Chapter 7

Lifecycle Analysis and Eco-Design: Innovation Tools for Sustainable Industrial Chemistry

7.1. Contextual elements

7.1.1. *The lessons of Easter Island*

The dramatic story of the Easter Islanders is, now more topical than ever and a lesson to remember for the sustainable development of our civilization. On Easter Sunday in 1722, the fleet of the Dutch admiral Jacob Roggeveen reaches the coast of the island Rapa Nui, "the great distant" in Maori language. Roggeveen was therefore the first European to set foot on this island, one of the most desolate and most uninhabited places on Earth. One hundred and sixty square kilometers that stretch in the Pacific Ocean, at 3,700 km from the Chilean coast and at 2,300 km from the nearest inhabited land, Pitcairn Island. The colonization of Easter Island belongs to the last phase of the long expansion movement of men across the globe during the 5th Century AD. Initially, the first Polynesians came from Southeast Asia, reached the Tonga and Samoa islands around 1,000 BC. From there, they moved to the east of the Marquesas Islands about 300 AD then, from the 5th to 9th Century, to Easter Island in the south east, Hawaii in the north, the Society Islands and then finally New Zealand. Once this colonization was carried out, Polynesians were the people most widely spread on Earth, occupying a huge triangle from Hawaii in the north to New Zealand in the south west and the Easter Island in the south: which is twice the area nowadays of the current United States.

Chapter written by Sylvain CAILLOL.

And when Roggeveen arrived on this island, he discovered a primitive society of some 3,000 people living in miserable reed huts or caves, in almost permanent state of war and forced to cannibalism to improve the meager available food resources. Yet, amid this misery and barbarism, the early European explorers discovered on this land the evidence of an ancient society. Indeed throughout the island lay more than 600 stone statues of at least 6 m in height. 20th Century anthropologists who have studied the history and culture of Easter islanders have established that these statues could never be the work of the destitute and primitive population discovered by the 18th Century colonists, but had been made by a once thriving and developed society.

Resulting from the about 30 Polynesians who originally colonized the island Rapa Nui in the 5th Century, the Easter Island society flourished and reached a population of over 7,000 inhabitants at the height of its civilization, in the 1500s. The Easter Islanders took most of their resources from the trees of the forests: energy for heating and cooking food, wood for building their houses, and fishing boats, for making weapons and nets for hunting and fishing, and organic enrichment of soil for agriculture. The villages were then spread all over the island in small groups of huts surrounded by cultivated fields. Social activities took place in ceremonial centers around the monuments of “ahu”, vast stone platforms similar to those found in other parts of Polynesia. They were used for burials, ancestor worship, and celebrations in the honor of the missing leaders. The Easter Island society was the most advanced Polynesian society of all and one of the most complex in the world considering the limited resources available. Islanders shared most of their time between elaborate rituals and the construction of religious monuments. Over 300 platforms were built on the island. Most of them were built according to sophisticated astronomical alignments, directed toward one of the solstices or the equinox. This is evidence of a high level of intellectual achievement. At each site there rose between 1 and 15 of the monumental stone statues that have survived today, the only vestige of the disappeared Easter Island society. They represented a male torso and a head crowned with a “bun” of red stone carved in stone quarries, weighing about 10 tons. The shape of the stones was made in various quarries on the island. The main difficulty was in transporting these monumental works across the island, and then erecting them at the top of the “ahu” (see Figure 7.1). The solution to this problem found by the islanders was also an element of ruin ... because of the absence of beasts of burden, they had to use a very large human labor to haul the statues by using tree trunks as rollers.

The rise in population led them to reduce forest areas to convert them into settlements and cultivable lands. And trees that are certainly a renewable resource, were consumed at a rate greater than their ability to renew themselves ... In a few decades, population growth was the cause of increased crop production, which led to land impoverishment and the reduction of forest area, thereby leading to soil erosion. Forest resources became scarce. As the population increased, they had to cut down more trees to provide land for agriculture, fuel for heating and cooking, construction material for houses, canoes for fishing, and trucks to transport the statues. Very large amounts of wood were consumed, and one day, there was not enough wood anymore ... and 600 stone giants, which had required so much wood for their erection, became witnesses to the extinction of this civilization.

Figure 7.1. *Photo: Yann Payoux, 2009*

In fact, the lack of trees continued until the complete disappearance of this resource. The social and cultural impacts of deforestation were very important. The inability to erect new statues must have had a devastating effect on belief systems and social organization and challenged the many foundations on which this complex society was built. But the deforestation of the island did not only just mark the end of a sophisticated social or religious life: it also had dramatic effects on the people's daily life. Thus, the tree shortage forced many people not to build any more wooden houses, but to live in caves. When about a century later wood completely disappeared, everyone had to make do with the troglodyte caves dug into the hillsides or flimsy huts of reeds cut from the vegetation that grew along crater lakes. It was no longer possible anymore to build canoes: reed boats did not allow them to undertake long journeys. Fishing also became more difficult because the mulberry wood with which they made nets was not available any more. The loss of forest cover further impoverished the soil of the island, which was already suffering from a lack of suitable animal manure to replace the nutrients absorbed by crops. Increased exposure to bad weather worsened erosion and made crop yields fall rapidly. Poultry became the main source of food. As their numbers increased, they had to prevent theft. But there were not enough to keep 7,000 inhabitants alive, and therefore the population declined rapidly. From 1600, the society in decline, Easter Island regressed to an even more primitive level of life. Deprived of trees and canoes, the islanders found themselves as prisoners thousands of kilometers from their native land, unable to escape from the consequences of the collapse of their environment for which they were responsible themselves: a massive degradation of the environment caused by the island deforestation.

Thus, if the first discoverers of the island in the 18th Century found it completely cleared with the exception of a few isolated trees at the bottom of the deepest crater of the island, contemporary scientific studies have proven that Rapa Nui had a thick vegetal cover in the 5th Century.

7.1.2. *On the carrying capacity*

This instructive historical example enables us to put the emphasis on the importance of a wise usage of our resources, whatever they are insofar as the concept of renewal capacity of any resource is intimately subjected to the rate of its consumption. This concept is developed in the concept of *carrying capacity*.

Carrying capacity, in agronomy, is defined as the number of animals (maximum or optimum) that a territory can tolerate without causing any damage to plant and soil resources. And we define overshoot, as the growth of a population beyond the carrying capacity of its region. These concepts are widely used in natural resource management. These fundamental concepts thus partly determine the bases for sustainable development:

– a rate of consumption of renewable resources that does not exceed their regeneration capacity;

– a rate of consumption of non-renewable resources not exceeding the development of alternative resources;

– a quantity of waste and pollution that does not exceed what can be absorbed by the environment.

Thus, life and Earth sciences and social sciences have offered various models for the study of the relationships between the population and environment, especially decomposition models (or multiplicative models). In these models, the total impacts on the environment are considered to be the product of population size, level of wealth or of consumption/production per inhabitant, and the level of environmentally harmful technologies. The empirical applications of this type of model were used to examine the increased use of specific resources, or discharge of specific pollutants associated with the increased supply of various goods or services. The results are more heterogeneous with respect to the role of demographic factors. But these models are still well summarized by the IPAT equation [7.1] of Ehrlich and Holdren. This equation is defined as:

$$I = P \times A \times T \qquad [7.1]$$

with:

– I = impacts: resource use, emissions of pollutants;

– P = population;

– A = abundance, wealth determined by GDP/person that defines the level of consumption;

– T = technology that quantifies the impacts/GDP;

– GDP: gross domestic product. It is an economic indicator that measures the production level of a country. It is defined as the total value of domestic production of goods and services in a given country during a given year by the actors residing within the country.

Population and abundance are the quantities defined, subjected, insofar as we do not seek to reduce them in our civilization. Therefore, the only factor that can allow us to reduce the *impacts I*, is the factor *T* of *technology*.

If we now introduce the concept of eco-design, it should lead us to seek the means to reduce the factor T of impacts/GDP.

7.2. The chemical industry mobilized against upheavals

7.2.1. *Global turmoils*

Our company has recently become aware – on the human scale– that it was mortgaging its collective future to meet its need for individual wealth. As long as there were only a few hundred million people on Earth to share most of the wealth and generate, consequently, most of the anthropogenic pollution, the balance – questionable, certainly – was maintained – Vilfredo Pareto's laws are thus made. But with the arrival in the last decades of nearly 3 billion people, Indians, Chinese, and so on, that claim – rightfully so – a high level of consumption, and with the prospect of an increasing world population in the forthcoming years, the international community calls for sustainable development: to establish a new truly sustainable balance.

The 20th Century has thus been marked by unprecedented population growth, economic development, and environmental changes. From 1900 to 2000, the world population grew from 1.6 billion to 6.1 billion people. However, as the world's population quadrupled, the global real GDP increased 20 to 40 times, thereby allowing the world not only to support a quadrupling of the population, but also to do so with much higher living conditions. However, this population increase and rapid economic growth has been uneven across the all countries, and all regions also have not equally benefited from the economic growth. In addition, the population growth and economic development, which occurred simultaneously, led to the increasingly unsustainable use of the physical environment of the Earth.

The analysis of the interrelationships among the population, environment, and economic development is much older than Thomas Malthus (late 18th Century). Since ancient times, statesmen and philosophers gave their views on issues such as the optimum number of people and disadvantages of excessive population growth. One of the recurrent topics was the balance between population and natural resources, which are defined as livelihoods, such as food and water. The reflections and activities of the United Nations devoted to the population, environment, and development are as old as the organization itself. In the 1960s, we became more and more aware that the world population growth had reached unprecedented levels, a situation considered seriously worrying in many studies and debates. A report of the Secretary-General entitled "Problems of the human environment" mentions the "explosive growth of human populations" as one of the signs of a global crisis concerning the relationship between humans and their environment. This report was an essential milestone of the process that led the United Nations to convene the United Nations Conference on Environment held in Stockholm in June 1972. This was the first global intergovernmental conference devoted to environmental protection. The 20th Century has been marked by an extraordinary increase in the world population from 1.6 billion to 6.1 billion, an increase that occurred at a rate of 80% since 1950. And the world's population should keep on growing. On the basis of the varying fertility average, the UN expects the global population to reach 9 billion by 2043 and 9.3 billion by 2050. However, small but steady deviations of fertility rates can influence the size of the population over time. Thus, a scenario of high fertility in which the fertility rate is higher than half a child to an average fertility scenario, provides a size of 10.9 billion individuals by 2050 (see Figure 7.2).

Urbanization is also another important trend. In fact, although the world population may double in the next 40 years, the urban population, now of 3 billion people, is expected to reach 6 billion, resulting in a doubling of the urban population, with energy requirements that will also increase considerably. By 2050, among these "neo-urbans", there will be around 1 billion climate refugees, driven away by large mining and dams projects and by the effects of global warming and conflict, inherent in the generated changes.

