance (followed by W4, W3 being relegated to third place due to its higher U-value) if at least 30% of the energetic needs are fulfilled. Figure 7.19 shows similar results but for the NPV of the total environmental, economic and energetic cost (complementing Figure 7.15). From this chart it is possible to conclude that W7 becomes the best option in a 3E *cost*-C2C perspective if at least 30% of the energetic needs are fulfilled. The alternative with the best environmental performance (W9, with the lowest NPV of the environmental cost) reaches second place if this level of consumption is considered. The latter can be preferable if the designer has a constraint at the design stage that limits the external wall thickness (including the claddings) due to its lower thickness (0.33 m instead of 0.35 m of W7).

These results are not presented for the remaining alternatives because they all have heating and cooling needs higher than W1 (see Figure 7.7, Figure 7.8 and Figure 7.9) and therefore the NPV of their environmental (*Cev*) cost and of their total environmental, economic and energetic cost are higher than the ones of W1 by a value of 30% or more of the energetic needs.

A discussion of the influence of the Hexa building location is also presented in this section. Therefore, three additional locations for Hexa are considered in order to allow the selection of the most adequate external wall for each national climatic region. As described in Chapter 3, RCCTE divides Portugal in three climatic regions depending on the winter conditions (I1, I2, and I3) and provides maximum admissible values for heat transfer coefficients (U) of the opaque areas of the envelope (which mainly corresponds to the external walls) in each of these three climatic regions (Santos, Carlos Pina, 2007). RCCTE also divides Portugal in three climatic regions depending on the summer conditions (V1, V2, and V3, that are also sub-divided in North and South zones and correspond to increasingly severe climate conditions), and defines a limit value for nominal annual cooling needs for each of these regions.

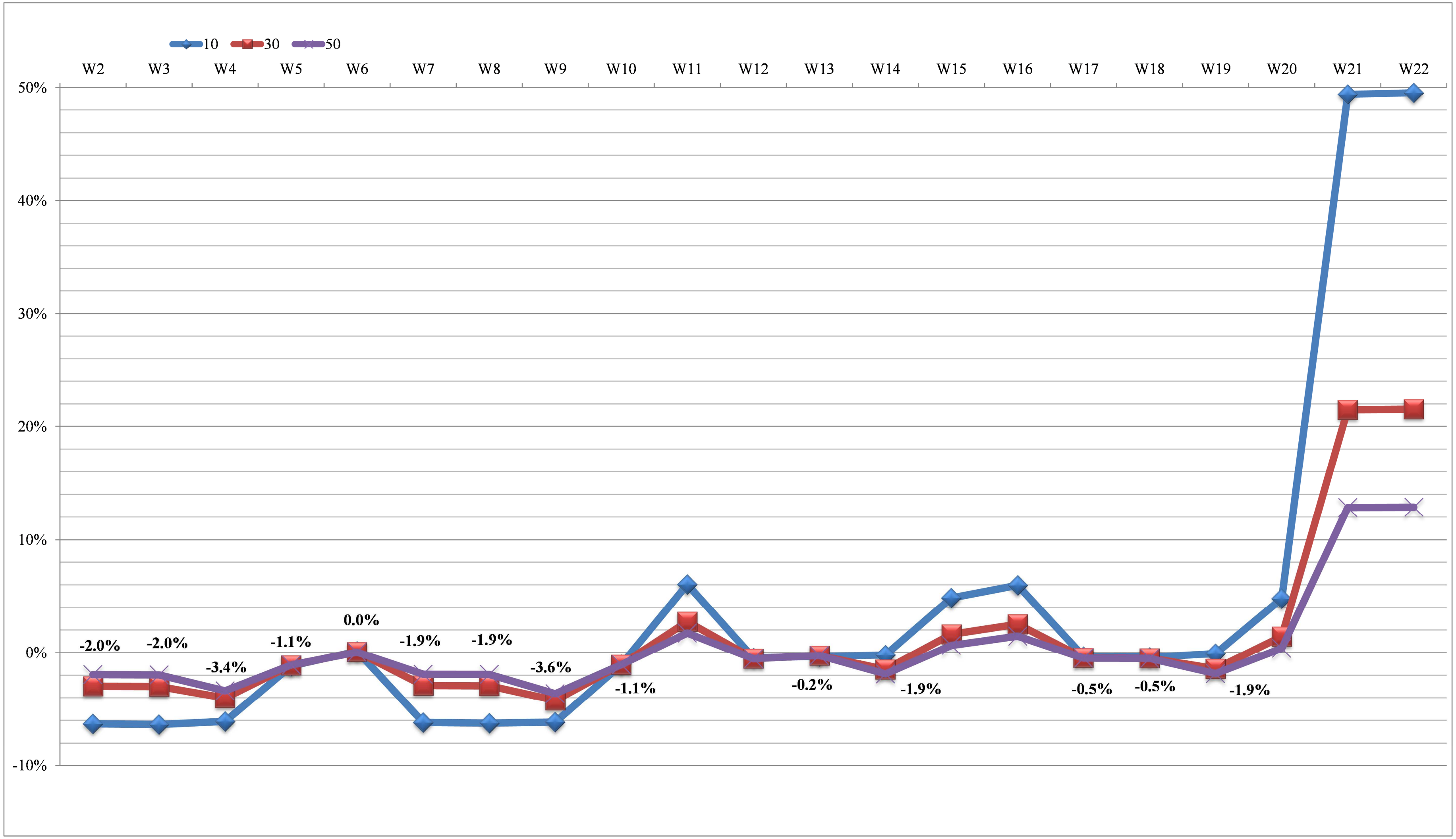

Figure 7.18 - Difference between the NPV of the environmental (*Cev*) cost of single leaf walls with external insulation and the *Cev* of W1 considering different consumption patterns for the use stage (guaranteeing 10%, 30% or 50% of the energy needs)

