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Social Life Cycle Assessment for Additive Manufacturing: A Review

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Resumo

O propósito desta dissertação é auxiliar no desenvolvimento do projeto FIBR3D - Processos híbridos baseados na Fabricação Aditiva de Compostos de Matriz Termoplástica Reforçados com Fibras, fornecendo uma visão da metodologia de Análise Social do Ciclo de Vida (SLCA) e outras metodologias relacionadas.

O objetivo principal da dissertação é apresentar uma revisão de literatura para identificar as metodologias existentes de análise do ciclo de vida, a qual fornecerá um conhecimento básico sobre como funcionam e como podem ser implementadas estas metodologias dentro do projeto FIBR3D. Este estudo poderá ajudar no desenvolvimento de um modelo de análise do ciclo de vida que será usado para avaliar a tecnologia de fabricação aditiva que está a ser desenvolvida no âmbito do projeto.

O intuito deste trabalho é estudar a metodologia de Análise Social do Ciclo de Vida (SLCA), embora se considere que primeiro é necessário entender como funcionam as metodologias de Análise Ambiental do Ciclo de Vida (LCA) e Análise Económica do Ciclo de Vida (LCC) porque elas têm algumas semelhanças entre si e podem ser ligadas para criar a metodologia de Análise da Sustentabilidade do Ciclo de Vida (LCSA). Após o estudo das outras duas metodologias, a Análise Social do Ciclo de Vida é analisada em maior detalhe.

Estas metodologias são estudadas tendo em conta a informação recolhida de artigos, capítulos de livros e normas. As palavras-chave que foram usadas na busca dos documentos selecionados são, por exemplo, "Análise Ambiental do Ciclo de Vida", "Análise Económica do Ciclo de Vida " e "Análise Social do Ciclo de Vida ".

Depois de analisar os documentos selecionados, a informação foi resumida em tabelas, de modo a ser possível observar o que poderá ajudar no desenvolvimento do projeto e o que ainda deve ser estudado com maior profundidade.

Nesta dissertação, são analisados 17 artigos sobre LCA e LCC e 13 artigos sobre SLCA. Além dos trabalhos e estudos publicados, algumas normas também foram analisadas, pois são consideradas essenciais no estudo destas metodologias.

De todos os artigos analisados apenas dois tentaram ligar a metodologia SLCA com a tecnologia de fabricação aditiva (AM), o que é inesperado, mas plausível porque a fabricação aditiva é uma tecnologia ainda em desenvolvimento.

Através da análise dos artigos é possível perceber que há uma grande necessidade de desenvolver estudos que apliquem estas metodologias para avaliar a tecnologia de fabricação aditiva e produtos/processos na fase de desenvolvimento.

No entanto, e apesar da escassez de estudos, já se vislumbra que a tecnologia de fabricação aditiva tem um potencial enorme que poderá vir a revolucionar as indústrias e mudar alguns padrões ao nível social e da sociedade.

Palavras-chave

Análise do Ciclo de Vida, Análise Económica do Ciclo de Vida, Análise Social do Ciclo de Vida, Fabricação Aditiva, Análise da Sustentabilidade do Ciclo de Vida, Análise do Design do Ciclo de Vida

Abstract

The aim of this dissertation is to assist in the development of the project FIBR3D – Hybrid Processes based on Additive Manufacture of Thermoplastic Matrix Composites Reinforced with Fibers, by providing a base insight on the Social Life Cycle Assessment methodology (SLCA) and other related methodologies.

The main objective of this dissertation is to present a literature review to identify the existing life cycle based methodologies, which will give a base knowledge on how they work and how they can be implemented within the project FIBR3D. This study will help in the development of a life cycle based parametric model that will be used to assess the Additive Manufacturing technology that is being developed within the project.

The main objective of this work is to study the Social Life Cycle Assessment methodology (SLCA), although it is considered that first it is needed to understand how the environmental Life Cycle Assessment (LCA) and the Life Cycle Costing (LCC) methodologies work, because they retain some similarities with each other and can be connected to create the Life Cycle Sustainability Assessment methodology (LCSA). After the study of the other two methodologies, the Social Life Cycle Assessment is analyzed with more detail.

These methodologies were studied by analyzing information from papers, book chapters and standards. The keywords that were used in the search of the selected documents were, for example, “Life Cycle Assessment”, “Life Cycle Costing” and “Social Life Cycle Assessment”.

After analyzing the selected documents, the information was summarized in tables so it is possible to conclude what can help in the development of the project and what can still be studied in more depth.

In this dissertation 17 papers about LCA and LCC and 13 papers about SLCA are analyzed. In addition to the papers, some standards were also studied, because they are considered essential in the study of these methodologies.

From all the analyzed papers, only two tried to link the SLCA methodology with the additive manufacturing technology (AM), which was unexpected, but plausible because the AM is a technology still under development.

With the analysis of the papers it is possible to perceive that there is a great need to develop studies that apply these methodologies to assess the AM technology and products/processes in the phase of development.

Apparently, despite the scarcity of studies, it is already clear that the AM technology is considered to have an immense potential to revolutionize industries and to change some standards at the social and society level.

Keywords

Life Cycle Assessment, Life Cycle Costing, Social Life Cycle Assessment, Additive Manufacturing, Life Cycle Sustainability Assessment, Life Cycle Design

Acronyms and Abbreviations

3D – Three-Dimensional

3DP – Three-Dimensional Printing

AM – Additive Manufacturing

AoP – Area of Protection

ASTM – American Society for Testing and Materials

CBA – Cost Benefit Analysis

CED – Cumulative Energy Demand

CV – Contingent Valuation

DDM – Direct Digital Manufacturing

DFA – Design for Assembly

DFM – Design for Manufacturing

DLP – Digital Light Processing

EBM – Electron Beam Melting

FDM – Fused Deposition Modelling

FIBR3D – Hybrid Processes based on Additive Manufacture of Thermoplastic Matrix Composites Reinforced with Fibers

FU – Functional Unit

H2020 – Horizon 2020

hAM – hybrid Additive Manufacturing

HDPE – High Density Polyethylene

I3N – Instituto de Nanoestruturas, Nanomodelação e Nanofabricação

IJP – Inkjet Printing

INEGI – Instituto de Ciência e Inovação em Engenharia Mecânica

ISO – International Organization for Standardization

LAETA – Laboratório Associado de Energia, Transportes e Aeronáutica

LCA – Life Cycle Assessment

LCAA – Life Cycle Attribute Assessment

LCC – Life Cycle Costing

LCD – Life Cycle Design

LCI – Life Cycle Inventory

LCIA – Life Cycle Impact Assessment

LCPD – Life Cycle Process Design

LCSA – Life Cycle Sustainability Assessment

LENS – Laser Engineered Net Shaping

LOM – Laminated Object Manufacture

NPC – Net Present Cost

PAC – Programas de Atividades Conjuntas

PRPs – Performance Reference Points

SETAC – Society for Environmental Toxicology and Chemistry

SLA – Stereolithography

SLCA – Social Life Cycle Assessment

SLCIA – Social Life Cycle Impact Assessment

SLM – Selective Laser Melting

SLS – Selective Laser Sintering

UNEP – United Nations Environmental Programme

UNIDEMI – Unidade de Investigação e Desenvolvimento em Engenharia Mecânica e Industrial (Universidade NOVA de Lisboa)

WTP – Willingness-to-pay

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1 Introduction

1.1 Problem Description

This dissertation aims to assist in the development of the project FIBR3D – Hybrid Processes based on Additive Manufacture of Thermoplastic Matrix Composites Reinforced with Fibers, by providing a literature review on "Social Life Cycle Assessment" (SLCA). As the FIBR3D project is still at an early stage, the main objective of this review is to identify existing (qualitative and quantitative) methodologies in various areas and how they can be applied within the scope of the project.

The FIBR3D project intends to develop a technology of hybrid processes based on additive manufacture of thermoplastic matrix composites reinforced with fibers. The main promoter is INEGI – Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial, and is being carried out in partnership with other four institutions: LAETA – Laboratório Associado de Energia, Transportes e Aeronáutica, I3N – Instituto de Nanoestruturas, Nanomodelação e Nanofabricação, Centro de Investigação ALGORITMI (Universidade do Minho) and UNIDEMI – Unidade de Investigação e Desenvolvimento em Engenharia Mecânica e Industrial (Universidade NOVA de Lisboa).

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Within the traditional industry subtractive manufacturing processes are common. These processes are characterized by removing material from the raw material to create a product, but with the development of new technologies manufacturing processes have evolved by improving the performance of processing tools and removing the variability that an operator can impose on the process. Thus, additive manufacturing processes have been created, that is, processes that add raw material to create a product, a more noticeable example are 3D printers.

The objective of this project is precisely the creation of a 3D printer, for industrial production, that brings together these two modes of processing (additive and subtractive), that is, a hybrid manufacturing process and the use of an innovative material, which improves the resistance of the product.

In order to design this industrial tool, it is necessary to study its life cycle, within the environmental, economic and social spheres, to be able to understand in advance the risks and possibilities for improvement that this new technology can bring.

This technology can be potentially integrated within the Industry 4.0 philosophy, which is what is now called a smart factory that is composed of modular structured stations where cyber-physical systems monitor physical processes. These systems communicate and cooperate with each other and with the operators.

1.2 Additive Manufacturing Technology

Nowadays the additive manufacturing (AM) technology has been standing out because of its enormous potential. As defined by the ASTM (American Society for Testing and Materials) F42 Technical Committee, which is responsible for overseeing the development of AM standards, the AM technology is “a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" (Gao *et al.*, 2015; ASTM International, 2015; Ford and Despeisse, 2016).

Unlike subtractive manufacturing in which the material is removed from a workpiece (for example, cutting, milling, stamping, etc.), the AM technology creates a product by adding materials layer by layer. This allows the manufacture of products to become more efficient in the usage of raw materials and to reduce the waste production (Huang *et al.*, 2013).

The computerized 3D model of the product allows the user to directly transform it into a finished product, just in a few hours, without the need of any tools. With this technology, it is possible to produce more complex parts with complex forms, which would be difficult to produce with subtractive manufacturing processes (Huang *et al.*, 2013). The ability to create more complex geometries also allows the consolidation of two or more parts of the product, that previously were separated, into a single part. Also, it is not necessary to consider the design for manufacturing (DFM) and design for assembly (DFA) principles in the product design.

The development of the AM technology started in the 1980s and its initial application was in the area of rapid prototyping, which allowed the reduction of time and costs in the development phase (Ford and Despeisse, 2016). With its development, the AM technology is showing immense potential in the manufacturing industry, with on-demand manufacturing, and other areas, like the medical and aerospace sectors. With the development and commercialization of the home 3D printers appeared the possibility of the design and production of personalized products.

The main advantages of AM technology are (Huang *et al.*, 2013):

- Material efficiency – With the AM technology it is possible to reduce production waste, because it adds material layer by layer to produce the necessary product and any materials that were leftover can be later reutilized. Unlike the subtractive manufacturing processes where the material that is removed to create the product is most of the time considered to be waste;

- Resource efficiency – On the contrary of the conventional manufacturing processes, the AM technology does not require additional resources, like cutting tools, etc.;

- Design or Part flexibility – This AM technology eliminates the constraints that exists by utilizing various tools, which allows to create more complex geometric shapes and consequently produce products with less parts. With this technology, it is not necessary to sacrifice the functionality of the part for the purpose of its manufacturing or assembly process;

- Production flexibility – The AM technology does not require setups, which reduces costs and wastes, it is economical in small batch production and the existence of production bottlenecks is greatly reduced because of the existence of less parts. The quality of the product does not depend on skills of the operator but rather on performance of the process.

The materials that can be used in the various AM processes are polymers, metals, ceramics and composites. The utilization of these materials depends on each of the AM processes. The most utilized AM processes are (Huang *et al.*, 2013; Ford and Despeisse, 2016):

- Fused Deposition Modelling (FDM);

- Stereolithography (SLA);
- Selective Laser Sintering (SLS);
- Selective Laser Melting (SLM);
- Digital Light Processing (DLP);
- Electron Beam Melting (EBM);
- Laminated Object Manufacture (LOM);
- Laser Engineered Net Shaping (LENS);
- Three-Dimensional Printing (3DP);
- Inkjet Printing (IJP).

Although, this technology shows immense potential, it is considered that it still cannot replace or even compete with the conventional manufacturing processes, due to some limitations in the mass production industry (Huang *et al.*, 2013). However, it can play an important role as complementing technology, like production of maintenance parts, prototypes, etc..

1.3 Research main topic

Considering that the Project FIBR3D is still in its early stage it is difficult to define what is needed and what must be done to help with its development, because it is unknown how it will work, what are the costs, if it causes any impact to society, how it can influence the existing industry and what materials should be used in its development in order to be a sustainable product.

Observing these, studies are needed for a life cycle assessment of the product and its material with regard to economic, social and environmental dimensions.

It is proposed to perform a literature review of Social Life Cycle Assessment and to define a procedure to evaluate this innovative manufacturing process. By assessing its impacts in society, it is possible to search for new alternatives that may lessen them.

Other partners of this project are to do the life cycle assessment of this manufacturing process, but their study will only take into account the environmental and economic impacts.

The main questions that were taken into consideration were:

- What is a Social Life Cycle Assessment methodology?
- How does the Social Life Cycle Assessment methodology work?
- Which scientific areas use it?
- If it has already been applied to a product in development phase, especially in the field of additive manufacturing (AM)?

- Which of the studies reviewed can help the most in the construction of a procedure to implement in the project FIBR3D?

By considering these questions, it is possible to conclude that a deeper research has to be done in these subjects and that they are very important for the understanding of the subject of this dissertation.

1.4 Objective

As said previously the objective of this dissertation is to present a literature review, which will allow a deeper knowledge on *Social Life Cycle Assessment* and create the basis for the development of a more specific protocol on how to make a SLCA to the mentioned research project.

This review, on the other hand, is intended to support the next stage (future work), which will be the development of a life cycle based parametric model to assess Additive Manufacturing (AM) and hybrid Additive Manufacturing (hAM) processes' performance with regard to economic, environmental and social dimensions.

1.5 Methodology

As already mentioned, the objective of this study is to perform a literature review to identify existing (qualitative and quantitative) methodologies that are already in use in various areas and how they can be applied within the scope of the FIBR3D project.

A typical systematic literature review follows the step-by-step approach illustrated in the diagram of Figure 1.1.

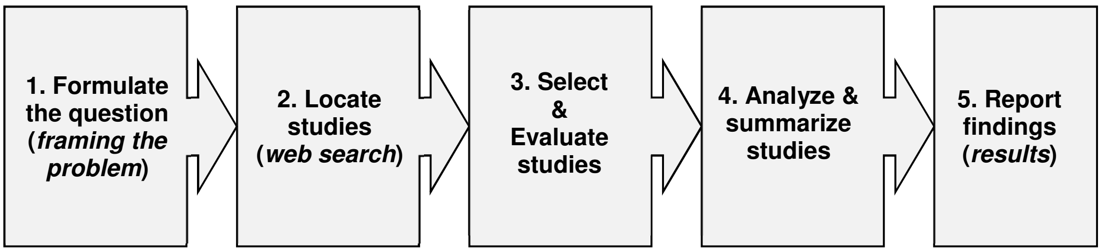


Figure 1.1 - Steps for performing a systematic literature review

(adapted from Torreglosa et al., 2016)

In the beginning of the research, to be able to characterize the environmental and economic impacts, a preliminary study was made on the Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methodologies. By studying these methodologies, it is possible to understand how they are structured and which phases the researcher must follow to reach conclusions.

After realizing how these methodologies are structured and how they work, the author of this dissertation has studied, in more detail, how a Social Life Cycle Assessment (SLCA) works and how it can be applied, quantitatively and qualitatively, to a product in the development phase. It is then possible to analyze the social impacts that this innovating product can cause and search for ways to solve them, i.e., avoid negative impacts.

This review will assist the research team to formulate a specific protocol to assess this pioneering 3D printing machine and search for ways to resolve the problems it can produce during its life time, from "cradle to grave".

The first step of this approach (Fig.1) shows what the objective in the study is and this can be translated into the questions:

"*What is a Social Life Cycle Assessment methodology? How does Social Life Cycle Assessment methodology work? Which scientific areas use it? If it has already been applied to a product in development? Which of the studies reviewed can help the most in the construction of a procedure to implement in the project FIBR3D?*"

In the search for papers, journals and book chapters (Step 2), the Scopus searching engine was used. The time-line of the publications reviewed is between 2007 and 2017, with an interval of 10 years, except for the ones that were added by cross-referencing and the ones that were considered very important in the history of the life cycle subject, since these are considered milestones.

It was not considered documents that were not written in English and that did not include a reference of any life cycle based methodology in the abstract or even in its content.

Because the life cycle assessment methodology can be used in different areas, it was necessary to limit the range of the search by selecting the most important areas. The areas of engineering, environmental science, social sciences, business, management and accounting, and materials science were considered in the search.

Some of the keywords that were used to find all the required information were "Life Cycle Assessment", "Life Cycle Assessment Review", "Life Cycle Costing", Life Cycle Thinking", "Social Life Cycle Assessment", etc.. The Scopus search engine helps the user to make a comprehensive search by chaining the key words inserted, allowing a rigorous search output. Also, all the papers using any language other than English were excluded from the search.

To examine the content of the search results, it is necessary to read and study all the titles and abstracts, to select the best results (Step 3), because even with such a rigorous search procedure a huge amount of results is usually found.

With a review, it is possible to analyze and summarize the information (Step 4) obtained in the search, and relate papers with other published materials to pinpoint the best data for the study. After this, conclusions can be drawn about what is known and unknown and what can help in the development of the project (Step 5).

1.6 Dissertation Structure

This dissertation is structured into four chapters. This first chapter presents the main topic of the research, the objectives and the global methodology of the dissertation.

The second chapter presents the concepts of life cycle assessment, life cycle design and life cycle costing, and it explains how they work. Then, a literature background about the previous subjects is made to understand what various researchers think about these methodologies and how they can be applied in real life scenarios.

In the beginning of the third chapter, an introduction to social life cycle assessment is given, describing what it is, how it works and its history. Also, a review of literature is carried out and presented in this chapter, where several papers about social life cycle assessment are analyzed.

In the last and fourth chapter, some conclusions are drawn about the research and what is the future of social life cycle assessment.

2 Life Cycle Assessment - Concepts and Background

2.1 Origin

In the 1960s emerged studies that allowed the quantification of the consumption of virgin materials and the energy efficiency of production processes. These studies began to be relevant due to the rapid increase in world population and the limited natural resources, with which also came the climate change caused by excessive emissions from the process of energy transformation (Giudice *et al.*, 2006).

At first, these studies focused on the evaluation of the costs, the environmental implications associated with conventional energy production and alternative sources of energy and the efficiency with which the energy produced was used in industrial processes. These energy studies also required the analysis of the flows of all the resources necessary, in order to quantify the consumption of raw materials and the generation of solid waste (Giudice *et al.*, 2006).

One of the most important studies in the rise of LCA was an investigation regarding products of mass consumption in the 1970s, which was conducted by the Midwest Research Institute and later by Franklin Associates on behalf of the Coca-Cola Company, because it was the first example of an inventory analysis of resources and waste. The objective of this study was to quantify the raw materials, fuels and environmental charges associated with the production of each type of container for soft drinks (Giudice *et al.*, 2006; Klöpffer, 2006; Guinée *et al.*, 2011).

