LIFE CYCLE ASSESSMENT OF EXTENSIVE GREEN ROOFS IN LISBON

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Abstract

The objective of this work is the environmental assessment of extensive green roofs in the life cycle (cradle to grave). The environmental (and energetic) performance of the evaluated components depends on their geographical location, assuming they are integrated into a generic building in Lisbon, temperate city with hot, dry summer.To achieve the goal, it was applied the methodology of Life Cycle Assessment, using the *GaBi* tool in a simplified comparative approach - based on extensive theoric body - of two existing product systems in the flat roofs market: extensive green roof and conventional roof. Although LCA is oriented to products, the results are also interpreted on an urban scale, which needs more research. At that level, the Life Cycle Energy Analysis shows that extensive green roofs may have energy consumption lower than those of conventional roofs due to the indirect effect of reducing the Urban Heat Island. At the product level and considering the adopted scenario, the results of the Life Cycle Impact Assessment show that the global warming potential (GWP 100 years) of the extensive green roof has a positive impact, explained by the CO_2 sequestration produced by the vegetation layer along their lifetime (90 years). Extensive roofs are sustainable products in the long term, but more research is needed in the area of the constituent materials of their functional layers (shape layer, waterproofing membrane, insulation and drainage layer), in order to improve environmental performance.

Keywords: Life Cycle Assessment, Green Roofs, GaBi, Building Rehabilitation, Lisbon

1. INTRODUCTION

The purpose of this dissertation is the environmental assessment of extensive green roofs throughout its life cycle (cradle to grave). The environmental (and energetic) performance of the evaluated components depends on their geographic location. Therefore, it was assumed that they are integral part of a generic building (not built), located in Lisbon (Portugal). Climatic data of this building correspond to a temperate climate with hot, dry summer (Csa), according to the *Köppen-Geiger.* classification.

To achieve the objective, it was applied the methodology of Life Cycle Assessment (LCA) in a comparative approach of two different existing building solutions in the market of flat roofs (with limited access and thermal insulation), performing the same functions: extensive green roof and conventional roof. The functional unit used is 1 m2 of component. The estimated service life is 90 years, alike defined in the “Declaração Ambiental de Produto - Sistemas de Impermeabilização de Coberturas com Membranas Betuminosas Totalmente Aderidas” (Imperalum, 2013). A simplified LCA level of detail was used.

2. STATE OF THE ART

Life Cycle Assessment first studies date back to the late 60s and early 70s.The period from 1970 to 1990 covered the decades LCA conception, with widely divergent approaches,terminology and results, having been, at internationally level, a clear lack of scientific discussion and exchange platforms (Guinée et al. 2010).

The phase 1990-2000 can be characterized as a convergence period, through coordination of SETAC and ISO standardization activities, thus providing a standardized framework, a terminology and a platform for debate and harmonization of LCA methods. Note, however, that ISO never aimed to standardize LCA methods in detail: "There is no single method for the realization of an LCA" (ISO14040).

The period 2000-2010 was a time of preparation, but again as a decade of differing methods. Because the ISO never aimed to standardize LCA methods in detail and as there was no agreement on how to interpret some of the ISO requirements, different approaches have been developed (Guinée et al 2010.):

The present decade can be considered as a stage of Life Cycle Sustainability (LCSA). The authors consider that the LCSA framework broadens the scope of the current LCA from the main environmental impacts, just to cover the 3 dimensions of sustainability (people, planet, and prosperity). It also extends the scope of related issues with the product (product level), industry (sector level) and vast levels of the economy (economy level). Unlike the LCA, the LCSA is a transdisciplinary integration framework of models, a model itself.

According to Cabeza et al. (2014), for a long time Life Cycle Assessment methods have been used for environmental assessment of product development processes in other industries, despite the application in the building sector has a state of the art of only 10 years (Singh et al, 2011; Buyle et al, 2013).

Because LCA develops a comprehensive systemic approach to environmental assessment there is an increasing interest in incorporating LCA methods in decision making of building sector for selecting environmentally preferred products as well as for the evaluation and optimization of construction processes (Asdrubali et al, 2013). In addition, a growing "body" of literature has been developed, using LCA methods in performance evaluation of buildings, in its design and construction practices. However, Cabeza et al. (2014) state that the LCA literature is still quite fragmented and dispersed by several publications and has therefore organized and completed the existing literature on LCA applied to the construction sector.

Cabeza et al. (2013) also consider that the case studies in the literature are difficult to compare due to their specific properties, such as: type of construction, climate, comfort requirements, local regulations, etc. The authors developed a compilation of case studies worldwide of buildings and the construction sector, using LCA methods (as well as LCEA (Life Cycle Energy Analysis) and LCCA (Life Cycle Cost Analysis)). The most important features of the LCA are compared (scope, lifetime, functional unit, system boundaries, location and construction type), and it was found that most of the case studies are conducted in developed countries.

The authors also assert that, compared to other products, buildings are more difficult to assess, considering large-scale, complexity in terms of materials and functional and temporal dynamics, linked to the limited lifetime of building components and changing requirements of users. Moreover, their production processes are much less standardized in most manufactured goods, because of the unique location and nature of each building. The limited quantitative information relative to environmental impacts from the prodution of construction materials or to construction and demolition processes makes environmental assessments of the construction industry a challenge. The assessment of environmental impacts of buildings involves more than mere aggregation of individual products and material evaluation. Consequently, several studies have attempted to evaluate complete buildings, building systems and construction processes. These efforts often identified lifecycle phases with major environmental impacts and have provided a basis for general assessment of the construction system (Cabeza et al, 2013).

Adopting a classification system (which will be partly used in this work), Ortiz et al. (2008) describe the LCA state of the art of building materials/component combinations (BMCC) *versus* whole process of construction (WPC) in an article considered a important benchmark in the LCA. This article includes, by the year of publication, literature on methodological approaches to preserve the environment and thus to achieve sustainable development both in developed and developing countries.

A systematic literature review was conducted in this thesis, trying to grasp and to complete the existing literature on LCA applied to the building sector. 82 LCA studies were selected,, following different classifications: since the entire building and several components to the respective elements (layers: materials/construction products) (Kellenberger et al, 2009).