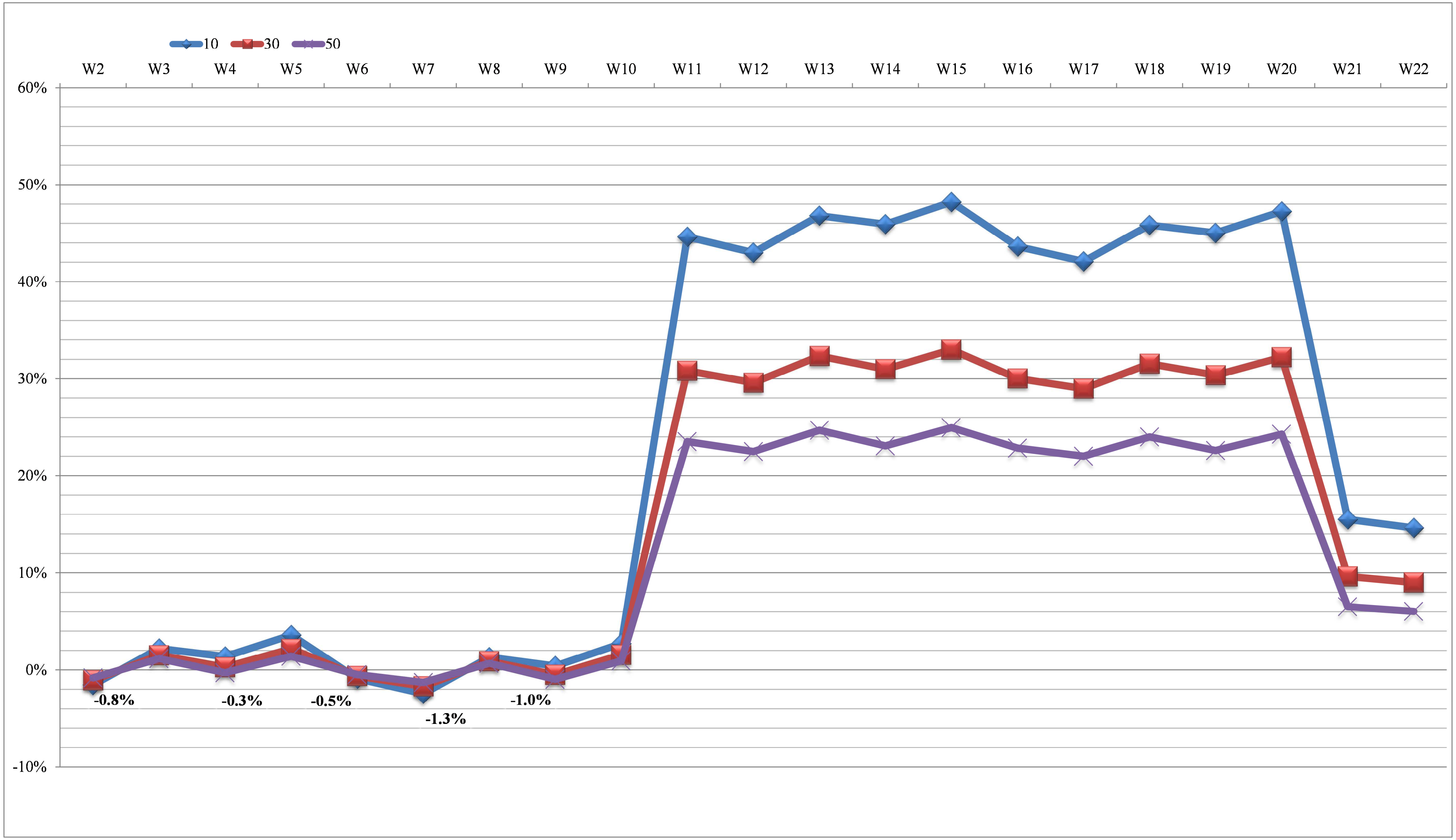

Figure 7.19 - Difference between the NPV of the total environmental, economic and energetic cost of single leaf walls with external insulation and W1 considering different consumption patterns for the use stage (guaranteeing 10%, 30% or 50% of the energy needs)

Thus, the four locations selected for this study reflect different combinations of these winter and summer conditions:

- Lisbon, the Portuguese capital city and the metropolitan area with the highest density of buildings in the country, is located in a region with a climate classified as I1, V2 South (such as Coimbra and Faro, the two most important cities of the centre and of the extreme South of Portugal, respectively);
- Porto, the second largest city of Portugal and the European city with the best performance in the Buildings energy efficiency category of the Green City Index (EIU, 2012), and is located in a region with a climate classified as I2, V1 North;
- Bragança, which has a temperate continental climate with the coldest, but moderate, winters of Portugal, and hot summers (although not as warm as in Lisbon) (Ferreira & Pinheiro, 2011), is located in a region with a climate classified as I3, V2 North;
- Évora, which has one of the hottest summers among the European Union (and the hottest of Portugal), but with a more rigorous winter than Lisbon (Ferreira & Pinheiro, 2011), is located in a region with a climate classified as I1, V3 South.

The consideration of different locations for Hexa not only influences the results of the energy performance and costs (B6 - see 7.1.5.4 and 7.1.6.3) of each alternative, but also the LCA of their A4 sub-stage (transportation from factory gate to the construction site - see 7.1.5.2) and their market acquisition cost (which also includes the transportation costs - see 7.1.6.1).

Table 7.14 presents the alternatives with the best NPV of the environmental cost, depending on the location of the Hexa building and on the consumption pattern for the use stage. W9 is the best option in all cases, except for Lisbon and for a consumption pattern of 10% of energy needs (but with a difference of only 0.2% for the best option: W3). This alternative only has 0.33 m thick and corresponds to a single leaf wall with ETICS with PUR boards as external cladding and gypsum plasterboard as internal cladding. Table 7.15 confirms that W33 has the best performance from a 3E *cost*-C2C point of view in all locations if a consumption pattern of 10% of energy needs is considered for the use stage. However, the best option becomes W9 for all locations, except Lisbon, if the consumption pattern is increased to 50% of energy needs for the use stage. This is mainly due to the closer location of the EPS boards (used in W7) production plant to Lisbon than to any of the other locations.

