Life-Cycle Assessment of Residential Buildings

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ABSTRACT: The quantification of the environmental impacts of a building can help decision-makers to identify processes of major environmental impacts. Therefore it can be used since the early stages of design to support decision makings which aim to promote lower environmental impacts and, as a result, more sustainable buildings. Life Cycle Assessment (LCA) is considered the most adequate method for evaluating the environmental pressure caused by materials, building assemblies and the whole life-cycle of a building. Nevertheless this method is not widely used in the building sector. This paper aims to present the main constrains that are hindering the use of LCA in the building sector. Moreover, it presents a solution to overcome the indentified barriers and to promote the use of LCA methods since the earlier phases of the design process.

1 INTRODUCTION

Construction is not an environmentally friendly process by nature. The cumulative environmental impacts of construction processes have been increasing in the world due to a large number of ongoing construction projects. Most of these impacts are related with the operation and maintenance phases of a building. A recent study (EPA, 2009) shows that construction is the third largest industry sector in terms of contributions to greenhouse gas emissions in the United States.

In Portugal, most of the impacts of the built environment in the sustainable development are related to the residential sector (Mateus, 2009). At the environmental level this sector is directly and indirectly linked to the consumption of a great amount of natural resources (energy, water, mineral, wood, etc.) and to the production of a significant quantity of residues. For example, although Portugal has a mild climate, residential sector accounts for about 17% of the total national energy consumption (DGGE, 2005). Additionally, it uses a considerable amount of water resources, about 132 l/inhabitant/day of potable water, being a significant part of this capitation used in toilets (INAG, 2005).

The use of improved materials and building technologies can contribute considerably to better environmental life cycle and then to the sustainability of the constructions.

Life Cycle Assessment (LCA) is a usable approach to evaluate the environmental impacts of products or processes during their whole life-cycle. It is basically quantitative, and it considers the material and energy flows. The methodology has been developed and used for tens of years, but it was only standardized in the mid-to-late 1990s', by the International Organization for Standardization (ISO14040-42). The LCA fits at best to the level of single product or material, but it is generally accepted to be applied for construction products and whole building, too. Environmental performance is generally measured in terms of a wide range of potential effects, such as global warming potential; stratospheric ozone depletion; formation of ground level ozone (smog); acidification of land and water resources; eutrophication of water bodies; fossil fuel depletion; water use; toxic releases to air, water and land.

It is widely recognised in the field of Building Sustainability Assessment that LCA is a much more preferable method for evaluating the environmental pressure caused by materials, building assemblies and the whole life-cycle of a building. Although there are several recognized LCA tools, these tools are not extensively used in building design and most of building sustainability assessment and rating systems are not comprehensive or consistently LCA-based. Reasons for this failure are above all related to the complexity of the stages of a LCA. Besides of being complex, this approach is very time consuming and therefore normally used by experts at academic level. For these reasons most of the building sustainability assessment methods are relied on singular material proprieties or attributes, such as recycled content, recycling potential or distances travelled after the point of manufacture (Carmody, et al, 2007).

The adoption of environmental LCA in buildings and other construction works is a complex and tedious task as a construction incorporates hundreds and thousands of individual products and in a construction project there might be tens of companies involved. Further, the expected life cycle of a building is exceptionally long, tens or hundreds of years. For that reason LCA tools that are currently available are not widely used by most stakeholders, including those designing, constructing, purchasing or occupying buildings. Due to its complexity most of LCA tools are used and developed only by experts, most times only at academic level.

In order to overcome this situation, most popular rating systems simplified LCA for practical use. The simplified LCA methods currently integrated in rating systems are not comprehensive or consistently LCA-based but they are playing an important role in turning the buildings more sustainable. Nevertheless, the LCA approach is not the same in the different sustainability assessment methods and therefore the results of the environmental performance assessment are not the same nor comparable. The integration of more accurate environmental assessment methods is needed to verify if the required performance has really been achieved, to accurate compare solutions and to compare the results from different rating systems (Bragança et al, 2008).