Between them, 34 studies are classified as WPC environmental impact assessments, conducted since 1982 (Bekker et al, 1982); 48 are classified as BMCC since 2000 (Citherlet et al, 2000).The search result is condensed in a list (Table 1).of 17 LCA studies (and non LCA- based) on "extensive green roofs", published in the building sector. (Baena, 2012; Bianchini et al, 2012; Blackhurst et al, 2010; Carter & Keeler, 2008; Castleton et al, 2010; Getter et al, 2009; Jaffal et al, 2012; Kosareo et al, 2006; Niachou et al, 2001; Ottelé et al, 2011; Pérez et al, 2012; Rocha e Silva, 2014; Sailor, 2008; Saiz et al, 2006; Santamouris et al, 2007; Valadas, 2014; Wong et al, 2003).

Studies“ non LCA-based” were also included in the extensive green roofs LCA research - usually focused only on the operational phase of the life cycle and on the energy component of buildings - as well other life cycle analyses (eg, IOA-LCA, CBA, LCC). They were found five case studies that are typical life cycle assessments (LCA) (Baena, 2012; Bianchini et al, 2012; Kosareo et al, 2006 Ottelé et al, 2011; Saiz et al, 2006).

Table 1 - LCA studies (and non LCA- based) of extensive green roofs published and applied in the field of building construction.

Reference	BMCC	Comments	Content	Country	Year
Baena	x		Estudi d'anàlisi de cicle de vida de cubicles amb coberta vegetada	**Espanha**	**2012**
Bianchini et al.	x		How “green” are the green roofs? Lifecycle analysis of green roof materials.	**Canadá**	**2012**
Blackhurst et al.	x	**escala urbana**	Cost-effectiveness of green roofs.	**EUA**	**2010**
Carter & Keeler	x	**escala urbana**	Life-cycle cost–benefit analysis of extensive vegetated roof systems.	**EUA**	**2008**
Castleton et al.	x	***revisao lit. LCA/non LCA***	Green roofs: building energy savings and the potential for retrofit.	**Reino Unido**	**2010**
Getter et al.	x	***non LCA***	Carbon sequestration potential of extensive green roofs.	**EUA**	**2009**
Jaffal et al.	x	***non LCA***	A comprehensive study of the impact of green roofs on building energy performance	**França**	**2012**
Kosareo et al.	x		Comparative environmental life cycle assessment of green roofs	**EUA**	**2006**
Niachou et al.	x	***non LCA***	Analysis of the green roof thermal properties and investigation of its energy performance	**Grécia**	**2001**
Ottelé et al.	x		Comparative life cycle analysis for green façades and living wall systems.	**Holanda**	**2011**
Pérez et al.	x	***non LCA***	Use of rubber crumbs as drainage layer in green roofs as potential energy improvement material	**Espanha**	**2012**
Rocha e Silva	x	***non LCA***	Simulação energética de coberturas verdes	**Portugal**	**2014**
Sailor	x		A green roof model for building energy simulation programs.	**EUA**	**2008**
Saiz et al.	x		Comparative life cycle assessment of standard and green roofs	**Espanha**	**2006**
Santamouris et al.	x	***non LCA***	Investigating and analysing the energy and environmental performance of an experimental green roof system installed in a nursery school building in Athens, Greece.	**Grécia**	**2007**
Valadas	x	***non LCA***	Avaliação experimental do comportamento térmico de coberturas verdes	**Portugal**	**2014**
Wong et al.	x	***non LCA***	Life cycle cost analysis of rooftop gardens in Singapore.	**Singapore**	**2003**

(BMCC - building materials and component combinations); (WPC - whole process of the construction).

It should be noted two other studies, conducted by Getter et al. (2009), which aimed to quantify the carbon storage potential of extensive green roofs and the effect of species selection on carbon accumulation. The first was developed over eight roofs in Michigan and the second covered four roofs in Maryland. All 12 green roofs were mainly composed of *sedum* species, having substrate depths between 2.5 and 12.7 cm.

Finally, the analysis of the constituent materials of green roofs performed by Bianchini et al. (2012) showed that these products are sustainable over the long term. In general, air pollution due to the polymer production process can be amortized by green roofs over a period of 13 to 32 years. However, the manufacturing processes of low density polyethylene and polypropylene have many other negative impacts on the environment, in addition to air pollution. According to the authors, it is clear that current green roofs materials need to be replaced by more environmentally friendly and sustainable products.

Thie state of the art also includes a review of environmental assessment tools for buildings.A variety of software and databases related to the construction industry provide standardized evaluation models and inventory data at multiple scales ranging from global data, sectorial industry data to product data (Singh et al, 2011; Haapio et al, 2008; Spatari et al, 2000; cited by Cabeza et al, 2013).

In addition, according with Haapio et al. (2008), the building environmental assessment tools field is vast, the latter have been developed by various institutes and for different purposes. The emerging role of environmental assessment tools for buildings encourages discussion of the content, the framework of different tools and also the context in which they operate. This discussion requires the categorization of tools based on two well-known environmental assessment tools classification systems of buildings: one was developed by the ATHENA Institute (Trusty, 2000), another by the IEA Annex 31 (2001).

Haapio et al. (2008) consider that industries (including building sector) have come to recognize the impact of their activities on the environment, in the 90.The authors state that significant changes were necessary to mitigate the environmental impact of the building sector, which had to focus on the way of how the buildings would be designed, constructed and used - the drivers were public policy, and the growing market demand for products and environmentally sound services. With the goal of reducing environmental impacts, it was necessary to adopt a yardstick for measuring the environmental performance (Crawley and Aho 1999). The specific definition of the term "building performance" is complex, since different buildings sector stakeholders have different interests and requirements (Cole, 1998) – economic performance, for example, interests to investors, while tenants are more interested in issues related to health and comfort.

The development of different tools in the building sector led to the different organizations and research groups contribute with new knowledge gained through experience, having the tools gained considerable success in recent years (Haapio et al, 2008). However, the success of evaluation tools neglected all other mechanisms for raising environmental awareness (Cole, 2005). The discussion on sustainability in the building sector gained international forum.

3. METHODOLOGY

As defined in ISO 14040, Life Cycle Assessment is the compilation and evaluation of inputs and outputs and of the potential environmental impacts of a product system throughout its life cycle. The International Organization for Standardization (ISO) adopted a standard for environmental management in the 90s, as part of their series of 14000, with 14040 focused on creating methodologies for LCA. An important facet of ISO consists of a four-step iterative grid for conducting LCA analysis: **i)** goal and scope definition; **ii)** inventory analysis (LCI); **iii)** life cycle impact assessment (LCIA); **iv)** interpretation (Figure 2).