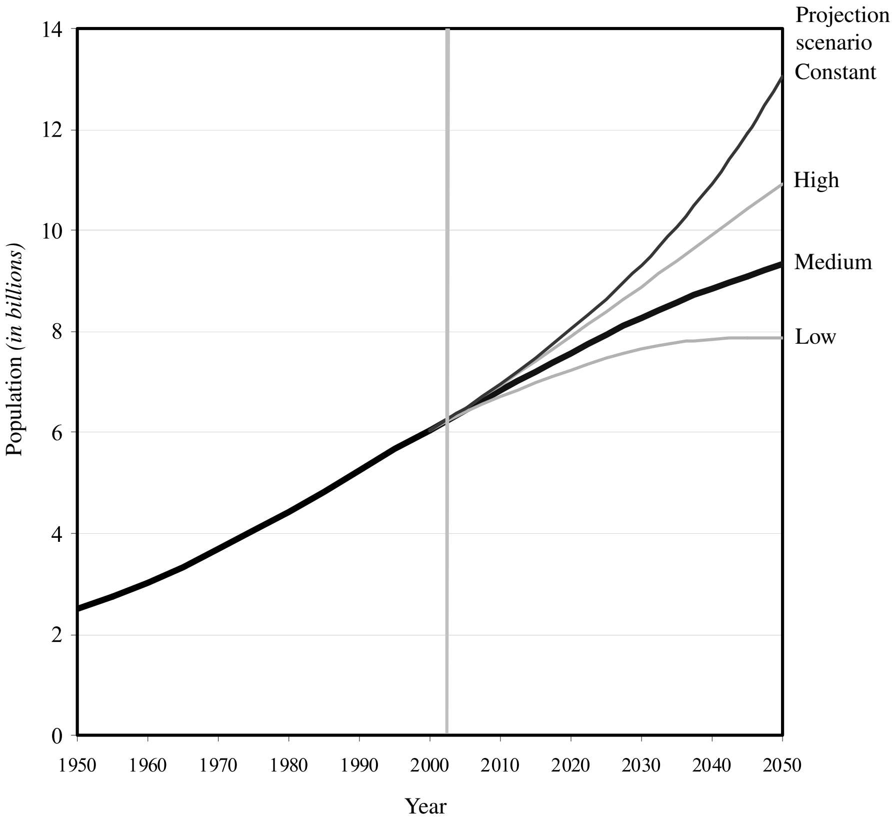

Figure 7.2. *World population projections under different scenarios of projection, 1950–2050 (Source: UN)*

In the forthcoming years, the expected population growth will also be accompanied by an increase in consumption per person. The first item of consumption will be energy consumption. Thus, IEA estimates lead us to imagine several worrying scenarios that might arise by 2050: a doubling to tripling of energy consumption compared to 11 Gtoe consumed in 2007!

Similarly, the *Global Footprint Network* has identified the global overshoot day the 23 September 2008. This means that between January 1 and September 23, 2008, people have consumed the resources that nature can theoretically produce in a year.

Thus, from September 24, 2008, and until the end of the year, people have lived beyond their means, overexploiting the environment and undermining its capacity to regenerate. According to the calculations of the *Global Footprint Network*, humanity's needs began to exceed the productive capacity of the Earth in 1986. Since then, as a result of the world population growth, the date when mankind has exhausted the resources theoretically produced in a year has been reached earlier and earlier. In 1996, our consumption exceeded 15% of the production capacity of the natural environment, and the "global overshoot day" fell in November. In 2007, it was October 6. In 2008, we have exploited the planet to 140%. Certainly, the accuracy of the calculations to arrive at this result can be challenged, but one thing is certain: we are in a bubble, and humanity is now living on credit.

7.2.2. *New constraints of industrial chemistry*

In addition, our society is currently based on the almost exclusive use of fossil fuels, especially for energy supply and consumer goods. The question is not to know whether there will be a peak production but rather *when* it will occur. In deed, almost all experts agree on the amount and duration of our global reserves of oil, coal, gas, nuclear fuel, and so on, based on our current consumption rate. Thus, at the end of this century, we will have exhausted all the land reserves that nature has taken millions of years to form. And yet this exploitation of fossil fuel resources – fossil carbon – is accompanied by a transfer of material, the transfer of carbon, which by oxidation (and *a fortiori* by combustion) will take the form of CO_2 in our atmosphere; accumulating and contributing to the increase in the concentration of the famous greenhouse gas emissions, which are responsible for the rise in average global temperatures.

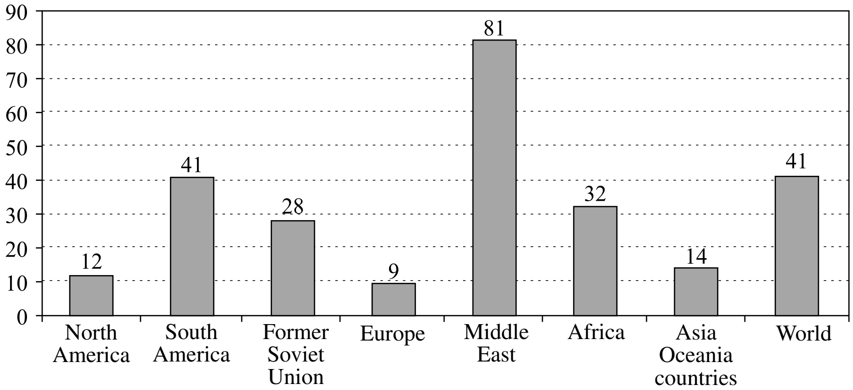

Figure 7.3. *Oil stocks in the world (in years of production in 2005) (Source: BP statistical review, 2007)*

These matters are all constraints on industry and, in particular, the chemical industry – the industry of industries, since over two-thirds of its products are intended for downstream industries. And because of these constraints, the chemical industry will undergo a revolution that is based on:

– anticipating the exhaustion of raw materials resulting from the fossil fuels with a higher price volatility. Thus, over the period of 2002–2007, the price of butadiene, a compound obtained directly by steam cracking of naphtha, has increased almost by a factor of 4. And the unequal distribution of fossil fuels, particularly oil, gives rise to significant speculations that jeopardize a stable supply (see Figure 7.3);

– an obligation to drastically reduce the polluting emissions of chemical processes and in particular the release of greenhouse gases (CO_2, NOx, etc.).

The evolution and procurement level of fossil fuels have increased significantly the amounts of fossil CO_2 emitted into the atmosphere each year (see Figure 7.4).

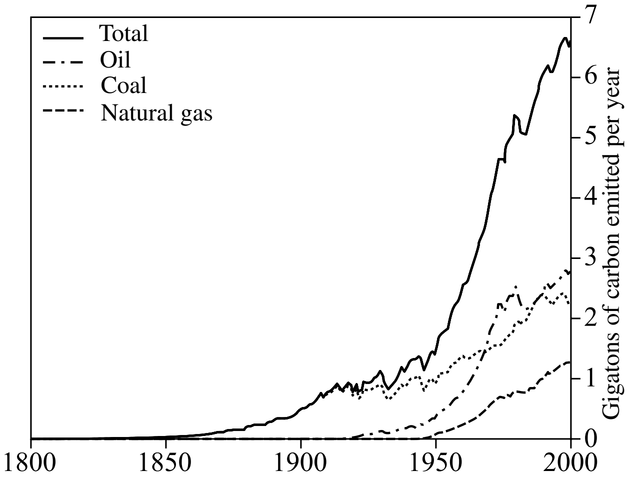

Figure 7.4. *Emissions of fossil carbon since 1800 (Sources: G. Marland, T.A. Boden, and R.J. Andres, 2003)*

The CO_2 cycle is in equilibrium on a global scale, with solubilization and vaporization balances at sea levels, and storage and release balances in the biomass. But this balance is challenged by anthropic activity that emits significant amounts of fossil CO_2 by oxidation (chemical process) and combustion (energy process) of the fossil fuels. The International Energy Agency forecasts an increase of 65% in greenhouse gas emissions by 2030, if no action is taken to reduce them. If the evolution of greenhouse gas emissions and their consequences have long been a subject of controversy, the IPCC has managed to develop a factual statement. The rise in atmospheric CO_2 concentration is of anthropogenic origin, and directly results in the rise of the average temperatures on Earth. Thus, the IPCC showed that an increase in CO_2 emissions in the 20th Century is responsible for an average rise of temperature of 0.3°C. The current concentration of CO_2 in the atmosphere is 385 ppm. Several *scenarios* are imagined for the 21st Century, depending on the stabilization level of CO_2 concentration. In the "medium" *scenario*, the concentration would reach 700 ppm, which would cause an increase in temperature of 3°C by the end of this century, accompanied with a rise in sea levels from 25 cm to 50 cm. In addition, Nicholas Stern has tried to estimate the cost of climate change and estimated in 2006 to about 5,500 billion of dollars, the optimistic *scenario* corresponding to the consequences of a rise to 550 ppm of CO_2;

– a strong regulatory pressure on toxicology and environmental toxicology related to the use of raw materials, synthetic intermediates, and products from chemical industry, with especially the REACH regulation, the Water Framework Directive WFD, but also many European directives regarding the end of life of materials (ELV directives, waste electrical and electronic equipment WEEE, directive on volatile organic compounds VOC emitted by paints, varnishes and vehicle refinishing products, etc.).

If the early regulations on industrial activities dating back to 1810 with a Napoleonic decree requiring compliance with a distance around production sites, the first European directive controlling the toxicity of chemical production was established in 1967 with the Directive 67/548/EC on the "classification, packaging, and labeling of dangerous substances". Since then, the number of EU directives related to the environment has increased dramatically, particularly since the late 1990s with a sharp increase (see Figure 7.5). All these regulations are severe constraints for the chemical industry, but may turn out to be stepping stones for innovation.

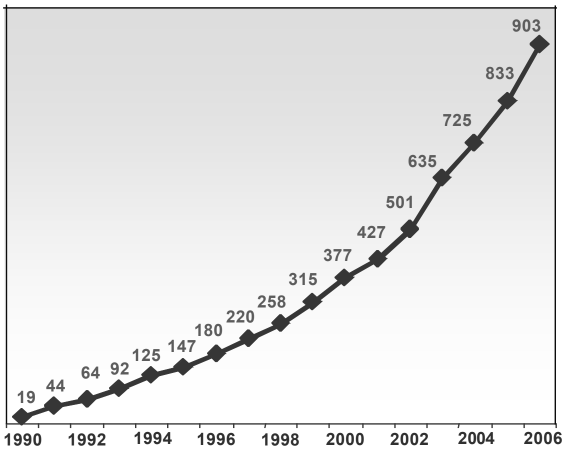

Figure 7.5. *Accumulation of European regulations on the environment (Source: Federchimica)*

Therefore, covering the needs of humanity (food, energy, health care, etc.) while respecting our environment is the challenge that lies ahead and that chemistry will have to face in the forthcoming years. Chemistry has already managed to win battles in the last century – fight against epidemics, increase in agriculture, food, and industrial productivity to meet the growing demands for food and consumer goods, and so on. Currently the demand is different, but *it is chemistry that has the keys to sustainable development*.