In order to standardize, facilitate the interpretation of results and comparison between different building sustainability assessment methods developed within the European Countries, in 2005 CEN (European Centre of Normalization) set up the Technical Committee 350 (CEN/TC 350), "Sustainability of Construction Works". This Technical Committee aims to develop voluntary horizontal standardization of methods for the assessment of the sustainability aspects of new and existing construction works and standards for the environmental product declarations (EPD) of construction products (CEN, 2010). As a result of the work carried out to date the following pre-standards and standards have been produced:

- EN 15643-1:2010, Sustainability of construction works - Sustainability assessment of buildings - Part 1: General framework;
- CEN/TR 15941:2010, Sustainability of construction works - Environmental product declarations - Methodology for selection and use of generic data;
- prEN 15643-2:2009, Sustainability of construction works - Assessment of buildings - Part 2: Framework for the assessment of environmental performance;
- prEN 15643-3:2008, Sustainability of Construction Works - Assessment of Buildings - Part 3: Framework for the assessment of social performance;
- prEN 15643-4:2008, Sustainability of Construction Works - Assessment of Buildings - Part 4: Framework for the assessment of economic performance;
- prEN 15978:2010, Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method.

Based in the work of CEN TC 350 and in the work of iiSBE Portugal in the development of the Portuguese rating system for residential buildings SBTool^{PT} - H, this paper will present and discuss the development of a method to simplify LCA for effective used during the design phase. The presented method is based in the developed of an LCA database that covers much of the conventional and non-conventional building technologies used in residential buildings in Portugal.

2 THE LIFE CYCLE ASSESSMENT APPROACH

LCA is a systematic approach to measure the potential environmental impacts of a product or service during its lifecycle. LCA considers the potential environmental impacts throughout a product's life cycle (i.e. cradle-to-grave) from raw material acquisition through production, use and disposal.

LCA is very important to compare several possible alternative solutions, which can bring about the same required performance but that differ in terms of environmental consequences. For constructions, such bridges, the embodied environmental performance of the building materials as well the construction impacts on landscape and biodiversity will often dominate the construction's life-cycle environmental impacts. For buildings, such as dwellings and offices, life-cycle environmental impacts are often dominated by energy consumption, in space heating or cooling, during the operation phase: it is estimated that the operation phase in conventional buildings represents approximately 80% to 94% of the life-cycle energy use, while 6% to 20% is consumed in materials extraction, transportation and production and less than 1% is consumed through 1% end-of-life treatments (Berge, 1999). In buildings, design teams should seek for more energy-efficient alternatives, while in other constructions, like for instance dikes and bridges, priority should be given to eco-efficient materials. Nevertheless, with the development of energy-efficient buildings and the use of less-polluting energy sources, the contribution of the material production and end-of-life phases is expected to increase in the future.

There are two combined standards developed specific to set the framework and requirements of a LCA that replaced the former four LCA standards (ISO 14040, ISO 14041, ISO 14042, ISO 14043) in 1st July 2006: ISO/FDIS 14040 2006-07-01 Environmental management – Life cycle assessment – Principles and framework; and ISO/FDIS 14044 2006-07-01 Environmental management – Life cycle assessment – Requirements and guidelines.

According to ISO 14040, framework for LCA includes:

- Goal and scope definition of LCA;
- Inventory analysis (LCI);
- Impact assessment (LCIA);
- Interpretation;
- Reporting and critical review;
- Limitations;
- Relationships between the LCA phases, and
- Conditions for use.

As presented in Figure 1, LCA is essentially an iterative process.