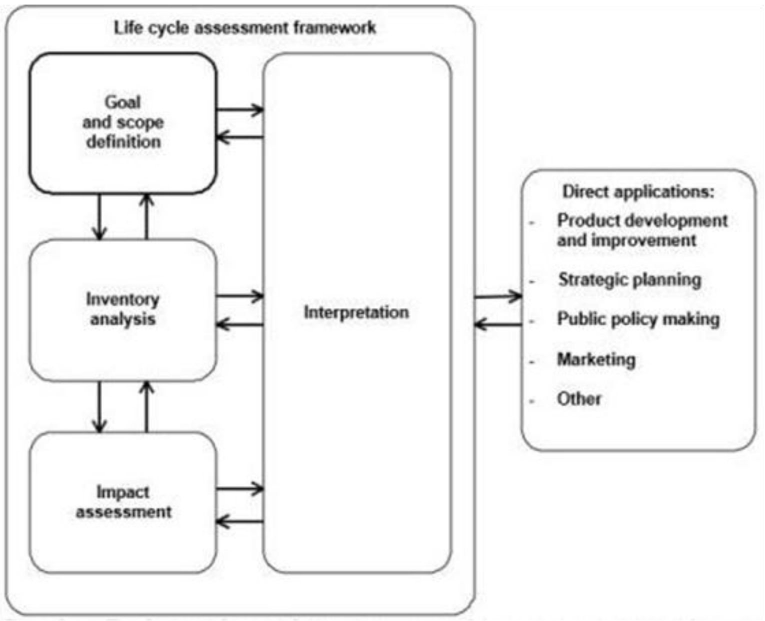


Figure 1 - Methodological framework of LCA (ISO 14040).

Based on this general LCA framework, the organization of this work follows the methodological framework exposed in GaBi software documentation (PE Int'l, GaBi. 2014).

The methodology used in this LCA study is based on the two following documents :**i)** A reference guide designed to encourage scientific debate - Life cycle assessment; An operational guide to the ISO standards; Part 3 - Scientific background (Guinée et al, 2001); **ii)** Documentation of the GaBi software (the recommendations for mandatory and optional information are based on international standards ISO 14040, ISO 14044, in ELCD (European Life Cycle Database), as well as the experience of PE International and LBP -University of Stuttgart) (PE Int'l, GaBi. 2014).

GaBi (*Ganzheitliche Bilanzierung Integrated Assessment*) GaBi is a software package, whose model is based on processes. It was developed at the University of Stuttgart (Germany), allowing life cycle assessments in accordance with ISO 14040 (Int'l PE, GaBi. 2014). It uses an integrated product database that was developed throughout the industry and technical literature review.

The selected LCA tool is called GaBi Education Version 6.0 (the developer is PE International). Can be classified as *level 1* (product comparison tools) according to the ATHENA system of classification or classified as an *level 1* interactive tool of "Environmental LCA for Buildings and Stocks of Buildings", according to the classification system IEA Annex.

The educational version provided has some limitations. However, this tool is fully functional, containing a comprehensive database aimed specifically at students and teachers. This extensive database contains datasets PE and USLCI (US Life Cycle Inventory Database). The databases provided with the GaBi software Version 6.0 Education, which were the basis for the present LCA, are the follows: **i)** PE: Education database 2014; **ii)** ELCD / PlasticsEurope: Education database 2014; **iii)** PlasticsEurope: Education database 2014; **iv)** Inventory of Carbon & Energy (ICE) Version 2.0, University of Bath, UK (database used when they were not found suitable processes data/flows in GaBi databases) (ICE 2011).

In addition, other documents served as the basis for this LCA study:**i)** An Environmental Product Declaration - Declaração Ambiental de Produto - Sistemas de Impermeabilização de Coberturas, com Membranas Betuminosas Totalmente Aderidas

(Imperalum, 2013); **ii)** Product Category Rules According to ISO 14025: 2006 Flexible sheets for waterproofing – bitumen, plastic or rubber sheets for roof waterproofing (PCR, 2014); **iii)** Product Category Rules According to ISO 14025, Product group classification: Multiple UN CPC codes construction products and construction services (PCR, 2015). These documents follow the reference standard ISO 15804 (EN 15804, 2012).

According to ISO 14040 standard, the first step of an LCA is the goal definition and scope. This important and essential step provides the fundamental starting point for the study and is subdivided into two distinct: **i)** Objective definition; **ii)** Scope definition.

The first stage is divided into 4 distinct modules: **i)** Intended use of LCA study; **ii)**. Purpose of the LCA; **iii)** Target audience of LCA; **iv)** Use of comparative analysis. The second stage is divided into 6 distinct modules: **i)** Product function; **ii)** Functional unit and reference flow; **iii)** System boundaries; **iv)** Level of detail; **v)** Allocation procedures and system expansion; **vi)** Data quality requirements. This study also follows the exposed methodological framework in the used *GaBi* software documentation (PE Int'l, GaBi. 2014).

The intended application of this LCA is primarily for comparing two products - an extensive green roof *vs* a conventional roof - and in addition to the improvement of these products (design), to the identification of "hot spots" in the life cycle of products and to the application of environmental performance indicators.

Considering the need of a comparative analysis it is important to define both “product-oriented” technosystems, which perform the same function (or functions). These two systems are called: **i)** Extensive green roof (Imperalum, 2015) (Figure 2); **ii)** Conventional roof (Imperalum, 2015)

Extensive Green roofs (EGR) are composed by 7 functional layers. Each of these layers (constituent elements of the extensive green roof assembly) satisfy several specific functions. This typology differs from the reference solution (conventional flat roof) concerning the protective layer, which is replaced by the vegetation and growth substrate layers (Figure 2 and Table 2).

