TECHNICAL BULLETIN: ISO 14044, CALCULATION OF ENVIRONMENTAL IMPACT USING LIFE CYCLE ANALYSIS (LCA)

POLINTER

1. Introduction

Life Cycle Analysis (LCA) is a method for evaluating the environmental impacts of products and technologies with a perspective that considers the effects on the environment from "cradle to grave". ", that is, from obtaining the raw material necessary for the manufacture of the product to its final disposal and that takes into account all the impacts that said production generates on the environment directly or indirectly. It is an essential tool for anyone that performs environmental analyzes or that uses the results of said analyzes for decision making.

The ISO 14040:20061 and 14044:20062 standards present the guidelines for performing a product life cycle analysis. This bulletin summarizes this procedure and presents an example calculation using a plastic bag.

2. Life Cycle Assessment (Lca).

LCA is based on evaluating the environmental loads associated with a product or process by identifying and quantifying the masses and energies used as well as the waste released into the environment, taking into account all the transformation processes that take place, including the extraction of raw material, processing, transportation, consumption, waste, among others3. A scheme of said concept, applied to the production of plastic bags is shown in Figure 1.

The analysis of the life cycle of a package allows determining which stages of its production, distribution and use have the greatest impact on the environment, both positively and negatively. In the case of plastic bags, the highest energy consumption (per kg of product) occurs in their synthesis, in comparison, the transformation of polyethylene into packaging consumes much less energy. This method makes it possible to include reductions in environmental impact when, for example, a product is recycled, by "saving" the impact of disposing of the product on the environment.

Additionally, an LCA measures the impact of the contaminants that are generated in the process and that end up in the environment. For example, among the gases that cause the greenhouse effect are carbon dioxide (CO2) and methane (CH4). La generation of greenhouse effect than the first.

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[1] ISO 14040:2006. Environmental management – Life cycle assessment – Principles and framework.

[2] ISO 14044:2006. Environmental management -- Life cycle assessment -- Requirements and guidelines.

[3] Gómez, Patricia y otros. Impacto Ambiental de Empaques Plásticos Flexibles. Jornadas Tecnológicas 2012. Junio 2012, Maracaibo, Edo. Zulia, Venezuela.

That is, if there is no other alternative, the use of processes that generate carbon dioxide should be chosen over those that generate methane.

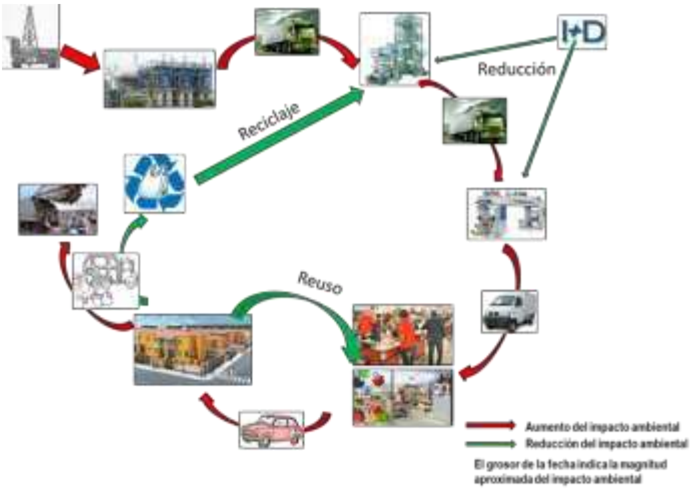

Figure 1. Diagram of the life cycle analysis of a package.

3. Steps To Make An Lca

To assess the environmental impacts of a product, process or service using the LCA methodology, four main steps must be followed (Figure 2), which are interrelated with each other:

1. Determine the objectives and scope of the ACL;
2. Compile an inventory of inputs and outputs of energy, materials and environmental outputs through all relevant life cycle stages;
3. Assess relevant environmental impacts associated with life cycle inputs and emissions; and
4. Interpret the results to lead to a more informed decision.

A proper life cycle analysis first defines an analysis system, that is, which process or sequence of processes is to be analyzed. This involves setting system limits; For example, it is not the same to evaluate the environmental impact of the transformation of plastic in a plastic bottle than to evaluate the environmental impact of the production of the polymer and its transformation in the same bottle.

Figure 2. Life Cycle Assessment Framework.