This methodological process of quantifying the consumption of resources and the generation of waste came to be known, in the United States, as Resources and Environmental Profile Analysis (REPA) and had an influential role in the oil crisis of the early 1970s. In Europe other studies introduced the concept of Eco-balance, that focused on the consumption of material and energy resources and on the generation of waste (Giudice *et al.*, 2006; Klöpffer, 2006; Guinée *et al.*, 2011).

From these first applications, it was possible to understand that making a single production process more efficient is not always the best answer, because the environmental benefits of the improved process may cause new environmental criticalities at some other part of the system. So, instead a complete analysis of the entire industrial production systems must be done, starting with the extraction of raw materials, through all the transformation processes until the disposal phase of the product (cradle to grave) (Giudice *et al.*, 2006).

According to Giudice *et al.* (2006), in the early 1980s, in addition to the saving resources subject, the management of polluting waste theme was taken into consideration, while the research on environmental profiles of products and processes, better yet on the energy efficiency of industrial processes and the production and use of packaging, was being continued.

By the end of the 1980s a common methodology for the environmental evaluation of products was developed and was characterized by two phases, which are the "inventory analysis" and the "assessment of the impacts to the environment" (Giudice *et al.*, 2006; Klöpffer, 2006; Guinée *et al.*, 2011).

Because of the need for a common structured methodology for the environmental evaluation and analysis of products, in 1990 the Society for Environmental Toxicology and Chemistry

(SETAC) organized a conference where the term Life Cycle Assessment was first defined as "an objective process to evaluate the environmental burdens associated with a product or activity by identifying and quantifying energy and materials used and wastes released to the environment, and to evaluate and implement opportunities to affect environmental improvements" (Fava, 1991, cited in Giudice *et al.*, 2006, p.86) and "The assessment includes the entire life cycle of the product, process, or activity, encompassing extracting and processing raw materials; manufacturing, transportation and distribution; use, reuse, maintenance; recycling and final disposal." (Giudice *et al.*, 2006).

After this event, and prior to the ISO, methodological frameworks for LCA started to be developed. The recognition of the usefulness of this methodology, from 1997 on, led to the international standardization with the publication of ISO 14040 series (Giudice *et al.*, 2006; Klöpffer, 2006; Guinée *et al.*, 2011).

In 2002, in order to spread the LCA methodology, it was created the Life Cycle Initiative with cooperation between SETAC – Society of Environmental Toxicology and Chemistry and the UNEP – United Nations Environmental Programme (Giudice *et al.*, 2006; Klöpffer, 2006; Guinée *et al.*, 2011).

2.2 Life Cycle Assessment

Although the main topic of the study is Social Life Cycle Assessment it was felt necessary to make a brief study on how a normal Life Cycle Assessment works, because the life cycle approach and associated methodologies can also be applied to the social and economic aspects.

In the first part of this background, some key factors of the ISO 14040 will be explained, talking about environmental management, the Life Cycle Assessment and its principles and framework, and the ISO 14044, that describes requirements and guidelines to be used in the application of a Life Cycle Assessment.

According to the ISO 14040 (The International Standards Organisation, 2006a) and ISO 14044 (The International Standards Organisation, 2006b), Life Cycle Assessment is a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. The life cycle includes the raw material acquisition (or extraction), production, use, end-of-life treatment, recycling and final disposal, this kind of assessment can also be called a cradle to grave interpretation.

Nevertheless, it is also possible to conduct a partial LCA (Giudice *et al.*, 2006), so the system can be broken down into additional variants. Some examples are: the cradle to gate interpretation which analyzes the portion of life cycle upstream from the gate; the gate to grave interpretation which analyzes the portion of life cycle downstream from the gate; and the gate to gate interpretation which analyzes the portion of life cycle between two gates, which means the analyzes of one or more processes in the entire production chain.

A Life Cycle Assessment can assist in (The International Standards Organisation, 2006a, b):

- the identification of opportunities to improve the environmental performance of products at various points in their life cycle;

- the gathering of information to help decision makers in industry, government or non-government organizations;

- the selection of relevant indicators of environmental performance, including measurement techniques;

- the marketing of a product, implementing an Eco-labeling scheme, making an environmental product declaration.

There are 4 phases for implementing a Life Cycle Assessment and these are (The International Standards Organisation, 2006a, b):

- the definition of a goal and scope;

- the execution of an inventory analysis;

- the assessment of the impacts;

- the interpretation of the results of the procedure.

The goal states the intended application, the reasons for carrying out the study, the intended audience, this means, to whom the results of study are intended to be communicated and what are the results intended to be used in comparative assertions also intended to be disclosed to the public (The International Standards Organisation, 2006a, b).

The scope definition should consider the following items (The International Standards Organisation, 2006a, b):

- the product system that is going to be studied;

- the functions of the productive system or, in the case of comparative studies, the systems;

- the functional unit, that provides a reference to which the input and output data are normalized;

- the system boundary, that determines which unit processes shall be included within the Life Cycle Assessment. It is helpful to describe the system using a process flow diagram showing the unit processes and their inter-relationships;

- the allocation procedures, that is the identification of the processes that are shared with other product systems;

- the Life Cycle Impact Assessment (LCIA) methodology and types of impacts;

- the interpretation to be used;

- the data requirements;

- the assumptions that were taken in the beginning of the study;

- the value choices and optimal elements;

- the limitations;

- the data quality requirements, because it is important to understand the reliability of the study results and properly interpret the outcome of the study;

- the type of critical review, if necessary;

- the type of format of the report required for the study.

The inventory analysis, or Life Cycle Inventory (LCI), is a record of input and output data regarding the system being studied (The International Standards Organisation, 2006a, b). It involves data collection and calculation procedures, to quantify relevant inputs and outputs of the system.

The assessment of the impacts, that can also be called Life Cycle Impact Assessment (LCIA), is aimed at evaluating the significance of potential environmental impacts using the LCI results. It associates inventory data with specific environmental impact categories and category indicators, so it is possible to understand these impacts (The International Standards Organisation, 2006a, b).

Finally, the interpretation phase should deliver results that are consistent with the defined goal and scope and which reach conclusions, explain limitations and provide recommendations (The International Standards Organisation, 2006a, b).

The following sections describe the concepts analyzed throughout this study. These concepts are presented in a book edited by Mary Ann Curran, named Environmental Life-Cycle Assessment and the book entitled Product Design for the Environment - A Life Cycle Approach written by Fabio Giudice, Guido La Rosa and Antonino Risitano (Curran, 1996; Giudice *et al.*, 2006).

Mary Ann Curran is an internationally recognized expert in Life Cycle Assessment and Environmental Sustainability. She worked with the United States Environmental Protection Agency and she was the EPA representative to the ISO 14000 subcommittee on Life Cycle Assessment (LCA). Now she offers her knowledge as an independent consultant.

These books have the essential knowledge necessary to begin the study, the first is among one of the most referred books in papers and is considered a milestone in the subject of LCA.

Over the years, companies are becoming more and more concerned with the environmental impacts of their activities (Curran, 1996). They want to be able to understand the environmental impacts they cause, in order to control or, even better, avoid them. They do so in a time of increasingly strict environmental regulations in an effort to stay within compliance and meet customer needs, while staying competitive and financially healthy.

The main driving force for the companies is the need to stay competitive in the marketplace.

Industrial processes and activities are interlinked, through their suppliers and customers, with other processes and activities (Curran, 1996). Outputs in the form of products and by-products transfer from one operation to another, making them all dependent on each other.

A system is a collection of connected operations that together perform one or more defined functions. Any industrial system can be represented by a system boundary that encloses all the operations of interest (Curran, 1996).

The inputs to the system are all raw materials taken from the environment and the outputs are waste materials released back into the environment. In the Figure 2.1 it is possible to see the flow of the inputs and outputs that exists in the system throughout its life cycle stages (Curran, 1996).

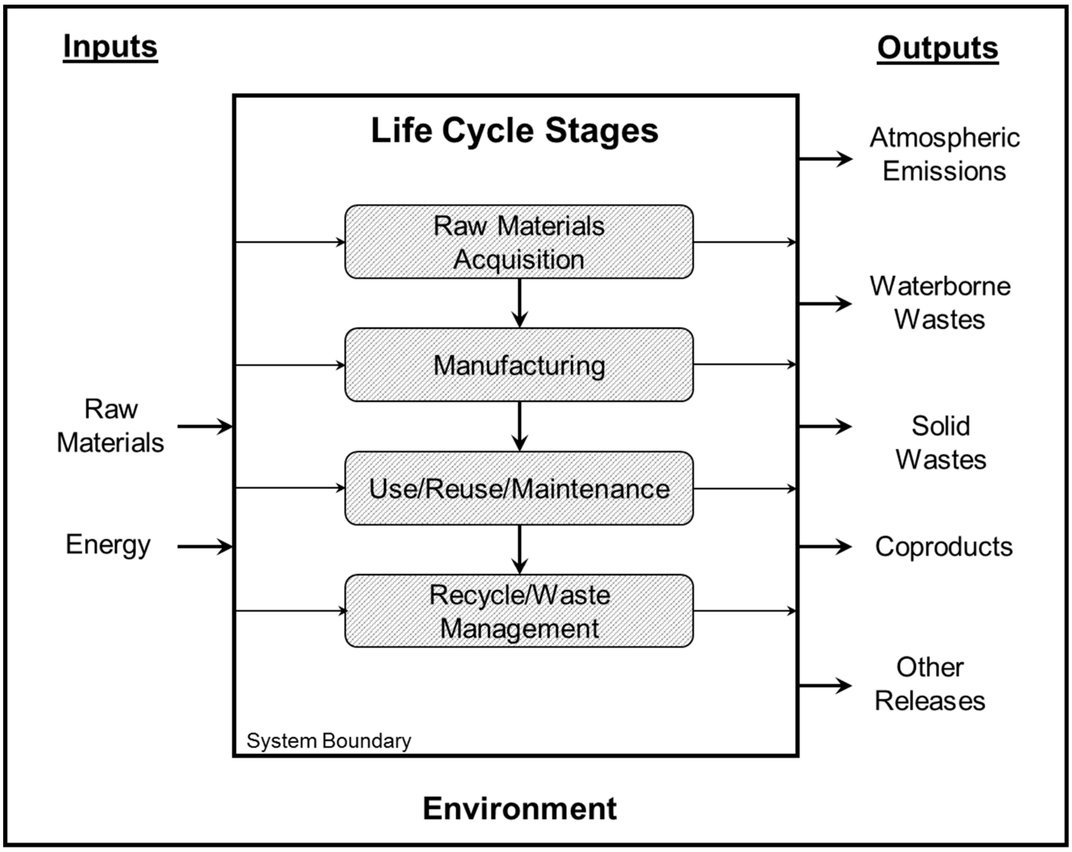


Figure 2.1 - Life-cycle assessment stages and boundaries

(adapted from Environmental Protection Agency, 1993, cited in Curran, 1996)

Initially, industry leaders expressed their interest in LCA so they could take a defensive position in trying to demonstrate the environmental superiority of their product over a competitor's product.

The consumer interest groups used the LCA methodology to compare products, in order to prove which ones were environmentally better.

Recently the motivation behind conducting an LCA (Curran, 1996) is to identify opportunities to alter a product, or process to improve its environmental profile (make it greener).

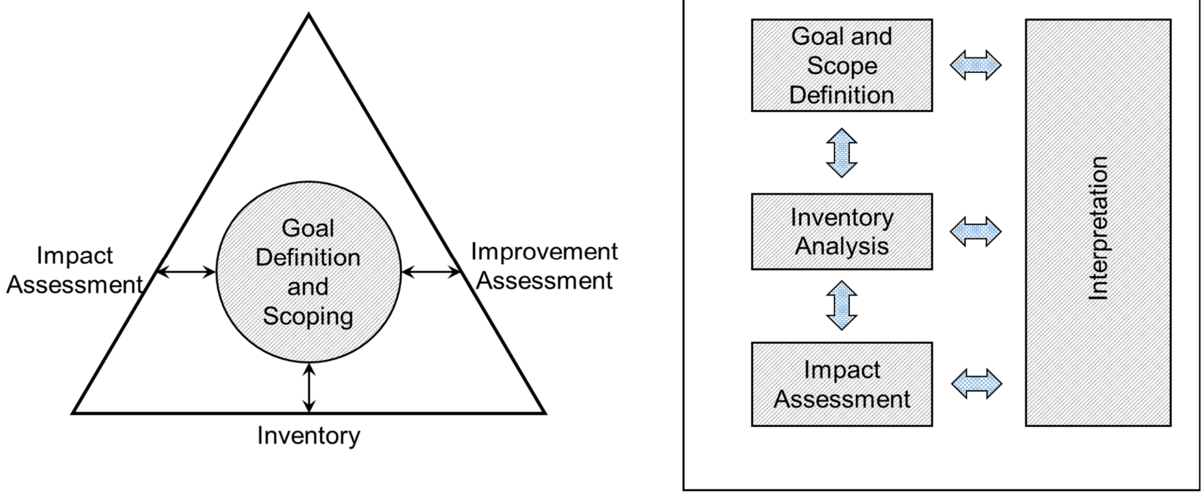
LCA is important for identifying when the selection of one product over another or when modifications made to any part of the system have the desired result of decreasing environmental impacts from all the life-cycle stages, from cradle to grave. Changes to any part of the product or process system can result in an unwanted shifting of burdens to another part of the system, unless a life-cycle framework is employed. The LCA helps in the identification of these unwanted shifts (Curran, 1996).

LCAs (Curran, 1996) are very data-intensive methodologies and the success of any given study is determined by the availability of good data, which can be an obstacle because of the lack of readily accessible and credible data. Another obstacle to performing LCAs is the need to develop a generally accepted impact assessment methodology.

Life cycle design is the application of the life-cycle concept the design phase of products and integrates environmental concerns with factors that are typical in product performance, cost, cultural and legal requirements.

The LCA methodology (The International Standards Organisation, 2006a, b) consists on the following four components:

- Goal definition and scoping
- Life cycle inventory
- Impact assessment
- Interpretation or Improvement assessment



SETAC Framework **ISO 14040 Framework**

Figure 2.2 - LCA framework and impact assessment according to SETAC
(Consoli et al., 1993) and (The International Standards Organisation, 2006a)

2.2.1 Goal and Scope Definition

This stage, defines the purpose of the study, the expected product of the study, the boundary conditions, and the assumptions. Setting boundaries and the definition of the specific life cycle system being studied is an essential first step.

2.2.1.1 Defining the purpose

Before a Life Cycle Inventory (LCI) or LCA begins, the purpose of the activity must be defined. Typically, LCI and LCA are performed in response to specific questions and the nature of these questions determines the goals and scope of the study. LCI and LCA are comparative methodologies and usually someone is seeking information to use in decision making (Boguski *et al.*, 1996).

Four examples (Boguski *et al.*, 1996) that show how the purpose of an LCA or LCI may be determined, are:

- To compare the product with several competitive products already in the market. The purpose is to discover any potentially negative environmental aspects of the new product before it is marketed. Use the information to make environmental improvements in the product so that it has an environmental profile similar to or better than those of competitive products;

- When a product of a company is being criticized because of environmental concerns. A comparison of the product to the most popular will help in proving its quality;

- The selection of different packaging options for a product may be performed using a comparative analysis of the LCI results of the different packages;

- When an environmental group is considering undertaking a campaign to discourage the public from buying a certain consumer product instead of using household ingredients that serve the same function. This is done by performing an LCI and a selective impact assessment of the two different alternatives.

2.2.1.2 Defining boundary conditions

After the determination of the goals and purpose of the LCI or LCA, the boundaries can be determined (Boguski *et al.*, 1996). All operations that contribute to the life cycle of the product, process, or activity of interest fall within the system boundaries. The environment is the surrounding for the system. Inputs to the system are natural resources, including energy resources. The outputs of the system are the emissions made to the environment (air, water, or land). If the system represents the manufacture and use of a product, then outputs include the postconsumer or discarded product.

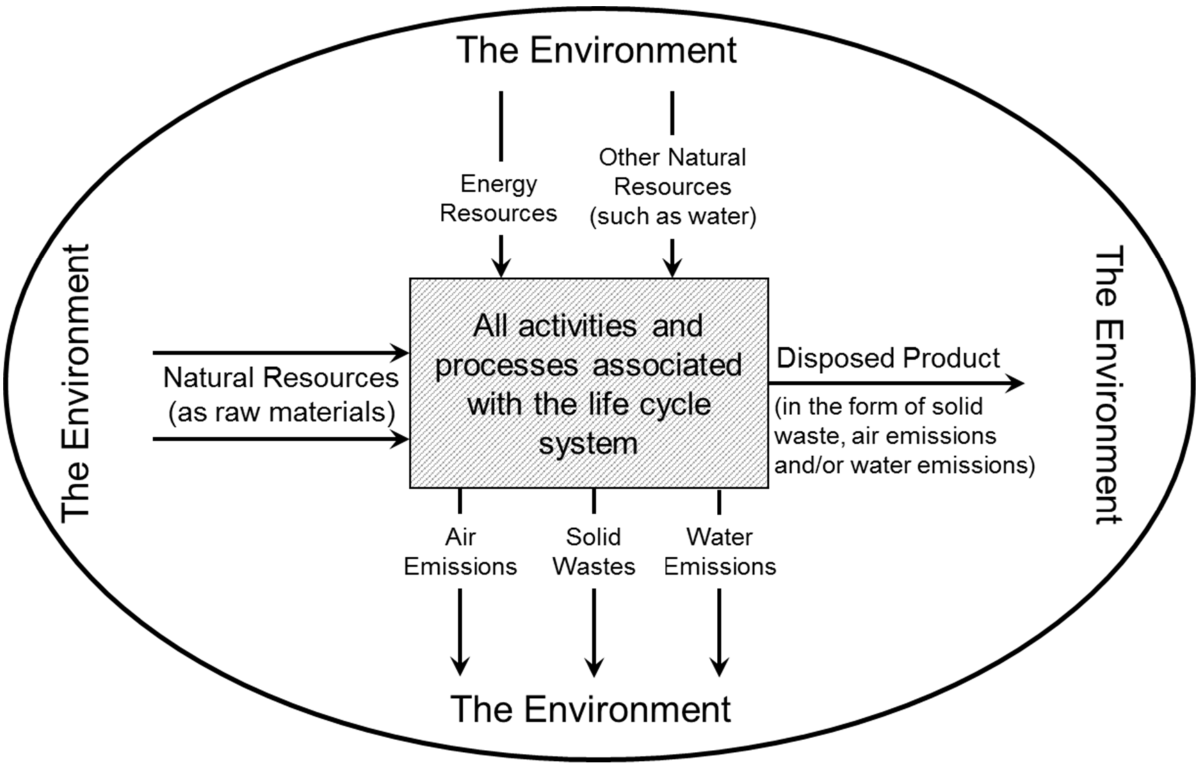


Figure 2.3 - Illustration of life-cycle system concept

(Boguski et al., 1996)

The system boundaries for an LCI or LCA of a product system can be illustrated by a “cradle to grave” materials flow diagram. The term cradle to grave means from the acquisition of the raw materials to the disposal of a product (Boguski *et al.*, 1996).