Table 7.14 - External wall solution that offers the best NPV of the environmental cost, depending on the location of the Hexa building, and on the consumption pattern for the use stage

Approach	EIAM	Performance aspects	Location	Consumption patterns for the use stage	Best performance/design choice	Following alternatives
NPV of the environmental cost	*Eco-costs*	Environmental and energy	Lisbon	10%	W3	W2, W8 and W7
				50%	W9	W4, W3 and W2
			Porto	10%	W9	W4, W3 and W8
				50%	W9	W4, W14 and W19
			Bragança	10%	W9	W4, W3 and W2
				50%	W9	W4, W14 and W19
			Évora	10%	W9	W8, W3 and W4
				50%	W9	W4, W19 and W14

Table 7.15 - External wall solution that offers the best 3E *cost*-C2C performance, depending on the location of the Hexa building, and on the consumption pattern for the use stage

Approach	EIAM	Performance aspects	Location	Consumption patterns for the use stage	Best performance/design choice	Following alternatives
3E cost-C2C	*Eco-costs*	3E	Lisbon	10%	W33	W28, W32 and W27
				50%	W7	W9, W2 and W6
			Porto	10%	W33	W32, W28 and W35
				50%	W9	W7, W2 and W4
			Bragança	10%	W33	W7, W2 and W32
				50%	W9	W4, W7 and W2
			Évora	10%	W33	W28, W32 and W27
				50%	W9	W7, W2 and W4

7.4. Conclusion and perspectives

This chapter proposes a method to aid in the choice of construction materials or assemblies closely related to a building’s thermal performance. This method provides an assessment of the environmental, energy and economic (3E) life cycle from cradle to cradle (3E-C2C) of these building elements in accordance with the most recent European standards for the environmental and economic assessment of construction works. Environmental performance is assessed from C2C following a LCA method; energy performance corresponds to the consumption of energy for heating and cooling; and the economic performance is based on the whole-life costing (WLC) method.

The description of the 3E-C2C method provided in this chapter, and its application to the process of selecting an external wall alternative for a building, proved useful for: comparing alternatives that comply with all the requirements but that are not functionally equivalent, without the need of changing their characteristics to make them comparable; quantifying various aspects of the performance of the alternatives in each stage of their life cycle, and also from cradle to cradle. There are methods with similar characteristics, but it was concluded that none of them is all-inclusive either in terms of life cycle stages or in the aspects of performance considered.

The 3E *cost*-C2C approach supplements the 3E-C2C method by establishing weights for each aspect of the assembly performance and for their quantification using the same unit. This approach uses a prevention-based environmental impact assessment method that converts the results of all environmental impact categories into an economic unit. This allows the potential cost of the environmental impacts to be added to the economic and energy WLC and a 3E performance C2C to be considered. The 3E *cost*-C2C approach therefore prevents contradictory conclusions that can arise from the individual analysis of each aspect of performance.

3E *cost*-C2C may become universal when the financial implications of each environmental impact have been sufficiently assessed. The use of this approach in building design allows the simultaneous comparison of different aspects of the performance of the alternatives (3E) by providing weights to each dimension that the designer usually cannot - or does not know how to - define.

The case study presented considers typical solutions for external walls in Portugal and identifies the best alternative in each aspect of performance (using 3E-C2C method) and in the overall assessment (using 3E *cost*-C2C approach). This example allows the discussion of the advantages of using a method that provides the combined assessment of all performance aspects in the same unit, thereby avoiding contradictory conclusions that can arise from the individual analysis of each one. The results of this case study showed the importance of acquisition costs in 3E-C2C performance of external walls. Due to the significance of the electricity consumption for heating and cooling during the use stage (both for the environmental and for the energetic performances), a discussion is also provided about the influence of the use rate of this type of equipment in the choice of the best alternative for an external wall. This chapter also includes a sensitivity analysis of the best alternative for an external wall depending on the location (between four Portuguese cities) of the corresponding building.

The applications already undertaken of the method proposed in this chapter (i.e. in the choice of an external wall from several alternatives) confirmed that it is suitable and validated, resulting in the improvement and refinement of each of its modules and steps. However, the 3E-C2C and 3E *cost*-C2C approaches should both be used to choose other construction materials or assemblies that are also closely related to a building's thermal performance to aid their continuous development.

It is also important to highlight that this Chapter presents two case studies in areas identified in Chapter 2 as being important within the present and future research in the application of LCA to building and construction (Ekvall, 2005): the relationship between durability and environmental effects (interdisciplinary research study of SLP and LCA presented in Appendix 7.V); and the combination of LCA with WLC (development and application of the 3E-C2C method).

7.5. References - Chapter 7

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8. CONCLUSIONS AND PERSPECTIVES FOR FUTURE RESEARCH

8.1. Final remarks

This chapter starts with the re-enunciation of the main and secondary research questions of this thesis (presented in Chapter 1), along with the description of the methods developed in the scope of, and proposed in, this thesis to answer these questions. The deliverables that resulted from the development of each of these methods are also enumerated.

The number of national LCA[1] research studies on the production of building products is still scarce (see Chapter 2). Therefore, this thesis aimed at completing a significant quantity (12) of these studies based on present production of Portuguese companies and following recent European Standards[2], in order to provide important data for building LCA practitioners (see Chapter 4 and 5 and Figure 8.1). These LCA studies include some products with a significant degree of innovation, both at a national and international level (five in the latter case, as no LCA data set was found for similar products – see Chapter 6), thus providing a higher potential for their publication in reference journals (such as the paper presented in Appendix 5.II).

The question of “how to select a coherent LCA data set of building products (from available ones in the European context) that can be used as generic for a national context” arises on a daily basis for building LCA practitioners. They also need a scientifically validated approach to confirm that available LCA data sets (namely from their own, or from someone else’s, research studies) are plausible in order to complete the LCA study of a building or building assembly, or an EPD[3] of a building product without an excessive expenditure of time and resources. An innovative methodology to deal with both problems is proposed in Chapter 6, and has been named NativeLCA because of allowing the selection of coherent LCA data sets to be used as generic data for a national context, namely for the Portuguese situation. This methodology has a wide scope (all building products with available LCA data sets, namely in Europe, including all life cycle stages: from C2C[4]) and can also be used in the selection of background LCA data sets for significant processes in environmental terms (e.g. raw materials). The development and application of NativeLCA resulted in a total of 16 case studies of selection of coherent LCA data sets of construction materials and products to be used as generic for a national context, namely for the assessment of external walls (see Chapter 6 and

[1] **LCA** – Life Cycle Assessment.
[2] **Recent European Standards** - developed by the Technical Committee (TC) 350 of the European Committee for Standardization (CEN/TC 350).
[3] **EPD** - Environmental Product Declaration.
[4] **C2C** - Cradle to cradle.