7.3. The lifecycle analysis, an eco-design tool – definitions and concepts

7.3.1. *Eco-design: a few definitions*

The production of goods and services is from now on under stress. It will no longer be sufficient to meet the specifications by technical means in accordance with the cost limit. Henceforth, we will have to integrate the respect for mankind and the environment, which means reducing the consumption of fossil fuels, limiting greenhouse gas emissions, comply with environmental constraints – this amounts to *limit environmental impacts*. However, taking into consideration all environmental impacts during the manufacturing process, and not only the measurement of the carbon footprint and CO_2 emissions amounts to integrate *eco-design* to the traditional design processes, but also consequently to the innovation process. This innovation process undergoes significant changes. We are not only waiting for a quick response, some time is taken, but to provide a comprehensive response on the environment, an eco-designed response.

In addition, eco-design is an integral part of the recommendations of the Grenelle Environment Forum held in 2007. Indeed, the Commitment no. 217 encourages analysis approaches of environmental products and eco-design "*Commitment no. 217: generalize the present environmental information about products and services: energy brand applied to all major energy consumer products, with a single reference point, development of eco-brands accompaniment of voluntary approaches to support the development of information on ecological impacts, with progressive obligation to provide these information; study of the development of the ecological price (double price to inform consumers about the environmental footprint of the goods they are buying) eventually going towards a collaborative eco-contribution*".

Finally, eco-design is from now on a regulatory requirement with the framework directive for Ecodesign which states, for energy consuming products, that: "*The eco-design of products is an essential axis of the community strategy on the Integrated Product Policy. As a preventive approach, aimed at optimizing the environmental performance of products while maintaining their quality, it provides new and real opportunities to the manufacturer, consumer, and society as a whole*". This directive was reinforced by a directive laying down eco-design requirements for the following products: hot-water boilers fed with liquid or gas fuel, refrigerators, freezers and household electrical appliances, and ballasts for fluorescent lamps. Eco-design is therefore starting to become an obligation. It is also a response to consumers' expectations. In fact, the end users are now awaiting for eco-friendly products. According to the IRSN barometer, since 2006, the environmental degradation is in the top three concerns of the French. Eco-design is thus a comprehensive approach, which is focused on the product. It mainly takes into account the environmental and human criteria from the design phase of a product. These criteria generally relate to the set of phases followed by a product: production, distribution, use and end of life, namely *the lifecycle* of a product (see Figure 7.6). Eco-design is a multicriteria preventive process, which seeks to identify and reduce at the source all impacts on the environment.

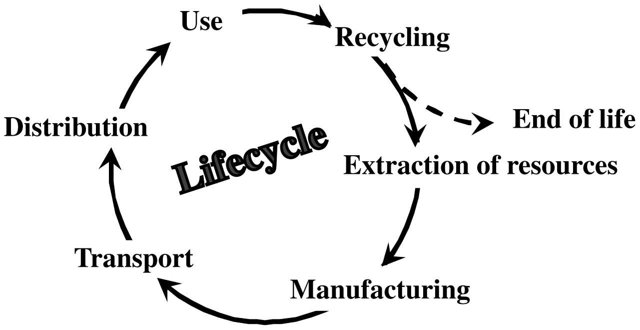

Figure 7.6. *The lifecycle*

The concept of eco-design is based on a powerful tool to identify the environmental impacts: the lifecycle assessment – LCA.

7.3.2. *The lifecycle assessment: history*

The lifecycle assessment, as practiced, is actually an environmental lifecycle assessment as the evaluated impacts are mainly environmental impacts (see Figure 7.7).

The "lifecycle assessment" thinking is a holistic way of thinking, which takes into account all impacts, environmental, social, and economic on the whole lifecycle of the product or service. This way of thinking should help to prevent local improvements from resulting in a transfer of problems (pollution, social conditions, etc.).

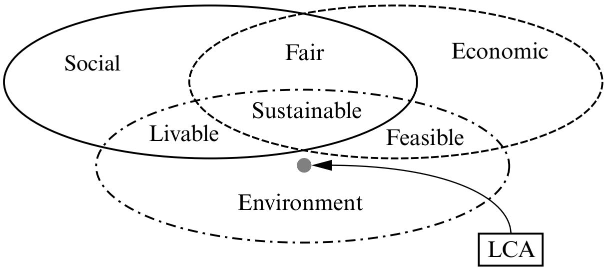

Figure 7.7. *LCA lay out*

LCA dates back to the late 1960s and to the early environmental assessments conducted in the United States on the REPA – Resource and Environment Profile Analysis model. These assessments intended to compare materials for packaging applications and focused on energy consumption, consumption of raw materials, natural resources, and waste production, in relation to the discussions of the moment on growth and environment (especially by the Club of Rome). In the early 1970s, following the first oil shock, industrial companies were essentially making the inventory of the energy flows consumed by their activities, under the form of analyses of environmental profiles and of use of resources, at the expense of real environmental analyses. In the late 1980s, a renewed interest emerged for environmental analyses, in relation to the issues of solid waste. Matter and energy inventories are also used for marketing purposes. The initial methods led to results that were difficult to use from one country to another, from one product to another, due to the heterogeneity of the data used and the various approaches. Industrialists and government had called for the development of a systematic, repeatable, and comparable methodology at least on regional scales. The SETAC (Society of Environmental Toxicology and Chemistry) and BUWAL (Swiss Ministry of Environment) had then responded to this call and the first Swiss method of environmental balance of BUWAL appeared in 1984.

The concept of *lifecycle assessment* appeared in reality for the first time during a seminar in Vermont (USA) of SETAC in 1990, which had put the emphasis on the need to extend the eco-balance based on material/energy balances to a real lifecycle assessment – the concept of impact assessment was established. The first lifecycle assessment was therefore performed in France on the steel packaging products of the SOLLAC company. In 1993, SETAC proposed a code of conduct that then constituted the reference frame for future developments. In 1997, the ISO – International Organization for Standardization – published the first International standard on the lifecycle assessment – ISO 14040: Environmental Management – Lifecycle assessment – Principles and framework. In 1998, the ISO published the international standard ISO 14041: Environmental management – Lifecycle assessment – Definition of the purpose and scope of study and analysis of the inventory. In 2000, the ISO published the international standard ISO 14042: Environmental management – life cycle assessment – evaluation of impact on the lifecycle and the international standard ISO 14043: environmental management – lifecycle assessment – lifecycle interpretation. LCAs were developed in France in the 2000s with the carrying out of LCA by specialized firms and the organization in 2005 of the first symposium on eco-design and chemistry in France by the French Federation of Science for chemistry FFC and ChemSuD chair. In 2006, ISO published the standard 14044: environmental management – lifecycle assessment – requirements and guidelines and established a new version of the standard 14040. These two new standards cancelled and superseded the previous ISO standards 14040, 14041, 14042, and 14043.

7.3.3. *Lifecycle assessment: concept and definitions*

The lifecycle assessment is an analytical method, which consists of quantitatively assessing all potential environmental impacts of a product or service by considering the entire Lifecycle.

This analysis can be applied to the entire Lifecycle, in a “from cradle to grave” approach, to the extent that at each stage of the Lifecycle there is energy and resource consumption, and generation of environmental, social, and economical impacts.

The lifecycle assessment therefore consists of assessing, within a system defined by some *limits,* the impacts due to *inputs* (consumption of natural resources) and *outputs* (emissions into air, water, soil, and other pollutions (see Figure 7.8)).

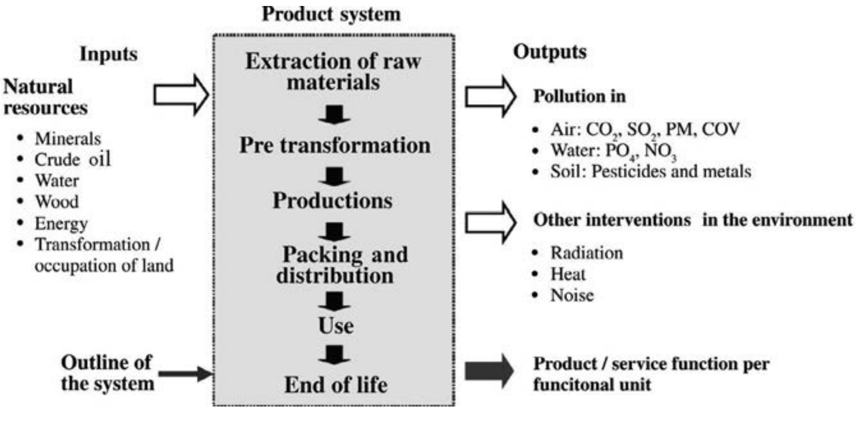

Figure 7.8. *Principle of the LCA*

This analysis is actually based on four really well-defined phases: *defining the objectives and framework* for the lifecycle assessment, lifecycle *inventory*, *evaluation* of the impact of the lifecycle, and finally, *interpretation* of the lifecycle. The analysis is based on a scientific methodology, which relies on computer software, supervised by the ISO standards 14040 and 14044 (see Figure 7.9).

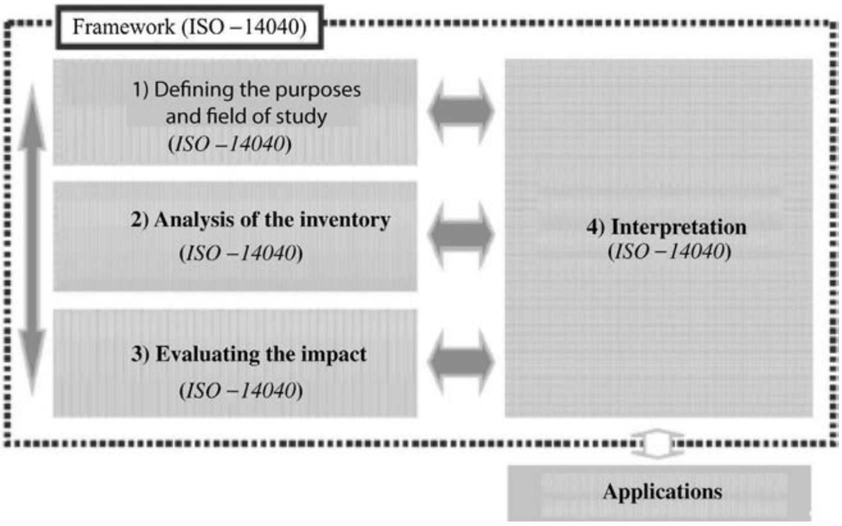

Figure 7.9. *Framework of the LCA (Source: CIRAIG)*

7.3.4. *Defining the objectives and scope of the lifecycle assessment*

Defining the objectives and scope of the lifecycle assessment is the subject of a reference document that is updated at each stage of the assessment. In general, lifecycle assessment studies are carried out in order to answer specific questions about the environmental impact by comparing different products or services. In all cases, these are comparative analyses that are *attributional*. They can be made to answer the questions related to the consequences of the massification of a process – for example, the consequences of the general implementation of a limited or localized behavior, in the case of which they are *consequential* lifecycle assessments.

To define the *objectives* of the study, we should initially specify the intended application, the reasons leading to conduct this study and the public concerned, namely those to whom it is intended to communicate the results of the study. In a second step, we should define the *scope of the study* that enables us to restrict the study to the given *limits* and establish the limits of the system studied, and also to define the activities and impacts that are included or excluded from the study. We define the *temporal* cover (system lifespan), *geographical* cover, *technological* cover, cover of the *processes* (system boundaries), cover of *environmental interventions* (inputs and outputs), and cover of the *potential impacts*.