On the other hand, the analysis must refer to a standard amount of product that allows an adequate comparison. For example, a life cycle study that analyzes the environmental impact of a 15-micron plastic bag is not as useful as one that studies the environmental impact of transporting 4 kg of goods in a plastic bag. The latter makes it possible to compare the environmental impacts of said bag with a alternative that also allows loading 4 Kg of goods.

3.1. Life cycle stages

To define the "stages of the life cycle", a plastic bag will be used as an example in this bulletin, describing below the different stages present in this product:

1. **Procurement of raw materials,** which includes the processes related to the extraction of raw materials and refining. For the plastic bag, made of high-density polyethylene (HDPE), the acquisition of raw materials would include the extraction of natural gas, its conversion into ethylene and its transport to a plant, such as Polinter, that produces HDPE.

2. **Manufacturing,** which includes the processes that convert raw materials into finished products. In this case, the plastic bags are manufactured by transforming plastic pellets, turning them into a film for the formation of the bags. Note that there are two manufacturing processes: obtaining the pellets and their conversion into film form.

3. **Distribution,** which includes the transportation and storage of products for consumption. For example, the plastic bag will be shipped from the manufacturer to a grocery store. It must also include the transport of the pellets and the transport of other supplies for the manufacture of the bag (ink, boxes, bags, consumables for transformation equipment).

4. **Use / reuse,** which is the stage where the products perform a useful service for the consumer. In this case, the plastic bag will be taken from the grocery store to the house. Some consumers might also reuse the bag for extra shopping or as a garbage bag.

5. **Disposal,** is the end of the life cycle, in which the products enter the waste management system. Depending on local waste management practices, the plastic bag can be recycled, placed in landfills, or incinerated to generate energy.

For each of these stages, the impacts (positive and negative) on the environment of the activities carried out on the product must be quantified. To keep the analysis within achievable limits, only those impacts that are relevant or significant should be considered. In this example, a relevant impact could be the combustion of diesel fuel in the transport trucks that transport the plastic bags, which releases carbon dioxide into the environment. On the other hand, the impact that the contamination generated by the transport of the inks from the bags would have could be so low compared to the previous one that it is not worth the effort of calculation. These assumptions must be explicitly declared in the study, so that analyzes carried out by different authors on the same basis can be compared.

3.2. Unit processes

The ISO 14040 standard for LCA defines a unit process as the "smallest portion of a product system for which data was collected when performing a life cycle assessment".

In Figure 3, a generic unitary process is observed. On the left are material and energy inputs needed to generate a useful product output. On the right are the outputs of the environmental emissions and by-products that are associated with the process, along with the product output itself. These inputs and outputs associated with a unit process are known as the "unit process inventory".

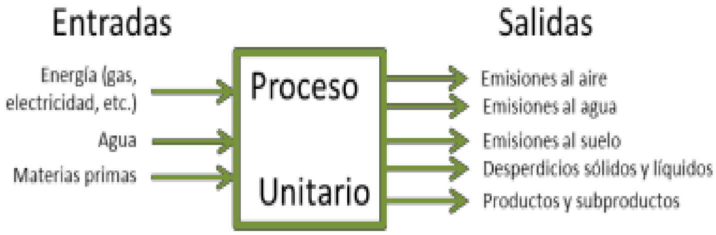

Figure 3. Generic unitary process.

For example, in the case of a plastic bag, the first process is to generate ethylene from gas, the second is to convert said ethylene into HDPE granules, and the third process is to melt the high-density polyethylene granules , the extrusion of a film, and forming the bags in the bag production process; each step is represented by a unit process in Fig. 4. Additional steps can be added to this, such as transporting the bag from the transformer and then from the distributor.

Figure 4. Manufacture of a HDPE bag.

Nature's inputs refer to flows, such as crude oil extracted from the ground or corn harvested from a field. Outputs to nature refer to the pollutants and residues that are released into the environment. Flows to the technosphere refer to any flow of energy or mass that originates from of a process carried out by the human being (example: the entry of pellets to the bag factory and their exit to the customer).

Under this convention, extensive databases have been designed that are ordered based on these four types of inputs and outputs, broken down by specific components. This makes the energy and mass flow analysis of a polyethylene production plant, which can seem very complex, easy to understand and use.

Unit process inventories refer to inputs and outputs as "flows" or "exchanges". Also, these

Flows are measured to or from nature and to or from the technosphere (see Table 1). For a plastic bag, natural gas extraction is described as a flow from nature. In the next unit process, where natural gas is converted to ethylene, because the gas has already had a previous human process, it is considered as input from the technosphere. Since ethylene is an intermediate product that is used by other unit processes, it is considered an outlet for the technosphere and so on.