Figure 8.1). A paper presenting the theoretical framework of this method was already submitted for publication in an international reference journal (and is presented in Appendix 6.IV).

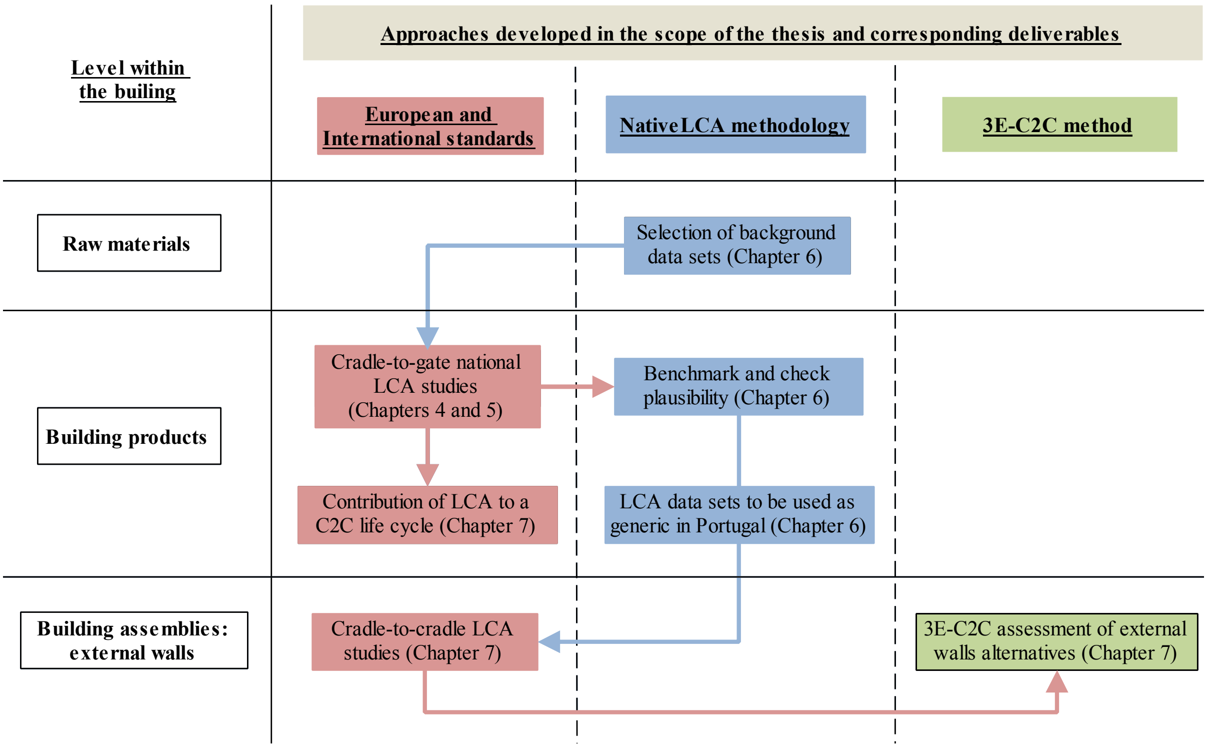

Figure 8.1 – Approaches developed in the scope of this thesis, with the corresponding deliverables divided according to the corresponding scope

LCA or economic data of the disposal of each waste stream that is generated during the life-cycle of building products is not abundant at an international level. However, this information is essential in evaluating how the minimisation of the quantity of CDW[5] produced, the maximisation of reuse or of recycling operations, or the increasing of recycled content in construction products maximises their C2C environmental and economic performance. To fill this gap and improve the contribution of LCA methodology to “close the loop” in the life cycle of building materials, a framework for the environmental assessment of CDW was developed in the scope of this thesis (and is presented in a paper submitted for publication in a reference journal and reproduced in Appendix 7.III) based on the provisions included in recent European Standards and in the experience from their application in national LCA studies of building products (Figure 8.1).

The sustainability assessment of construction products has to consider their environmental and economic performance (along with the social one). In building design, the process of selection of each building product or assembly has to be holistic, taking into account

[5] **CDW** - construction and demolition waste.

all the dimensions of performance of the latter. To answer these needs, an innovative method that provides the simultaneous assessment of three dimensions of performance – environmental, economic and energy - of these elements from cradle-to-cradle (3E-C2C), following recent European standards, is proposed in this thesis. The application of 3E-C2C to external walls resulted in two papers (one chosen by the scientific committee of an International Conference to be published, and the other submitted for publication, in an International Journal (Silvestre *et al.*, 2011, 2012)) and in the case study presented in Chapter 7 (with the environmental performance based on cradle to cradle LCA studies – see Figure 8.1).

8.2. General conclusions

This thesis presents a research study that intends to improve the coherence (using the NativeLCA methodology) and to ease the applicability (via 3E-C2C method) of the environmental, economic and energy life-cycle assessment from cradle to cradle of building materials and assemblies, taking into account the procedures included in recent European Standards. The scope of the study corresponds to the external walls of buildings and the main conclusions drawn during its development are reported in the following paragraphs.

Concerning the application of LCA methodology to buildings, and to their elements and assemblies, it was concluded in **Chapter 2** that:

- Despite being standardised at an international level, the LCA methodology still has some limitations, and many barriers have been identified concerning the application of this methodology to the construction sector. However, the development of software, databases and standards to support the detailed application of LCA to buildings standardises its procedures and results, and encourages its regular use;
- The process of environmental certification of construction materials and assemblies is still absent in Portugal, but national construction products with the biggest exportation potential have already had their environmental performance certified by international systems. However, a national program of environmental certification of building products and services for the built environment (DAPHabitat (DAPHabitat, 2012)) based on type III environmental declarations is at the starting point. This program can contribute to the harmonisation of the methodological procedures of the LCA studies of building products, namely through the development of PCR[6], and will increase the number of third-party verified EPD of building products from national companies, which are essential for the LCA of buildings in the national context;

[6] **PCR** - Product Category Rules.