To determine the impacts related to the proposed project, we can rely on a list of environmental references. The study of this list will help us to eliminate unnecessary impact categories, to arrange the categories with insignificant impacts at a low level of analysis, and therefore to identify the critical impacts. This amounts to setting an *inclusion threshold* for the impacts on the lifecycle analysis.

Inclusion threshold: It is in fact usually impossible to consider all the compounds forming a complex product. The head of the LCA is required to set an inclusion threshold, which corresponds to the rules of *negligibility* whose principle is as follows: all components representing less than X% the total mass of the product are neglected. Secondly, we verify that the sum of what is taken into account remains above a fixed percentage, which is always close to 100% and, qualitatively, that the neglected compounds do not have particularly dangerous characteristics (e.g. toxic substances, radioactive waste, etc.) or other specific established problems (e.g. compound whose achievement is known as highly polluting and energy consumption). If not, these compounds will be reintegrated into the analysis, whatever their quantity.

The system definition also includes the definition of the *functional unit* and of the *reference flow*.

The functional unit is a quantity used to quantify the function of the studied product system and to compare different systems performing the same function.

EXAMPLES.–

– In the framework of an LCA to evaluate different packaging, the function studied is packaging. The functional unit to be defined is a packed volume V (m^3) and not a packed mass (kg) or a mass of packaging materials;

– In the framework of an LCA to evaluate various means of hand drying, the function studied is drying. The functional unit is thus a N number of dry hands, and not a surface of tissue paper. We can thus compare reference flows, such as a quantity of paper or a volume of hot air;

– In the framework of an LCA to assess the environmental impacts of two mural paintings, P1 and P2, the function studied is the cover of a wall surface. The functional unit to be defined is thus a painted surface S (m^2). The Direct comparison of the impacts of a liter of paint P1 to those of a liter of paint P2 is meaningless and

could even lead to completely wrong results. In fact, if per liter, the paint P1 is 30% cleaner than the paint P2, during the application, P1 requires two layers when one is enough for P2. We can thus obtain wrong results. In fact, a liter to liter comparison would lead to recommend the use of the paint P1, while it would have no interest for the environment or the user;

– if the analysis focuses on the comparison of processes or waste treatment process (storage, incineration, recycling), the functional unit may be, for example, the processing of one ton of waste.

This definition phase is really crucial, as the results of LCA depend greatly on the objectives and framework that have been previously set (but usually not on the sponsor or the director). Thus, the LCA of a plastic yoghurt pot from a particular manufacturer, knowing the precise transport distance of their products as well as the composition and the different modes of production of energy that it uses, will not give the same results as the LCA of the European yogurt pot, which is made based on the average member of European production. Therefore, to avoid inaccurate interpretations or generalizations in the subsequent use of results, the objective and scope of the study should clearly explain the studied issue.

7.3.5. *Lifecycle inventory analysis*

This phase is the one, which was the most developed at the methodological level. It benefited from the methods resulting from raw materials/energy balances of the 1970s. The definition of the Lifecycle inventory analysis according to international standards is: “Phase of lifecycle assessment involving the compilation and quantification of inputs and outputs for a given product system during its lifecycle”. The inventory is the basic objective of the LCA, as it is constituted by the basic processes obeying the physical laws of conservation of mass and energy. This type of inventory is not, however, absolute. Indeed, this approach involves a phase of data collection related to the achievement of working hypotheses. The data can indeed be collected not only on production sites but also with complete data from trade associations or organizations.

It consists here of gathering data or collecting the existing data and making calculations according to a precise sequence: flow chart, description of each basic process, data collection, and data validation. The quantitative input and output data of each elementary process calculated with respect to the reference flow are put in relation to the functional unit.

All environmental interventions (use of resources and emissions of pollutants) for product system, for each of the unitary processes at each step of the lifecycle (see Figure 7.10), are thus summarized into an inventory table and expressed with respect to the system reference flow. At this point, during this aggregation, the spatial (place of emission) and temporal characteristics (time of emission) are generally lost. This may be harmful to the actions to be taken after a lifecycle assessment, in so far as the inventory is very spatialized in our global economy (e.g. oil production in the Middle East, refining in the U.S., production of synthesis intermediates in Europe, mineral production in Asia, etc.) and also registered in time as technologies change rapidly and thus also their environmental impacts.

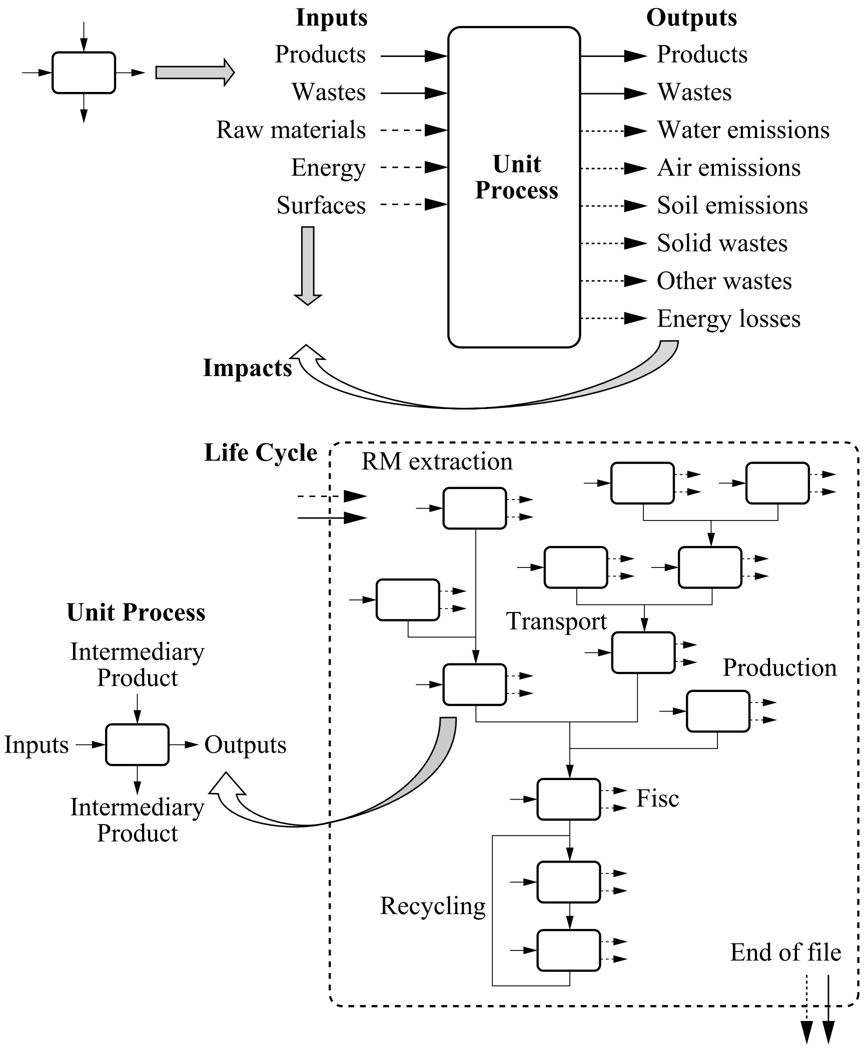

Figure 7.10. *Lifecycle inventory*

Inventory data are composed of material flows (mineral iron, bauxite, water, etc.) and energy (oil, gas, coal, etc.) entering the system under study and of corresponding outflows (solid waste, liquid, or gaseous emissions, etc.). There are some lifecycle inventory databases especially for common raw materials, energy, and transport. These data are accessible at low cost in the form of public or published databases (e.g. database *Ecoinvent data v2.1*).

Some groups or professional federations have also collected data on the environmental impacts of their material throughout its lifecycle or, more frequently, on the upstream part of the cycle, to make them available to the users of those materials, so that they incorporate them into their own LCA. For specific data to the study, data collection has often to be carried out on an individual basis, for a collection on industrial sites, through bibliographic researches, or through the perspective of previous studies.

Case of plastics: The APME (Association of Plastic Manufacturers in Europe) provides for free by mail and on its Website, the "Eco-profiles" of major plastics, in the form of lists of averaged inventory results, which are easily usable in spreadsheets or calculation software.

7.3.6. *Assessing the impact of the lifecycle*

The impact assessment phase consists of explaining and interpreting the results obtained during the inventory, in terms of impacts on the environment, and in the form of an adequate summary that could be understood by a non-specialist. This phase should help to prepare the disclosure of elements related to the product environmental impact. It is particularly sensitive.

The two previous phases – inventory and assessment – are those that are mostly related to chemistry since the entire manufacturing process is divided into material and energy balances, and deconvoluted in primary inputs: oil, gas, electricity, and so on. At each step of this process, by-products, effluents, and so on, are identified and their future is evaluated in terms of directly or indirectly possible pollution.

To conduct the impact assessment phase, we must first select the *impact categories* to be remembered (see Figure 7.11), define the *impact indicators* and characterization models, and carry out *the allocation* of inventory results in different impact categories (*classification*).

For each indicator category, we must calculate the results (*characterization*), the amplitude of the results in comparison to reference values (*normation*), the grouping and ranking of indicators, and finally *the weighting* of indicators.

Basic impact categories	**Supplementary impact categories**
Depletion of abiotic resources	Loss of biodiversity
Land occupation	Ionizing irradiation impacts
Climate change	Odors
Destruction of stratospheric ozone layer	Noise
Human toxicity	Drying out
Ecotoxicity	
Formation of photo oxidant chemicals	
Acidification	
Eutrophication	

Figure 7.11. *Impact categories*

The impact indicators rely on various methods, which come from various sources. Thus, in general, we retain the following indicators (see Figure 7.12).

Indicator	**Inventory flow**	**Method**
Greenhouse effect (kg_{eqCO2})	CO_2, CH_4, N_2O, CFC …	Greenhouse effect 50.100 or 500 years – IPCC International Panel on Climate Change
Air acidification (kg_{eqH+})	NO_x, SO_x, HCl …	Potential acid – Ecole Polytechnique Fédérale de Zurich
Formation of smog/of tropospheric ozone (kg_{eqC2H4})	Volatile organic compounds …	Oxidants – World Meteorological Organization (UN)
Eutrophication of water (kg_{eqPO4})	Chemicals demands for oxygen, NH_3, NO_3, PO_4 …	Institute of Environmental Sciences of the University of Leiden CML

Figure 7.12. *Impact indicators*

EXAMPLE.– *For an inventory outcome identifying the release of various components such as cadmium,* CO_2, NO_x, SO_2, *and so on, we will define acidification as one of the impact categories. In this case, the inventory outcome allocated to the selected* *impact category includes acidifying emissions due to* NO_x *and* SO_2*. Modeling the indicator category is the release of* H^+ *protons. The chosen indicator is aggregated acidification potential AP and* SO_2eq*. For aggregating, the weighting coefficients to be used are as follows: 1 for the emissions of* SO_2 *and 0.7 for* NO_x *emissions. The category application* point *is composed of ecosystems such as forests, vegetation*, *and so on*.

It is imperative that the chosen indicator provides an adequate representation, i.e. that the low indicator corresponds to a low impact and that the indicator shows a relevant environmental phenomenon.