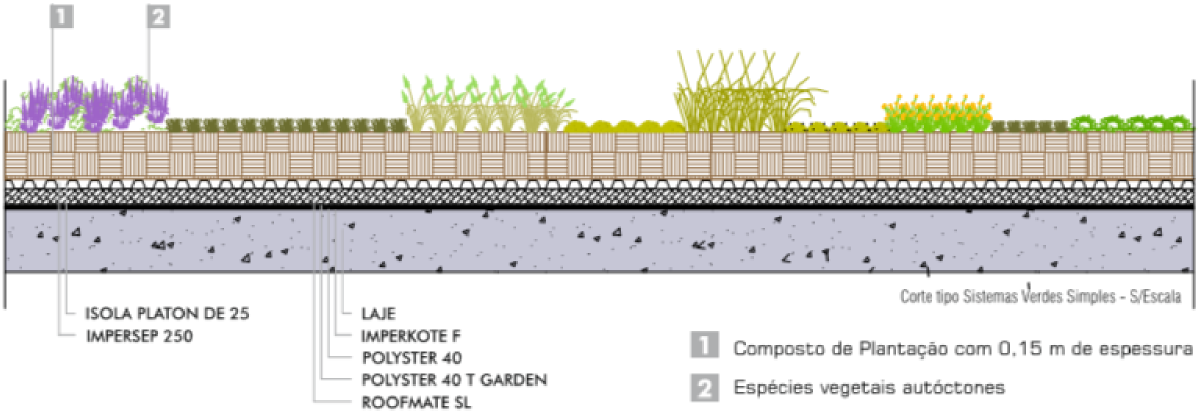


Figure 2 - Characteristics of commercial building system (functional layers) (Decoverdi, 2015).

Table 2 - Characteristics of commercial building system (functional layers)

Layers	Produto	Material	Descrição do Material	Peso [Kg]	%	Cond. Térmica λ (W/m2 C)	Esp (m)	Esp / λ	Comentários
1	**DECOPLANT RUSTIC**	Camada vegetal		**34,00**	**10,70%**				Plantas tapizantes muito resistentes (planta rasteira que pode ser utilizada para cobrir o solo; abafa/controla as ervas daninhas). Autóctones e Adaptadas. Plantas adaptadas a temperaturas extremas, seleccionadas em função da localização geográfica e climática. Este sistema procura ter uma maior preocupação estética/visual. Profundidade do substrato de crescimento (cm): Musgos – sedum < 4 a 8 ; Sedum – musgos – pequenas herbáceas 6 a 10; Sedum – musgos – pequenas gramíneas 10 a 15 Gramíneas e herbáceas 15 a 20
2	**DECOPLANT RUSTIC**	Substrato de crescimento	Composto de Plantação ou Turfa vegetal	**225,00**	**70,83%**	**1,75**	**0,15**	**0,0857**	Composto de Plantação constituído por: - Argila expandida / rocha vulcânica (1/3); - Terra vegetal enriquecida com nutrientes (2/3); Este composto rico em nutrientes deverá ter, em média, uma espessura de 15 cm.
3	**IMPERSEP 200**	Manta geotêxtil de fibras sintéticas	Manta geotêxtil de fibras sintéticas como camada separadora tipo IMPERSEP 200	**0,20**	**0,06%**	**0,04**	**0,0015**	**0,0375**	Tecido não tecido de fibras sintéticas com uma gramagem de 200 g/m2 (+10% ; -15%). Tecido NÃO com peso Uma Tecido de 200 g / m2 fibras sintéticas (+ 10% , -15%). Um geotêxtil é uma tela permeável e flexível de fibras sintéticas, principalmente de polipropileno e de poliéster, que pode ser fabricado de forma não-tecida (*non-woven*) ou tecida (*woven*) dependendo da utilização ou função a desempenhar. *Thermally strengthened, UV-stabilized filter sheet made of 100 % polypropylene, highly resistant to mechanical stress.*
4	**ISOLA PLATON DE 25**	Polietileno de alta densidade (PEAD)	Lâmina granular de polietileno de alta densidade tipo ISOLA PLATON DE 25	**0,96**	**0,30%**	**0,5**	**0,001**	**0,0020**	Placas de drenagem perfilada: Placa em PEH guarnecida, com canais em ambas as direcções entre grânulos. Os grânulos numa das faces da lâmina têm uma distância aproximada entre si de centros de 60 mm em ambas as direcções, proporcionando a circulação de ar à construção subjacente. Todos os canais estão dotados de septos de drenagem dispostas alternadamente entre as filas de grânulos, apenas numa direcção.
5	**IFOAM / COBERTURAS**	Poliestireno extrudido (XPS)	Placas de poliestireno extrudido, tipo IFOAM COBERTURAS/PAVIMENTOS	**2,10**	**0,66%**	**0,034**	**0,06**	**1,7647**	Placas em espuma rígida de poliestireno extrudido (XPS) na cor cinza grafite para isolamento térmico de edifícios. Composição: Betume de destilação (sem alcatrão), polímeros plastoméricos, elastoméricos e outros, carbonato de cálcio, aditivos. As membranas podem conter poliéster e/ou fibra de vidro, como armaduras, bem como ardósia, cortiça, areia, filme de polietileno ou poliéster, alumínio e/ou pelicula autoadesiva recoberta com papel siliconizado, como acabamentos.
6a	**POLYSTIR 40 GARDEN**		Membrana de impermeabilização de betume polímero APP, tipo POLYSTIR 40 GARDEN	**4,00**	**1,26%**	**0,2**	**0,0031**	**0,0155**	As membranas POLYSTER 40 e POLYSTER R40 são obtidas por recobrimento das duas faces das respectivas armaduras – poliéster de 150 g/m2 , no caso das membranas POLYSTER 40, e de fibra de vidro de 45 g/m2 e poliéster de 150 g/m2 , no caso das membranas POLYSTER R40 – com uma mistura contendo cerca de 60% de betume, 20% de polímero plastómero APP e 20% de cargas minerais de carbonato de cálcio. Estas membranas podem ser acabadas com filmes de polietileno ou com areia fina.
		Aditivo anti-raízes	Aditivo anti-raízes na massa betuminosa						
		60% de betume							
		20% de polímero plastómero APP							
		20% de cargas minerais de carbonato de cálcio							
		Poliester de 150 g/m2	Armadura de poliester protegida a polietileno em ambas as faces.						
		Polietileno	Armadura de poliester protegida a polietileno em ambas as faces.						
6b	**POLYPLAS 30**		Membrana de impermeabilização de betume polímero APP, tipo POLYPLAS 30	**3,00**	**0,94%**	**0,2**	**0,0023**	**0,0115**	mistura contendo cerca de 60% de betume, 20% de polímero plastómero APP e 20% de cargas minerais de carbonato de cálcio.
		60% de betume							
		20% de polímero plastómero APP							
		20% de cargas minerais de carbonato de cálcio							
		Poliester de 150 g/m2	Armadura de poliester protegida a polietileno em ambas as faces.						
		Polietileno	Armadura de poliester protegida a polietileno em ambas as faces.						
7	**IMPERKOTE F**	Emulsão betuminosa	Emulsão betuminosa como primário de impermeabilização, tipo IMPERKOTE F	**0,40**	**0,13%**	**0,001**		**0,0000**	Composição: Betume de destilação (sem alcatrão), emulsionante natural (bentonite e/ou outro), água. Nalguns casos (IMPERKOTE L) contém latex. Constituição: É uma emulsão betuminosa não iónica de aspecto pastoso, solúvel em água e misturável com areia, cimento, gravilha, fibras minerais, etc. É constituída por betumes e resinas, filerizada e estabilizada com emulsionantes minerais coloidais que asseguram a sua estabilidade. Uma vez dada a rotura da emulsão, por evaporação da fase aquosa, consegue-se uma camada contínua que não flúi a temperaturas elevadas. Utilizações: Como primário em impermeabilização diluído 2/3 de emulsão e 1/3 de água.Emulsões betuminosas para utilização como primário em sistemas de impermeabilização ou outras utilizações
8	**Betão leve de argila expandida**	Betão leve de argila expandida		**48,00**	**15,11%**	**0,156**	**0,1**	**0,6410**	