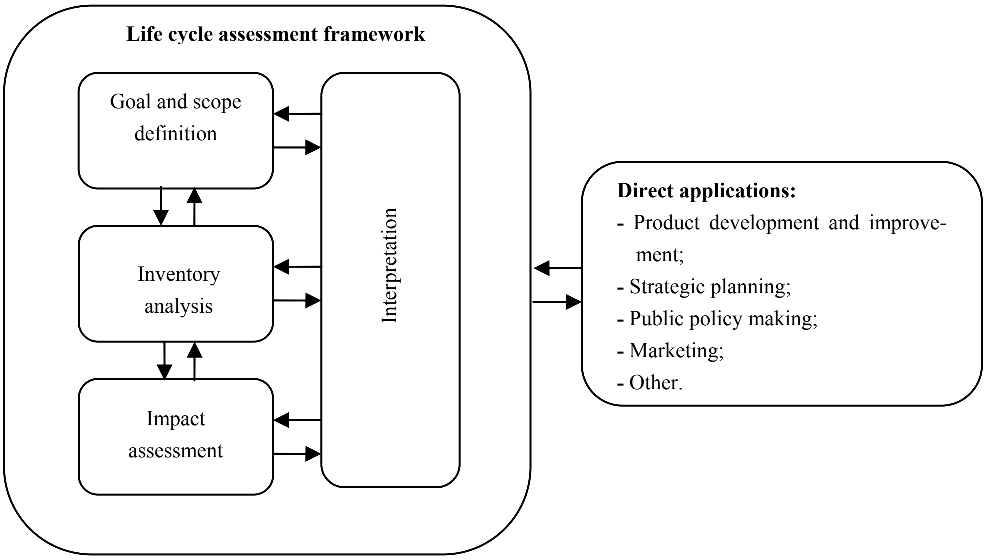


Figure 1. Stages of an LCA in ISO 14040:2006.

LCA can be applied to a single product or to an assembly of products, such as a building. For building and other constructions (B/C) the general framework for LCA involves the following goals and LCA steps (Kotaji, Schuurmans & Edwards, 2003):

1) The lifecycle of the B/C is described. What is included in the study will depend on the scope. It may include how the B/C is constructed, used, maintained and demolished and what happens to the waste materials after demolition. These are processes that contribute to the life-cycle performance of a B/C, but which will not be included in all studies.
2) The B/C is "broken down" to the building material and component combinations (BMCCs) level. This is the composition of the B/C to be analysed. The way in which the BMCCs are defined is not necessarily important; what matters is that the B/C is completely described through the addition of the BMCCs.
3) For each BMCC, the LCA of the production process (cradle-to-gate) is carried out. Their LCAs may include the transport processes to the B/C site, the construction process, the operation and maintenance processes, the demolition processes, and the waste treatment processes for each of the waste materials defined in the B/C model. This would be a cradle-to-grave analysis.
4) The BMCC-LCA results are added together, resulting in the LCA of the B/C. The various BMCC-LCAs should be carried out consistently according to the goal and scope.

3 THE DEVOLOPMENT OF THE LCA DATABASE

3.1 *Environmental impact categories*

Sustainability assessment systems are the tools normally used by project teams to support decision making which aim to lower the environmental impacts of buildings. Nevertheless, the number and type of environmental impact category indicators are different in the several sustainable assessment methods. There is a wide range of impact category indicators, normally categorized according to the endpoints or the midpoints. Endpoints are also known as damage categories and express the effect of the product in the Human Health, Ecosystems Quality, Climate Change and Resources. LCA methods that use this type of impact categories are damage oriented and they try to model the cause-effect chain up to the endpoint, or damage, sometimes with high uncertainty. The midpoints, also referred as indicators, are the measures between the emissions and resource extraction parameters from life-cycle inventory (LCI) and the damage categories. These impact categories are used in the classic impact assessment methods to quantify the results in the early stage in the cause-effect chain to limit the uncertainties. Midpoints uses to group LCI results in the so-called midpoint categories according to themes as "destruction of the stratospheric ozone layer", "acidification of land and water resources" or "global warming".

LCA can be incorporated into rating systems for buildings to quantify environmental burdens associated with the manufacture of building products. Such burdens include the consumption of primary resources and the output of gaseous, liquid, and solid wastes. Most of the rating systems use midpoint impact categories but do not assess the B/C's environmental performance in a LCA consistent way, because they do not include LCA-based indicators.

The differences between the environmental impact assessment approach in the several rating methods – because some of them are not LCA-based, not based in a reliable LCA method (because do not integrate the most common impact categories) or do not share the same impact categories – difficult the comparison of results from different rating systems.