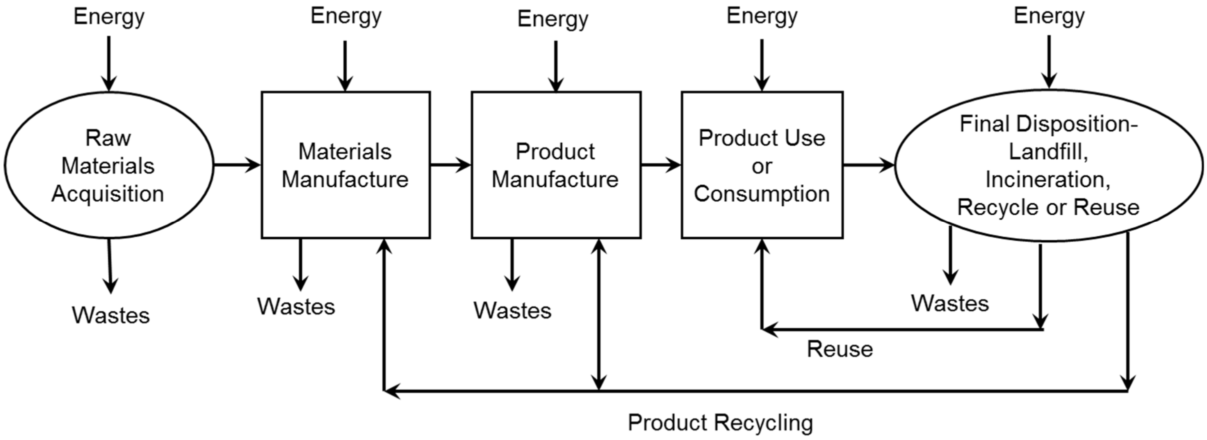


Figure 2.4 - General materials flow diagram for a product life cycle

(Boguski et al., 1996)

There are other ways to study the system of a product (Boguski *et al.*, 1996) like for example the term "cradle to gate". The term cradle to gate means from the acquisition of raw materials to the manufacture of a usable product. This normally is used to study subsystems that exist within the system, for example the production of each component is a subsystem of the final product. A subsystem can be linked to other subsystems to form a complete life cycle system.

It is necessary to discuss any steps that have been excluded from an LCI or LCA study, when one is reporting the results of the assessment, and to explain the reasoning for exclusion of these steps. This allows the reader of the report to better understand the meaning of the conclusions of the study.

In addition, to determine which operations are within the LCI or LCA system boundaries, the practitioner must choose time and spatial boundaries, because the data for each operation and subsystem within an LCI or LCA system should be representative of the stated time and spatial boundaries (Boguski *et al.*, 1996).

Spatial boundaries are important because industrial practices, legislative requirements, consumer habits and physical realities (type of environment of the location) are different for some cities and countries (Boguski *et al.*, 1996). It is possible to use data collected for operations in one location to represent operations in another, but sometimes this could lead to erroneous conclusions because of different situations the system is in. To prevent this from happening it is necessary to aggregate data from operations in several locations in order to better model the actual flow of materials in the marketplace.

Time boundaries are important because industrial practices, legislative requirements and consumer habits vary over time. Since LCI and LCA studies require large amounts of data it is necessary that all data for each operation to be collected within the relevant time period (Boguski *et al.*, 1996).

2.2.2 Inventory Analysis

The main objective of an inventory analysis is to provide data which will be elaborated and analyzed to obtain evaluations that help in decision-making situations.

The LCI methodology focuses on material and energy balances for each operation within the system and for the whole life cycle system itself. It quantifies the resource use, energy use, and environmental releases associated with the system being evaluated (Boguski *et al.*, 1996).

The analysis involves all steps in the life cycle of each component of the product being studied. This includes the acquisition of raw materials from the earth, the acquisition of energy resources from the earth, processing of raw materials into usable components, manufacturing products and intermediates, transportation of materials to each processing step, manufacture of the product being studied, distribution of the product, use of the product and final disposal (which may include recycling, reuse, incineration, or landfill).

Practitioners must make three major types of LCI decisions (Boguski *et al.*, 1996):

1. Allocation of inputs and outputs from an industrial operation to the various products that are produced;

2. Analysis of recycling systems;

3. Report of the energy that enters and exits the system.

There are five basic steps to an LCI study (Boguski *et al.*, 1996):

1. Defining the scope and boundaries – This part of the LCI is a continuation of the previous goal and scoping definition, where the systems to be evaluated were determined and various geographic, spatial and time parameters were set. In addition to these parameters, specific information about the system is necessary, like the specifications of each component and package and the functional unit (unit output for which results will be presented) must be determined. To do a comparative study it is necessary to decide the equivalent-use ratio. In order to set the boundaries, all the operations that contribute to the life-cycle of the product, process or activity must fall within the system boundaries, all the steps (component manufacture, material definition, final disposal) must be defined and quantified;

2. Gathering of the necessary data – The gathering of data begins with the research necessary to set the scope and the boundaries of the LCI study. Then it necessary to identify the process steps necessary to manufacture each component of a product. It is also necessary to identify all the process steps within the system and quantify the resources usage (raw materials, energy, …), in order to have this data it is essential to rely upon data of similar studies, of databases (secondary data) or supplied by the interested industries (primary data). Once the collected data is analyzed certain calculations are necessary to put the data into the desired format for entry into a computer model (usually this is the functional unit);

3. Creation of a computer model – This step may not be necessary, but it helps in the assessment of a large number of complex calculations. The objective of the computer model is to combine and compile the input and output data for each step of the system, this way the results can be displayed in greater or lesser detail;

4. Analysis and report of the study results – Once the necessary calculations are made or the computer model is completed, the results of the LCI must be analyzed and reported in a meaningful way that conveys all the LCI information;

5. Interpretation of the results and conclusions – Once the results of the LCI are presented in the desired format, they can be interpreted and conclusions can be drawn. In this stage conclusions and improvement analysis are limited too seeking less resource use, less energy use and lower levels of emissions to the environment (no attempt is made

to determine the relative impact of each of these on the environment or on human health).

LCI results are needed to perform any type of quantitative impact assessment. Once the inputs and outputs of a system have been quantified by the LCI, the impact assessment can be performed.

2.2.3 Impact Assessment

The development of measures of actual impact on human health, ecological quality, and natural resource depletion enables impact assessments. Impact assessments converts the results from an LCI to a set of common impact measures that allows interpretation of the total environmental effects of the system being evaluated (Boguski *et al.*, 1996). Because the impact assessment methodology requires a way of combining complex LCI data outputs into small number of impact categories, it requires the existence of a conversion mechanism.

The only difference between the LCA methodological framework proposed by SETAC and the standardization defined in the ISO 14040 norms is in the impact assessment phase and the interpretation or improvement phase.

The SETAC method for impact assessment has 3 stages (Boguski *et al.*, 1996):

- Classification – Assignment of LCI inputs and outputs to impact categories (ex: use of fossil fuels may be assigned to the impact group “depletion of finite resources”). The Society of Environmental Toxicology and Chemistry (SETAC) lists four general impact categories: environmental or ecosystem quality, quality of human life (including health), natural resource utilization and social welfare;

- Characterization – Process of developing conversion models to translate LCI and supplemental data to impact descriptors (ex: carbon dioxide and methane LCI outputs may be converted to units of global warming potential);

- Valuation – Assignment of relative values or weights to different impacts, allowing integration across all impact categories. When valuation is completed, the decision makers can directly compare the overall potential impacts of each product.

As shown in the lines above, the SETAC method uses 3 stages, Classification, Characterization and Valuation. The last of this stages is where the difference is, because instead of doing a mandatory weighting of the different impact types, to be able to make comparisons, the ISO method uses optional procedures.

The ISO method for impact assessment also has 3 stages (Giudice *et al.*, 2006):

- Selection – The selection of the environmental effects that are to be taken into consideration and the matching environmental indicators that represent these effects;

- Classification;

- Characterization.

In the ISO method, it is possible to choose one of the optional procedures (Normalization, Grouping and Weighting) in the elaboration of the results of the Characterization phase so it is possible to acquire concise indices that can be used to enable a complete evaluation (Giudice *et al.*, 2006).

The next table (Table 2.1) presents the various *impact assessment* methodologies that help in the quantification of the different impacts.

The table was firstly based on Giudice *et al.*, (2006), and then it was updated by the author of this dissertation with newer information from the SimaPro Manual (Pre' Consultants, 2014).

Table 2.1 - Impact Assessment Methods

European Methods	CML-IA – developed by the Center of Environmental Science of Leiden University *
	Ecological Scarcity 2013 **
	EDIP 2003 *
	Environmental Product Declarations 2013 (EPD 2013) **
	Environmental Priority Strategies 2015 (EPS 2015) *
	IMPact Assessment of Chemical Toxics (Impact 2002+) **
	ILCD 2011 Midpoint+ **
	ReCiPe *
North American Methods	Building for Environmental and Economic Sustainability (BEES) **
	Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI 2.1) **
Methods for specific problems	Cumulative Energy Demand (energy resources availability) **
	Cumulative Exergy Demand (potential loss of useful energy resources) **
	Ecosystem Damage Potential (characterization of land occupation and transformation) **
	Greenhouse Gas Protocol (greenhouse gas emissions) **
	IPCC 2013 (climate change factors) – developed by the International Panel on Climate Change **
	Selected LCI results (selected substances emitted) **
	USEtox (characterization of human and eco-toxicological impacts) **

* Items updated or ** added by the author using new information from the SimaPro Manual (Pre' Consultants, 2014)

There is not a widely accepted impact assessment methodology, because of the lack of adequate data to support impact assessment studies.

2.2.4 Interpretation or Improvement Assessment

The interpretation or improvement phase can provide an interpretation of the data obtained in the previous phases and identify the actions that must be done to lessen the environmental impact of the system (Giudice *et al.*, 2006).

As previously said, this is one of the steps of the SETAC and ISO methods that has a different point of view. In the SETAC method this phase is only to discuss the possibility of improving the system in study so it is possible to improve its environmental performance. In the ISO method, this phase can also be used to make a sensitivity analysis, an assessment of the uncertainty of the results and the final recommendations to improve the system.

2.3 Life Cycle Design

Life cycle design (Keoleian, 1996) is a systems-oriented approach for designing more ecologically and economically sustainable product systems. It is the application of the life cycle concept to the design phase of the product development process, this intervention must take into consideration all the phases of the product life cycle in the design stage. It couples the product development cycle with the physical life cycle of a product. One of the main characteristics of the life cycle design concept is the assumption that the interventions to the product are most effective when these are made in the first phases of design.

Life cycle design integrates environmental requirements into the earliest stages of design so the impacts that may be caused by the product systems can be reduced. In life cycle design, environmental, performance, cost, cultural, and legal requirements are balanced.

To develop a successful product design, it is no longer reliable to create a product only to satisfy a need, but it must also take into consideration a vast range of physical and functional requisites associated with the different phases of the product´s life cycle, which means to consider factors like resources utilization, manufacturing planning, life cycle costs, product properties, company policies and environmental protection (Giudice *et al.*, 2006).

The design of a product or process offers an excellent opportunity to reduce environmental burdens associated with products and processes, which can lead to a more sustainable relationship between economic and ecological systems (Keoleian, 1996). It is required the use of a framework, tools and innovation in order to develop a sustainable product in phase of design. In product design, decisions concerning the material selection, useful product life, packaging systems, manufacturing processes, strategies for product service and retirement must be made, because these make the environmental profile of a product.

These days, designers face pressing issues in the development phase such as the design of products with short development cycles, the expanding competitiveness, increasing and inconsistent regulations and the continually shifting market demand, in addition to these there are performance and cost requirements and the incognita of not knowing what an environmentally optimal design is.

A life cycle development process is an iterative procedure, where ideas, requirements and solutions are continuously modified and polished until the detailed design is fixed (Keoleian, 1996).

A product life cycle can be represented by a closed loop and can be organized into the following stages (Keoleian, 1996):

- Raw material acquisition;
- Bulk material processing;
- Engineered and specialty materials production;
- Manufacturing and assembly;
- Use and service;
- Retirement;
- Disposal.

The life cycle development process is shown in the Figure 2.5.

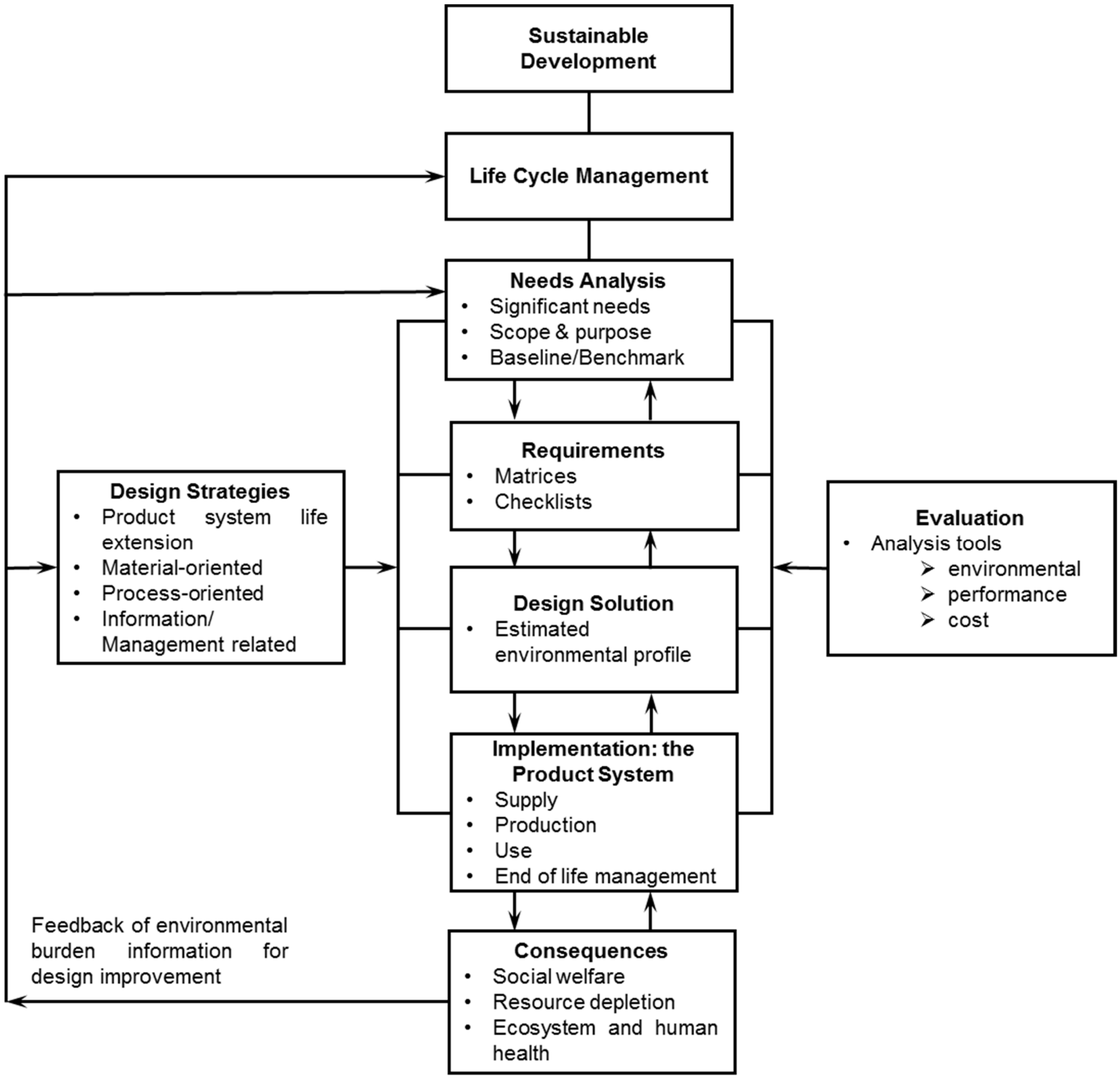


Figure 2.5 - Life cycle development process

(Keoleian, 1996)

As can be seen in the Figure 2.6 about the life cycle stages, there are two ways of postconsumer recycling, these are the closed-loop recycling and the open-loop recycling.

In the closed-loop recycling method the material is diverted from disposal and recycled many times (for example the fabrication of glass bottles), the energy and emissions of the initial virgin material manufacture are divided between the original product and all the subsequent products made from the recycled material (Boguski *et al.*, 1996). By the end, the initial impacts become insignificant and the only energy and emissions are those that result from the recycling and fabrication processes.

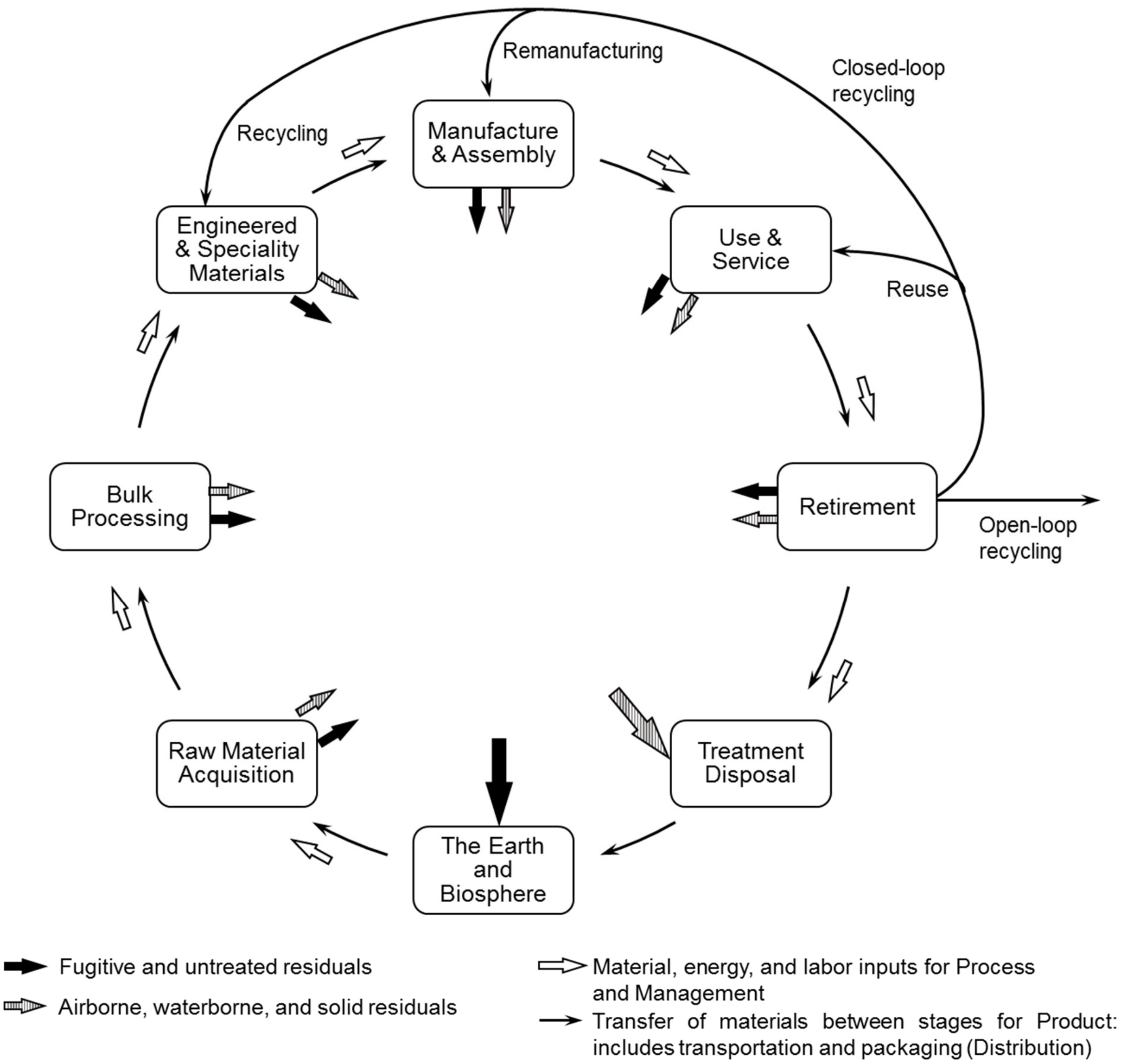


Figure 2.6 - Life cycle stages

(adapted from Keoleian, 1996)

On the contrary, in the open-loop recycling method the virgin material is used to manufacture the original product and then recovered for recycling, to be manufactured into a new product that is not recycled at the end of its life cycle (Boguski *et al.*, 1996). The energy and emissions of the initial virgin material manufacture and disposal of the recycled material are divided between the first and second products.