For this, the number of indicators must be limited, indicators should be determined from the data and existing models, and the calculations should be executable in a limited time at a reasonable cost.

Category indicators actually represents the amount of potential impact. They are distinguished according to two main types, depending on their position in the causal chain between emissions and impacts (see Figure 7.13): midpoint and endpoint indicators.

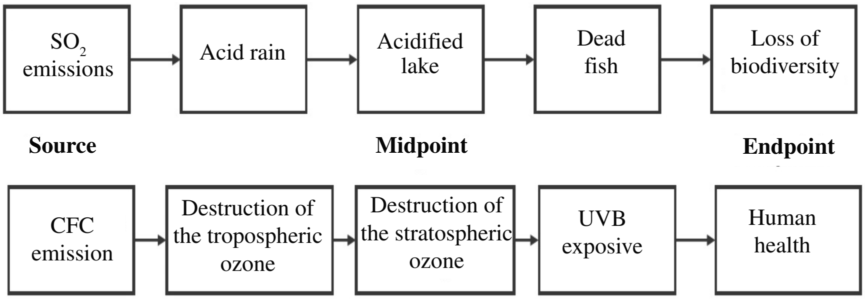

Figure 7.13. *Midpoint and endpoint indicators*

Midpoint indicators correspond to the aggregation by type of impact (acidification, destruction of the ozone layer, etc.). They are more easily accessible, with a limited uncertainty, but have a low environmental relevance. Endpoint indicators reflect the impact on targets (loss of biodiversity, human health, etc.). They are not easily accessible, with a high uncertainty but are of great environmental relevance.

Another way of classifying the impacts is to separate them in terms of *direct* and *indirect impacts*. Direct impacts correspond to the actions of sources on specific targets such as the depletion of natural resources by the extraction of raw materials.

Indirect impacts actually correspond to cascades of effects: the emission and dispersion of SO_2 cause acid rains, which will in turn lead to the acidification of soils, lakes, and air. The consequences of acidification will cause an alteration of flora, the death of fish, and human toxicity, with as the ultimate consequences the loss of biodiversity and agricultural and human productivities. The general form of an indicator is as follows [7.2]:

$$Ind_i^{cat} = coeff_i^{cat} \times pond_i^{cat} \times m_i \qquad [7.2]$$

with:

– Ind_i^{cat} : indicator of flow *i* for the impact category cat;

– $Coeff_i^{cat}$: coefficient of contribution of the flow *i* to the impact category cat;

– $pond_i^{cat}$: weighting of flow *i* for the impact category cat;

– m_i : mass of the flow *i*.

EXAMPLE 1.–

– *Type of impact: climatic change*;

– *Net Asset:* CO_2*, 20 kg;* CH_4*, 1 kg; and* N_2O*, 0.1 kg*;

– *Characterization model: IPCC model defining the global warming potential by greenhouse gas emissions*;

– *Characterization factor: potential PR warming*;

– *PR* $CO_2 = 1\ kg_{eqCO2}$;

– *PR* $CH_4 = 21\ kg_{eqCO2}/kg\ CH_4$;

– *PR* $N_2O = 310\ kg_{eqCO2}/kg\ N2O$;

– *Indicator Outcome:* $Ind\ (PR) = 20 \times 1 + 1 \times 21 + 0.1 \times 310 = 0.72\ kg_{eqCO2}$.

EXAMPLE 2.–

– *Type of impact: eutrophication*;

– *Net asset: 2 kg of* NH_3*, 4 kg of* NO_3*, and 0.2 kg of* PO_4;

– *Characterization model: potential contribution to the formation of aquatic biomass of average composition (16 moles of N, 1 mole of P)*;

– *Characterization factor: potential PE eutrophication*;

– *PE* $NH3 = 0.35\ kg_{eqPO4}/kg_{eqNH3}$;

– $PE\ NO_3 = 0.1\ kg_{eqPO4}/kg_{eqNO3}$;

– $PE\ PO_4 = 1\ kg_{eqPO4}$;

– *Indicator Outcome:* $Ind\ (PE) = 2 \times 0.35 + 4 \times 0.1 + 0.2 \times 1 = 1.3\ kg_{eqPO4}$.

7.3.7. *Interpretation of the lifecycle*

The two previous phases, impact inventory and assessment are the areas of expertise of the lifecycle assessment. Indeed, the approach is technical and the data are numerous. In the interpretation phase of the lifecycle assessment, users, managers, and decision makers, will use the results of the impact analysis to identify the key actions, which will have to be taken into accounts other sizes (research and development, marketing, production, financial services, etc.).

LCA results are expressed as a series of data that has both potential impacts (*e.g. X* $kgeqCO_2$ *for the greenhouse effect*) and physical flows (*e.g. Y MJ of non-renewable energies*). They are the subjects of a report and, in the case of communication, of a public summary document.

For a LCA comparing the two products A and B, the results for each impact can be expressed for each step of the lifecycle, to compare and identify the steps presenting the greatest impacts. This can also help to compare the contribution of each product at each stage of the Lifecycle. The following results (see Figure 7.14) enable us to establish that the product A contributes more to the greenhouse effect than the product B for the steps of raw materials extraction and production, but its ability to recycle at the end of life, enables it to absorb CO_2. This representation enables us to identify the steps on which efforts have to be made in order to reduce impacts.

The aggregation of results for the contribution to the greenhouse effect per product enables us to identify macroscopic trends (see Figure 7.15), but annihilates the differences in the lifecycle. This representation enables us to make a global selection of the product causing the least impact.

The essential phase of interpretation is the report writing that should contain the main elements of the lifecycle assessment: a reminder of the context and objectives of the lifecycle assessment, detailed definition of the chosen functional unit, methodology of the lifecycle assessment, basic information and sources used and their limitations, encountered technical, methodological, and scientific difficulties. This report must necessarily include a critical review, i.e. the review of the study by an independent expert. This expert can act either alone or within a critical review committee involving experts of the studied field and key stakeholders: the key is to ensure the impartiality of the experts regarding the LCA in the studied domain.

Comments and responses to recommendations resulting from the critical review should be included in the summary report.

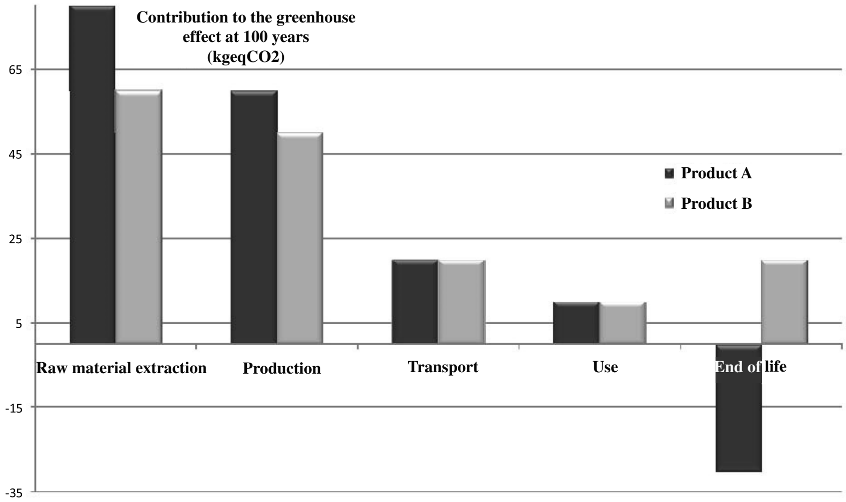

Figure 7.14. *Contribution to the greenhouse effect of the lifecycle of products A and B*

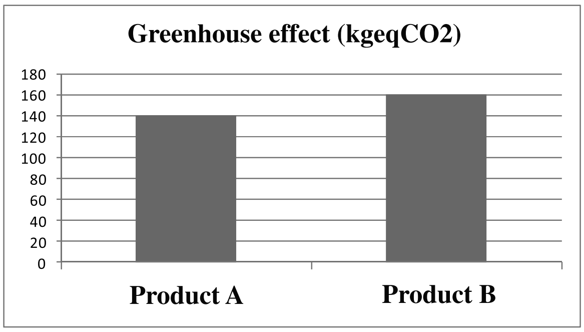

Figure 7.15. *Aggregation of the "greenhouse effect" impact*

The results of an LCA can also be conveyed as an environmental statement, and are then called "Type III environmental declaration", or *eco-profile*, which can be printed on the product. This is the international ISO standard 14025, published in 2006, which establishes the principles and procedures for developing Type III environmental declarations and the use of the ISO 14040 series of standards for developing Type III environmental declarations. Type III environmental declarations described by ISO 14025 are mainly intended for inter-company communication, but their use for the communication between a company and private individuals under certain conditions is not ruled out. The search for improvements is the component of the lifecycle assessment, in which the options to reduce environmental impacts of the system are identified and assessed. This stage includes the identification, assessment, and selection of options for the improvement of the environmental load of products or processes.

Currently, lifecycle assessments are most of the time used to meet certain requirements, such as the environmental performance of an industrial process, the environmental sales pitch, the comparison of environmental impacts of two products (or more), and the calculation of environmental balances.

In addition, the initial characteristics of the product generally determine the possibilities of valorization at the end of life. Finally, this approach shows a strategic advantage in terms of communication. Indeed, the results obtained in this type of approach may be shared with customers and bring about a competitive advantage that differentiates the product from its competitors.

7.3.8. *LCA software*

There are now dozens of software for analyzing the lifecycle assessment. Initially, the first software that emerged in the 1990s that have replaced the spreadsheet programs of 1980s, have been developed by consultants, at first for their own needs and then for their customers. We can thus name some early versions of *TEAM d'Ecobilan, Sima Pro, PRé Consultants,* etc. These various types of software were designed as sophisticated spreadsheets adjusted to the calculations of inventory and have provided with their different versions, more extensive features in terms of input and modification of models, display and print of the results as tables and graphs. The following versions have integrated various methods of assessment, based on the structure of LCA defined by the SETAC also with sensitivity analyses.

The latest generation of LCA tools is derived from the previous software, to which were added a user interface and a database specific to a type of use, such as product design (*Eco-It* derived from *Sima Pro*). Other types of software are dedicated to a specific industry, such as *EIME* for French electrical, electronic, and communication industries or *WISARD* for household waste management; both of them are derived from *TEAM*.

Suppliers of LCA software, who usually have initially developed the software for their own use, are now divided into three categories:

– public research institutes;

– environmental consulting offices, especially in LCA;

– industrialists, who, after having developed a software for their own needs in the early 1990s without marketing it, now often associate with consultants or research institutes to develop a new software.

7.4. Innovation through eco-design

LCA does not provide solutions to design products or processes of low environmental impact but is a guide to select which stages to improve. The LCA is thus a tool that helps to make choices and to guide researches to foster innovation. In fact, the results of the lifecycle of a given initial product (see Figure 7.16) help us to identify that the highest *X impact* is related to the production stages of raw materials. Therefore, the research should be conducted on this stage in order to identify access channels or raw materials of lesser impact to develop a *eco-designed* new product. It is in this research process that innovation is found, and it is in this sense that eco-design is a real innovation tool.