From the review of LCA results of more than ten years of international research studies on the environmental impact of a building's external walls also included in Chapter 2, it was concluded that:

- These studies differ in their scope, objectives, level of simplification, completeness and transparency, thus avoiding the inter-comparison of their results;
- It is of paramount importance to develop LCA studies from cradle to grave of the traditional external wall solutions of each region, with production data from the same regional source, including the operation energy, thus allowing the comparison of alternatives without a compulsory equivalence of thermal performance, and increasing the number of options that the designer can consider;
- LCA studies of external walls should focus more on the less-studied stages, such as construction, life-long maintenance and end-of-life;
- LCA studies can be complemented by an economic assessment of each alternative;
- LCA studies should be based on International Standards in order to enable direct comparison between them.

The object of this Thesis - the opaque areas of the external walls of buildings – is described in detail in **Chapter 3**, from which it was possible to conclude that:

- An external wall has a significant contribution to different characteristics of the performance of a building during its whole life cycle: it can represent up to 15% of the overall environmental impacts of a building over a 60-year life cycle, and this percentage can be even higher in energy efficient buildings;
- The functional requirements that external walls have to fulfil (e.g. thermal, acoustic and fire performance) at a national, European and international level are essentially performance-based. Moreover, some of its primary components - elements of the wall structure, insulation materials, internal and external claddings and ancillary components - contribute individually to the accomplishment of several other significant requirements (e.g. visual and tactile comfort). Thus, only the holistic characterisation and assessment of this building assembly and of each of its layers can lead to a satisfactory result in the assessment of different dimensions of the building's performance.

The description of the "Life Cycle Inventory analysis" (LCI) phase of the LCA methodology in **Chapter 4**, and its application to the 12 building products studied in this Thesis, allowed the verification that:

- The selection of the building products for which a cradle to gate LCI study have been completed were conditioned by the limited dimension of the Portuguese market and by the difficulty in receiving a positive answer from some companies. The final range of products was therefore defined by the companies that gave a prompt response and by the degree of innovation of the products, both at a national and international level;

- The theoretical explanation of the principles of LCI, and their practical choice (following the guidelines defined in standards) to allow their application in the study of each building product, confirmed their foremost importance in guaranteeing the scientific validity of the LCA results presented in Chapter 5.

From the 12 LCI studies completed and presented in Chapter 4, the author:

- Confirmed the time-intensive and iterative nature of data collection;
- Characterised the quality of the information (site-specific data) used in each LCI study and found that it varies between studies. Nevertheless, this quality has an average value of 1.7 in the 12 studies (on a 1 to 5 scale, 1 corresponding to the best quality), which can be considered a good and appropriate value for the aim of this thesis;
- Identified the specificities that must be taken into account in the LCI of building products, namely the diversity and leading environmental impacts of each stage of their life cycles, and the importance of giving permanent attention to allocation in many system processes.

Chapter 5 includes the description of the “Life Cycle Impact Assessment” (LCIA) phase of the LCA methodology, the characterisation of LCA tools and corresponding databases, and the full presentation and analysis of the LCA results of the studies completed in the scope of this thesis, which were essential to conclude that:

- A detailed analysis of the differences between available LCA tools and databases is advised in order to allow for the founded selection of the pair that are the most adequate to a given use, namely to the purpose of this thesis (to provide innovative LCA data from cradle to cradle of construction materials and assemblies used in buildings in Portugal);
- The use of an updated national electricity mix is essential for a cradle to gate LCA, and it is even more important when the manufacturing is energy intensive and most of the environmental impacts of the life cycle of the product come from this stage. Therefore, the author used the latest information available concerning the Portuguese electricity mix to accurately estimate the environmental impacts of the companies from the consumption of energy for production of the construction products studied in this thesis;
- The assumptions made in the LCIA of the building products studied in this thesis (i.e. the choice of processes for modelling raw material production and background processes, the allocation procedures followed, and the choice of the EIAM[7] and environmental

[7] **EIAM** – Environmental impact assessment method.

categories) were adequately described and justified in order to allow their critical revision. Furthermore, a sensitivity analysis[8] was made for two insulation materials to evaluate the consequences of physical (e.g. volume or mass) and economic allocation in LCA results;

- "Raw material extraction and processing of secondary material input" (A1) has a significant contribution to the cradle to gate environmental impacts of many construction materials, independently of their nature (e.g. cement-based, natural or oil-based) or production process (more than 75% in all the elements of the wall structure, and more than 50% in oil-based insulation materials and in claddings, for almost all environmental categories). This highlights the importance of the selection of the most adequate databases and corresponding processes for modelling this life cycle stage;
- Transportation of raw materials (A2), and packaging and packaging waste (A3.1 and A3.3, respectively), are life cycle stages that may not be discarded in a cradle to gate LCA study because of their significance in some environmental categories and construction products. In fact, these stages can have a contribution of 10% or higher in many impact categories for some of the building products studied;
- ODP[9] category should continue to be considered in LCA studies, because some LCI of background processes are not updated and still consider the use of CFC[10] in industry and because HCFC[11] emissions can occur in current manufacturing processes;
- The LCA results achieved for the products used in external walls of buildings in Portugal are innovative, up-to-date, and also scientifically sound, having been achieved through a consistent methodology that takes into consideration recent European Standards.

In the development of the first chapters of this thesis (namely when completing the state-of-art presented in Chapter 2, and modelling the production processes of the construction products - Chapter 4 and Chapter 5), the author found that:

- The selection of the LCI data sets to model the background process of the "production" of a raw material (between available data sets) for a given product is of paramount importance in LCA studies of building products, and the LCA practitioner relies on available data sets to make his choice;
- LCA practitioners also frequently deal with:

[8] **Sensitivity analysis** - procedure to determine how changes in data and methodological choices affect the results of the Life Cycle Impact Assessment (LCIA) (ISO, 2006b, p. 22).
[9] **ODP** - Ozone depletion potential.
[10] **CFC** - Chlorofluorocarbons.
[11] **HCFC** - Hydro-chlorofluorocarbons.