A product system can be defined by the material, energy, information flows and conversions associated with the life cycle of a product. It can be organized into three components in all the life cycle stages (Keoleian, 1996):

- Product – Consists of all the materials (virgin and recycled materials) that constitute the final product and the forms that these materials take throughout the various life cycle stages;

- Process – Transformation of materials and energy to a variety of intermediate and final products. This component includes any direct and indirect material inputs used in the production of a product. The resources consumed during research, development, testing and product use are included in the process component;

- Distribution – Consists of packaging systems and transportation networks used to contain, protect, and transport products and process materials. The sale and retail activities are also considered part of the distribution component. This component can also be shown between connecting life cycle stages to indicate that either transportation and/or packaging has been used to carry the product or process materials.

The process and distribution components of the product system share some subcomponents like: facility, plant, office, unit operations, process steps, equipment's, human resources, direct and indirect input materials, energy, etc.

Management (Keoleian, 1996) also comprises activities that can generate environmental burden and so it should not be ignored. Management and the information network that supports the decision making process occur throughout the process and distribution components in all life cycle stages.

The main goal of life cycle design is to promote sustainable development at the global, regional and local levels, by reducing the environmental burden associated with product development, with the application of sustainable principles to the product system (Keoleian, 1996).

Sustainable development seeks to meet the needs of the present generation without compromising the ability of future generations to fulfill their needs. The principles for achieving sustainable development are (Keoleian, 1996):

- Promote Sustainable Resource Use and Efficiency
    - Conserve resources, minimize depletion of nonrenewable resources and use sustainable practices for managing renewable resources.
    - The amount and availability of resources are ultimately determined by geological and energy constraints.

- Promote Pollution Prevention
    - Proactive approach based on source reduction avoids the transfer of pollutants across the air, water and land.
    - Addressing environmental issues in the design phase is an effective approach to pollution prevention.

- Protect Ecological and Human Health
    - Healthy, functioning ecosystems are essential for the planet's life support system.
    - Avoiding irreversible damage to the ecosystem such as loss of biodiversity is necessary to protect human health.

- Promote Environmental Equity
    - Address the distribution of resources and environmental risks.
    - Intergenerational equity – meet current needs of society without compromising the ability of future generations to satisfy their needs.
    - Intersocietal equity – change patterns of resource consumption and associated environmental risks within developed and less developed countries to achieve

sustainable development and to address the inequality among socioeconomic groups within a country.

2.4 Life Cycle Costing

The integration of cost analysis into the life cycle assessment methodology helps to translate inventory and impact studies into a metric that business managers understand.

To be competitive in the market the manufacturing companies must be able to bring out its products with the right timing, guaranteeing their functionality and quality, and limit their cost (Giudice *et al.*, 2006).

These days, controlling and reducing only the costs of resource acquisition, production and disposal is considered an unfinished task.

In life cycle costing all the costs associated with a product system throughout its life cycle, from raw material acquisition to disposal, are studied. It is the sum of all the economic resources expended, directly and indirectly to a product, from the moment of its design up until the production, use and disposal phase.

The manufacturer of the product and the buyer have different perceptions of the life cycle. As shown in the figure below the only stages which are the same in both views are Use, that includes operation, maintenance and support services, and Retirement and Disposal.

The first phase in the producers point of view (Giudice *et al.*, 2006) is the identification and analysis of the consumer's needs and the definition of the design objectives, then starts with the design phases, which include the concept, the system and the detailed design, and then it's time for prototype testing. Then the product can be manufactured and distributed.

The buyer starts with the evaluation of his needs and the identification of the requirements that he demands of the product, then gathers information of the products that satisfy his demands and evaluates the alternatives, in order to choose the best possible option. The last phase of the acquisition stage is the selection and the purchase of the product (Giudice *et al.*, 2006).

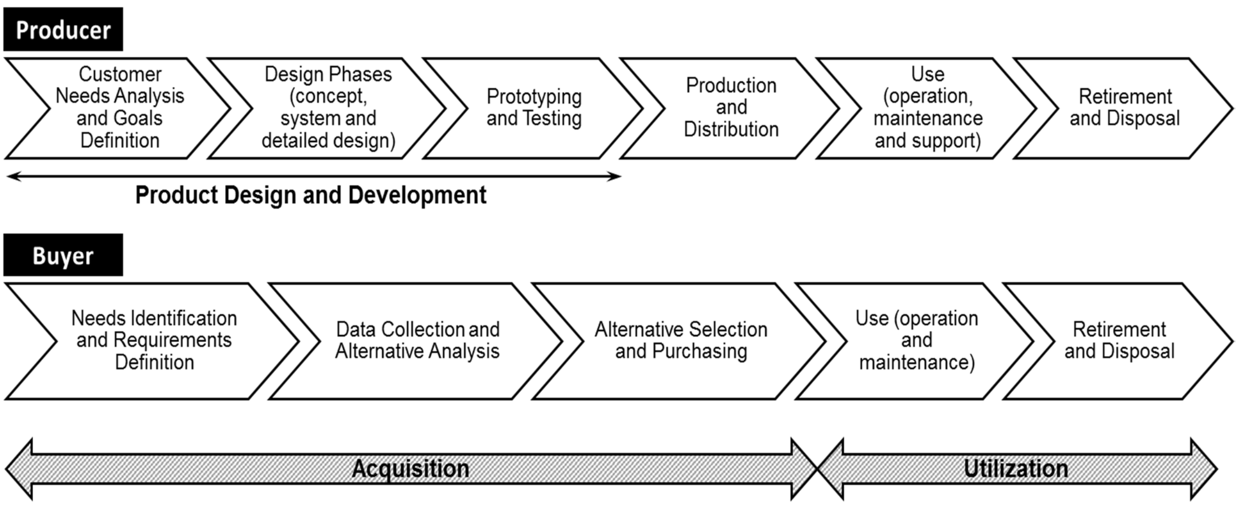


Figure 2.7 - Perception of life cycle from the Producer and Buyer point of view

(Giudice et al., 2006)

Figure 2.8, next, shows the methodological framework that can be considered as a reference procedure.

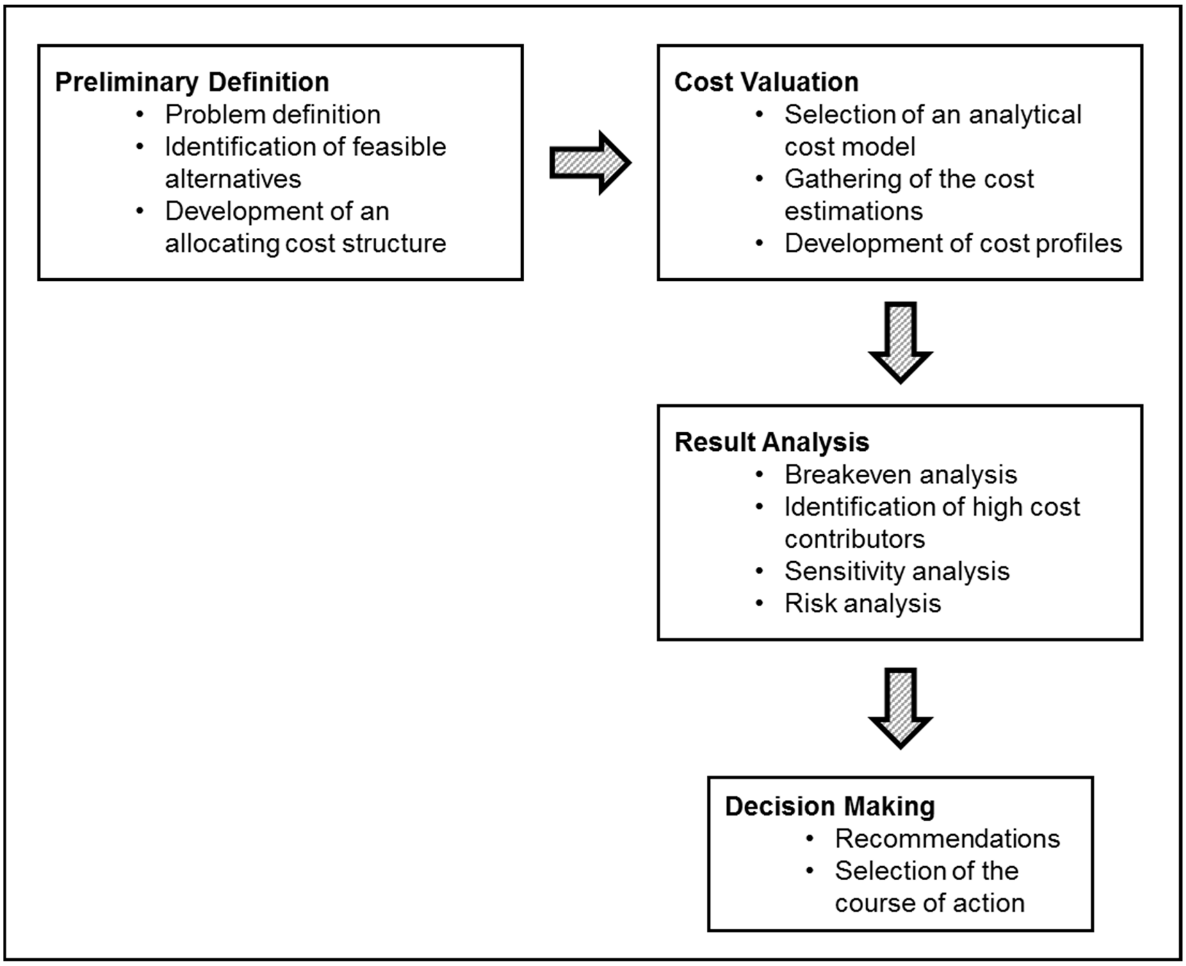


Figure 2.8 - LCC Framework

(adapted from Giudice *et al.*, 2006)

This methodology can be characterized by four main stages (Giudice *et al.*, 2006):

1. Preliminary definitions – In this stage it is necessary to do a detailed definition of the problem to be able to identify correctly the subject that is going to be analyzed. Afterwards it is essential to identify the possible alternatives, based on the defined requisites of the main activities that are incorporated in the life cycle, and study the consequences that the possible alternatives could have on the entire life cycle. Finally, it is necessary to develop a structure of cost allocation and collection, that should permit the classification on the cost typologies and then relate them to the main life cycle activities, this can be done through the definition of relations that allow to estimate costs;

2. Cost valuation – This stage must show the selection of the cost model that is most appropriate for the study, the cost estimations that are made and then the development of cost profiles, that indicates the future cost projections for each alternative under consideration, so it is possible to compare their influence over the entire life cycle;

3. Results analysis – In this stage, first a breakeven analysis must be done to compare the performance of the different alternatives over time, then the high cost contributors must be identified to reveal the criticalities of each one of the alternatives that can be

improved, a sensitivity analysis must also be done in order to know if the data is reliable and what is their influence over the final results and finally a risk analysis to help to identify and manage the possible risks;

4. Decision making – The last stage serves to identify the best alternative, the recommendations and actions for improvement.

With a life cycle cost analysis, it is possible to quantify and evaluate all the environmental costs of a product system.

Life cycle environmental costs can be divided into the following categories: internal costs, these are the costs of the company, and external costs. The internal costs can also be divided into the conventional company costs and the less tangible, hidden and indirect costs (White *et al.*, 1996).

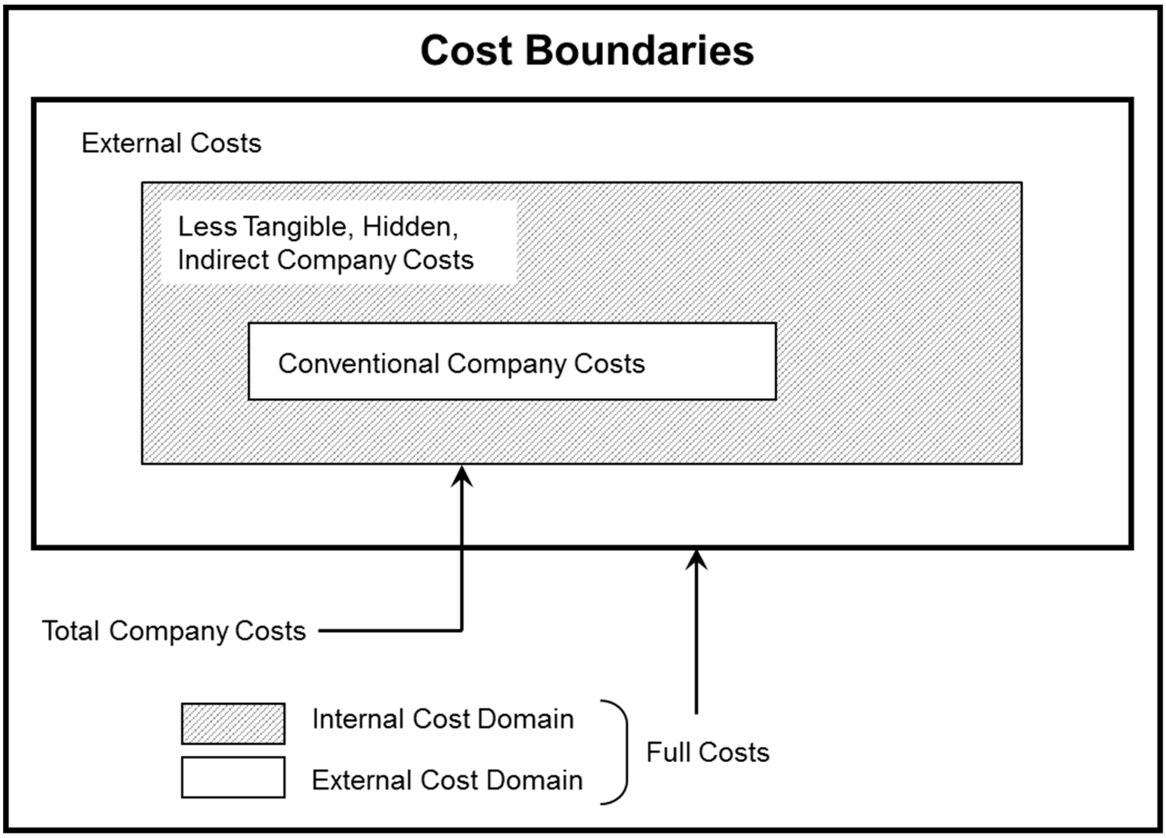


Figure 2.9 - Definitions and boundaries

(adapted from White et al., 1996)

The conventional costs (White *et al.*, 1996) are the ones that appear in the company's general accounts, these are the costs related to use in process control, product costing, investment analysis, capital budgeting and performance evaluation. These costs also include operational costs, such as labor, materials, product transformation, maintenance and the one-time capital costs (normally for acquisition of new equipment's or installations).

The less tangible, hidden and indirect costs include costs associated with environmental permitting, licensing, reporting, waste handling, storage and disposal activities (White *et al.*, 1996).

The sum of both costs shows all the costs for which a company is responsible.

The external costs (White *et al.*, 1996) are those for which a company is not responsible, normally these are associated with the emissions, health and environmental impacts of each one of the auxiliary industries that are within the life cycle of the final product, like the suppliers' activities (for example an external cost can be natural resource depletion, crop impacts, human health impacts, ecological impacts, …).

The life cycle costing methodology includes all internal and external costs sustained throughout the entire life cycle of a product or process.

The only difference between a life cycle assessment and a life cycle costing lays in its impact assessment, because normally an impact assessment would address the environmental and human health effects from emissions and resource use, whereas in the life cycle costing it is placed a monetary value to these impacts (for example calculation of the market value of crop loss caused by air pollutants).

To be able to assign monetary values to each of the impacts caused in the life cycle of a product or process, methods were developed that help in accomplishment of this task.

These methods are (White *et al.*, 1996):

- Contingent valuation – relies on surveys to estimate how much people would be willing to pay to prevent environmental degradation or other adverse impacts;

- Hedonic pricing – examination of market behaviors for the environmental impact in question. This method is based on the assumption that nonmarket characteristics (like clean air) have values that are reflected in what people are willing to pay for tangible goods;

- Regulators' revealed-preferences approach – it is an empirical mean of establishing willingness to pay, by identifying specific instances where control measures have been required to determine the cost that society is willing to pay to reduce emissions, through environmental regulators.

2.5 Background: LCA and LCC

In this section, 17 papers, about LCA and LCC, were analyzed and studied. To understand these papers, their content was summarized and organized in Table 2.2 shown below.

This table has 6 subjects, which are: the focus of the article, which in this case can be cost oriented, environmental oriented or both; the reference, that tells the reader who is the author/s of the paper and the year it was published; the title of the paper; the area of application of this paper; the type of paper, that can be divided into review paper, quantitative assessment or study, qualitative assessment or study and the standards; and the paper summary where the objective of the paper and some of its important aspects are described.

These papers were chosen by considering the year of publication and the amount of citations made by other researchers. It is important to note that all the selected papers were analyzed and the following table was created selecting the most relevant items.