The *GaBi* tool is structured in a hierarchy of objects, of which is worth mentioning the following: **i)** Plans; **ii)** Processes; **iii)** Flows. *GaBi* calculates the potential environmental impacts, as well as other important quantities of a product system, based on a plan. A plan is the system with its boundaries. The system to be studied is composed of processes that represent the occurring actual processe. Flows represent all material and energy flows between processes and transferred to and from the system (input/output flows). Figure 2 represents the *Gabi* plan of the analysed EGR (PE Int'l, GaBi 2014).

Figure 2 - Plan of processes: extensive green roof (PE Int'l, GaBi 2014)

The European standard EN 15804 provides the Product Category Rules (PCR) for all products and construction services. It provides a framework which ensures that all the Environmental Product Declarations (EPD) of building products, construction services and construction processes are derived, verified and presented in a harmonized manner (EN 15804, 2012). The standard divides the life cycle of a building in life-cycle stages and modules. Within the new *GaBi* database for construction, each data set is modeled, grouped and marked in accordance with this methodology and modularity. These datasets may be used to model the life cycle of a building.

The EN 15804 divides the life cycle of a building in the following steps: **i)** Production; **ii)** Installation; **iii)** Use; **iv)** End of life; **v)** Benefits and drawbacks derived from the lifecycle process. Each of these steps are further divided into more detailed steps, called modules. The modules are continuously numbered in the stages of the life cycle, using a capital letter and a number. The nomenclature system for the individual modules of the life cycle is shown in Table 3. This LCA adopts the methodology and modularity of EN 15804. This streamlined LCA adopts the methodology and modularity of EN 15804, taking into account the following aspects: **i)** Does not include B2, B3, B4 and C1 modules; ii) Includes the B1 module use phase (use of the the installed product.

able 3 - Modules of the life-cycle stages according to EN 15804.

PRODUCT STAGE			CONSTRUCTION PROCESS STAGE		USE STAGE					END OF LIFE STAGE				RESOURCE RECOVERY STAGE
A1	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**C1**	**C2**	**C3**	**C4**	**D**
raw material extraction and processing, recycling processes for recycled material input	transport to the manufacturer	manufacturing	transport to the building site	installation process. In particular, the following information shall be provided:	use of the installed product	maintenance	repair, production of repaired part, use of energy, transportation of repaired part, waste handling of repaired part	replacement, production of replacement part, use of energy, transportation of replenishment part, waste handling of replenishment part	refurbishment, production of components used for refurbishment, related energy used, transport of waste of the refurbishment	transport to the product's waste processing	waste processing for reuse, recovery and/or disposal	disposal	reuse, recovery or recycling and/or recovery potentials	Recyclability potentials: benefits and loads beyond the product system

4. INTERPRETATION OF RESULTS

The interpretation phase is an integral part of an LCA, showing the results of Life Cycle Assessment and the conclusions and recommendations for decision-making. The life cycle interpretation is an iterative process in which the results are recorded and evaluated, and should be consistent with the requirements of the study goal and scope. This phase includes three main stages (PE Int'l, GaBi 2014): **i)** Identification of significant issues; **ii)** evaluation (review methodology and results in completeness, sensitivity and consistency; prepare draft conclusions and ceck consistency); **iii)** final conclusions and recommendations (if the conclusions are consistent will be considered as final conclusions, and recommendations made to the target audience of the LCA).

- Comparative Life Cycle Energy Analysis (LCEA): energy resources.

In this analysis (including operational energy) all the energy needs of the evaluated product systems are accounted. The LCEA was applied to 2 roofing systems, components of a building in design phase (not built) with an thermal behavior equivalent to the average of three case studies located in Lisbon for two solutions studied by Rocha e Silva (2014) - extensive green roof vs conventional white roof.

Relative to the A scenario (includes operational energy), the next Table 4 presents the results of the comparative LCEA. It was observed that the extensive green roof consumes more energy resources - 33% more than conventional roof. Observing in a temporal perspective of the life-cycle stages contribution to the results of this LCA, it appears that the *downstream* stage (gate to grave) reveals energy resource values substantially higher than the *upstream_core* stage (cradle to gate). This is expected due to the operational energy cumulative effect during the service life (90 years) of the evaluated building component.

Table 4 - Energy resources (MJ): comparison between extensive green roof and conventional roof (scenario A).