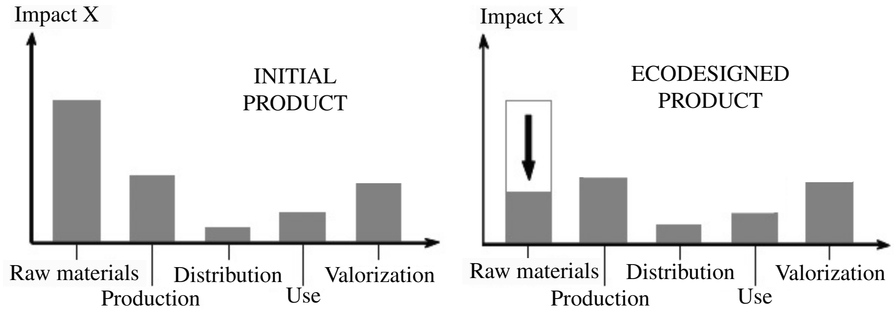

Figure 7.16. *Innovation process*

We propose to study the examples of case studies to detail the whole process applied to industrial products and processes.

7.4.1. *Example: LCA of supermarket shopping bags*

The example of the comparative lifecycle assessment of the shopping bags distributed in supermarkets is very informative. This study was conducted in 2004 by an expert office in LCA, for a distribution company. It was completed by a critical review organized by ADEME. This study *aimed* at quantifying and comparing the environmental impacts of four types of shopping bags available to customers in supermarkets: a disposable polyethylene (PE) bag, a reusable shopping bag made of soft polyethylene, a disposable paper bag, and a single-use biodegradable bag. *The* *inventory* was conducted by using data collected by the bag suppliers of the distribution company and completed by the Ecobilan database.

Eight *indicators* were selected for this study:

– consumption of non-renewable energy resources;

– water consumption;

– greenhouse gas emissions;

– atmospheric acidification;

– the formation of photochemical oxidants (smog);

– contribution to the eutrophication of aquatic ecosystems;

– production of solid residual waste;

– the relative risk of disposal of bags in the environment.

The functional unit defined for this study corresponds to the service rendered by the bags, i.e. packing the purchases made by customer in stores. The *hypotheses* defined in the framework of this study report 45 visits per year per customer on average in the stores, with 200 L of purchase by visiting (a cart filled to 80%), corresponding to 9,000 L of goods per year. The functional unit selected is thus "*packing 9,000 goods in the shops of the group*". Bags compared within the framework of this study have the following characteristics (see Figure 7.17).

	PE Bag	**PE Soft bags**	**Paper bags**	**Biodegradable bags**
Material	Virgin HDPE	Virgin LDPE	Recycled paper	50% amidon/50% polycaprolactone
Volume (L)	14	37	20.5	25
Mass (g)	6.04	44	52	17
Use	One time	Reusable	One time	One time
Nb of bags for UF	*643*	*Case 1 use: 243* *Case 3 uses: 83* *Case 20 uses: 12*	*439*	*360*

Figure 7.17. *Characteristics of shopping bags*

The *boundaries* of the system take into account the production and transportation of materials for bags, the manufacturing and printing of bags, transport of bags, phase of usage, and various end of life possibilities. The *inclusion threshold* defined is 5%: this means that the sum of the *inputs* whose production is not included in the system represents less than 5% of the total mass of the system inputs. Some *process*es are also *excluded* from the lifecycle. Thus, the study does not include the assessment of impacts related to the construction of buildings for industrial sites, or to the manufacturing of machine tools or delivery trucks. In fact, in a steady state of stabilized operation, the amortization of all this equipment is carried on throughout their whole lifespan, and then becomes negligible in the studied lifecycle. The study does not address the transport of full bags to shoppers' homes.

In calculating the impacts identified in this study, the *reference flows* identified are as follows:

– natural resources: consumption of oil, coal, natural gas, uranium, and water;

– air pollution: CO_2, CH_4, N_2O, NO_x, SO_x, and COV;

– water pollution: discharges of nitrogen, phosphorus, and oxidizable substances (COD);

– total waste production.

The impact of relative risk by disposal, was evaluated using the following parameters:

– volume of bags used to be processed: this volume is directly correlated to the number of bags that are disposed off;

– probability of disposal: this probability depends on the mode of acquisition, it is low when the bag is purchased, strong when it is free;

– probability of flying off: this probability depends on the density of the bag, it is strong if the bag is "light", weak if it is "heavy";

– persistence of the bags in the environment: this parameter depends on whether the material of the bag is biodegradable or not.

The LCA has focused on the *lifecycles* of the four types of bags being considered. For example, the lifecycle of the disposable HDPE bag (see Figure 7.18) first takes into account the use and refining of oil for the synthesis of ethylene, the polymerization of ethylene by Ziegler Natta catalyst, production of HDPE pellets, and their transport. These data are resulting from the inventory databases of 1999 of APME (average on 24 European sites producing LDPE 3.87 Mt/year or 89.7% of the production of Western Europe). The lifecycle also takes into account the production of titanium dioxide (data from a production site – 1992), calcium carbonate (data from the Swiss Ministry of Environment), and linear PE with low density (averages of the APME), which are the loads in the bag. The production of glue and ink is also taken into account.

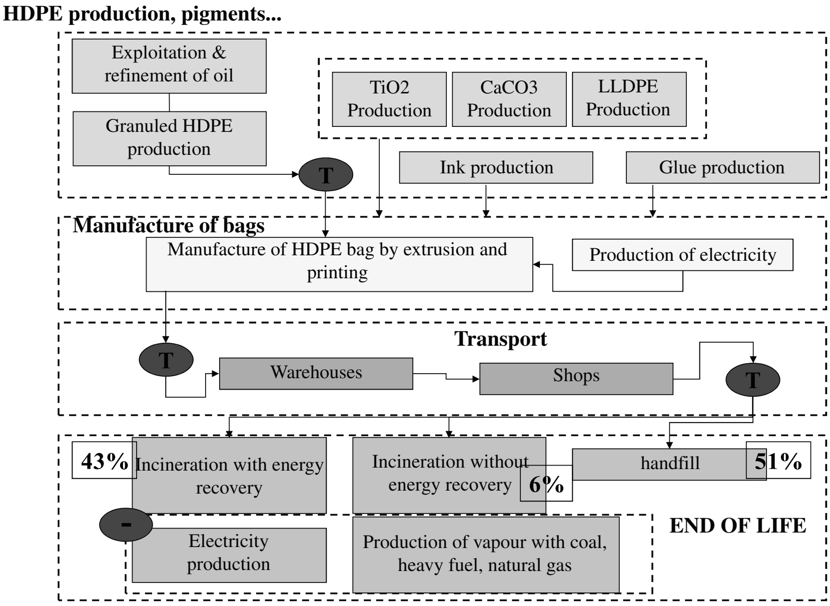

Figure 7.18. *Lifecycle of disposable HDPE bags*

In these lifecycles, energy production is modeled based on the energy ratios of electricity production of countries producing bags, namely France, Italy, Spain, and Malaysia. The differences are particularly significant for the impacts concerning the consumption of natural resources and the production of greenhouse gas emissions. Thus, the electricity in France is 75% of nuclear origin, whereas the electricity in Malaysia is 75% produced by the combustion of hydrocarbons. In addition, the calculations made to assess the impacts related to transport stages are based on the fuel consumption by trucks. The model takes into account the average consumption of a truck with full load (38 L/100 km) weighted by one-third the mass of the load, including the influence of *empty* return. The equation is therefore as follows:

Actual consumption (L) = number of kilometers traveled × 38/100 × (2/3 + 1/3 × real load/ payload + empty return rate × 2/3) [7.3]

Finally, the end of life stage was modeled using data from ADEME for household waste. Thus, 51% of waste are brought to landfills and 49% are incinerated. And 88% of incinerated waste are recycled to produce energy, 5% is exhausted as vapor and 22% is generated as electricity.

The *impacts* of this lifecycle assessment are presented in two forms: for each stage of the lifecycle of each bag being considered (see Figure 7.19), or agglomerated for each bag by considering the number of reuses of soft bags (see Figure 7.20).

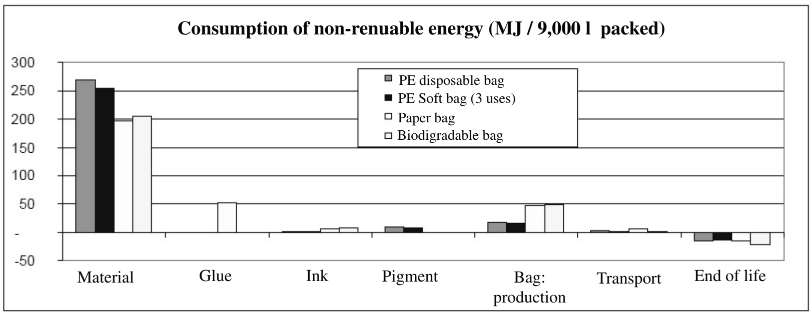

Figure 7.19. *Non-renewable energy consumption*

The interpretation of the results of impacts enable us to identify the following trends:

– consumption of renewable energy, greenhouse gas emissions, and formation of smog are impacts that are due to the phases of material production (see Figures 7.19 and 7.22);

– paper bags are the highest water consumers, due to the paper recycling process (see Figure 7.21);

– paper and biodegradable bags are the source of the impacts of eutrophication, due to the paper recycling process or the use of fertilizer for corn crop from which we get starch (see Figure 7.24);

– phases of material and bag production are the strongest contributions to atmospheric acidification (see Figure 7.23);

– the formation of solid waste is the end of life stage, which is the largest contributor to this impact;

– for the set of relevant impacts, soft bags show impacts: higher than other types of bags meant for a single reuse; equivalent from three uses; and lower than a number of reuses higher than three;

– The relative risk presented by disposal is very high for disposable PE bags, and low in all other cases.

The broad guidelines of the findings are also that the reduction of the mass of the bag and reuse of the bag are two major factors that reduce the impacts on the environment. The *conclusions* of this study are therefore strongly favorable to the use of soft LDPE bags – with the assumption of reuse of these bags for at least three times.