Table 2.2 – Relevant Literature on LCA and LCC

Focus	Reference	Title	Area of application	Type	Relevant Items
Costing	(Swarr *et al.*, 2011)	Environmental life-cycle costing: a code of practice	Sustainable Development	Review Paper	This paper is about the LCC code of practice published by SETAC. This code of practice provides a framework for evaluating decisions with consistent, but flexible system boundaries, as a component of product sustainability assessments. It presents a review of historical developments of life cycle methods, outlines the technical requirements and guidelines for LCC and illustrates various methodological choices with a detailed case study. This paper also points out the similarities between LCC and LCA, how the LCC methodology works and what are the difficulties in its application.
Costing & Environmental	(Bovea and Vidal, 2004)	Increasing product value by integrating environmental impact, costs and customer valuation	Integrated LCA and LCC methodology	Assessment/Studies Quantitative	The aim of this paper is to illustrate how an equilibrium between company and society goals can be achieved by adding value for the customer. For this reason, was proposed a model that highlights the importance that the customer gives to different environmental requirements of a product, by integrating environmental impacts, costs and customer valuation during product development. This model is based on the combination of LCA, LCC and Contingent Valuation (CV), which serves to quantify the customer's willingness-to-pay (WTP) for a product that incorporates certain environmental improvements. This paper also talks about the four stages of a LCA. It advises the use of different impact assessment methods and the application of a sensitivity analysis that allows a correct interpretation of the results obtained. The LCC must include all internal and external costs incurred throughout the life cycle of a product. The CV is a survey-based method that is frequently used for placing monetary values on environmental goods not bought and sold in the marketplace. This questionnaire is an attempt to obtain the customer willingness-to-pay for the incorporation of different environmental improvements during the process of product design. The model contains four stages: (1) the initial analysis of the product, where the LCA and LCC of the product is done; (2) the generation of alternatives, where the LCA gives alternative materials that enhance environmental behavior; (3) the analysis of the alternatives, where the LCA and LCC of each alternative is done and the consumer's willingness-to-pay for each alternative is calculated; (4) the selection of the ecological alternatives. In the end of the paper the authors show a case study of an office desk. This model can be of help in the development of the procedure for the project. They used the software SimaPro and Eco-Indicator 95, Eco-Indicator 99, EPS and Tellus impact methods.
Costing & Environmental	(Deng *et al.*, 2016)	Research on eco-balance with LCA and LCC for mechanical product design	Mechanical Engineering	Review Paper	This paper presents the research on eco-balance with LCA and LCC for mechanical product design. The authors present a LCA methodology for product design by evaluating each process throughout the life cycle of the product, and the environmental LCC methodology, that uses environmental costs of the input and output of the processes (fuel costs, cost for disposal, etc.). The paper also suggests the use of an improved version of the SETAC methodology for impact assessment and an algorithm for product optimization (multidisciplinary design optimization). For better understanding of these methodologies the paper presents a case study of a 4135G diesel engine.

Table 2.2 (continued)

Focus	Reference	Title	Area of application	Type	Relevant Items
Costing & Environmental	(Fazeni *et al.*, 2014)	Methodological advancements in life cycle process design: A preliminary outlook	Process Design	Review Paper	This paper is about the use of LCA methodology for process design and presents the initial findings of this analysis. The goal of this paper is also to apply LCA and LCC at the early stages of design of novel biorefinery process. In the beginning of this paper the authors present a table with an overview of the approaches for environmentally conscious design, so it is possible to see the role that LCA and LCC play in the presented methodologies and how they help in process design. The novelty of the Life Cycle Process Design (LCPD) approach lies in the fact that LCA and LCC start in parallel with basic process development with the objective of providing substantial information and feedback to process engineers. The combination of LCA and LCC can serve as one of the major tools and be the starting point for all improvement measures. The authors show the general framework for conducting LCC and they say that LCA methodology that is applicable in process design is not different from the normal methodology. The problem of LCA related to process development is data collection and generation. The LCC analysis comprises the following four steps: definition of objectives and scope; information gathering; interpretation and identification of hotspots; and a sensitivity analysis and discussion. In the end, they present an application of the LCPD method, where LCA and LCC are used in combination, in a biorefinery process. This paper might have good information for the application of LCA and LCC for products or processes in phase of development, because it encompasses environmental and economic assessments that can help to create better products or processes that have in mind the entire life cycle.
Costing & Environmental	(Hoogmartens *et al.*, 2014)	Bridging the gap between LCA, LCC and CBA as sustainability assessment tools	Environmental Engineering	Review Paper	The aim of this paper is to provide clarity about the methodological differences between LCA, LCC, Cost Benefit Analysis (CBA) and their most relevant sub methodologies. So, it is possible to develop a framework that simplifies interactions and supports complementary use of these different methodologies. The developed framework is then applied to a case study about the treatment of end-of-life automotive glass. There are three pillars that support the sustainability method, these are the environment, economy and society. The environment pillar is composed by the environmental LCA (eLCA), the environmental LCC (eLCC) and full environmental LCC (feLCC) and the environmental CBA sub methodologies. The economy pillar is composed by the financial LCC (fLCC) and the financial CBA (fCBA) sub methodologies. The third pillar, the social, is composed by the social LCA (sLCA), the societal LCC (sLCC) and the social CBA (sCBA) sub methodologies. In this paper, the authors comment on how these sub methodologies work, what are their differences and problems and how they can complement each other. In the end of the paper they show the implementation of the framework to the treatment of end-of-life automotive glass and discuss this implementation.

Table 2.2 (continued)

Focus	Reference	Title	Area of application	Type	Relevant Items
Costing & Environmental	(Mistry *et al.*, 2016)	LCA and LCC of the world's longest pier: a case study on nickel-containing stainless steel rebar	Sustainable Construction	Assessment/Studies Quantitative	The aim of this paper is to provide a combined comparative assessment of two piers using LCA and LCC for the application of stainless steel as reinforcements of concrete structures in a marine environment, to demonstrate the value of stainless steel products from an environmental as well as from a cost perspective. The subject of analysis is the Progreso Pier, in Yucatan (Mexico), that was constructed with stainless steel reinforcement and was compared to an hypothetical carbon steel reinforced concrete pier with size and function equivalent to the Progresso Pier. In this study, everything is equivalent except the type of steel and the corrosion resistance of each pier, which means that the carbon steel pier has more frequent maintenance and reconstruction. The time line of this study is 79 years (1941-2020) so it is possible to catch the past performance and the expected performance. The boundaries of this system include materials, the maintenance over the life cycle, the transport of materials and end of life of the pier. The piers comprise four life cycle stages: raw materials production; construction; maintenance; and end-of-life. The data used in the LCI came from three inspections made to the pier and a database from the software GaBi 6. One of the problems was the almost inexistent data about the construction impacts and the not knowing how much material is needed for repairs. They used CML2001 impact assessment methodology to identify the impacts of these piers. After the LCA, the authors determined the economic impact by doing a LCC. The cost information necessary for this study was provided by the Life-365 software. To be able to determine the future costs in relation to present costs they calculated the NPC, which means net present cost. In the end, they did a sensitivity analysis for two variables (the discount rate used in the NPC formula and the construction costs). Finally, they concluded that the concrete pier built with stainless steel rebars (reinforcing bars) demonstrated lower potential environmental impacts and cost implications than the pier built in carbon steel rebars.
Costing & Environmental	(Rebitzer *et al*, 2003)	LCC – The Economic Pillar of Sustainability: Methodology and Application to Wastewater Treatment	Sustainable Development	Assessment/Studies Quantitative	The aim of this paper is to present a LCA based LCC method as part of life cycle management activities. This methodology utilizes an LCA model as a basis for cost estimations in product/process development and planning. This paper also shows the relevance of addressing the environmental issues and life cycle costs at a development phase. This methodology takes into account all the life cycle of a product from cradle to grave and are accounted the costs of physical processes and materials, and all the expenses, like labor costs, marketing expenses, etc.. The costs are calculated by multiplying the quantities of flows, provided by the LCI of an LCA, by the respective company costs or market prices. The LCA based LCC aims to: compare life cycle costs of alternatives; detect direct and indirect cost drivers; identify trade-offs in the life cycle of a product; utilize the full costing to identify new products; record the improvements made by a firm in regards to a given product. This methodology is only meant to be used for rough cost estimations, which means it cannot replace more detailed cost management methods. The authors also present a case study where the LCA based LCC is used to assess the impacts and costs of a wastewater treatment plant. In this study, the system is analyzed according predetermined variables.
Environmental	(Guinée *et al.*, 2011)	Life Cycle Assessment: Past, Present, and Future	Sustainable Development	Review Paper	The aim of this paper is to explore the development of LCA methodology in the context of past, present and future. To do this they started by describing the historical development of LCA and then they proceeded to discuss the developments of the past decade up to the present. They also present some results from the CALCAS project, which is an EU concerted action. They also speak about the LCSA as the next stage of the evolution of LCA.

Table 2.2 (continued)

Focus	Reference	Title	Area of application	Type	Relevant Items
Environmental	(Heijungs *et al.*, 2010)	Life cycle assessment and sustainability analysis of products, materials and technologies. Toward a scientific framework for sustainability life cycle analysis.	Sustainable Development	Review Paper	This paper discusses the concept of sustainability, life cycle analysis or assessment and how both can be combined in a scientific framework for decision making. They study the concept of sustainability and life cycle analysis separately and then they bring both subjects together to create the Life Cycle Sustainability Assessment. Sustainability is different from sustainable, because sustainability is a property of a thing that is sustainable and something is sustainable when maintained in a specific state for an indefinite time. The authors show that sustainability has three pillars that support it, which are the areas that need to be assessed in a sustainability assessment: economic, environmental and social pillars. Life cycle assessment is the “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (The International Standards Organisation, 2006b). To be possible to combine both, sustainability assessment and life cycle assessment, the scope of the LCA needs to be broadened by adding the social and economic dimensions to the environmental dimension of the LCA, which is called LCSA. In the end of this paper they built a general framework by remodeling the LCA framework from the ISO 14040 that has the 4 steps for a LCA (goal and scope definition, inventory analysis, impact analysis and interpretation). In this new framework, they merge the inventory and impact analysis together into one modeling step. They also address what the LCA, LCC and SLCA have in common that allows them to create LCSA, and what are problems that appear by merging them together.
Environmental	(Klöpffer, 2006)	The Role of SETAC in the Development of LCA	LCA Consult	Review Paper	This paper shows the importance that SETAC has in the development of LCA. They show the importance of SETAC’s role by telling the story of LCA, why it was developed, how it evolved over the years and why it was the only environmental assessment method judged worthy to be standardized by ISO. This paper shows where a researcher can search to obtain knowledge about the methodology and who are the experts in this area.
Environmental	(Kreiger *et al.*, 2014)	Life cycle analysis of distributed recycling of post-consumer high density polyethylene for 3D printing filament	Additive manufacturing	Assessment/Studies Quantitative	The aim of this paper is to do a life cycle assessment of distributed recycling of post-consumer high density polyethylene (HDPE) for 3D printing. The reason behind this research is because of the increase in plastic usage which results in a substantial burden to the environment, since plastics are slow to decompose and its processing, use and disposal also embrace a significant source of energy consumption. This study also explores the possibility of using a distributed network of RecycleBots to process post-consumer plastic goods into 3D printing feedstock and if it is a feasible alternative to the conventional recycling method. In the LCA they start by defining the scope, functional unit and the system boundary. The system boundary is different from the normally seen LCAs because they talk about a gate-to-gate approach, which means starting at the end of the first useful life of the HDPE within the consumer’s home and ending immediately after production of a recycled filament or pellet. They used the software SimaPro 7.2 and the database EcoInvent 2.2 as resources for the LCI and LCIA. The Cumulative energy demand (CED) was used to analyze the overall energy costs and IPCC 2007 for global warming potential over a 100 year time period. The CO2 equivalent emissions for recycling comparisons were calculated. They show diagrams of both the systems analyzed. The conventional recycling can be divided into three different scenarios: for regions with a highly populated area; low populated area with biweekly recycling trips; and low populated area with monthly recycling trips. In the end, the results showed that distributed recycling of HDPE uses less energy than conventional recycling. This paper shows one of the main environmental issues that 3D printing could solve and a way to recycle plastic material as a source of raw material for 3D printing.

Table 2.2 (continued)

Focus	Reference	Title	Area of application	Type	Relevant Items
Environmental	(Lu *et al.*, 2011)	Systematic Lifecycle Design for Sustainable Product Development	Product Development/ Mechanical Engineering	Review Paper	This paper is about the systematic life cycle design for sustainable product development and a simplified LCA for product development considering each process and each stage that exists in a life cycle of a product. Because the product is in its early stages of development and the detailed specifications being difficult to obtain, the author suggested the use of qualitative analysis techniques. This paper explains that there are 4 stages of a product life cycle structure (extraction, production, operation and retirement). The paper also suggests a way for the assessment of the materials used in each process, for the assessment of the processes that exist in each stage and for the assessment of the stages in the life cycle by evaluating the impacts in tables. This work may be a good example for the project because it was directed to a product development, without previous data to help in the improvement or development of the product.
Environmental	(Rubin *et al.*, 2014)	Utilization of life cycle assessment methodology to compare two strategies for recovery of copper from printed circuit board scrap	Electric and Production Engineering	Assessment/Studies Quantitative	The aim of this paper is to apply a LCA to evaluate and compare two electrochemical processes for recovering copper from printed circuit boards scrap, one using sulfuric acid and the other using acqua regia. The rapid evolution of technology combined with a strong incentive for consumption causes rapid obsolescence of a wide array of products and, therefore, generation of waste electrical and electronic equipment. This electrical and electronic waste contains many substances that are high-valued and highly toxic. This study was done in Brazil, because it did not have a complete recycling chain (collection, sorting, dismantling, processing and refining or disposal). The authors do a small literature review about LCA and Life Cycle Thinking. They use the principles of ISO 14040 series. In the application of the LCA, they define the system function, the functional unit and the allocation procedure. The data for the LCI came from the GaBi software and database for life cycle engineering and other articles about the same subject. The existence of site-specific data was not taken into consideration. For the LCIA they used the EDIP methodology to identify the environmental impacts. As they expected, the biggest issue is the acidification, because of the nature of the substances used in both processes and the sulfuric acid-based process presented the most significant potential impact. This study demonstrates the importance of LCA as a useful tool in decision making.
Environmental	(Sierra-Pérez *et al.*, 2015)	Environmental implications of the use of agglomerated cork as thermal insulation in buildings	Sustainable Construction	Assessment/Studies Quantitative	The aim of this paper is to do a cradle to gate LCA to assess in detail the sustainability of cork as an insulation material, quantifying the environmental impact of producing cork insulation boards. The building sector is one of the main environmental challenges, accounting for more than 40% of the energy consumption and environmental impact. The market is dominated by two types of insulation products, which are glass wool and stone wool (60% of the market), there is also organic foamy materials that represent 30% of the market. The rest of the market is composed of other materials, like renewable materials (cork, cotton, etc…). The importance of these renewable materials has been increasing due to the strategic minimization of the use of non-renewable materials to reduce the environmental impact of buildings. A LCA was done to analyze the environmental impact of the production of cork insulation boards produced in Catalonia and it was based on ISO 14040. This assessment includes both forest and industrial stages and transportation to the manufacturer, which means that the usage and end-of-life stages have not been included in the study. The data for the inventory was obtained with the manufacturer and with the database EcoInvent 3.1, and for the impact assessment they used the software SimaPro and CML 2002 methodology. This way, the authors could identify the most influential stages and processes. In this assessment, they concluded that the most influential stages were the transportation and the energy consumption. In the end, they analyzed the influence of other energy sources and transport scenarios on the system, as well as the influence of different end-of-life scenarios in the emission of the biogenic carbon stored in the cork boards.

Table 2.2 (continued)

Focus	Reference	Title	Area of application	Type	Relevant Items
Environmental	(Van Den Heede and De Belie, 2012)	Environmental impact and life cycle assessment (LCA) of traditional and 'green' concretes: Literature review and theoretical calculations	Civil Engineering	Review Paper	This paper is about environmental impact and life cycle assessment (LCA) of traditional and 'green' concretes, by doing a review of papers that use the LCA methodology in the production of concrete. This paper shows that it is possible to evaluate the environmental impacts of its production and how to assess it. It presents comparisons and Life Cycle Assessments between common concrete and eco-concrete. It also describes the methodology for the implementation like previous paper. The authors demonstrate a quantitative assessment of the life cycle of concrete by showing the global, regional and local impacts and by presenting numerical values of emissions for different materials in the production of concrete.
Environmental	(Rodrigues *et al.*, 2016)	Life cycle assessment (LCA) applied to the manufacturing of common and ecological concrete: A review	Civil Engineering	Review Paper	This paper is a review about Life Cycle Assessment (LCA) applied to the manufacturing of common and ecological concrete. It also presents comparisons of life cycle assessments between normal concrete and eco-concrete. They start by introducing the story and definitions of LCA, which might help to understand where it came from and why it was developed, and then the authors explain the methodology by introducing the 4 phases of the implementation. The paper explains the 3 kinds of approaches to the Life Cycle Assessment of a product: cradle to gate which means that is from the moment of birth until the moment the product exits from the factory, cradle to grave that is the traditional approach from the moment of birth until the waste phases of the product and cradle to cradle approach that is from moment of birth until the reutilization of the waste of the product. This paper also describes two approaches in the impact assessment phase that can be divided into single-category or multi-category methods. The multi-category methods are the most commonly used and can be problem-oriented (midpoint), showing the results that contributes to the problem, or damage-oriented (endpoint), showing the results of the damage caused. Always with the same goal of classifying, characterizing, standardizing, and valuing the potential impacts on ecosystems, human health, and the depletion of natural resources. The authors indicate some of the LCA software's that can help with the assessment and LCI databases used to collect and calculate the data.
Environmental	(Vignali, 2016)	Environmental assessment of domestic boilers: A comparison of condensing and traditional technology using life cycle assessment methodology	Industrial Engineering	Assessment/Studies Quantitative	The aim of this paper is to apply the LCA methodology to evaluate two boilers for hot water production (comparing condensing and traditional boilers). This research was made because household heating is one of the main contributors to the impact on the environment, due to the high levels of energy required. Central heating boilers with gas-fired systems represent 79% of market share and less than 10% of these are equipped with condensing technology, which is the best available technology in the market. The authors present a literature review on the environmental impact of domestic heating systems. They say that the LCA is considered by the European Commission to be the best tool to evaluate the environmental performance of a product or system. In their assessment, they also use the four stages to implement a LCA. This paper might be a good example of how a LCA should be applied. They define the functional unit and the system boundaries in the beginning of the study, by identifying a reference unit and by dividing the system in upstream, core and downstream processes. The data collected in the LCI stage was done for three regions in Italy with different climates and the energy consumption was calculated considering different scenarios for each climatic zones (like the insulation systems of dwellings built during the 1990s and the ones adopted since 2000). They used the software SimaPro 7.3.3 and the CML2001 LCIA method at the midpoint. The results show that the impacts of the conventional boiler are consistently higher than the condensing boiler for each of the scenarios considered.

From the analyzed papers, it is possible to observe that all the papers that use the LCA methodology apply the 4 steps procedure as recommended by ISO 14040, which means that the standardized methodology is not being ignored. The only thing that differ from one paper to another is the impact assessment methodology, because there is not a generally accepted methodology nor there is a standardized one.

The papers that address assessments of products or processes were the most interesting ones, because it was possible to see how the authors applied the LCA and LCC methodologies in order to improve the performance. There are many papers in different areas that use these two methodologies and can serve as guidance for the implementation in new studies. Almost all of these assessments contain a quantitative analysis, because of the transition between the inventory assessment and the impact assessment in either one of the methodologies.

The inventory assessment can be a problem when the product or process under analysis is in the phase of development, because there is no previous available data about the inputs and outputs of the life cycle in study.

The database that is generally used to obtain the inventory data is the Eco Invent database.