	Cobertura verde extensiva			**Cobertura convencional**			**Diferença**			**Diferença %**		
Energy (gross calorific value) MJ	**TOTAL**	**UPSTREAM_CORE**	**DOWNSTREAM**	**TOTAL**	**UPSTREAM_CORE**	**DOWNSTREAM**	**TOTAL**	**UPSTREAM_CORE**	**DOWNSTREAM**	**TOTAL**	**UPSTREAM_CORE**	**DOWNSTREAM**
Energy resources	37 555,54	838,91	36 716,63	28 136,02	750,94	27 385,08	9 419,52	87,97	9 331,55	**33%**	**12%**	**34%**
Non renewable energy resources	23 266,64	716,35	22 550,28	17 533,46	716,35	16 817,10	5 733,18	0,00	5 733,18	**33%**	**0%**	**34%**
Renewable energy resources	14 185,56	19,21	14 166,35	10 587,18	19,21	10 567,97	3 598,37	0,00	3 598,37	**34%**	**0%**	**34%**
Energy embodied EE	103,35	0,00	103,35	15,38	15,38	0,00	87,97	-15,38	103,35			

Relative to the B scenario (does not include operational energy) Table 5 shows the results of comparative LCEA. It was observed that the extensive green roof consumes more energy resources - 15% more than conventional roof of reference, but with a value 18% lower than the result of A scenario. This is due to a factor: the difference between the process *1a Seixo rolado:* conventional roof *(EE = 0,083 MJ/kg; Material Profile: Aggregate; General Aggregate)* and the process *Substrato de crescimento:* extensive green roof (EE = 0,45 MJ/kg; Material Profile: Soil; General (Rammed) Soil) (ICE, 2011).

Regarding the life cycle stages contribution to the results, inversely to the A scenario A, the *downstream* stage (gate to grave) reveals energy resource values substantially below the *upstream_core* stage (cradle to gate), as this scenario does not include the using phase B1 module .

Tabela 5 - Energy resources (MJ): comparison between extensive green roof and conventional roof (scenario B).

	Cobertura verde extensiva 1			Cobertura convencional 1			Diferença			Diferença %		
Energy (gross calorific value) MJ	TOTAL	UPSTREAM_ CORE	DOWNSTREAM	TOTAL	UPSTREAM_ CORE	DOWNSTREAM	TOTAL	UPSTREAM _CORE	DOWNSTREAM	TOTAL	UPSTREAM_ CORE	DOWNSTREAM
Energy resources	944,36	838,91	105,45	823,45	750,94	72,51	120,91	87,97	32,94	**15%**	**12%**	**45%**
Non renewable energy resources	815,44	716,35	99,09	784,48	716,35	68,13	30,96	0,00	30,96	**4%**	**0%**	**45%**
Renewable energy resources	25,57	19,21	6,36	23,59	19,21	4,38	1,98	0,00	1,98	**8%**	**0%**	**45%**
Energy embodied EE	103,35	103,35	0,00	15,38	15,38	0,00	87,97	87,97	0,00			

- <u>Comparative Life Cycle Impact Assessment (LCIA): Impact categories indicators</u>.

CML 2001 Characterization factors: version 3.9 (November 2010) is the LCIA method used in the current LCA study. Note that the carbon sequestration of extensive green roofs is considered in both scenarios. Relative to the A scenario, it can be observed, from the comparative analysis of the extensive green roof vs conventional, two impact category indicators showing significant differences (Table 6). It appears that the differences are much more pronounced in the *gate to grave* stage (downstream) in favor of the reference conventional solution (minor impact): **i)** CML2001 - Nov. 2010 Abiotic Depletion (ADP fossil) [MJ]; **ii)** CML2001 - Nov. 2010 Global Warming Potential (GWP 100 years) [kg CO2-Equiv.].

These results are due to the substantial "weight" of thermal energy consumption of the building component during the use phase, which was modeled in detail in *Electricity grid PE mix: PT* process.

Tabela 6 - Comparison "extensive green roof" *vs* "conventional roof" (scenario A) - Impact categories indicators.

	Cobertura verde extensiva			Cobertura convencional			Comparação			
	TOTAL	UPSTREAM_CORE	DOWNSTREAM	TOTAL	UPSTREAM_CORE	DOWNSTREAM	TOTAL	UPSTREAM_CORE	DOWNSTREAM	
CML2001 - Nov. 2010, Abiotic Depletion (ADP elements) [kg Sb-Equiv.]	0,000313	0,000021	0,000292	0,000237	0,000021	0,000216	0,00	0,00	0,00	
CML2001 - Nov. 2010, Abiotic Depletion (ADP fossil) [MJ]	20 580,68	645,80	19 934,88	15512,16	645,80	14866,35	5068,52	0,00	5068,52	
CML2001 - Nov. 2010, Acidification Potential (AP) [kg SO2-Equiv.]	9,160482	0,101200	9,059282	6,86	0,10	6,76	2,30	0,00	2,30	
CML2001 - Nov. 2010, Eutrophication Potential (EP) [kg Phosphate-Equiv.]	0,702832	0,007500	0,695332	0,52	0,01	0,52	0,18	0,00	0,18	
CML2001 - Nov. 2010, Global Warming Potential (GWP 100 years) [kg CO2	1 619,46	30,73	1 588,73	1223,23	26,17	1197,07	396,23	4,57	391,66	
CML2001 - Nov. 2010, Ozone Layer Depletion Potential (ODP, steady state	0,000450	0,000000	0,000450	0,000310	0,000000	0,00	0,00	0,00	0,00	
CML2001 - Nov. 2010, Photochem. Ozone Creation Potential (POCP) [kg E	0,748631	0,009173	0,739459	0,561718	0,009173	0,55	0,19	0,00	0,19	

In scenario B, from the comparative analysis it can be observed two impact category indicators that show significant differences (Table 7):

i) CML2001 - Nov. 2010 Abiotic Depletion (ADP fossil) [MJ]: the difference "extensive green roof" vs. "conventional roof" presents a significant positive value, which means that the "extensive green roof" has a greater relative impact in terms of *ADP fossil* , located temporarily in the *gate to grave* lifecycle stage (downstream);

ii) CML2001 - Nov. 2010 Global Warming Potential (GWP 100 years) [Kg CO2-Equiv]: The difference "extensive green roof" vs. "conventional roof" features a signifcant negative value, which means that the EGR has a lower relative impact, in terms of the *GWP 100 years*, partially located in the *downstream* lifecycle stage These *GWP 100 years* indicator quantities are explained by the input (CO_2 flow) in extensive green roof *downstream* process, produced by the vegetation functional layer and equivalent to carbon dioxide sequestration contributor.