  - The selection of a coherent LCA data set of building products that can be used as generic for a national context, namely in LCA of buildings;
  - The need for a scientifically validated approach to confirm that available LCA data sets (namely from their own, or from someone else’s, research studies) are plausible;
- Despite the frequency and the influence of these selection procedures in the final results of a LCA study, a straightforward and coherent approach to support them is not available yet;
- The increasing number of LCI and LCA data sets available in Europe (namely in databases but also from EPD and environmental profiles from industrial organisations) makes this approach increasingly more required.

It is therefore of paramount importance to provide a decision framework for the practitioner to make his decisions always coherent and based on a scientifically robust approach. This need defined the first main research question of this thesis and led to the development of an innovative methodology: NativeLCA[12] (proposed in **Chapter 6**, for the selection and benchmarking of LCA data sets of construction materials and products available in the European context to be used as generic data for a national context). The process of development of NativeLCA allowed the following conclusions to be drawn:

- NativeLCA is innovative because of its wide-ranging scope, straightforward approach, and single focus (the selection of a LCA data set to be directly used by the practitioner, avoiding inventory analysis and modification), and because it provides LCA data required by recent European Standards;
- NativeLCA can be essential for the selection of a coherent LCA data set to be used in the early design stage even in European countries where many EPD from the construction sector are available (while individual EPD can be considered in the following design stages), also allowing the identification of the sources of variability of these data sets based on the corresponding meta data;
- NativeLCA is useful in: providing robust results that can be used in simplified LCA or early design assessment of buildings; aiding LCA practitioners in the selection of a data set for background processes, namely in EPD development; assisting LCA experts in checking the plausibility of LCA results in critical review.

Chapter 6 also presents a NativeLCA practical application in order to assess its applicability and analyse its results. The corresponding 12 case studies (four in its full form

[12] NativeLCA was developed with the additional scientific supervision of Sébastien Lasvaux (Post-doctoral researcher) during the internship of the author in January-February 2012 in the Environment Division of the *Centre Scientifique et Technique du Bâtiment* (CSTB), in Grenoble, France.

and eight in its "simplified" form) proved its feasibility and benefits, and allowed the identification of its limitations and potential improvements. They also showed that the whole potential of this methodology is revealed when no national LCA data set is available for a given product, and it is also a scientifically-based aid for the verification of the plausibility of the LCA studies completed in the scope of this thesis.

Concerning the limitations and potential improvements of NativeLCA methodology, the following ones can be highlighted:

- Data from French EPD considered in this study was provided by SLCA, which is the only database that provides data from these documents disaggregated by life cycle stage. Therefore, the use of this data by other practitioners to apply NativeLCA from cradle to gate implies their access to SLCA;
- The different level of aggregation of LCA results per life cycle stages in available data sets can be one of the most significant barriers for their inter-comparison, avoiding therefore NativeLCA application;
- The case studies showed that generic data sets can be discarded, and not considered to be used as generic in a national context, because of their lack of geographical, technological or temporal representativeness, or due to their high "genericness" and wide scope;
- Many LCA data sets have not yet been subjected to external review and therefore the validity of their methodological procedures cannot be confirmed;
- NativeLCA includes consistency and representativeness verification procedures which verify the meta data of each data set. However, the improvement of this methodology is advisable by creating a Data Quality Indicator (DQI) to be assessed for each data set. The use of DQI can provide a quantitative classification and corresponding ranking of available data sets in order to ease the choice of the ones that can be considered in NativeLCA.

The scope of this thesis corresponds to external walls of buildings and its final chapter intends to provide the environmental, energy and economic (3E) assessment from cradle to cradle. To achieve this goal, it is advisable to have a method that:

- Allows the comparison of alternatives, even if they are not functionally equivalent, without having to change their characteristics to make them comparable;
- Is in accordance to LCA international standards and with recent European standards related to the assessment of construction work sustainability;
- Provides the simultaneous comparison from cradle to cradle of these three dimensions of performance, by using suitable weights (that are essential but can introduce subjectivity in the assessment).

An appraisal of the available methods for 3E assessment of building assemblies found that such an integrated approach has not yet been developed (see Chapter 7). Thus, the second main research question of this thesis was found and a method to provide an assessment of the 3E life cycle from cradle to cradle (3E-C2C) of building materials and assemblies was developed in the scope of this thesis (**Chapter 7** - Environmental, energy and economic assessment of external walls of buildings from cradle to cradle (3E-C2C)), revealing the following outcomes:

- The 3E-C2C method has its maximum usefulness in the choice of construction materials or assemblies closely related to the thermal performance of buildings, providing the comparison of alternatives that comply with all the requirements but that do not have to be functionally equivalent;
- The quantification of three dimensions of performance in each stage of the life cycle of the alternatives, and from cradle to cradle, using standardised criteria makes the 3E-C2C method innovative in comparison with existing approaches with similar characteristics;
- The 3E *cost*-C2C approach establishes weights that allow the quantification of each dimension of performance using the same unit, thus allowing the potential cost of the environmental impacts to be added to the economic and energy WLC[13], supplementing the 3E-C2C method and preventing contradictory conclusions that can arise from the individual analysis of each aspect of performance.

In order to be tested and validated, the 3E-C2C method was used in the selection of an external wall of a building from 60 alternatives (taking into consideration the LCA results of the "Product stage" of each construction product from Chapters 5 and 6), and it was concluded that:

- The case study proved that the 3E-C2C method can aid building designers in minimising the C2C cost and environmental impact of building assemblies, maximising simultaneously their environmental performance;
- Concerning the contribution of each life cycle stage to the potential environmental (discounted) cost C2C of each alternative:
  - The production of the components of each wall can represent between 31% and 56%, while the transport to site varies between 1.1% and 2.2%;
  - The installation in the building can represent 5.9% as a maximum, but, on the other hand, can contribute up to -1.6% of the environmental cost (or 1.6% of the environmental benefits) in other alternatives;

[13] **WLC** - Whole-life cost.