The goal of the work undertaken by CEN/TC 350 standardization mandate is to overcome this problem at the European level, through the development of an approach to voluntary providing environmental information for supporting the sustainable works on construction. The document prEN 15643-2:2009 sets the environmental indicators that should be used in the European building sustainability assessment methods. The aim of the list of the impact categories is to represent a quantified image of the environmental impacts and aspects caused by the object of assessment during its whole life cycle. As referred in Table 1, according to the future CEN standard the assessment of the environmental performance of an building should be made through the evaluation of five quantified indicators for environmental impacts expressed with the impact categories of the life cycle impact assessment (LCA) and nine quantified indicators for environmental aspects expressed with data derived from LCI and not assigned to the impact categories of LCA.

The assessment approach of this future CEN standard is applicable to new and existing buildings. It provides a calculation method that covers all stages of the building life cycle (assembly, operation and disassembly phases) and the list of environmental indicators is developed in such way that potentiates the use of the LCI data issued from Environmental Product Declarations (EPD).

Table 1. Quantified indicators for environmental impacts/aspects assessment according to prEN 15643-2:2009.

Environmental impacts expressed with the impact categories of LCA	Environmental aspects expressed with data derived from LCI and not assigned to the impact categories of LCA
• Climate change expressed as Global Warming Potential; • Destruction of the stratospheric ozone layer; • Acidification of land and water resources; • Eutrophication; • Formation of ground level ozone expressed as photochemical oxidants.	• Use of non-renewable resources other than primary energy; • Use of recycled/reused resources other than primary energy; • Use of non-renewable primary energy; • Use of renewable primary energy; • Use of freshwater resources; • Non-hazardous waste to disposal; • Hazardous waste to disposal; • Nuclear waste (separated from hazardous waste).

In future, all standardized European sustainability assessments should consider the same list of indicators, the new sustainability rating systems should be consistent with it and it is expected that the existing ones will be adapted to this new approach. The Portuguese building sustainability assessment method (SBTool^{PT}) it is already updated according to the requirements of this future standard. Therefore the developed LCA database covers the five environmental indicators expressed with the environmental impacts of LCA together with the embodied energy in the materials and construction technologies.

3.2 *Considered life-cycle phases*

A typical life cycle of a building can be separated into three distinct phases, each consisting of one or several life cycle stages, as illustrated in Figure 1. The assembly phase refers to the collection of raw materials through resource extraction or recycling, the manufacture of these raw materials into products, the assembly of products into a building, the replacement of building products and assemblies, and intermediate transportation. The operation phase refers to heating and electricity requirements, water services and other services excluding material replacement. The disassembly phase refers to the decommissioning and demolition of the building, the disposal/recycling/reuse of building products and assemblies, and intermediate transportation steps. Each life cycle stage can consist of many unit processes.

The LCA database for building technologies covers the “cradle-to-gate” impacts, i.e. the environmental impacts from the raw material extraction to the manufacturing of building products and assemblies and the disassembly phase. Additionally the database covers the environmental impacts derived from the transport of the demolition waste to the treatment units and with its treatment. The considered processes are highlighted in Figure 2.

3.3 *Quantification of the environmental indicators*

The two most important barriers to the quantification of the environmental indicators and therefore to the incorporation of LCA in rating systems are: a lack of LCI data for all building products and the inherent subjectivity of LCA. Environmental Product Declarations (EPD) are a good source of quantified information of LCI environmental impact data. In order to potentiate their use, rating systems should be based in the same LCA categories, as stated in the future CEN standard. Nevertheless, at the moment, there are important limitations on this approach, since there is only a small number of companies either having or making publicly the EPD of their products. The solution proposed to overcome this problem is to develop and use databases with the LCA data of the most used building materials and components. The developed database is continuously updated and covers common building technologies for each building element (floors, walls, roofs and windows, doors) and the most used building materials