Table 7 - Comparison "extensive green roof" *vs* "conventional roof" (scenario B) - Impact categories indicators.

	Cobertura verde extensiva1			Cobertura convencional1			Comparação		
	TOTAL	UPSTREAM_CORE	DOWNSTREAM	TOTAL	UPSTREAM_CORE	DOWNSTREAM	TOTAL	UPSTREAM_CORE	DOWNSTREAM
CML2001 - Nov. 2010, Abiotic Depletion (ADP elements) [kg Sb-Equiv.]	0,00005	0,00002	0,00003	0,00004	0,00002	0,00002	**0,00001**	0,00000	0,00001
CML2001 - Nov. 2010, Abiotic Depletion (ADP fossil) [MJ]	738,30	645,80	92,50	709,40	645,80	63,60	**28,90**	0,00	28,90
CML2001 - Nov. 2010, Acidification Potential (AP) [kg SO2-Equiv.]	0,12520	0,10120	0,02400	0,11770	0,10120	0,01650	**0,00750**	0,00000	0,00750
CML2001 - Nov. 2010, Eutrophication Potential (EP) [kg Phosphate-Equiv.]	0,06432	0,00750	0,05682	0,04656	0,00750	0,03906	**0,01776**	0,00000	0,01776
CML2001 - Nov. 2010, Global Warming Potential (GWP 100 years) [kg CO2	26,55	30,73	-4,19	34,89	26,17	8,73	**-8,35**	4,57	-12,91
CML2001 - Nov. 2010, Ozone Layer Depletion Potential (ODP, steady state	0,00045	0,00000	0,00045	0,00031	0,00000	0,00031	**0,00014**	0,00000	0,00014
CML2001 - Nov. 2010, Photochem. Ozone Creation Potential (POCP) [kg E	0,01388	0,00917	0,00471	0,01358	0,00917	0,00441	**0,00030**	0,00000	0,00030

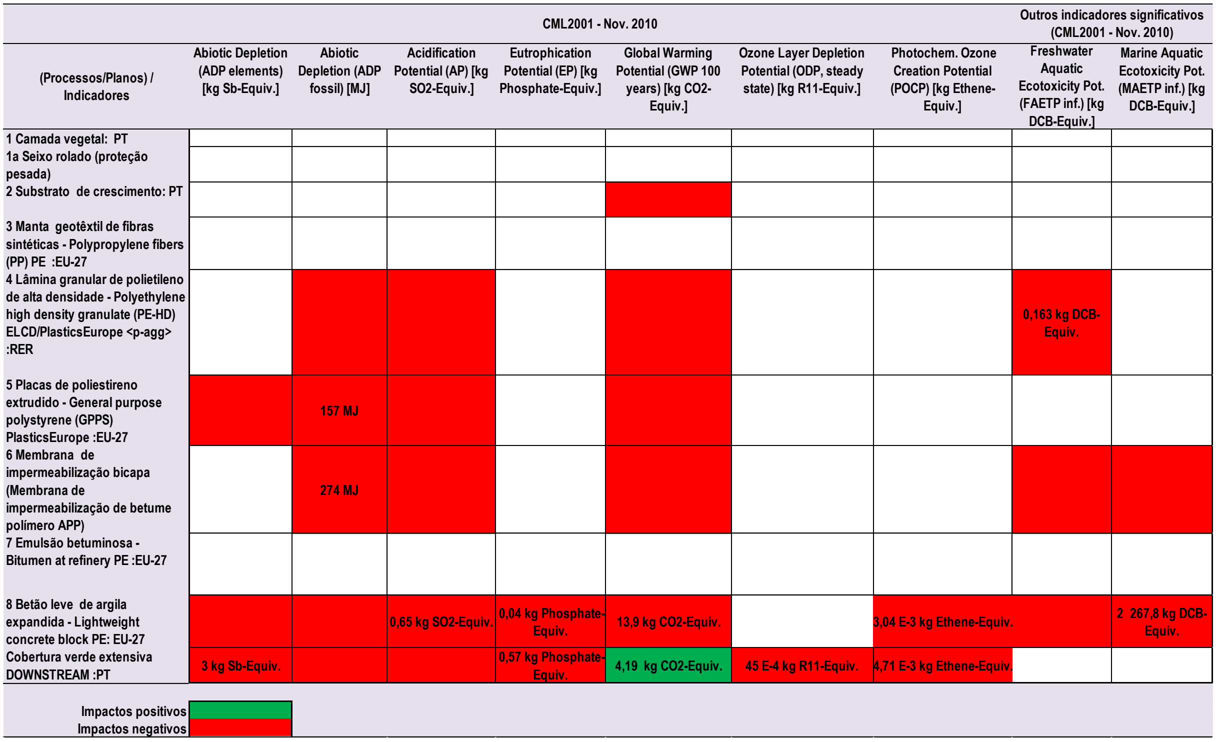
- <u>Analysis of processes: LCIA (Life Cycle Impact Assessment).</u>

This analysis interprets the results of the LCIA in the scenario B (not including operational energy), comparing the respective processes for each individual functional layer of the extensive green roof. The values refer to 1 m^2 of functional unit. The Table 8 summarizes the functional layers with the greatest impact (positive or negative) on the environment. The process of extensive green roof points for a positive impact on the environment (GWP 100 years), considering the *gate to grave* stage. These impacts have been quantified through *CML2001 impact category indicators - Nov. 2010*.

It is presented in descending order of relevance :i) *8 Betão leve de argila expandida*; ii) *Membrana de impermeabilização bicapa;* iii) 5 *Placas de poliestireno extrudido*; iv) 4 *Lâmina granular de polietileno de alta densidade*.

The process “*extensive green roof downstream*” has a positive impact on the environment of 4.19 kg CO2-Equiv. per m2 (GWP 100 years), which occurred in the *gate to grave* life cycle stage. For negative impact on the environment it can be concluded the following: **i)** The most significant contributions to Abiotic Depletion (ADP fossil) relate to 2 functional layers*: 6 Membrana de impermeabilização bicapa; 5 Placas de poliestireno extrudido*; **ii)** The most significant contributions to Acidification Potential (AP) pertain to the functional layer *8 Betão leve de argila expandida*; **iii)** The most significant contributions to Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB-Equiv.] relate to functional layer *4 Lâmina granular de polietileno de alta densidade*; **iv)** The most significant contributions to Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB-Equiv.] pertain to the functional layer *8 Betão leve de argila expandida*.