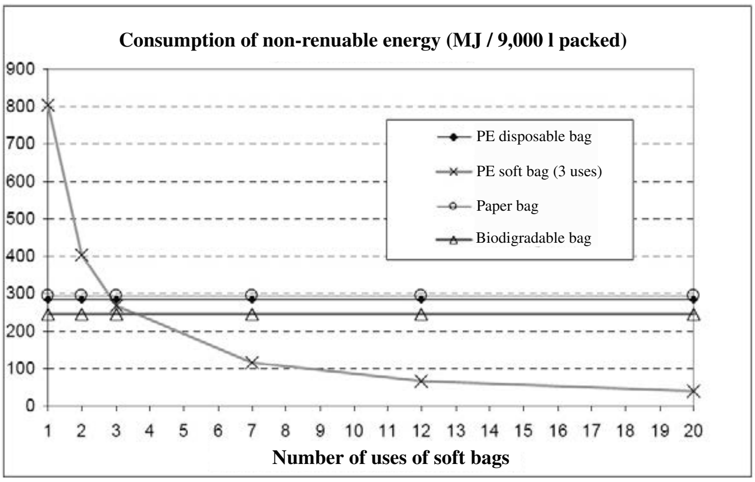

Figure 7.20. *Consumption of renewable energy for N uses of soft bags*

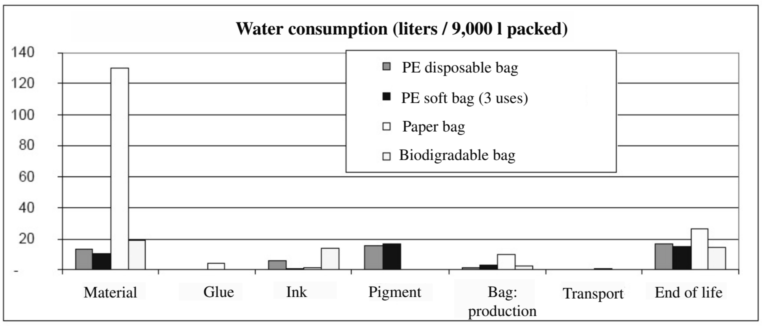

Figure 7.21. *Water consumption*

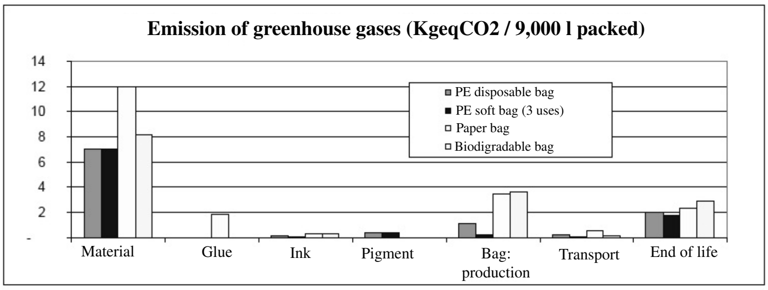

Figure 7.22. *Emission of greenhouse gases*

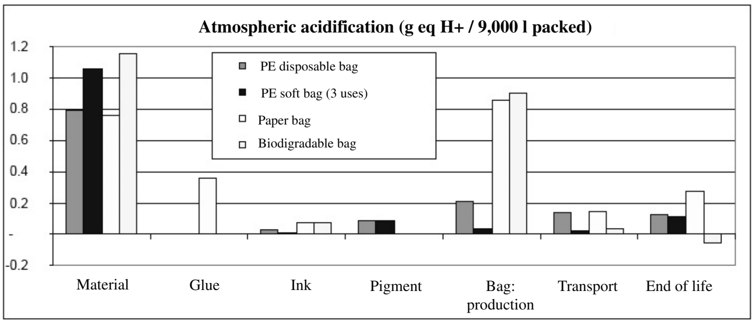

Figure 7.23. *Atmospheric acidification*

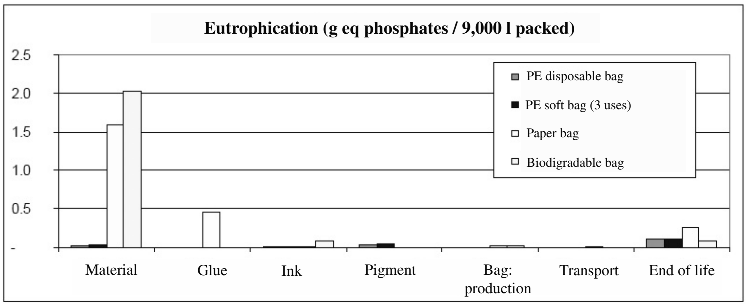

Figure 7.24. *Water eutrophication*

7.4.2. *Example of eco-design by a manufacturer of office furniture*

The company considered offers solutions for office layout, has routinely used the evaluation of the lifecycle for each of its products. A lifecycle assessment of an office chair made in this company had therefore underlined the preponderant impacts of the stages of production of materials and seat. To reduce these impacts and to identify an eco-designed innovative solution for office chairs, the company has promoted the use of recycling and reuse for office chairs (see Figure 7.25). Thus, the materials that made this seat were at 44% recycled, free of heavy metals. This chair can be dismantled completely and each part can be replaced individually by the company. The seat and packaging are also recyclable at 99%. This seat was reduced to 7 kg and packed volume was reduced by 30%. The environmental impacts of the material and seat production are thus reduced, as well as impacts related to transport. Finally, the end of life was supported by the company that had established a recovery and replacement of parts and seats service. This product had been voted “Best French eco-designed product” at Pollutec in 2004 and has won the gold medal of Focus Green Award in 2008 in Germany.

Figure 7.25. *Eco-designed seat (Source: A. Malsch)*

7.4.3. *Example of eco-design from a manufacturer of detergents*

Conducting lifecycle assessments has also led a detergent company to offer innovative eco-designed products. Thus, in the framework of the development of detergents, very detailed lifecycle assessments of laundry have highlighted the main environmental impacts and the stages with the highest impact. These results have thus shown that the most important environmental impacts were related to the usage phase of detergent. In fact, 75% of the energy consumed in the lifecycle come from the energy consumption of the washing machine during the usage phase. This energy consumption is especially linked to the operating temperature of the washing machine. To reduce environmental impacts and to suggest an eco-designed innovative solution, the company has developed a detergent in order to reduce the washing temperature without reducing the performance of detergent. This "cold active" detergent makes it possible to significantly reduce overall environmental impacts and nearly 50% of major energy consumption have been consumed in the total lifecycle. Marketing material made to promote this product has also highlighted the savings for consumers, which will reduce their energy bills.

7.4.4. *The integration process of eco-design in the company*

These examples highlight the achievements of design and marketing of eco-designed products. These products have been designed in the innovation process based on lifecycle assessment to identify the axes of improvement related to the most important environmental impacts, the most contributing strategic stages to the lifecycle. We can thus, in the light of these examples, try to describe the integration process of eco-design in the company in five steps and extract the appropriation process from it.

To start an eco-design approach in the company, the first step is *to choose the product* on which the company wants to work. This choice is made based on the product strategy by studying the portfolio of technologies available, the current product range, and by achieving an appropriate *benchmark*. At this stage, the eco-design approach can already point out the product and company environmental problems and enable us to estimate the environmental improvement potential of the product.

The second stage defines the *design* goals associated with the chosen product, and will therefore have to convey the need in terms of function, based on market researches and a functional analysis. At this stage, an initial lifecycle assessment should be carried out on a reference model by choosing eco-design guidelines.

The third stage should enable us to bring out *technical solutions*, i.e. block diagrams accompanied with a cost estimate. The eco-design approach helps us to search for solutions of lower environmental impact and to conduct an environmental report.

In the fourth phase, *industrialization*, the company must optimize the production parameters, logistics, and supply. This work is accompanied with a collection on site of impacts such as energy consumption, real mass flow, amount of waste, etc, in order to conduct an environmental assessment of the final product and to prepare an environmental report.

The fifth stage concerns *marketing and communication*. Distribution channels as well as possible maintenance contracts are selected ... Communication about the product is made internally and externally based on the environmental report to establish a sales point, extract key figures, and communication media.

Beyond these five stages, this approach must also take into account the end of life of the product by providing recovery solutions for products, packaging management, reuse, recycling, etc. Finally, any further development of the product (features, packaging, etc.) should be reflected on the impact assessment and communication messages.

For a company, the appropriation of such an approach lasts and involves three phases, several stakeholders, and several deliverables. In a preliminary decision-making phase, management must signal its involvement by the drafting of guidelines. In a first *piloting* phase, the integration process must rely on an eco-design “pilot” experiment, with the support of management and with the help of an expert from outside the project team, from a consulting firm that acts as a provider. After this phase, the following stage of *framing* aims at formalizing the process within the company, with an in-house person in charge of the coordination of eco-design projects, helped by the outside firm to conduct training in house. In the last phase *of extension*, the approach becomes integrated to the company and is widely applicable to all design projects, coordination is done in-house and all members of the project are competent in so far as the company is able to generate self-training. Management can then communicate about the external approach.

7.5. Limits of the tool

The lifecycle assessment is thus a support tool for eco-design. This tool can be powerful, but also has some limits especially due to the complexity of its implementation. Indeed, resorting to expert software and often expensive databases reduces its use to a few multinationals and limits its contribution to the analysis of existing products and processes. LCA is therefore a particularly interesting tool because it enables a multicriteria analysis, on the entire lifecycle, without limiting itself to a single stage (end of life, etc.) or a single impact (carbon footprint, etc.). In addition, this tool is standardized through the ISO standards describing it. Moreover, a single impact, estimated at each stage, can be "added" to give a clear vision and helps decision-making. And finally, nothing is published without having been previously submitted to the journal of a group of experts.

However, if the LCA enables the identification during a given process of the stages generating the highest environmental impacts – such as stages of raw materials extraction – LCA gives a vision *a posteriori* but does not direct the course of the innovative process. LCA is indeed a study performed on an already developed or commercialized product and helps to identify the steps that have the greatest impact on the environment during the manufacture of this product. The objective of an eco-designed process is to bring about, in a second phase, some solutions to reduce the most significant impacts during the previously identified stages. Innovation is thus born from the search for solutions during the second generation, or from the improvement of the product manufacture process. Therefore, the primary objective of these lifecycle analyses is rather data compilation, the conducting of an environmental assessment, the production of results for the communication on the manufacture a product; the support for eco-design is performed a second time because LCA is best suited to evaluate its final impact of a product, rather than guiding its design. Furthermore, other limitations of this tool lie in the defining stages of the assumptions, in the allocation rules followed or the considered end of life. We will try to illustrate this through the following examples.

7.5.1. *On the importance of hypotheses*

In fact, in the lifecycle assessment of shopping bags described in section 7.4, conclusions strongly support the use of soft LDPE bags – in the event of reuse of these bags at least three times. The broad guidelines of the findings are that the reduction of the bag weight and reuse of the bag are two major factors reducing the impacts on the environment. But at no time is considered a possible reuse of other considered bags (especially HDPE and biodegradable bags, which could be reused a second time, or at least as garbage bags). In addition, the study is comparing bags with very different volumes, which involves quite variable amounts of material depending on the bags. And yet knowing that the weight of the bag is an important parameter, it would have been appropriate to consider the solutions showing larger volumes for the same bag. Thus, we can clearly identify that the LCA evaluates selected products and helps in choosing the best product *within* this selection. But experience shows that solutions to a problem can often be found outside a preselection ... We must therefore be innovative to really find eco-designed solutions.