  - The maintenance operations can signify between 0.7% and 7.5%, while the energy use can contribute between 36% and 65%. The external walls that present these values are the same with extreme values for the product stage, but in inverse order;
  - The end-of-life stage can represent a maximum of 0.4% but, on the other hand, can contribute up to -1.4% of the environmental cost (or 1.4% of the environmental benefits) in other alternatives.
- This case study also:
  - Showed the importance of acquisition costs in 3E-C2C performance of external walls (which accounts for between 68% and 81% of the 3E discounted cost of the alternatives, while environmental costs contribute between 8% and 16%, similar to the energy costs contribution - between 10% and 18%);
  - The acquisition price of insulation materials (highest of XPS[14] boards and lowest of EPS[15] boards) highly contribute to the final ranking of the alternatives;
  - Allowed the discussion of the influence of the use rate of heating and cooling equipment in an external wall's selection;
  - Is complemented by a sensitivity analysis of the best alternative depending on the location of the building;
- The three applications[16] made of the 3E-C2C method confirmed its suitability and validation, and contributed to the improvement and refinement of each of its modules and steps.

The 3E-C2C case study, along with another one presented in Chapter 7, belong to research areas identified in Chapter 2 as important within the present and future research in the application of LCA to building and construction (Ekvall, 2005): the relationship between durability and environmental effects (interdisciplinary research study of SLP[17] and LCA presented in Appendix 7.V); and the combination of LCA with WLC (development and application of the 3E-C2C method).

In the development and application of the 3E-C2C method, the following limitations and potential improvements were identified:

- It is generally agreed that the third aspect of sustainability (which concerns socio-cultural issues such as welfare, health, safety and comfort) should be included in a holistic assessment in the construction sector. However, because there is not yet an agreement

[14] **XPS** - Extruded Polystyrene.
[15] **EPS** - Expanded Polystyrene.
[16] **Three applications of 3E-C2C** - presented in two papers (one chosen by the scientific committee of an International Conference to be published, and the other submitted for publication, in an International Journal (Silvestre *et al.*, 2011, 2012), and presented in Appendixes 7.I and 7.II, respectively) and in the case study of Chapter 7.
[17] **SLP** - Service life prediction.

on the assessment of these issues due to their fuzzier nature (Gervásio, 2010), they were not included in this method;

- *Eco-costs* (used in the 3E *cost*-C2C approach) was built based on the Dutch reality, but according to the developers (Delft University of Technology) it can be applied to other Western European countries. However, it is advisable to develop a sensitivity analysis of the weighting factors defined by this method to each environmental impact category, in order to assess potential changes in the final results of the case studies;
- *Eco-costs* includes toxicity impact categories which are not usually used in LCA studies because of their high uncertainty and lack of scientific robustness. Due to this fact, these impact categories were not considered in the 3E *cost*-C2C approach;
- According to LCA International Standards (ISO, 2006b), the weighting procedure (3E *cost*-C2C approach) of this method can only be used if the corresponding results were not to be disclosed to the public as a comparative assertion, namely of overall environmental superiority or equivalence. Moreover, the interpretation and evaluation of the results of the single score results are out of the scope of LCA International standards (ISO, 2006a, 2006b);
- Because the information related with all the stages after the production (characteristics and periodicity of maintenance operations, expected service life of materials and end-of-life) is based on scenarios, the latter should be subjected to a sensitivity analysis in order to assess potential changes in the final results of the case studies;
- This method does not consider the environmental impacts of the energy or water required for installation or maintenance of the walls, due to their variable and unpredictable nature;
- The environmental impacts (and economic costs) of the demolition of the walls are not considered as they are considered independent of the alternatives assessed;
- The amount of time needed to collect the information necessary to assess each alternative using the 3E-C2C method can be considered excessive by building designers. However, this amount can decrease if a database devoted to external walls (and integrating their 3E performance adapted to the national context) is integrated in a building design support tool;
- The results of the case study are influenced by the geometric and architectural characteristics of the building selected;

- The most common external wall solutions in Portugal, and the construction products for which a LCA study was completed within the scope of this thesis or to which NativeLCA methodology was applied, conditioned the range of alternatives considered in the case study;
- The results of the case study are highly dependent on the inherent uncertainty of market prices for acquisition and on maintenance operations (the first are more important because it occurs in year 0), because of the importance of economic cost in the assessment of all alternatives.

8.3. Perspectives for future research

The future development of the research work initiated with this thesis can be composed of many research streams. The ones considered by the author to be the most promising, and that can be initiated immediately, are:

- Profiting from the extensive, detailed and varied LCI data collected from 12 Portuguese plants, several simulations can be done (using suitable LCA software) to provide interesting results in industrial terms, namely of potential environmental improvements of each production process[18];
- Based on the LCA results of the studies completed in the scope of this thesis, and considering the significant degree of innovation of some of these products, many research questions arise and can constitute interesting departure points for the continuation of this research:
    - Does the innovation in design and production of construction materials or in building assemblies (e.g. based on eco-design, or to comply with thermal performance regulation) lead to better environmental results from cradle to cradle?
    - How can LCA results from cradle to cradle lead to innovations in the design and production of building materials and assemblies?
    - Does the search for better environmental performance lead to innovation in the industry of construction materials?
    - Is there a correlation between the criteria used for the selection of construction materials (e.g. local or durable materials, or produced from natural raw materials) and their increased environmental performance (namely presenting better LCA results from cradle to cradle)?
- Despite the fact that LCA studies completed in the scope of this thesis are not intended

[18] Such as the collaboration of the author with a national company in a proposal that won a “Good Environmental and Energetic practices” award (AEP, 2012).

to be used directly in EPD, it is expected that some producers will use them to apply for an EPD (possibly with the collaboration of the author), namely within the national program. The improvement of the skills of the author thanks to the LCI studies completed in the scope of this thesis, along with the multiplicity of constraints, limitations and methodological choices faced, provided the adequate knowledge to collaborate in the development of PCR of some groups of building materials within the national program of environmental certification of building products and services for the built environment (DAPHabitat, in which he is already a member of the technical commission);