Table 8 - Summary table of *CML2001 impact category indicators - Nov. 2010* - functional layers of the extensive green roof.



	CML2001 - Nov. 2010							Outros indicadores significativos (CML2001 - Nov. 2010)	
(Processos/Planos) / Indicadores	Abiotic Depletion (ADP elements) [kg Sb-Equiv.]	Abiotic Depletion (ADP fossil) [MJ]	Acidification Potential (AP) [kg SO2-Equiv.]	Eutrophication Potential (EP) [kg Phosphate-Equiv.]	Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	Ozone Layer Depletion Potential (ODP, steady state) [kg R11-Equiv.]	Photochem. Ozone Creation Potential (POCP) [kg Ethene-Equiv.]	Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB-Equiv.]	Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB-Equiv.]
1 Camada vegetal: PT									
1a Seixo rolado (proteção pesada)									
2 Substrato de crescimento: PT					🟥				
3 Manta geotêxtil de fibras sintéticas - Polypropylene fibers (PP) PE :EU-27									
4 Lâmina granular de polietileno de alta densidade - Polyethylene high density granulate (PE-HD) ELCD/PlasticsEurope <p-agg> :RER		🟥	🟥		🟥			🟥 0,163 kg DCB-Equiv.	
5 Placas de poliestireno extrudido - General purpose polystyrene (GPPS) PlasticsEurope :EU-27	🟥	🟥 157 MJ	🟥		🟥				
6 Membrana de impermeabilização bicapa (Membrana de impermeabilização de betume polímero APP)		🟥 274 MJ	🟥		🟥			🟥	🟥
7 Emulsão betuminosa - Bitumen at refinery PE :EU-27									
8 Betão leve de argila expandida - Lightweight concrete block PE: EU-27	🟥	🟥	🟥 0,65 kg SO2-Equiv.	🟥 0,04 kg Phosphate-Equiv.	🟥 13,9 kg CO2-Equiv.		🟥 3,04 E-3 kg Ethene-Equiv.	🟥	🟥 2 267,8 kg DCB-Equiv.
Cobertura verde extensiva DOWNSTREAM :PT	🟥 3 kg Sb-Equiv.	🟥	🟥	🟥 0,57 kg Phosphate-Equiv.	🟩 4,19 kg CO2-Equiv.	🟥 45 E-4 kg R11-Equiv.	🟥 4,71 E-3 kg Ethene-Equiv.		
Impactos positivos	🟩								
Impactos negativos	🟥								

5. FINAL CONCLUSIONS AND FUTURE DEVELOPMENTS

These conclusions are based on previously assumed simplifications of the analyzed processes, due to the resources limitation of this LCA study. In the future, it is suggested a development of this simplified (streamlined) LCA, in order to improve the level of detail.

The lifecycle sustainability analysys can be held at three different levels: product, meso or economy. The LCA of this work took place on the first level. However, the results of LCA can be interpreted in two different views: product scale (building) and urban scale (city or district).

In the first, the results of the comparative Life Cycle Energy Analysis (LCEA) demonstrate that extensive green roof does not have advantages over conventional reference roof, since it consumes more energy resources throughout their life cycle. On the contrary, on the second level (installation of extensive green roofs on urban scale) and based on the results of the literature, it is shown that extensive green roof has advantage over conventional roof, since - due to the indirect effect of reducing Urban Heat Island (UHI) - consumes less energy resources throughout their life cycle, with a consequent reduction in environmental impacts. This confirms the potential of extensive green roofs as an environmental tool for urban intervention (PDM, 2012).

Returning to the level of product, the results of the comparative Life Cycle Impact Assessment (LCIA) demonstrate that extensive green roof only has advantage over conventional roof, in the context of a scenario (B) that does not include the operational energy, ie, the extensive green roof has a lower relative impact in terms of global warming potential (GWP 100 years) due to input of CO_2 produced by the vegetation functional layer, equivalent to carbon dioxide sequestration throughout its lifetime (90 years).

The positive impact on the environment is equivalent to aprox. 4.2 kg CO_2-Eq. per m2 (GWP 100 years). At urban scale, the application of the previous value in a 10 million m2 deployment area of extensive green roofs (approx. 10% of Lisbon municipality) would be equivalent to the CO_2 emissions savings of more than 300 million km traveled by new cars, a large net removal of CO_2 from the atmosphere during a sustained period. "A large part of climate change caused by anthropogenic CO_2 emissions is irreversible in a multi-secular to millenar time frame, except for a large net removal of CO_2 from the atmosphere over a sustained period" (IPCC, 2013).

The extensive green roofs are sustainable products in the long run, but it is clear that certain constituent materials, such as plastics, need to be improved or replaced by more environmentally friendly and sustainable products..It can be concluded that more research is needed in the following areas of the field of functional layers materials (shape layer, waterproofing membrane, insulation and drainage layer), aiming to improve their environmental (and energetic) performance: **i)** improving the energy efficiency of housing and equipment - reducing operational energy levels; **ii)** improving the energy efficiency of producing industries – reducing embodied energy levels of materials; **iii)** reuse of building materials - greatly reducing embodied energy levels of materials; **iv)** recycling materials for reprocessing - reducing embodied energy levels of materials; **v)** selection of new materials - reduced energy levels incorporated materials.

The embodied energy can be equivalent to many years of operating energy. In addition to the effort that has been placed on operational energy reduction by improving the energy efficiency of the building envelope, it should also be directed attention to the initial embodied energy content of the material, which occurs once in industrial production stage .

Another issue requiring further consideration is the indirect effect of the decrease in temperature – reduction of the Urban Heat Island (UHI) - due to the installation of extensive green roofs at urban scale in Lisbon. This effect would reduce the power requirements in the building use phase, a factor that has not been accounted for in this LCA. Therefore, life cycle impacts could be considerably reduced if this constructive solution was used at a city or district level.

Finally, the positive impact on the environment generated by the analyzed extensive green roof - in terms of global warming (GWP 100 years) - confirms the potential of this product as an environmental tool for urban intervention, considering the requirements defined in the Master Plan of Lisbon that "intends to increase the presence of green and permeable areas on the top of buildings " (PDM, 2012).

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