Why is it necessary to distinguish between flows to and from nature and flows to and from the technosphere? In addition to better visualizing the origins and destinations of the flows in the inventory, it allows quantifying the environmental impacts generated by the processes specific.

Table 1. Inventory of unit processes: From Ethylene to HDPE *

Tickets of the nature	**Flow name**	**Category**	**Subcategory**	**Value**	**Unit**	**Notes**
	Natural gas	resource/elemental	Groun			
	Bituminous coal	resource/elemental	Suelo			
	Hydroelectric power	resource/elemental	Water			
	Nuclear	resource/elemental	Groun			
	Oil	resource/elemental	Suelo			
	Wood	resource/elemental	Biosphere			
	Water	resource/elemental	Water	1.5	litros	
Tickets of the technosphere	**Flow name**	**Category**	**Subcategory**	**Value**	**Unit**	**Notes**
	Olefins (ethylene)	Product		1.02	kg	
	Water	Product				
	Electricity	Product		0.178	kWh	
	Natural gas	Product		0.035	m^3	
	LPG	Product		0.000038	litros	
	Waste oil	Product		0.006	litros	
	Gasoline	Product				
	Diesel	Product				
Outings to the nature	**Flow name**	**Category**	**Subcategory**	**Value**	**Unit**	**Notes**
	Carbon dioxide - fossil	resource/elemental		0.1	kg	
	Methane	resource/elemental		0.000014	kg	
	Nitrous oxide	resource/elemental				
	Carbon Dioxide - non-fossil	resource/elemental				
	Particles (unspecified)	resource/elemental		0.000018	kg	
	Nitrogen oxides			0.000029	kg	
	Sulfur Dioxide					
	Others			0.000000048	kg	
Outings to the technosphere	**Flow name**	**Category**	**Subcategory**	**Value**	**Unit**	**Notes**
	High density polyethylene	Product		1	kg	

* Note: The flows and values indicated here are referential for educational purposes and do not represent actual measurements in Polinter or any other polyethylene plant.

Once the flows have been identified and classified, they are arranged in a spreadsheet, where the flow data must appear in the rows of the inventory table. Table 1 shows a didactic and simplified example of an inventory for a HDPE production plant. It should be noted that this table is presented for the purposes of this bulletin and includes only a fraction of the flows that occur in a plant of this type. Note that for ease of calculation, the flows are estimated based on 1 kg of PEAD.

Depending on the depth of the analysis, additional information may be included. In this case, the second column allows substances and energies to be grouped into pre-established categories in order to measure the environmental impact for said items; the third column contains additional information on the origins and destinations of the flows to and from nature; and the fourth column is reserved for subcategories of the third column, also pre-established.

The fifth column in the inventory table must contain the value of the flow and the sixth column the unit in which that value is expressed, per unit of product. Based on the example in Table 1, 0.178 kWh is required to produce 1 kg of HDPE. This electricity is what is consumed by the entire plant (reactors, pumps, warehouses, offices, etc.), which facilitates the analysis. In the notes part, information about the origin of the data is usually added. The quality of the data used is crucial to obtain a reliable analysis. There are numerous databases compiled by specialized institutes, and they are available free and paid. One of the most recognized and used is the one provided free of charge by the National Renewable Energy Laboratory4. In the area of plastics, a free consultation source is that of the Association of Plastic Producers of Europe5. The database that best represents the process under study should be selected, from the point of view of the process itself, as well as its inputs and outputs, its geographical location and even cultural aspects (in the case of the plastic bag, which takes taking into account the consumption patterns of people in the region under study).

Note finally that this inventory aggregates all the components of PE production, from when the ethylene enters until the granules are packaged. For those interested, this process can be segmented, separating it into more specific phases, such as, for example, polymerization, drying, granulating and packaging. The more it is segregated, the more difficult it will be to obtain the information, but the greater detail of the specific processes that have the greatest impact on the environment will be available.

3.3. Conventions for energy flows

Energy flows are common to almost all types of unit processes, and for many products energy related emissions with energy represent

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[4] Ver http://www.nrel.gov/lci/ (consulted in October 2015).