- The framework for the environmental assessment of CDW developed in the scope of this thesis can be improved in order to evaluate how the minimisation of the quantity of CDW produced, the maximisation of reuse or of recycling operations, or the increasing of recycled content in construction products maximises the C2C environmental and economic performance of building products. Putting into practice this framework can allow: the best end-of-life options to be chosen; the identification of the barriers that avoid the selection of the best end-of-life options; the evaluation of the potential of implementation of industrial symbiosis;
- Improvement of NativeLCA methodology through the creation of a Data Quality Indicator to be assessed for each data set, thus providing a quantitative classification and corresponding ranking in order to ease the choice of the ones that can be considered in NativeLCA;
- The continued application of NativeLCA to the products studied in the scope of this thesis, both at a national and at an international level (namely within the on-going collaboration of the author with French and Czech researchers), is highly recommended because LCA represents a static analysis. This procedure allows the consideration of each new (or updated) EPD and of the advances in manufacturing and processing technologies reflected in these documents;
- NativeLCA case studies included in this thesis, and the application of this methodology to other construction products and to life cycle stages after manufacturing, will allow the creation of a LCA database C2C to be used as generic in Portugal (identified in a dashed text box in Figure 8.2) based on available data sets at a European level. This can be an essential source of information for EPD development and for the LCA of buildings;

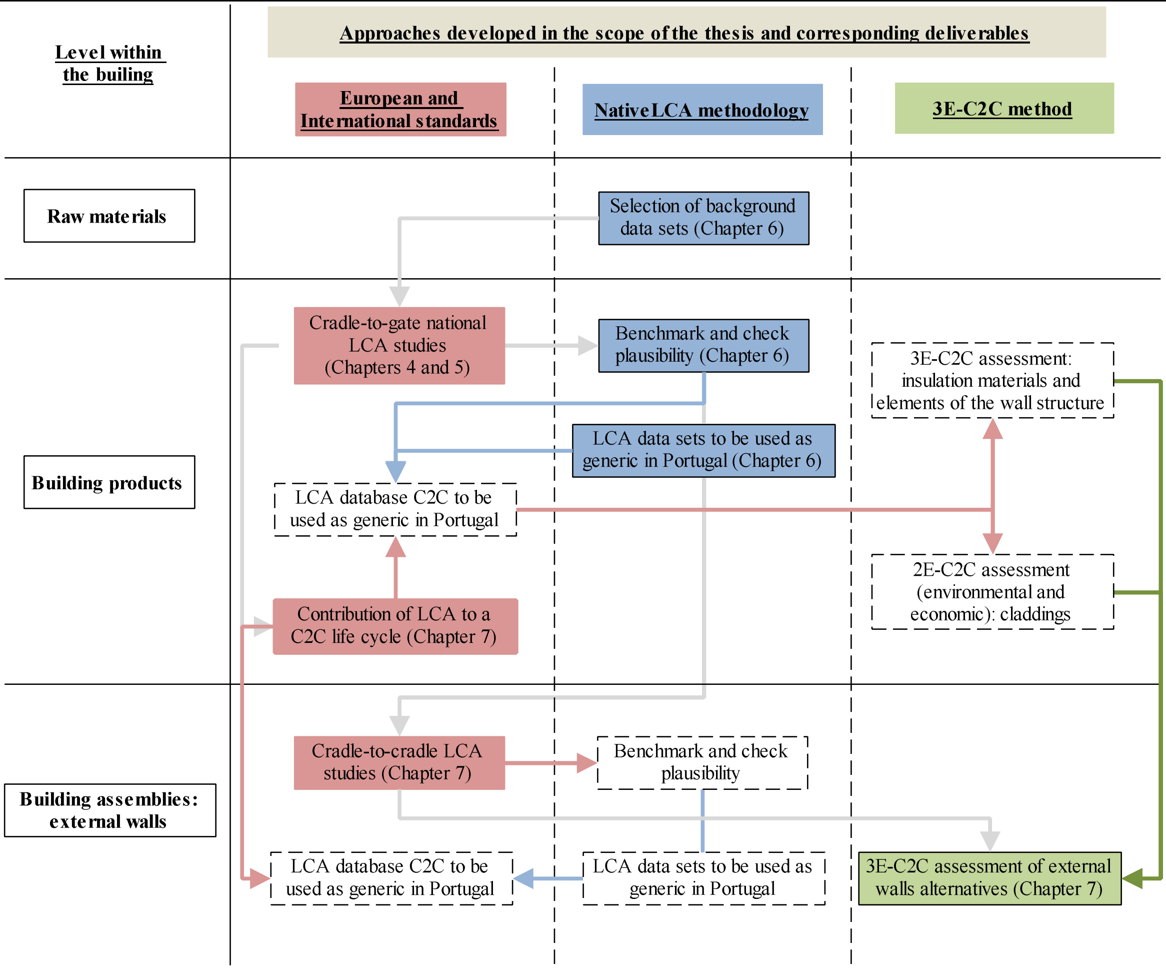

Figure 8.2 – Approaches developed in the scope of this thesis, corresponding deliverables, and identification of areas for future research (in dashed text boxes)

- The scope of NativeLCA methodology can be extended to the selection (and/or benchmarking) of LCA data sets of building assemblies available at an international level, in order to be used as generic data for a national context. For instance, the plausibility of the LCA results achieved for the 60 external wall alternatives (see Chapter 7) can be tested using NativeLCA and considering the data sets available at European, and at international levels. Thus, essential data can be gathered for the creation of a LCA database C2C of this type of assembly (or of other assemblies) to be used as generic in Portugal, namely in LCA of buildings (all these procedures and deliverables are identified in dashed text boxes in Figure 8.2). The integration of this database in a building design support tool can ease the comparative evaluation of the environmental (and also economic and energy) performance of building assemblies;
- NativeLCA can also be used to create benchmarking (or patterns) of environmental performance of each type or family of construction product (or of building assemblies), to be used namely in Type I environmental declarations or in green public (or private) pro-

curement (see Chapter 3);

- LCA results of 60 external wall alternatives can be subjected to a sensitivity analysis of the scenarios defined after the product stage, namely in terms of maintenance operations, expected service life of materials and end-of-life scenarios (see Chapter 7);
- The 3E-C2C method and the 3E *cost*-C2C approach can also be applied to building products closely related with the building’s thermal performance, besides building assemblies. The assessment (or comparison at design stage, namely for refurbishment projects) of the performance of insulation materials and elements of the wall structure can follow a procedure similar to the one applied to the external walls, while a 2E (environmental and economic) C2C approach must be chosen in the case of cladding solutions (these procedures are identified in dashed text boxes in Figure 8.2).

8.4. References - Chapter 8

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