In all the analyzed assessments, the software SimaPro was used as a support tool in the life cycle analysis, because it allows the users to analyze complex life cycles in a systematic way, measure the environmental impacts of the products across all the stages of the life cycle and to identify the hotspots in every link of the supply chain.

Some of the analyzed papers talk about LCA and LCC as a small part of a larger methodology, which is the Life Cycle Sustainability Assessment (LCSA). With this review, it was possible to observe that the LCSA subject is becoming more common, because researchers started to realize that environmental issues are not the only problems that they have to overcome and that there are other ways, beyond this one, that can help improve the processes and products. This way, it is possible to improve the social, economic and environmental aspects of the products/processes.

LCSA allows to incorporate the LCA, LCC and SLCA, by applying them simultaneously. The problem that exists when they are applied simultaneously is that the impact categories are different from the LCA and LCC to the SLCA and the measuring unit from the LCC and SLCA are also different from the LCA. Although the scope of the system in study is the same, it only needs to be broadened to encompass the social and economic dimensions.

In some of the analyzed papers it was possible to observe interesting attempts, in addition to the LCSA methodology, that combines the LCA and the LCC methodologies and even more, like combining them with Contingent Valuation (VA) or Cost Benefit Analysis (CBA). There may be some other methodologies that can complement them or even help in their integration with each other.

Table 2.3 - ISO 14040 and 14044

Focus	Reference	Title	Area of application	Type	Relevant Items
Environmental	International Organization for Standardization	ISO 14040- Environmental Management-Life cycle assessment- principles and framework	Environmental Engineering	Standards	Methodology description. Definitions
Environmental	International Organization for Standardization	ISO 14044- Environmental Management-life cycle assessment- requirements and guidelines	Environmental Engineering	Standards	Methodology description. Definitions and guidelines. Examples

As shown in Table 2.3, the ISO 14040 and the ISO 14044 are the most important documents about LCA and its implementation. According to some of the authors of the papers in Table 2, the Society for Environmental Toxicology and Chemistry (SETAC) had a significant influence in the standardization of the LCA methodology, which led to the ISO 14040 series, and also wrote guidance documents in the same subject. Currently SETAC is working in the Life Cycle Initiative in cooperation with the United Nations Environmental Programme (UNEP).

The LCSA methodology is composed of three pillars, which are the social (SLCA), economic (LCC) and environmental (LCA) pillars. Although, the social pillar is still a methodology under development, the next chapter is going to study the SLCA methodology.

3 Social Life Cycle Assessment - A Review of Literature

3.1 Social Life Cycle Assessment

In this section, the theoretical background of the Social Life Cycle Assessment (SLCA) methodology is presented, explaining what it is, its origins and its steps, in order to give an overview of this methodology.

The concept of SLCA was studied based on the “Guidelines for Social Life Cycle Assessment of Products", which is a document that was produced by the UNEP/SETAC Life Cycle Initiative project (UNEP Setac Life Cycle Initiative, 2009), and from chapter 20 of the book entitled “Life Cycle Assessment Handbook – A Guide for Environmentally Sustainable Products”, edited by Mary Ann Curran and written by Catherine Benoît Norris (Norris, 2012).

3.1.1 Social Life Cycle Assessment Origin

The interest for the SLCA concept started two decades ago with the Life Cycle Assessment research community, which proposed to study the social dimension of sustainability. A SETAC workshop in 1993 and its respective report is believed to be the beginning of the development of methodologies on this subject and what encouraged the creation of the UNEP/SETAC international working group, that later produced the Guidelines for Social Life Cycle Assessment of Products (UNEP Setac Life Cycle Initiative, 2009). The first paper published on this subject was in 1996 (O’Brien *et al.,* 1996) and with the guidelines in 2009 (UNEP Setac Life Cycle Initiative, 2009) this area has captured the interest of many businesses (Norris, 2012).

Since 1996, many papers were published about this subject in scientific journals like the International Journal of Life Cycle Assessment, the Journal of Cleaner Production and many others (Norris, 2012). These papers present the development of new frameworks and methodologies, and the discussion of case studies.

The UNEP/SETAC Life Cycle Initiative working group on Social Life Cycle Assessment (SLCA) started in 2004 and it was composed by more than 70 members, many of them were authors of SLCA papers. This project had five objectives (Norris, 2012):

- The conversion of the environmental LCA methodology into a triple bottom line sustainable development tool;
- The establishment of a framework for the inclusion of socio-economic benefits into LCA;
- The determination of the implications for life cycle inventory analysis;
- The determination of the implications for life cycle impact assessment;
- The creation of an international forum to share experiences that integrate social aspects into LCA.

The UNEP/SETAC working group met its objectives by publishing the guidelines, creating methodological sheets that provided further guidance on each of the impact subcategories and by creating a forum where it was possible to share methodologies and ideas. For this reason, the Guidelines for Social Life Cycle Assessment of Products (UNEP Setac Life Cycle Initiative, 2009) is considered a cornerstone in SLCA methodology development (Norris, 2012).

The guidelines are still being applied in many case studies and projects around the world, which allows for the improvement of the methodology.

3.1.2 What is Social Life Cycle Assessment?

The SLCA can be considered as a methodology that is within the context of sustainable development, next to the environmental LCA and the LCC methodologies.

As written in the guidelines (UNEP Setac Life Cycle Initiative, 2009), the Social Life Cycle Assessment (SLCA) “is a social impact assessment technique that aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle encompassing extraction and processing of raw materials; manufacturing; use; re-use; maintenance; recycling; and final disposal”.

The data used in this methodology can be generic or site-specific. The social aspects assessed in this methodology are those that may directly influence the stakeholders, that interact with the life cycle of a product and that can affect the stakeholders in a positive or negative way (UNEP Setac Life Cycle Initiative, 2009). These social aspects can also be associated to the behaviors of the enterprises, to socio-economic processes or to impacts on social capital.

Depending on the scope of the study, indirect impacts on stakeholders can also be assessed.

The purpose of the SLCA methodology is not to answer the question of whether a product should or should not be produced since it only provides information on the social conditions of production, use and disposal of the product, which may not be sufficient to answer that question (UNEP Setac Life Cycle Initiative, 2009). This methodology can also identify ways to improve the product, but it does not provide the solution for sustainable consumption and living.

Briefly, the SLCA methodology has the objective of identifying information on social and socio-economic aspects for decision making, inciting the development of production and consumption by analyzing these aspects, which can help in the improvement of the performance of organizations and the well-being of stakeholders (UNEP Setac Life Cycle Initiative, 2009).

The SLCA methodology has a lot of similarities with the environmental LCA and the most important one is that both have the same four phases of procedure, which are the goal and scope of the study, the inventory analysis, the impact assessment and the interpretation. Before analyzing each one of these phases, some important concepts are going to be presented (UNEP Setac Life Cycle Initiative, 2009).

Social impacts can be defined as consequences of positive or negative pressures on social endpoints, which means social impacts are consequences of social interactions that are linked to an activity (production, use or disposal) or caused by it. The causes of these social impacts are (UNEP Setac Life Cycle Initiative, 2009):

- Behaviors – Social impacts can be caused by a specific behavior or decision;
- Socio-economic processes – Social impacts are the downstream effect of socio-economic decisions;
- Capitals – Social impacts that are related to the attributes possessed by an individual, a group or a society.

The subcategories are socially significant attributes that are assessed by analyzing inventory indicators (UNEP Setac Life Cycle Initiative, 2009). These subcategories are aggregated into impact categories and then linked to stakeholder categories, this is the classification of social and socio-economic indicators.

The SLCA methodology assesses the social impacts of all the life cycle stages from cradle to grave and each stage may be associated with different geographic locations, where more than one activity can be processed. Because of this, the social impacts that are associated to each one of the stakeholder categories have to be assessed for each one of these geographic locations (UNEP Setac Life Cycle Initiative, 2009).

The stakeholder categories can be defined as a cluster of stakeholders that are expected to have shared interests due to their connection to the product's system that is being assessed. There are five main stakeholder categories (UNEP Setac Life Cycle Initiative, 2009):

- Workers/employees;
- Local communities;
- Society;
- Consumers (covering not only the end-consumers but also the consumers that are part of each section of the supply chain);
- Value chain actors.

In addition to these ones, additional stakeholder categories can be added, which implies more detailed and precise subcategories.

In the next subsections, the four phases needed for the implementation of the SLCA methodology will be analyzed.

3.1.3 Goal and Scope Definition

The goal is the first thing that needs to be addressed when applying the SLCA methodology. In this step, it is needed to clearly define the purpose, by describing the intended use and the goal that is being pursued (UNEP Setac Life Cycle Initiative, 2009). In the end, the study must meet the purpose that was defined and be within any constraints.

The information about the goal of the study should be provided to the data collectors, in order for them to select the data that is most appropriate to the study. The goal must also specify if the final results of the study are going to be used for comparative assertions or are planned to be revealed to the public (UNEP Setac Life Cycle Initiative, 2009).

The scope must present the function and the functional unit of the product, since this information can later help model the product system using process and input-output data (UNEP Setac Life Cycle Initiative, 2009). The definition of the depth of the study and which unit processes have the need for generic or site-specific data are also made in this phase. The depth of the study can be defined by using activity variables.

In the scope, the limits are defined on the product´s life cycle and on the detail of the data that is going to be collected and studied. It also identifies what is the origin of the data, how recent it is and how it will be analyzed (UNEP Setac Life Cycle Initiative, 2009).

A flow chart of the process, that shows the main sequence of production, is also in the scope phase (UNEP Setac Life Cycle Initiative, 2009). In this chart, the flow from resource to product waste and the inputs that support the production are presented, like energy and auxiliary materials.

After defining the goal and scope, the practitioner has to decide whether he wants to expand the system's scope (UNEP Setac Life Cycle Initiative, 2009). This can be done, first, by defining the ideal system, then by defining the actual system to be modeled and, lastly, by deciding which processes need specific data and which processes need generic data.

In the guidelines (UNEP Setac Life Cycle Initiative, 2009) the items that should be considered in the scope of a SLCA study are specified. The items presented below were amended from ISO 14044. As considered by the guidelines, the amended points are in italics (UNEP Setac Life Cycle Initiative, 2009):

- the product system to be studied;
- the functions of the product system or, in the case of comparative studies, the systems;
- the functional unit *(with special emphasis on product utility)*, defined in time and space;
- the system boundary *(ideal system and actual system)*;
- *the activity variable to be used (to inform on the relative importance of each unit process);*
- the data type to be collected (generic, specific);
- *the stakeholder categories to include;*
- *the subcategories to include;*
- *the types of impacts to be considered;*
- *the inventory indicator and data related to those impacts;*
- *the methods for impact assessment;*
- the allocation procedures;
- the interpretation planned;
- the assumptions;
- the value choices and optional elements;
- the limitations;
- the data quality requirements;
- the type of critical review, if any;
- the type and format of the report required for the study.

In SLCA, the function of the product is not only its technical utility to the consumer, but also its social utility (for example, convenience, prestige, etc.).

In the SLCA methodology, it may be difficult to link data to the functional unit, because sometimes this data may be qualitative. But it is still necessary to create a functional unit, because it provides the necessary basis for the product system modeling (UNEP Setac Life Cycle Initiative, 2009). In order to specify the functional unit, it is necessary to describe the properties and social utility of the product, to determine the relevant market segment and product alternatives, to quantify a functional unit according to the required product properties of the market and to determine the reference flow for each of the product systems.

As defined by ISO 14044 (The International Standards Organisation, 2006b), the reference flow is “the measure of the outputs from the processes in a given product system required to fulfill the function expressed by the functional unit”.

Briefly, in the goal and scope definition phase a practitioner must specify (UNEP Setac Life Cycle Initiative, 2009): the purpose of the study; the function of the product; the product utility; the functional unit and other characteristics; the unit processes that are to be studied and the activity variable; which data needs to be collected for each one of the impact categories and subcategories; which stakeholders are involved with each of the processes.

3.1.4 Inventory Analysis

The inventory analysis is the second phase of the SLCA methodology where the data is collected, the systems are modeled and the LCI results are obtained. The goal and scope definition gives the necessary information to conduct the inventory phase, by identifying the type of data that is required, the unit processes being studied, the functional unit, etc. The life cycle inventory has 8 steps (UNEP Setac Life Cycle Initiative, 2009):

1. Data collection (prioritization, generic data, hotspots assessment);
2. Preparation for the main data collection;
3. Main data collection;
4. Collection of data needed for the impact assessment (characterization);
5. Validation of data;
6. Relating the main data to the functional unit and unit processes;
7. Refining the system boundary;
8. Data aggregation.

The functional unit is what allows the modulation of the product system and the definition of the system boundaries (UNEP Setac Life Cycle Initiative, 2009). The most time demanding step in the inventory analysis is the collection of data, that is then used to verify how the organizations linked to the production chain perform on social and socio-economic aspects.

The application of an activity variable and social hotspots assessment will create results that can guide the decision process regarding the “if” and “where” to conduct case specific assessment (UNEP Setac Life Cycle Initiative, 2009). The activity variable provides information about the importance of the unit process, and the hotspots assessment can identify where the issues of concern may be the most significant in the product’s life cycle.

In the first step of the inventory analysis, it is needed to collect data about where are the unit processes located, which organizations are involved in them and which activities can be linked to an activity variable (UNEP Setac Life Cycle Initiative, 2009). Also, it should be identified what and where are the hotspots of the product's life cycle.

For a better understanding, the social hotspots assessment provides information about where a situation can cause a problem, be a risk or be an opportunity for improvement.

After the decision of which site-specific data needs to be collected and which unit processes the generic data is considered enough, the practitioners can start collecting the main data about the social and socio-economic inventory indicators. The subcategories that were selected in the goal and scope definition are what guides the collection of data (UNEP Setac Life Cycle Initiative, 2009).

Inventory indicators provide the most direct evidence of the condition or result of what is being measured, these indicators can be qualitative or quantitative and have a unit of measurement.

The site-specific data collection is very frequent in this methodology and can be carried out by auditing the documentation of the enterprise and other organizations, interviews, questionnaires and surveys and other methods (UNEP Setac Life Cycle Initiative, 2009).

The third step of data collection can deliver detailed information about the production chain's social impacts by doing a desktop screening, which can be done through a literature review and web search of the organization's specific information in the life cycle of the product (UNEP Setac Life Cycle Initiative, 2009). With this step, it is possible to identify some hotspots in the generic analysis that may end up not being an issue in the production chain and, the other way around, some issues may appear where the generic analysis did not find.

In addition to the previous data, some background information may also be needed to help assessing impacts at the characterization step of the impact assessment phase, like minimum wage, etc.

The data validation step serves to evaluate if the data collected fulfills the data quality requirements.

To relate data to a functional unit and unit process, an appropriate flow must be determined for each one of the unit processes, then the quantitative input and output data of each unit process can be calculated according to the determined flow (UNEP Setac Life Cycle Initiative, 2009). After relating the flows of all unit processes to a reference flow, the final calculation should present all system input and output data referenced to the functional unit.

Relating the collected data to a functional unit and unit process may be difficult, because many times the data used in the SLCA methodology is qualitative, which means that it is not expressed per unit of process output (UNEP Setac Life Cycle Initiative, 2009). Even quantitative data may be difficult to express from a social perspective.

With the application of a sensitivity analysis the system boundary can be refined, because this analysis can inform the practitioner if a change to the system can, significantly, affect the results (UNEP Setac Life Cycle Initiative, 2009).

The final step of the inventory analysis is to aggregate the collected data and this aggregation should not be done in a way that the information about the location of the unit process can no longer be observed, because this information can be important in the impact assessment phase (UNEP Setac Life Cycle Initiative, 2009).

3.1.5 Impact Assessment

The third phase of the SLCA methodology is the impact assessment, which can be called social life cycle impact assessment (SLCIA). The SLCIA phase consists of the following three steps (UNEP Setac Life Cycle Initiative, 2009):

- Selection of the impact categories, subcategories and characterization methods and models that are going to be applied;
- Classification, by linking the inventory data to SLCIA subcategories and impact categories;
- Characterization, by calculating the results for the subcategory indicators.

The purpose of this phase is to aggregate inventory data within subcategories and categories and to utilize additional information to help understand the magnitude and the significance of the data collected in the inventory phase.

The first step of the impact assessment is the selection of the impact categories, subcategories and characterization models, which depend of what was defined previously in the goal and scope of the study (UNEP Setac Life Cycle Initiative, 2009).

The impact categories are logical groups of SLCA results, which can be linked to social issues that are of importance to the stakeholders and decision makers (UNEP Setac Life Cycle Initiative, 2009). In the environmental LCA, these impact categories can be related to endpoints and midpoints, where the impacts can be evaluated by studying a cause-effect chain from the inventory flows to the midpoint indicators and, if necessary, it can continue further until the endpoint indicators.

On the contrary of environmental LCA, SLCA can present some difficulties in the evaluation of social and socio-economic impacts, because there are situations where the cause-effect relation cannot be evaluated with enough precision to allow a quantitative cause-effect modeling.

In the SLCA there are two types of social and socio-economic impact categories (Figure 3.1), which are the Type 1 and the Type 2 (UNEP Setac Life Cycle Initiative, 2009). The Type 1 impact categories result from the aggregation of the subcategories that are of concern to a stakeholder, like, for example, human rights. This Type 1 characterization model does not incorporate casual relationships and the aggregation of the indicators is done with a scoring system. The Type 2 impact categories are where the results from the subcategories are modeled into impact categories according to a casual chain model, which consists of midpoint and endpoint categories. The Type 2 is very similar with the environmental LCA, because the inventory indicators are linked with midpoint and endpoint impact categories through impact pathways, using casual relationships.

The Type 1 impact categories are governance, human rights, working conditions, socio-economic repercussions, health and safety and cultural heritage (UNEP Setac Life Cycle Initiative, 2009). The Type 2 impact categories are more generic; they correspond to a model of the social impact pathways to the endpoints human capital, cultural heritage and human well-being. The midpoints for the latter endpoint indicators are health, autonomy, safety, security and tranquility, equal opportunities, participation and influence and resource (capital) productivity.

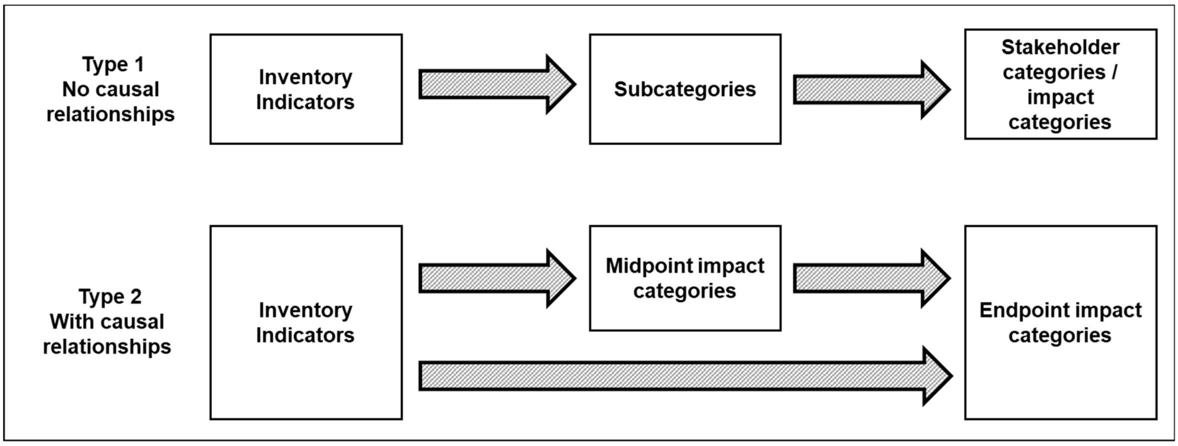


Figure 3.1 - Type 1 and 2 characterization models

(adapted from Wu, Yang and Chen, 2014)

The subcategories represent the impacts that are within an impact category, like the hours of work or fair salary of the workers (UNEP Setac Life Cycle Initiative, 2009). A subcategory can be represented by a group of inventory indicators, like, for example, the subcategory social security and benefits can be represented by the inventory indicators percentage of employees which are covered by health insurance, retirement insurance, paid maternity and paternity leaves, legal contracts and more. This subcategory is included in the impact category working conditions.