Another interesting example is the informative case study described by Jolliet *et al*. The goal of the presented LCA is to develop an environment-friendly computer by comparing the environmental impacts of two computers, a desktop PC with a CRT monitor and a LCD laptop. The functional unit given is 10,000 hours of usage of the computer (i.e. 2,000 h/year over 5 years). In the hypotheses considered, we compare two computers with similar functions, ignoring the transportability of the laptop. Infrastructures and manufacturing machine tools of computers are not included in the limits of the study and the battery of the laptop is not taken into account (production and disposal). The results of this lifecycle assessment show the following differences: the desktop computer has the most significant environmental impacts. The impacts of the laptop are actually lower by almost 40% to those of the desktop PC in all categories. And the screen is responsible for nearly 50% of impacts. So, the findings clearly guides us toward the laptop solution. But this case study shows that the results obtained are related to unrealistic and not rigorous hypotheses. In fact, the manufacture and disposal of the laptop battery are not included in the LCA. And yet this type of component and significant mass contains toxic and eco-toxic substances, its disposal is governed by the Waste Electrical and Electronic Equipment (WEEE) Directive. It is inconceivable not to include it in the LCA. In addition, as the screen supports up to 50% of impacts, it seems less rigorous to compare the PC with screens of different technologies. It would be more appropriate to compare a PC with an LCD screen. And finally, the life span of two PCs is not comparable; indeed, the life span of the laptop is reduced not only because of the potential damage caused during transport phases but also because it is difficult to replace its components. In contrast, the lifespan of a desktop PC can be extended, in so far as some components or materials will be reused in a new configuration (screen, keyboard, etc.). In this case, the functional unit can be changed. Therefore, this educational case study highlights the faults of the LCA tool when we lack rigor in the choice of the functional unit and hypotheses.

The example taken from the study of Kim *et al*. is also very illustrative of the importance of choosing the hypotheses of the LCA. Indeed, in their study, this team compared the environmental impacts of two types of polymers, the polystyrene

PS – obtained from the polymerization of styrene, a monomer coming from oil, and a *PHA* polyhydroxyalkanoate – polyester derived from the fermentation of sugars extracted from corn kernels, from agricultural source, by bacteria. The comparison is carried out at similar mass, despite any possible differences in properties. The results presented in this study show initially that the impact on the greenhouse effect is lower for the manufacture of polystyrene (2.9 kg_{eqCO2} for PS and 3.5–4.4 kg_{eqCO2} for PHA). However, in a second study/case, we add in the lifecycle the production of sugars from the co-produced straw and also the recovery of energy coming from straw valorization. And in this case, the production of PHA becomes a CO_2 well, to the extent that the indicator is -1.2 to -1.9 kg_{eqCO2}. This example perfectly illustrates the importance of choosing the right hypotheses and limits on the final result.

7.5.2. *On the relevance of inventory data*

Let us return to the lifecycle assessment of shopping bags described in section 7.4. The LCA has studied the *lifecycles* of four types of bags. For example, the lifecycle of the disposable HDPE bag (Figure 7.18) first takes into account the exploitation and refinement of oil for the synthesis of ethylene, the polymerization of ethylene by Ziegler-Natta catalysis, the production of HDPE pellets and their transport. However, these data come from the inventory database of 1999 APME (average on 24 European sites producing LDPE 3.87 Mt/year, i.e. 89.7% of Western European production). And yet in the study, we learn that the HDPE is manufactured in France, but also in Asia and Brazil. Not only the inventory data from APME related to the manufacture of HDPE date back to 5 years, but also they are not more representative anymore of manufacturing carried out in Brazil or Asia – they thus cannot be used to assess the environmental impacts. Similarly, the lifecycle of the HDPE bag also takes into account the production of HDPE bags. In this case, the data from inventory databases of the APME (1993 average of eight production sites in the UK). And yet, these HDPE bags are made in France. Thus, not only are these data old (over 10 years), but they also represent only part of the British situation and can never be representative of the French situation – in terms of energy consumption only. In fact, if the electricity production in France is mainly nuclear (78%) and then thermal (11%) and renewable (11%), this report is completely different in the UK, where electricity is mainly of thermal origin (75%), then nuclear (20%) and renewable (5%). As a result, environmental impacts are completely different (contribution to global warming) and cannot be used from one country to another.

7.5.3. *On the influence of allocation rules*

The rules for allocating waste can also play a role in the results of a lifecycle assessment. Thus, if we compare two LCA on bioethanol as biofuels (a LCA conducted by ADEME in 2002 and another one conducted by EDEN in 2006), the results are very different. In fact, the energy performance of bioethanol of wheat (returned energy/mobilized renewable energy) varies from single to double for both studies: 1.10 for EDEN and 2.05 for ADEME. These differences may be explained by the differences in the choices made for the allocation of waste from the bioethanol sector. Thus, EDEN has chosen to include, in its LCA, all the impacts generated by the waste from the bioethanol sector, thereby promoting a systematic approach, while ADEME allocates only 43% of the impacts of waste. ADEME has done for this LCA the choice of mass allocation – the bioethanol, product targeted by the sector, representing only 43% of mobilized dry matter. These two options can be chosen, but it is important to understand that the results can be radically changed because of this choice.

7.5.4. *On the choice of recycling*

Concerning the rules of comparison on the end of life stage, the CIRAIG draws our attention on the relevance of the comparison of different ways of valorization. In fact, it is usually impossible to directly compare the environmental impacts generated by the two ways of valorization of a product. If we wish to process 1 ton of waste paper, we cannot directly compare *recycling* – that will produce X t (X < 1) of recycled paper – and *thermal valorization* – which will produce a Y MJ quantity of electricity. In fact, in the first case, we will always need a power generation and in the second case, we will still need paper – these two systems do not render the same service. It is therefore necessary to complete this comparison by adding to each system the process avoided depending on the chosen option (see Figure 7.26).

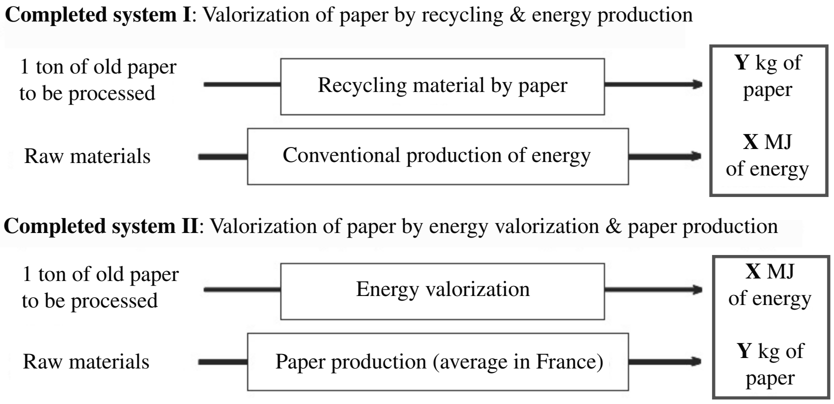

Figure 7.26. *Comparison of two completed systems*

Therefore, in the first case (paper recycling), we must also take into account in the impact assessment, the production of Y MJ of electricity depending on local conditions of conventional electricity generation. And in the second case (the thermal valorization), we must also consider the conventional production of X t of paper from wood in the impact assessment. We can from now on compare strictly two systems that have the same products: X t of paper and Y MJ of electricity.

The LCA is a particularly interesting tool as it enables a multicriteria analysis, on the entire lifecycle, without limiting ourselves to a single stage (end of life, etc.) or a single impact (carbon balance, etc.). This tool is standardized through the ISO standards describing it and guarantees an expert review before publication. And the same impact, estimated at each stage, can be "added" to give a clear idea and help decision-making. However, this tool has certain limitations that particularly lie in the careful selection of the hypothese definition, limits, and functional unit. Similarly, the followed allocation rules or the considered end of life may significantly alter the results. But the most restrictive limitations of this tool are qualitative and methodological. In fact, the impacts calculated are only potential impacts and do not reflect the local reality. In addition, this tool is not dynamic. Thus, inventory data, even when they come from measurements made on site, are only valid for a limited time and are rarely updated. As for the quality of the data, it is unreliable. When the inventory data are derived from databases (EU averages or others), they are not necessarily representative of local realities and are also limited by a low frequency of updating. In all cases, the results obtained are rarely updated. More importantly, the LCA does not enable taking into account the margin of technological progresses that it compares. Indeed, if we compare a very well-established and highly optimized technology with a new technology, it may be necessary to conclude that the first older, technology, causes less environmental impacts without realizing that the new technology has more room for progress. And we can thus decide not to develop this new technology even though it would cause less impact after a few optimizations. LCA eases everything, and does not include time as dimensional variable.

7.6. Conclusion: the future of eco-design

Design processes in industry and in particular in chemical industries are now changing. They must now respond to a holistic challenge of reduction in environmental impacts at each stage of the manufacturing process. They must integrate eco-design of the product or process. In this approach, lifecycle assessment – LCA – is a crucial tool to support environmental assessment. And in doing so, the lifecycle assessment, by identifying the progress margin in terms of environmental impacts, of energy and resource consumption, becomes a strategic tool for innovation. This tool makes it possible to guide the efforts of research and development, thereby leading to the identification of innovative solutions to reduce environmental impacts, to lead to new products, which are "greener", eco-designed, and responding to the more and more pressing demands of the market and regulations.

However, the process of lifecycle assessment is performed *a posteriori* on an existing product or process and helps us to analyze the environmental impacts of this product or process. The results of this LCA thus put the emphasis on the stages that have the greatest impact on the environment. We will have to work on these stages to reduce the environmental impact but only during a phase of product improvement or during the design phase of the "second generation" of this product. In the first approach, the lifecycle assessment only enables us to compare the environmental impact of two products to find the best compromise. And this tool has both qualitative and methodological limitations. Thus, the definition of the hypotheses, limits, functional unit, and followed allocation rules or of the considered end of life may significantly alter the results.

But the most restrictive limitations of this tool are qualitative and methodological. Qualitative, because the relevance of the data is essential when assessing impacts and because these data are not always relevant or updated in the databases, they are not always representative of the local reality. Methodological, as this tool only enables a comparison in time, an assessment of the relative impacts and does not take into account the margin of technological progress that it compares. Thus, we wish for this lifecycle assessment tool to evolve, remedy these limitations and to better assess impacts associated with the toxicity and pollution. In addition, to meet the new constraints in the innovation processes, to be upstream of the project phases, to support the design of the products and processes in the chemical industry, and to take into account the new regulatory aspects, we need new tools giving guidelines to be followed to guide the choices of researchers and chemists. It becomes more and more important to assist the innovation process with a tool that helps piloting, *gate to gate*, instead of concluding it from a comprehensive analysis *a posteriori*. And it is essential to extend this environmental design to all projects in the chemical industry to make eco-design emerge in this sector. For this, product and process designers in the chemical industry are in need of a suitable tool, easy to use and not just made for environmental balance experts, a tool that can guide them from the choice of access routes on final environmental impact. And industrialists must also expand the collection of inventory data and share these inventory data to contribute to update the database inventory, which is a real "Achilles heel" of LCA. In addition, it is crucial to link the inventory databases to those of the classification of dangerous substances. How can we imagine nowadays the identification of a chemical access way without anticipating the constraints imposed by regulations and in particular the REACH regulation? It is also important to be able to generalize the use of such a tool for smaller companies to increase their competitiveness. It is thus necessary to provide them with a tool usable at all stages of the project early in the stages of innovation, includes guiding the choices of R&D. Existing tools do not necessarily respond to this objective, particularly for SMEs in the chemical industry, which are looking for a simplified reference frame to enable them to integrate the concept of sustainable development in the design of their products. Thus, if quality management began in 1992 for major groups, these actions have only started about 2004–2006 for smaller structures. Nowadays, in the industrial sector, only a quarter of the companies provided for the end of life of its products, and there are eco-design practices among 40% of them. Finally, it is essential for companies to take over the involvement in research and education and to help to mobilize the public research teams in this area.

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