[5] Ver http://www.plasticseurope.org/plastics-sustainability-14017/eco-profiles/browse-by-list.aspx (consulted in October 2015)

a significant fraction of the total life cycle impacts. There are two different types of energy flows: energy as fuel and energy in materials. Fuel energy refers to energy that performs useful work in a process, such as diesel, gasoline, electricity, and natural gas. Energy in materials refers to the inherent energy value of the materials used to create products. In this example, the bag itself could be used as a fuel after it is thrown away, and it is often found in waste to power incinerators. This is denoted as "feedstock energy."

Life cycle analyzes must take into account all the energy losses that occur when converting primary energy sources into energy carriers, bearing in mind that a significant fraction of the thermal energy in the input fuel is lost as waste heat to the fuel. environment by being converted into electricity. Likewise, part of the generated electricity is used in the power plant itself, resulting in additional energy losses. Lastly, there are also energy losses in the systems that transmit and distribute electricity from the power plant to the consumer. As a result of all these losses, only a fraction of the thermal energy (usually about a third of it) that was contained in the input fuel remains in the electricity used in the product.

Why is it important to consider these types of conversion losses? The environmental impact of the final product must take into account all these losses because they are generated to convert a raw material into a finished product. The lower these losses (for example, by using a more efficient electrical transmission system), the lower the environmental impact of the product. This also shows that it is important to know the origin of the material and energy flow data: the percentage of losses will be different from country to country, for example. Another aspect that should not be neglected is the technology used. A modern and efficient one, which has been designed with environmental criteria, is preferable to an outdated and inefficient technology. This applies not only to energy conversion, but to all unit processes under consideration.

4. Assessment Of Environmental Impacts: Mass Balances

Once all the sources of mass and energy flow and their impact on the environment have been identified, a balance must be made of the masses that enter and leave the system to be analyzed.

Mass balance is the last of the structural foundations of an LCA. The principle of the law of conservation of mass must be applied in the LCA; that is, all the mass that enters, leaves or accumulates in a life cycle system must be accounted for either as a product flow within the system or as an elemental flow of the system. Each flow or process has a certain environmental impact. Usually this is measured as kg CO_2 Greenhouse effect equivalent to environmental impact under study. This makes it possible to "add up" all the environmental impacts (to the soil, air, water, humans, etc.) and have a global measurement of the environmental cost of the production, use and disposal of the product.

This concept will be illustrated with a very simplified example. The analysis of the life cycle of a plastic bag will be considered again, specifically in the stage of the end of its useful life (Figure 5). This analysis will be done by quantifying the greenhouse gas emissions resulting from the waste of the bag, measured in Kg of CO2 equivalent of the disposal of the bag in two scenarios: a) that all the bags end up in a landfill and b) that a fraction of them is recycled. In the second case, the environmental impact is reduced, since by recycling the bag, it is not necessary to use energy and raw material to extract natural gas from the subsoil, convert it into ethylene and then into polyethylene; nor should this polyethylene be transferred to the plants. Although there is an additional process (recycling), the environmental impact of this process is much less than that of obtaining a bag with virgin material.

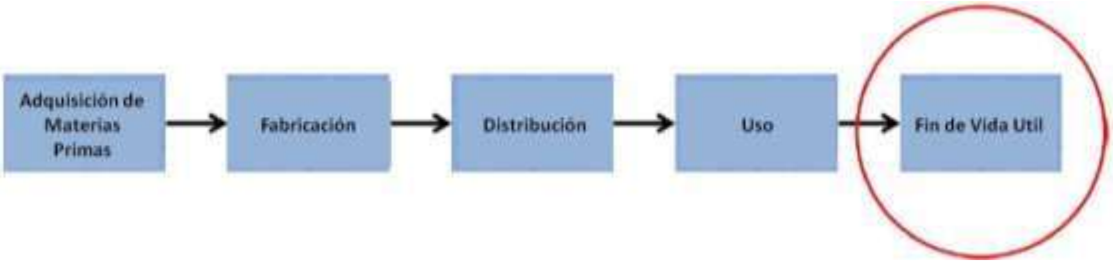


Figure 5. Life cycle of a plastic bag.

In a case where there is no recycling, the simplest flow model is the one shown in Figure 6. In this figure, m represents the quantity (in Kg) of discarded bags and av represents the environmental cost (measured in Kg CO2 equivalent per Kg of bags). Thus, the total environmental impact is

$$\mathbf{CA = m \bullet av}$$

For example, if 100 Kg of bags are discarded and the environmental impact is 0.0005 Kg CO2 / Kg bag, the environmental cost of those 100 Kg of bags will be 0.05 Kg CO2 total.