The relations between the subcategories with each stakeholder category and each impact category of Type 1 are presented in the Table 3.1. In this table are presented 5 stakeholder categories and 33 subcategories, and each are linked to a Type 1 impact category.

The indicators can be quantitative, semi-quantitative and qualitative. The quantitative indicators can be directly related to the unit process, because they already are expressed in a numeric way. The qualitative indicators try to describe issues using words. The semi-quantitative indicators are categorizations of the qualitative indicators (for example, a scale or scoring system) and cannot be expressed per unit of output process, although it is possible to assess them by taking into account the relative importance of each unit process in relation to the functional unit (UNEP Setac Life Cycle Initiative, 2009).

Life Cycle Attribute Assessment is one of the ways to assess the semi-quantitative indicators, by allowing the practitioner to calculate the percentage of an activity across a life cycle that possesses or lacks an attribute of interest.

The second step of the impact assessment is the classification, where the inventory results are assigned to a specific stakeholder category and/or impact category.

In the last step of the impact assessment phase are used characterization models, which can be a basic aggregation step, by bringing together all kinds of inventory information, or a more complex operation where additional information is used such as performance reference points. The performance reference points may be internationally set in the beginning, like goals or objectives (UNEP Setac Life Cycle Initiative, 2009).

In the SLCIA, a scoring or weighting system can be used to assess the inventory data that is based on performance reference points. This system can help to define an estimation of the impact, by providing a way to handle the distribution of positive and negative impacts in relation to the stakeholder needs (UNEP Setac Life Cycle Initiative, 2009).

Table 3.1 - Relationship between the stakeholder categories with the subcategories and Type 1 impact categories
(Norris, 2012)

Stakeholder Categories	Subcategories	Site-Specific Only	Type 1 Impact Categories					
			Governance	Human Rights	Working Conditions	Socio-Economic Repercussions	Health and Safety	Cultural Heritage
Worker	Freedom of Association and Collective Bargaining				✔			
	Child Labour				✔			
	Fair Salary				✔			
	Working Hours				✔			
	Forced Labour				✔			
	Equal Opportunities/Discrimination				✔			
	Health and Safety					✔		
	Social Benefits/Social Security				✔			
	Education and Training				✔			
	Management System	✔	✔					
Consumer	Health and Safety						✔	
	Feedback Mechanism	✔	✔					
	Consumer Privacy		✔					
	Transparency	✔	✔					
	End of Life Responsibility					✔		

Table 3.1 (continued)

Stakeholder Categories	Subcategories	Site-Specific Only	Governance	Human Rights	Working Conditions	Socio-Economic Repercussions	Health and Safety	Cultural Heritage
			Type 1 Impact Categories					
Local Community	Access to Material Resources					✔		
	Access to Immaterial Resources					✔		
	Delocalization and Migration			✔				
	Cultural Heritage							✔
	Safe and Healthy Living Conditions						✔	
	Respect of Indigenous Rights			✔				
	Community Engagement	✔	✔					
	Local Employment	✔				✔		
	Secure Living Conditions			✔				
Society	Public Commitments to Sustainability Issues	✔	✔					
	Contribution to Economic Development					✔		
	Prevention and Mitigation of Armed Conflicts			✔				
	Technology Development					✔		
	Corruption		✔					
Value Chain Actors (not including consumers)	Fair Competition	✔	✔					
	Promoting Social Responsibility		✔					
	Supplier Relationships	✔	✔					
	Respect of Intellectual Property Rights		✔					

3.1.6 Interpretation

The last step of the Social Life Cycle Assessment (SLCA) methodology is the interpretation phase, where the objective is to assess the results in order to draw conclusions, to explain the limitations of the study, to provide recommendations and to report.

This phase consists of the following steps (UNEP Setac Life Cycle Initiative, 2009):

- Identification of the significant issues, which may include key concerns, limitations and assumptions made during the study;

- Evaluation of the study, which includes considerations of completeness and consistency;

- Report on the level of engagement of stakeholders in the study;

- Conclusions, recommendations and reporting. This step can present results like the level of detail, the high-level hotspots or impacts (positive or negative), most problematic social impacts in the life cycle, the uncertainties, changes in scenarios, etc.

3.2 Literature Review

This section provides a review of 13 papers about SLCA and social impacts. Within these papers, 8 are review papers and 5 are assessments/studies. Only 2 of the papers found and reviewed mention the social/societal dimension and the impacts of additive manufacturing. However, it was not found any studies that tried to implement the SLCA methodology to assess additive manufacturing, the reason for this is because the SLCA methodology is still in development and the additive manufacturing is a new technology, that not all people have at their disposal.

The inexistence of assessments applying SLCA to AM processes constitutes a relevant “gap” in the current state-of-the-art, the reason why the review produced in this dissertation is considered not only necessary, but also very timely. This dissertation serves as base insight that can help in the development of innovating studies to apply SLCA to AM technology and, at the same time, further advancing the SLCA methodology.

Just as explained in the previous chapter (concerning LCA and LCC background), the SLCA papers selected were individually analyzed, after which the Table 3.2 was prepared to show the most relevant items.

Table 3.2 – Relevant Literature on SLCA

Reference	Life Cycle Phases	Title	Target Industries / Area of Application	Type	Relevant Items
(Arcese *et al.*, 2016)	All Phases except Design	Modeling Social Life Cycle Assessment framework for the Italian wine sector	Agri-food Industry	Assessment/Study Qualitative	The aim of this paper is to implement a basic framework for applying SLCA to the Italian wine sector. The Italian wine can be characterized by the existence of many small and medium enterprises (SMEs) and family-owned businesses. The SLCA is defined and follows the principles of the Guidelines (UNEP Setac Life Cycle Initiative, 2009). The authors of this paper start by doing a theoretical background on SLCA by researching various authors. In this paper, the authors analyzed papers by taking into account whether the socio-economic impact assessments, of the papers, followed the Guidelines specifications and whether the assessments included the entire life cycle and all the stakeholder categories. Also, in the literature review of this paper the authors indicate if the papers do a cradle to grave assessment and what are the stakeholders that were taken into consideration. The paper defines the goal and scope of the study. It also outlines the phases of the life cycle that were studied and the respective processes. After defining the goal and process, the authors identify the stakeholder categories that are affected by the socio-economic impacts. The stakeholder categories studied were the workers, local community, value chain actors, consumers and society. After determining the stakeholders the authors assess each one of them by creating impact subcategories for each one and they evaluate the impact effects on the stakeholder. The paper also presents the impact categories and inventory indicators description per stakeholder category. In this paper the authors consider that the analyzed system should include not only the material flow but also the service flow. These services can be defined as co-products. In the end of the paper the authors discussed the problems of the use of this method and how these problems could be solved.
(Benoît *et al.*, 2010)	All Phases except Design	The guidelines for social life cycle assessment of products: just in time!	Social and Environmental Engineering	Review Paper	This paper is a review about the guidelines for SLCA of products. To introduce the SLCA methodology the authors explain how SLCA appeared and described the writing process of the guidelines presented by SETAC. Then the paper describes how the methodology works by presenting the Guidelines. The Guidelines contain four main sections: historical context of the guidelines for SLCA; comparison of SLCA with LCA and LCC, showing the differences and commonalities between them; technical framework for SLCA; the possible applications, limitations of the methodology, communication of the results and the development needs. The SLCA methodology has the same four steps (goal and scope definition, inventory analysis, impact assessment and interpretation) of the LCA. SLCA is best used for increasing knowledge, informing choices and promoting improvement of social conditions in the product life cycle. The SLCA has some similarities with the environmental LCA, which are the functional unit, system boundaries, requires a huge amount of data and operates as an iterative procedure. The difference between them is that the SLCA also gathers information at management level, may require site-specific LCIA, may need information about political attributes and the data can be subjective (information given by employees). The LCIA is based on information provided by inventory indicators that define the data to be collected for LCI, which can be quantitative or qualitative, and are linked to subcategories that are grouped into impact categories and stakeholder categories. With this, the impact assessment, can identify the positive and negative impacts.

Table 3.2 (continued)

Reference	Life Cycle Phases	Title	Target Industries / Area of Application	Type	Relevant Items
(Chen *et al.*, 2015)	Design and Production	Direct digital manufacturing: definition, evolution, and sustainability implications	Additive Manufacturing	Review Paper	The aim of this paper is to clarify and analyze the main aspects of Direct Digital Manufacturing (DDM) and its sustainability with the objective to provide a basis for manufacturers in enhancing their manufacturing systems. In DDM the products are manufactured right at or close to the customer utilizing additive manufacturing (AM) and are consequent of a digital model. As an introduction, the authors of this paper present a review about AM, how it works and how it has evolved into DDM. They also show how the manufacturing process has evolved from since the craft manufacturing process to the direct digital manufacturing, addressing subjects like mass production, customization and personalization of products. The paper also refers the sustainability implications of DDM, by studying the implications in each of the three pillars of sustainability (environment, economic and social). For this subject, it assesses each one of these dimensions introducing subthemes and indicators for the manufacturing phase. In the end of the paper, the authors present a case study where they compare the energy used in mass production with the energy used in DDM, by also taking into consideration other perspectives of manufacturing, like for example materials, tools, supply chain and transportation effects.
(Huang *et al.*, 2013)	Raw Material Extraction, Design, Production and End of Life	Additive manufacturing and its societal impact: a literature review	Additive Manufacturing	Review Paper	The aim of this paper is to gather and analyze information about the societal impacts of additive manufacturing (AM). This paper is organized in six parts: a brief introduction of AM; analysis of the impacts of AM on population health and wellbeing; discussion of the environmental impacts of AM; exploration of the possibility of revolutionizing the delivery of products made with AM through supply chain reconfiguration; discussion of the potential occupational hazards of AM; and a summary. In the first part the authors present what AM is, how it works, they identify all the types of AM and the advantages and disadvantages of AM. In the second part the paper identifies the impacts of AM on population health and wellbeing. They refer that one of the societal challenges of the twenty-first century is to deliver high quality, economically efficient healthcare to improve health and wellbeing and that personalized care is the answer to this challenge, producing customized products that meet individual needs. The third part examines the energy consumption and environmental impacts of AM and conventional manufacturing, by analyzing studies that compare both. The fourth part of this paper shows how AM can influence the supply chain, by analyzing the benefits and the drawbacks of its implementation. It presents some approaches for the implementation of AM in the spare parts supply chain. In the fifth part the authors show that AM can solve some occupational hazards but it can also create others, like toxicological and environmental hazards that may occur due to handling, using, and the disposal of the materials. In the end of the paper the authors present a summary of the content where they identify the most important points and areas that need more research.

Table 3.2 (continued)

Reference	Life Cycle Phases	Title	Target Industries / Area of Application	Type	Relevant Items
(Hunkeler, 2006)	All Phases except Design	Societal LCA Methodology and Case Study	Social and Environmental Engineering	Review Paper/Case Study	This paper is a preliminary attempt on the elaboration of a methodology for midpoint based societal life cycle assessment for comparative product assertions. The goal of this paper is to render this methodology compatible with LCA and LCC, therefore, both methodologies are based on the same functional unit and system boundaries. The main difference between the societal LCA and LCA is that in the LCA impacts are geographically homogenized and in the societal LCA the impacts can depend on the region. The societal LCA proposed in this paper is comprised of five steps: a geographically specific LCI is established for each unit process; the employment hours for each unit process is calculated in each one of the regions; an overall employment table is calculated based on the LCI, employment between regions and unit processes by combining the data of the first two steps; estimation of the regional characterization factors; and the characterization result that is calculated from the geographical employment data and characterization factors. This societal LCA was presented in a mathematically way, because the LCI data from an LCA needs to be transformed into labour hours, having into account the geographical region. In the end of this paper, it presents a case study comparing two detergents using this methodology.
(Jørgensen *et al.*, 2008)	All Phases except Design	Methodologies for Social Life Cycle Assessment	Social and Environmental Engineering	Review Paper	This paper is a review that analyses the existing methodologies and approaches of SLCA. The SLCA methodology came from the idea of integrating social aspects in LCA, because of that they have a similar framework. This paper discusses the goal and scope definition, the inventory analysis and the impact assessment of the various approaches to SLCA. Unlike the LCA methodology, which is based on an aggregated inventory of input and output for processes, the SLCA has no relation with the process but rather with the companies performing the process. One of the biggest issues is how to decide which impact categories are to be included in the assessment and how it must be measured. There are two types of impact categories to choose for the assessment: midpoint indicators that are closer to the stressors and more understandable for decision making; and endpoint indicators, that can reflect the potential damage or benefit. The inventory analysis presents another issue that is how to measure the social impacts, because some approaches support a detailed and site specific investigation and others support statistical sources. The impact assessment is composed of three steps: classification; characterization; and normalization and valuation of impacts. In this section, the authors assess some of the reviewed impact assessment methodologies in each of the steps.

Table 3.2 (continued)

Reference	Life Cycle Phases	Title	Target Industries / Area of Application	Type	Relevant Items
(Jørgensen *et al.*, 2010)	All Phases except Design	Defining the baseline in social life cycle assessment	Social and Environmental Engineering	Review Paper	This paper tries to address the validity of one of the assessment procedures needed in order to assess the social consequences of a decision. The validity of the assessment means if it is possible to assess what is intended to measure, in this case what it is assessed are the social consequences of a decision. The goal of SLCA is to improve the social conditions and socio-economic performance of a product throughout its life cycle for the stakeholders on which impacts are assessed. SLCA main functionality is to provide decision support for decision makers, allowing them to choose the alternative with the most favorable social consequences. That’s why in this paper they only considered the direct effect, which means the effect created from decisions makers after the advice of the assessment. The stakeholders can be divided into three groups: the workers throughout the life cycle; the society in which the life cycle is included; and the users of the product. This classification of stakeholders can be divided even further, like for example future generations, etc... The purpose of this paper is also to investigate how the stakeholder’s life would have been if the process had not been done. This paper also addresses the impacts associated with life situations (production/non-production and use/non-use), by analyzing the consequences of these situations on the workers and users, and suggests indicators for their measurement.
(Macombe *et al.*, 2013)	Raw material extraction and Production	Social life cycle assessment of biodiesel production at three levels: a literature review and development needs	Bioenergy Industry	Review Paper and Assessment/Study Qualitative	The aim of this paper is to address the case of three different raw materials, which are palm oil, forest biomass and algae, in biodiesel production. The authors consider the comparison of the three raw materials as an opportunity for challenging SLCA methods, by doing a literature review of 50 papers and by analyzing the needs in the development of the SLCA methodology. In the comparison of the three alternatives they use the biodiesel production based on palm oil as a reference scenario and the other two as alternative scenarios. For the definition of SLCA they use the one that was defined in the Guidelines (UNEP Setac Life Cycle Initiative, 2009). As clarified in the paper, social impacts are caused by changes which involve effects and some of these effects directly cause a phenomenon that are experienced by the stakeholders, this phenomenon are social impacts. The authors describe the production system of each one of the three alternatives and specify that the functional unit is the same for all of them. Also, they do not consider the use phase because it is the same in all alternatives. The scenarios presented in this paper are based on the production of bioenergy and are addressed at the company, region and state/country levels.

Table 3.2 (continued)

Reference	Life Cycle Phases	Title	Target Industries / Area of Application	Type	Relevant Items
(Manik *et al.*, 2013)	Raw material extraction and Production	Social life cycle assessment of palm oil biodiesel: a case study in Jambi Province of Indonesia	Bioenergy Industry	Assessment/Study Qualitative	The aim of this paper is to assess the social implications of a palm oil production system. The objective of this work is to unveil the hotspots in social sustainability aspect which is useful for the design of strategies and policies to support the development of sustainable palm oil biodiesel. The study conducted by the authors took place in Jambi province in Indonesia, because of the forest conversion into numerous land-use allocations, particularly into palm oil plantations. This paper considers all stages of palm oil biodiesel supply chain. The SLCA methodology in this study consists of four steps (in the paper the authors show a diagram with the steps): definition of the goal and scope; development of a weighting criteria; assessment of the biodiesel system based on the criteria; and score the assessed system. This weighting system was adopted from the Guidelines (UNEP Setac Life Cycle Initiative, 2009) and was realized by doing a literature review and a survey. This survey allows experts to assign a direct ranking on every criteria and impact category according to their importance (the weighting of the impact categories and criteria can be seen on the paper). The stakeholders involved in this survey were the value chain actors, workers, local community and society. The authors also show the results from the survey of the stakeholders' perspective by doing a radar chart that compares the situation when the perceived condition meets the expectations and the perception of the stakeholders' during the study. After showing the results they analyze each of the impact categories to identify the problems.
(Martínez-Blanco *et al.*, 2014)	All Phases except Design	Application challenges for the social life cycle assessment of fertilizers within life cycle sustainability assessment	Agro Industry	Assessment/Study Qualitative	This paper explains and discusses the potential application of SLCA to three different types of fertilizers and proposes possible solutions. In this paper, SLCA is defined as a social impact assessment technique that aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle. The challenges in SLCA are: the selection and the analysis of social indicators; the definition of the functional unit and system boundaries; and the impact assessment. The three fertilizers that were studied were compost, nitric acid and potassium nitrate. Just like in any other LCA the authors describe the production system and define the system boundaries and functional unit. In the assessment of this system the authors describe both the foreground and background processes. The authors had already written papers regarding the environmental and economic performance of these fertilizers. The biggest problem they identified was the availability of data, because databases like those of environmental LCA are lacking in SLCA and the on-site data collection is very time demanding. The SLCA that was implemented follows the guidelines and were considered 4 out of the 5 stakeholders that are defined in the guidelines, the stakeholders that were considered were workers, local community, society and consumers, the value chain was not considered. They also specified another stakeholder group, which is "citizens collecting the organic fraction of municipal solid waste (OFMSW)" with four subcategories and their corresponding indicators. They also decided to do a data collection and assessment of subcategories of the social aspects on three different geographical scales: country, sector and company. There are two approaches for social impact assessment: the taskforce approach; and the quantitative approach. The approach that was chosen is the taskforce approach, where the indicator results are weighted by the relative importance of processes on the life cycle and then aggregated. This aggregation can be called Life Cycle Attribute Assessment and utilizes an activity variable, which can be the added value or the working time. The last variable was the chosen one. In this part, the authors present in tables all the results that were obtained. The databases that were utilized for this study were GaBi 5.0 and the Social Hotspots Database (SHDB).