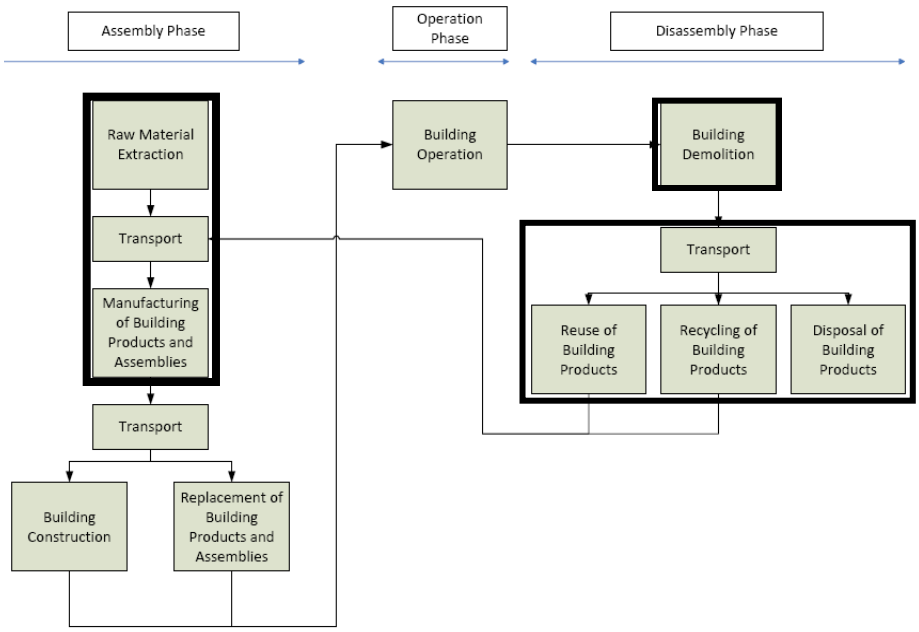


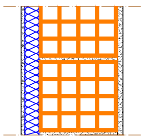
Figure 2. Life cycle of a building (Optis, 2005).

The environmental indicators were quantified using the SimaPro software and several LCI databases with the average environmental impacts of each used building material (e.g. EcoInvent, IDEMAT 2001, etc.). Table 2 shows the six environmental impact categories covered by the database and the LCA methods used to quantify the environmental categories.

Table 2. Environmental impact categories declared in the built-in LCA database for building technologies

Environmental impact categories	Unit/declared unit	LCA methods
Depletion of abiotic resources	[kg Sb equiv.]	CML 2 baseline 2000
Global warming potential (GWP)	[Kg CO_2 equiv.]	IPCC 2001 GWP 100a
Destruction of atmospheric ozone (ODP)	[KgCFC-11 equiv.]	CML 2 baseline 2000
Acidification potential (AP)	[Kg SO_2 equiv.]	CML 2 baseline 2000
Eutrophication potential (NP)	[Kg PO_4 equiv.]	CML 2 baseline 2000
Photochemical Ozone Creation (POCP)	[Kg C_2H_4 equiv.]	CML 2 baseline 2000
Non-renewable primary energy	[MJ equiv.]	Cumulative Energy Demand
Renewable primary energy	[MJ equiv.]	Cumulative Energy Demand

Figure 3, presents how the information is organized in the LCA database for a building component and the list of environmental indicators and LCA methods used to quantify it. In the database of the building components the quantification is presented per each component's unit of area (m^2) and in the materials database values are available per each unit of mass (kg). Quantification is presented for two life-cycle stages: "cradle to gate" and "demolition/disposal". SBTool^{PT} uses a bottom-up up approach in the quantification of the whole building environmental performance. The quantification begins at the level of the embodied environmental impacts in building materials and ends at the whole building scale. Figures 4 e 5 illustrates the calculation method of the whole life-cycle environmental impact of a building using the data from the SBTool^{PT}'s LCA database.

Building component:	Hollow brick single wall (11cm) with an external thermal insulation composite system								Ref: Wall 3
	Life cycle stages	Environmental impact categories of LCA						Embodied energy	
		ADP[1]	GWP[2]	ODP[3]	AP[4]	POCP[5]	EP[6]	NR[7]	R[8]
	Cradle-to-gate	2,48E-01	5,00E+01	3,02E-06	1,16E-01	1,23E-02	1,45E-02	5,63E+02	5,39E+01
	Dismantling and disposal	1,12E-01	1,65E+01	2,67E-06	7,60E-02	2,90E-03	1,58E-02	2,57E+02	1,57E+00
	Total	3,60E-01	6,65E+01	5,69E-06	1,92E-01	1,52E-02	3,03E-02	8,20E+02	5,54E+01
Comments:	**Considered materials:** Hollow brick, Portland reinforced mortar (external and internal finishing and brick joints), EPS (thermal insulation) **LCA methods:** CML 2 baseline 2000 method (version 2.04, to quantify the environmental impact categories of LCA) and Cumulative Energy Demand (version 1.04, to evaluate the embodied energy) **LCI librarie(s):** Ecoinvent system process								