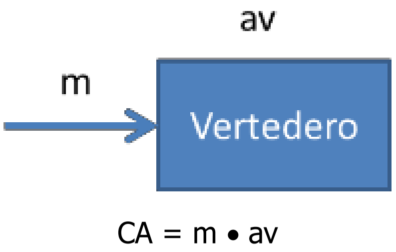
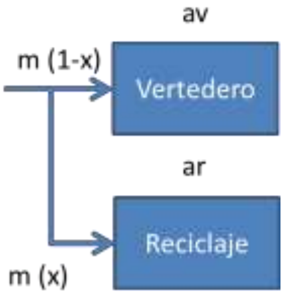


Figure 6. Variables that define the environmental impact of plastic bag disposal in landfills.
CA means total environmental cost (in Kg CO$_2$); m Kg of bags discarded and av the environmental impact of said waste (in Kg CO$_2$ / Kg of bags)

Suppose now that a fraction x of those 100 Kg of bags that are discarded can be recycled. The new mass flow is depicted in Figure 7. In this case, **ar** represents the environmental impact of the recycling process, which must be less than the environmental impact of the landfill for recycling to be justified from an environmental point of view. Suppose, for the purposes of this example, that **ar** is 0.0002 Kg CO2 / Kg bag.



CAv = m • (1-x) • av
CAr = m • x • av CA
= CAv + CAr

Figure 7. Mass balance of waste with recycling.

CAv means landfill environmental cost; CAr means environmental cost of recycling; x represents the fraction (between 0 and 1) of the product that is destined for recycling

Depending on the value of the fraction **x**, a greater or lesser amount of mass will go to landfills. Using the same 100 kg of bags as a reference, if **x** is 0.1 (10%), **m • x** will be 10 kg (100 x 0.1) of bags that are recycled; the difference (90 kg) continues to be disposed of in landfills.

To calculate the environmental cost of this new recycling scheme, it is necessary to add the two costs: the cost of 90 kg of bags sent to waste **(CAv)** and the cost of 10 kg sent to recycling **(CAr).** Both are calculated in the same way: by multiplying the mass of bags going to each destination by their impact. In the case of bags going to landfills, the cost is calculated as the product:

CAv = m • (1-x) • av

That is, 100 Kg of bags x 90% that goes to landfills x 0.0005 Kg CO_2 / Kg bag. This gives a value of 0.045 Kg CO_2. In the case of bags that are recycled, the environmental cost would be measured as:

CAr = m•x•ar

Using the values of the example, the environmental cost of recycling 10% of the bags would be 100 Kg x 10% x 0.0002 Kg CO2 / Kg bag = 0.002 Kg CO2. The total environmental cost of using 100 Kg of bags would be given by the sum of what is generated by sending to landfills **(CAv)** plus what is generated by recycling **(CAr)**, that is,:

CA = CAv + CAr

Which in the case of this example would be 0.047 Kg CO_2 (0.045+0.002), which is less than the option of disposing of all the bags in a landfill. Using the same reasoning, the reader can verify that if the recycling rate increases from 10% to 35%, the environmental cost is reduced from 0.047 to 0.039 Kg CO_2.

The environmental impact of recycling is lower than that of disposal because, although energy is consumed in the process of recycling and transporting the recycled product, there was no need to carry out the polymerization process again. In a mannersimplified, the environmental impact of recycling is given by the impact of recycling the packaging **less** the impact of the processes that are not necessary to carry out (polymerization, transport of pellets, etc.).

In the case of reuse, a similar reasoning is used, but in this case the savings are much higher, since the reprocessing of the material is not incurred and the savings now include the transformation of the raw material and its transportation.

It is important to note that this is a very simple example presented to illustrate how a life cycle analysis works. If all unit flows and processes are included, the calculation can be so complex that the use of specialized software will be required.

5. Interpretation.

The last step in a life cycle analysis is the interpretation of the data. These have had to be generated with the most reliable information possible. Care must also be taken with the extrapolation of data to conditions other than those used in that database. If, for example, the database was built using the distance between Guarenas and Caracas as the transport criterion, this should be used with some caveat if the analysis is based on the transport of products from Cumaná to Barquisimeto.