Table 3.2 (continued)

Reference	Life Cycle Phases	Title	Target Industries / Area of Application	Type	Relevant Items
(Parent *et al.,* 2010)	All Phases except Design	Impact assessment in SLCA: sorting the sLCIA methods according to their outcomes	Social and Environmental Engineering	Review Paper	The aim of this paper is to clarify the different SLCIA methods covered in the Guidelines (UNEP Setac Life Cycle Initiative, 2009) and to analyze their specific outcomes. This paper analyzes three social LCIA methodologies. These methodologies were written by Hunkeler (2006), Weidema (2006), and the UNEP/SETAC Life Cycle Initiative's Taskforce. In this paper the authors say that the SLCA methodology follows the same four main steps as those used in LCA and explain the similarities and differences in all the steps. In the inventory analysis phase, the authors specify that there are three types of data that can be used in the SLCA: the activity variable; the data related to social conditions or stressors; and the performance reference points that is used in characterization models. The social LCIA methods can differ in the way that the social burdens of the product system are approached. In the Guidelines two types of impact categories are proposed. In this paper, instead, it is suggested that the fundamental difference is not in the impact categories but the SLCIA methods, by using two characterization models, which are the impact pathways and performance reference points models. In this paper, the performance reference points are considered the "Type 1" impact categories characterization model and the impact pathways is considered the "Type 2" impact categories characterization model. The "Type 1" social LCIA is the one created by the UNEP/SETAC Taskforce, where it is proposed the use of performance reference points such as internationally accepted levels of minimum performance, to help understand the magnitude and the significance of the data collected in the inventory phase. In this methodology, a weighting system for the evaluation of semi quantitative indicators that are aggregated resulting in a subcategory indicator, is used. The "Type 2" social LCIA uses characterization models that seek to represent the impact pathways, as in the environmental LCA. These models are exemplified by Hunkeler (2006) and Weidema (2006). These characterization models, based on impact pathways, imply that the inventory data are mostly quantitative and represent causal–effect chains. After defining them, the authors do a comparative analysis of both characterization models, by analyzing the indicator results, the sources of stressors and the approaches used to link the indicator results to the product system.
(Reitinger *et al.*, 2011)	All Phases except Design	A conceptual framework for impact assessment within SLCA	Social and Environmental Engineering	Review Paper	The aim of this paper is to address how the Area of Protection (AoP) and the impact categories in SLCA can be understood from an applied philosophy perspective. This paper is divided in three parts: a review on impact assessment; a framework proposal employing the capabilities approach to address questions like what is important in a human live and what information can be used for evaluating human lives; and how the AoP, in SLCA, can be divided into impact categories and subcategories regarding the intrinsic values of peoples' capabilities. The capabilities approach addresses what can be made for a valuable human life, which is realized by the existence of functionings and the corresponding freedoms. The AoP in SLCA is a normative concept that tells which intrinsic values should guide our actions. As in the other papers the inventory data can be classified into subcategories that can be aggregated into impact categories and stakeholder groups. The presented framework for SLCA was built with resort in the capabilities approach, which allows the definition of the AoP and the impact categories. By applying the explained approach, they could define that the AoP is constituted by autonomy, wellbeing/freedom and fairness and the subcategories for each of the stakeholders.

Table 3.2 (continued)

Reference	Life Cycle Phases	Title	Target Industries / Area of Application	Type	Relevant Items
(Siebert *et al.*, 2016)	All Phases except Design	Social life cycle assessment: in pursuit of a framework for assessing wood-based products from bioeconomy regions in Germany	Bioenergy Industry	Assessment/Study Qualitative	This paper aims to propose a regional context-specific SLCA framework for assessing a wood-based production system in a German bioeconomy. It also reviews and analyses existing SLCA approaches. This assessment also considers the Guidelines (UNEP Setac Life Cycle Initiative, 2009) and the ISO 14040. In the beginning of the paper the authors do a small introduction of Germany's wood-based bioeconomy and present the importance of the necessity to identify, evaluate and monitor the social sustainability of wood-based bioeconomy chains in a regional level. For this reason, the authors use SLCA, which is an approach that can assess the social effects associated with the organizations in a production system. By improving the social performance of organizations, it is also possible to positively influence the well-being of affected stakeholders. The authors present the goal and scope, the systems boundaries, which activities are included within the production system, the stakeholder categories, the activity variables, the social LCI and the characterization model at different levels. Three stakeholders are considered: the workers, local communities and national society. The authors consider that one of the challenges of SLCA is the ability to relate the social effects to a functional unit (FU). For this reason, they use an activity variable in order to generate SLCA results related to a FU, because a SLCA can deal with qualitative and quantitative data. The activity variable was defined as mass, but it can also be working hours or value added per activity. Afterwards they elaborated a Life Cycle Inventory (LCI), in order to estimate the social indicators, and try to identify the social hotspots, at a global and regional level, throughout the product's life cycle. The authors used the Performance Reference Points (PRPs) characterization model for each organization in the production system as an impact assessment tool. This characterization model can be used to calculate the level of an indicator value's social performance. This is done at an international, national and regional level. The reason why this study was done at various levels is because this SLCA framework tries to provide results for specific production chains at a regional level, so it can identify social hotspots and opportunities, while still providing an overview of potential social effects outside of the region. In the end of the paper, the authors present an overview of the SLCA framework that was utilized.

Of the 8 review papers, 6 were reviews about SLCA and 2 were about additive manufacturing. Firstly, it is presented a brief discussion on the 6 review papers, trying to understand their similarities, differences and what were the problems found in them. Then, the 2 papers on additive manufacturing are analyzed.

Most of the papers about SLCA mention that there are some similarities with the environmental LCA, like the existence of the four steps, the functional unit, the system boundaries and the need for a large amount of data for the inventory analysis. Despite the similarities, there are some differences in the application of some of the steps. The SLCA is not only a process oriented methodology, because it gathers information at the management level and information external to the company (for example, political attributes, etc.). The LCI data can be subjective, like, for example, the information given by employees and more.

The biggest issues of the SLCA methodology that are mentioned in these review papers are:

- How to decide which categories are to be included in the assessment;
- How these categories must be measured;
- What should be within the systems boundaries;
- The almost nonexistent databases, that are needed to gather data about social impacts;
- On-site data collection is very time demanding;
- There is no impact assessment methodology recognized by experts.

With the review of these papers it is possible to perceive that the SLCA methodology is still in development, because of its gaps in the goal and scope definition, inventory and impact assessment phases. There are not many applications of this methodology to real life situations, which does not help in its development.

Because these papers are from different years, it is possible to see that there was an evolution in the development of the SLCA methodology and this evolution started more or less in the year 2009 with the publication of the document called Guidelines for Social Life Cycle Assessment of Products, which was produced by the UNEP/SETAC Life Cycle Initiative. This document serves as a guide, by describing the key concepts and tools. Many researchers and organizations use this document as a guide to assess real life situations.

The 2 papers that talk about additive manufacturing make a literature review about the subject and present the types of existing additive manufacturing. One of these two papers talks about the sustainability implications, where the social dimension is mentioned, and the other talks about the societal impacts of AM. The difference between these two terms, social and societal, is that social is related to a part or a group of society while societal considers society as a whole.

The paper written by Chen *et al.* (Chen *et al.*, 2015) considers the sustainability implications where there are three dimensions: the environmental, economic and social. This paper also shows the evolution of the manufacturing process, from craft manufacturing to additive manufacturing, and how the additive manufacturing is integrated in the modern-day industry.

The paper written by Huang *et al.* (Huang *et al.*, 2013) tries to identify the impacts of additive manufacturing on the population health and wellbeing. As the term societal infers, this paper talks about the impacts to society as a whole.

The two papers agree that additive manufacturing is a game changing technology, because of its ability to produce personalized products that meet individual needs and to produce more complex individual parts with high quality.

Next, the other 5 papers about the SLCA methodology, applying it in real life situations, are going to be analyzed.

These studies were made on industries like: the agro-industry, the agri-food industry and the bioenergy industry. In this case, 3 of the papers are applications in the bioenergy industry.

All these papers used the guidelines produced by UNEP/SETAC as a guidance document in the implementation. With this it is possible to realize that this document is of great importance and that it is a starting point for the standardization of this methodology.

The SLCA methodology is used frequently with the purpose of making a comparison with other products or raw materials, in order to identify the impacts that these may have on the stakeholders, detect opportunities for improvement and select the one with the most benefits.

The main difference between these works is that some use a comparison system to choose products or raw materials and others just want to assess the social impacts of their production system, in order to improve it.

As expected, the researcher selects the impact assessment methodology that is most suitable to the situation, taking into account the system that is being studied, the data that is available and the stakeholders that are influenced by the system.

The main problem found in these 5 papers is the data availability. The reason behind this problem is the lack of social databases and because the on-site data collection is very time consuming. According to the authors, the existing social databases are lacking in the information of some processes and are still in development. The only paper that gives the name of the used database was the paper written by Martínez-Blanco *et al.* (2014), and still the authors thought that the information that it contained was not enough. The databases that were used are the Social Hotspots Database (SHDB) and the GaBi 5.0.

The review papers also identified the same issues that were presented in the papers about assessments/studies. Some tried to solve these issues by taking into account the situation that is being studied and applying the most compatible method to it.

In Table 3.3, the same 13 papers were identified by the phases of the life cycle and by characterizing the type of industry or area in which they were included.

In the next chapter, some conclusions are drawn on all the life cycle methodologies that were studied in this work and some comments will be made.

Table 3.3 - Characterization of the reviewed papers according to the life cycle phases and the target industry/area of application

	Variables	References
Life Cycle Phases	**Raw Material Extraction**	(Hunkeler, 2006; Jørgensen *et al.*, 2008, 2010; Benoît *et al.*, 2010; Parent *et al.,* 2010; Reitinger *et al.*, 2011; Huang *et al.*, 2013; Macombe *et al.*, 2013; Manik *et al.,* 2013; Martínez-Blanco *et al.*, 2014; Arcese *et al.,* 2016; Siebert *et al.*, 2016)
	Design	(Huang *et al.*, 2013; Chen *et al.*, 2015)
	Production	(Hunkeler, 2006; Jørgensen *et al.*, 2008, 2010; Benoît *et al.*, 2010; Parent *et al.,* 2010; Reitinger *et al.*, 2011; Huang *et al.*, 2013; Macombe *et al.*, 2013; Manik *et al.,* 2013; Martínez-Blanco *et al.*, 2014; Chen *et al.*, 2015; Arcese *et al.,* 2016; Siebert *et al.*, 2016)
	Use	(Hunkeler, 2006; Jørgensen *et al.*, 2008, 2010; Benoît *et al.*, 2010; Parent *et al.,* 2010; Reitinger *et al.*, 2011; Macombe *et al.*, 2013; Martínez-Blanco *et al.*, 2014; Arcese *et al.,* 2016; Siebert *et al.*, 2016)
	End of life (disposal, recycling)	(Hunkeler, 2006; Jørgensen *et al.*, 2008, 2010; Benoît *et al.*, 2010; Parent *et al.,* 2010; Reitinger *et al.*, 2011; Huang *et al.*, 2013; Macombe *et al.*, 2013; Martínez-Blanco *et al.*, 2014; Arcese *et al.,* 2016; Siebert *et al.*, 2016)
Target Industries / Area of Application	**Social and Environmental Engineering**	(Hunkeler, 2006; Jørgensen *et al.*, 2008, 2010; Benoît *et al.*, 2010; Parent *et al.,* 2010; Reitinger *et al.*, 2011; Macombe *et al.*, 2013; Martínez-Blanco *et al.*, 2014)
	Agro-Industry	(Martínez-Blanco *et al.*, 2014)
	Agri-food Industry	(Arcese *et al.,* 2016)
	Bioenergy Industry	(Macombe *et al.*, 2013; Manik *et al.,* 2013; Siebert *et al.*, 2016)
	Additive Manufacturing	(Huang *et al.*, 2013; Chen *et al.*, 2015)

4 Conclusions and Final Comments

This final chapter briefly presents the main conclusions derived from the review work that was made within this dissertation covering Life Cycle Assessment Methodologies. In particular, it draws conclusions on the case of SLCA, identifying what as well can be the limitations of the implementation of the SLCA methodology in the study of additive manufacturing. It also presents which phases in these methodologies need to be developed, in order to give more accurate results.

4.1 Conclusions

This dissertation tried to answer the questions that were proposed in Chapter 1, which are presented again below:

- What is a Social Life Cycle Assessment methodology and how does it work?
- Which scientific areas use it?
- If it has already been applied to a product in development phase, especially in the field of additive manufacturing (AM)?
- Which of the studies reviewed can help the most in the construction of a procedure to implement in the project FIBR3D?

This concluding section will follow the reasoning and the order of the above-mentioned research questions, as an attempt to give their respective answers and provide new directions for future work.

Three different Life Cycle Assessment methodologies, which are the LCA, the LCC and the SLCA, were analyzed in this study. This study will allow other researchers to acquire a deeper knowledge on how these methodologies can be applied in the context of the project FIBR3D and understand how they work.

In the first part of this dissertation the LCA and LCC methodologies were studied by analyzing their frameworks and by making a literature review. With this literature review it was possible to understand how these methodologies work, the different ways they can be applied with the analysis of case studies, and how they evolved with time.

Although this phase of the project intends only to implement the SLCA methodology to the industrial tool that is still in development, it was considered that before studying the SLCA methodology it is necessary to understand how the other two methodologies work, because of their similarities and all three of them can be connected to create the Life Cycle Sustainability Assessment Methodology (LCSA).

After the LCA and LCC methodologies chapter, the SLCA methodology was analyzed by studying its framework with the help of the guidelines written by the UNEP/SETAC taskforce, which can be considered an essential document in this area, and by doing another literature review dedicated to SLCA. In this literature review, it was possible to understand its analytical procedure and how it was applied in various case studies.

Because this dissertation aims to assist in the application of the SLCA methodology to the new additive manufacturing tool, the social implications of this technology were also studied. Since both the SLCA methodology and additive manufacturing technology are recent, it was not possible to analyze papers that covered them together.

In this work 17 papers about LCA and LCC, combined, and 13 papers about SLCA were analyzed. In addition to the papers, some standardized documents were analyzed which were considered essential for the study of the methodologies and very helpful to be used in future studies.

Some of the 17 papers about LCA and LCC were reviews and others were case studies where the authors tried to apply them, in their respective areas, and sometimes they tried to create a procedure where both could be combined.

Surprisingly, it was not possible to find any papers showing an application of the LCA and LCC or even both methodologies together to the additive manufacturing technology (AM). This case could have served as a guiding document when applying SLCA to the AM technology that is going to be studied in the project FIBR3D. However, the case studies, which utilized these methodologies in other areas, can also serve as examples of how they can be applied and how they work.

The same happened with the papers that studied SLCA, because there were not many papers which applied this methodology to the AM technology. The reason for the lack of studies like these is because the AM technology is still an emerging process that is in the development phase. As in the LCA and LCC papers, the case studies, which utilized the SLCA methodology to analyze products or processes in other technological areas, can serve as reference to later apply in the AM industry. These studies identify social issues in their respective areas which might also be valid in the case of the AM technology. To date, as far as the author of this dissertation is aware, there are no publications describing the practical use of SLCA to assess social impacts of AM technology. Apparently, this is a domain still waiting for exploration.

More recent papers talked about Life Cycle Sustainability Assessment (LCSA) which is the methodology that analyzes the environmental, economic and social dimensions of a product or process, combining each of the three life cycle methodologies that were mentioned previously. Also, some papers try to fix some of the problems that these methodologies have by combining them with other methodologies.

From the 13 papers about the SLCA methodology, only 2 papers addressed SLCA and social impacts when applied to the AM technology. Even so, they are rather superficial and theoretical by nature. Both of them agree that the AM technology is going to revolutionize industries by introducing the personalized production and the manufacture of more complex parts, which leads the way to products that need less assemblage time. However, the authors of both papers agree that this technology is not yet capable of replacing the conventional manufacturing processes, because it is not able to mass producing.

The biggest problems that were found in the application of the life cycle methodologies, mainly with the SLCA methodology, is the lack of previous data to later perform the impact assessment, and there is not a fully recognized impact assessment method.

AM is an emerging technology that is still in development with little data available about its inputs and outputs, which may prove to be a drawback in the application of the SLCA methodology. Especially the project FIBR3D where the technology is still undeveloped, this means that almost all the inventory data needed for the assessment would be hypothetical or subjective.

The almost nonexistent databases of social impacts data difficult the consideration of this methodology and even the existing ones have little information to help assess the social impacts of the AM technology.

According to the presented SLCA review, the areas in which the SLCA methodology is more frequently used are the bioenergy industry, the agro-industry and the agri-food industry. Although these industries have nothing to do with the AM technology, their assessments can serve as an example of how SLCA can be applied and some of these methods may be useful to evaluate inventory data and impacts.

Through what has been studied, it is possible to determine that there is a great need of developing studies that apply these life cycle methodologies to assess the AM technology. Even the existence of more studies that apply the SLCA methodology to assess other areas, can help in the further assessments of the AM technology.

As far as the state of the art discloses, there is not yet enough information on how the SLCA methodology can be used to assess a product in development. The SLCA methodology itself needs to be more developed in order to help assess situations where the user needs to study a product or process in the phase of development, where the data available is scarce.

4.2 Limitations and Contributions

This section presents the limitations that were found in the realization of this study and it also identifies how this work can contribute for the project FIBR3D.

4.2.1 Limitations

The limitations that were found during the realization of this study are:

- Time constraints – This type of work needs a great amount of time to allow collecting and analyzing a large quantity of information;
- Limited access to documents and databases;
- There is a relatively low number of studies that apply the LCC and LCA methodologies to AM technology, which makes it more difficult to understand how to assess its impacts;
- There is a very limited amount of publications which link SLCA methodology with AM technology, especially practical applications;
- There is only a small number of case studies that apply the SLCA methodology;
- The SLCA methodology and AM technology are still in development. It is difficult to apply the SLCA methodology to a product in the phase of development, because there is not previous data.

4.2.2 Contributions

This work was elaborated with the objective of giving a base insight of the life cycle methodologies, especially the SLCA methodology, for application in the project FIBR3D. Also, this study can provide a base knowledge that will help in the development of new models to improve the assessment of products and processes.

This work also presents the flaws of each the methodologies, in order to identify the places where they can be improved. The improvement of these flaws can make these methodologies more reliable and usable.

4.3 Future Work

With this dissertation, it was possible to observe that there is a need to make studies that later can positively influence the development of the project, the SLCA methodology and of the AM technology.

As referred previously, the possibility of assessing a product or process in the phase of development with the SLCA methodology must investigated, because it can help researchers to analyze their products at early stages and to improve the SLCA framework.

Another study that can be developed in the AM area is the assessment of the social impacts of each of the different raw materials that the AM technologies can use. The different materials used may create different impacts to society and the environment.

A study that uses the SLCA methodology to compare the AM technology of the project FIBR3D with the conventional manufacturing process may be developed, to see how the AM technology can lessen the impacts to society and/or change current societal patterns.

The creation of a database which contains data about social implications on various technologies, even the AM technology, could be a great step that help in future studies and assessments.

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