Notes:

[1]Abiotic depletion potential in kg Sb equivalents;

[2]Global warming potential in kg CO_2 equivalents;

[3]Ozone depletion potential in kg CFC-11 equivalents;

[4]Acidification potential in kg SO_2 equivalents;

[5]Photochemical ozone creation potential kg C_2H_4 equivalents;

[6]Eutrophication potential in kg PO_4 equivalents;

[7]Non-renewable embodied energy in MJ equivalents;

[8]Renewable embodied energy in MJ equivalents.

Figure 3. Part of the SBTool^{PT} LCA database.

The quantification of the environmental impacts using the LCA database is divided in two phases: i) quantification of the global embodied environmental impacts (Figure 4); and ii) quantification of the whole building's life-cycle impacts (Figure 5). In the first phase, using the above-mentioned bottom-up approach, the global embodied environmental impacts per square meter and year are quantified. This process is based in the contribution of each material and building element (available in the database) for the total embodied impact. In the second phase, the result from the previous phase is summed up with the impacts related to the maintenance scenarios, resulting in the whole building's life-cycle impacts.

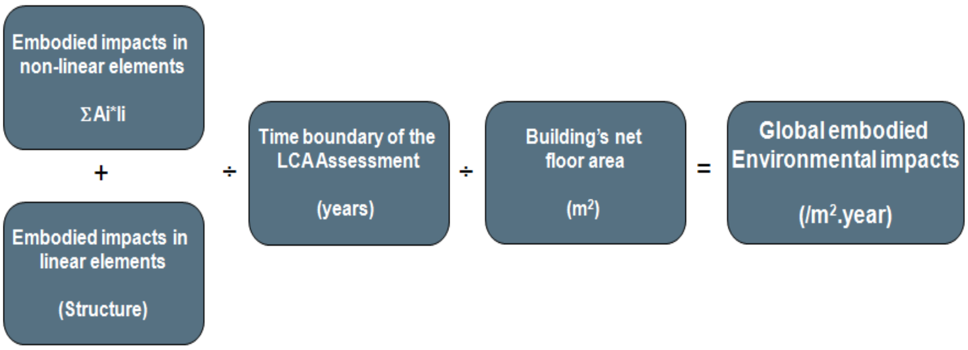


Figure 4. Phase 1 – quantification of the global embodied environmental impacts.

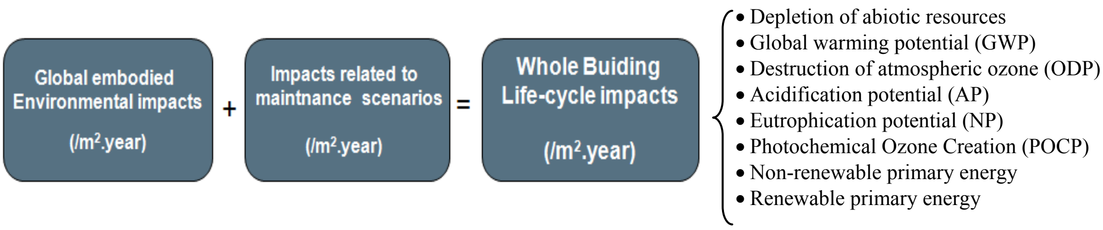


Figure 5. Phase 2 – quantification of the whole building's life-cycle environmental impacts.

4 CONCLUSIONS

Although, LCA is considered the best method available to assess the environmental performance of a product, its application in construction is very complex. This is because the huge number of different materials, products, actors, processes and also the wide life cycle span of a construction product.

Based in the work of CEN TC 350 and in the development of the Portuguese sustainability rating system (SBTool^{PT}), this paper presented some solutions to overcome the difficulties in using an LCA-based approach to support decision-making which aims at promoting lower environmental building design since the earlier design phases. The development by experts of databases with the LCA data of the most used building technologies and materials is a good solution to overcome some of the presented barriers that are hindering the widespread use of the LCA-based approaches by the design teams.

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