Once the previous point has been verified, the LCA study can serve to inform the public about the environmental costs of producing, using and disposing of a certain article for a specific function (in this case, a bag plastic to transport 4 Kg of goods); It can also be used to evaluate the benefits of environmental impact reduction strategies: for example, comparing whether it is more environmentally friendly to reduce the thickness of the bag or increase the recycling rate by 15%.

The best known use is to compare similar products: for example, which product is more environmentally friendly to transport 4 kg of goods between the options of a plastic bag, a cloth bag, or a cardboard box? Regarding this last point, the analysis should be based on comparing the same function and not the same product. In this case, note that the transport action of a specific mass of goods is being compared, not the packaging used. Likewise, it should be compared under the same assumptions. Thus, a study that limits the system to the manufacture of the cloth bag once the thread is available (which is a human product) and is compared against a plastic bag since the natural gas is extracted, lacks validity. All LCA studies must clearly indicate these premises, as well as the source of the data used, in order to make this type of comparison.

LCA studies are not linear; At any stage the researcher may realize that more data are needed, or that the boundaries of the system to be studied must be redefined to include unit processes or flows not previously considered. Similarly, at the time of interpretation, new considerations may arise that force a recalculation of the analysis under new premises.

6. Utility.

Life cycle studies have made it possible to measure, on a fair and objective basis, how a product manufactured by human beings impacts the environment. There are three great benefits that justify its use:

1. It provides a uniform basis of comparison for analyzing products made from various materials and conversion processes. The analysis is done based on the function of the product and not based on the product.
2. Done correctly, it includes **all** the sources of environmental impact generated by the production and use of a given article. Consumers tend to focus on the impact generated by disposing of the product, but they rarely analyze that to produce it, it was necessary to extract raw material, process it, transport it, handle by-products, consume energy, etc.

   A life cycle analysis weighs all these impacts globally and under the same unit of measurement.
3. An LCA makes it possible to identify the so-called "hot spots", that is, those processes or flows that are the main responsible for the global environmental impact of a product. In the case of plastic packaging, it is known that the process of converting gas into polymers is the one with the highest energy consumption compared to the rest of the unit processes that define the use of the product. That is why all the environmental impact analyzes of plastic bags conclude that the most effective strategy to reduce their environmental impact is by promoting their reuse and recycling, to take advantage of the already manufactured polymer and save raw materials.

7. To Expand Knowledge.

There is so much information freely available on the Internet on the subject of LCA that it would be impossible to summarize it in this article. There is a free course on the subject on the Coursera[6] portal that includes the development of the LCA calculation tool in Microsoft Excel®, which is taught by specialists from NorthWestern University in the United States. A good starting point to start an analysis are the ISO 14040 and ISO 14044 standards. These two standards are complemented by the ISO/TR 14047:2012[7] and 14049:2012[8] technical reports that show examples of the application of life cycle studies. The Carnegie MellonMellon University

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[6] Masanet, E., Chang Y. How Green is That Product? An Introduction to Life Cycle Environmental Assessment (¿Cuán verde es ese producto? Una introducción al Impacto Ambiental del Ciclo de Vida). https://www.coursera.org/course/introtolca.

[7] ISO/TR 14047:2012. Environmental management -- Life cycle assessment -- Illustrative examples on how to apply ISO 14044 to impact assessment situations.

[8] ISO/TR 14049:2012. Environmental management -- Life cycle assessment -- Illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis.

has made available to the general public an LCA textbook and additional resources associated with that text; this material is used in the courses on the subject of said university9. Some web pages with technical information for the interested reader are:

- Coalition for Sustainable Packaging: (http://www.sustainablepackaging.org/)
- National Energy Laboratory renewable (http://www.nrel.gov/).

There is also a lot of software available in the market. The most recognized are: SimaPro10 and Ga-Bi[11]. For packaging design, COMPASS[12] and PackageSmart[13] are specialized programs for comparing the environmental and human impacts of packaging. OpenLCA[14] is a free version for environmental impact analysis.

[9] See https://cmu.app.box.com/s/5mnzyq1y3gcyjrveubf4 (accessed October 2015).

[10] See http://www.simapro.es/ (accessed October 2015).

[11] See https://www.thinkstep.com/software/gabi-lca (accessed October 2015).

[12] See https://www.design-compass.org/ (accessed October 2015).

[13] See http://www.earthshift.com/software/packagesmart (accessed October 2015).

[14] See http://www.openlca.org/ (accessed October 2015)

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