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Life Cycle Assessment of PET Bottle Recycling: A Case Study for Mexico

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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Vienna, 03.06.2013

Affidavit

I, **DANIELA IZÁBAL NOGUEDA**, hereby declare

1. that I am the sole author of the present Master's Thesis, " LIFE CYCLE ASSESSMENT OF PET BOTTLE RECYCLING: A CASE STUDY FOR MEXICO", 58 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

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Abstract

Mexico is the world's largest per capita consumer of bottled water and soft drinks; both of which are contained in PET bottles. The extensive use of PET bottles in Mexico has become a severe environmental problem due to the lack of proper governmental management and public awareness. Most PET bottles end up pilled in landfills around Mexico. The lack of recycled PET bottles represents not only a serious environmental and social problem, but also a missed business opportunity. Throughout the last decade, significant efforts have been made by the private sector in order to increase the collection and recycling rate of PET bottles; however, the results are still far from sufficient. Hence, this thesis has three main objectives. The first is to gain further knowledge about the LCA methodology. The second objective is to analyze the PET flows in Mexico, and finally, the third objective is to determine which parameters need to be considered so as to carry out an LCA for PET recycling in Mexico. A complete LCA is not performed due to the lack of available information; nevertheless, it does establish the system necessary to carry out a proper LCA. The results should provide useful information that can assist various stakeholders in the development of PET recycling programmes in Mexico that are economically advantageous, environmentally friendly, and socially accepted.

Acknowledgements

I would like to thank my parents for all their support; without them this accomplishment would not have been possible. Moreover, I would like to thank my supervisor for his guidance and assistance during this “scientific” adventure. Finally, I am very grateful with Yann Huguenard for his moral support and motivation.

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List of Abbreviations

PET	Polyethylene Terephthalate
LCA	Life Cycle Assessment
ISO	International Standards Organization
UNEP	United Nations Environmental Programme
SETAC	Society of Environmental Toxicology and Chemistry
REPA	Resource and Environmental Profile Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
CLCA	Consequential Life Cycle Assessment
ALCA	Attributional Life Cycle Assessment
DQI	Data Quality Indicators
MSW	Municipal Solid Waste
PTA	Purified Terephthalic Acid
EG	Ethylene Glycol
TCCC	The Coca Cola Company
PETRA	PET Resin Association
EEE	Electronic and Electric Equipment
SMA	Environment Improvement Sub-secretary
MT	Metric Tons
ECOCE	Ecology and Corporate Commitment
MXN	Mexican
IMER	Industria Mexicana del Reciclaje

FDA	Food and Drugs Administration
IFC	International Finance Corporation
CPR	Centro de Procesado de Resinas
BTB	Bottle To Bottle

1. Introduction

In the quest for better materials to achieve technological development, scientists have created man-made polymers that are resistant, stable and long-lasting; materials which have become essential for scientific innovation and high living standards. Polyethylene Terephthalate (PET) is one of them. This versatile polymer that can be easily transformed to consumer products by automated machines has a plethora of different applications. PET is largely used in the textile industry, alone or combined with cotton or wool, to increase the durability and resistance of textiles. In fact, it represents more than 50% of the synthetic manufacture in the world (Sinha et al., 2008).

Furthermore since the 1950s, it has been widely used as a film for video, photos and x-rays. Finally, in recent decades, it has positioned itself internationally as the most convenient packaging bottle material for most beverages (Sinha et al., 2008). This attainment is due to the inherent characteristics of the material; its low weight compared to similar packaging materials, good barrier properties towards moisture and oxygen, durability, and high transparency (Vest, 2003). PET bottles have partly replaced glass and metal cans and as a result the global demand for PET is exponentially increasing. These bottles are mainly use to pack water and carbonated soft drinks; however, they have been recently introduced to the market for energy drinks, ice teas, beer, wine and juices.

According to Smithers Pira, the global average demand for PET will increase by 4.8% for the period 2010-15. It will reach 14.5 million metric tons (Mt), which represents 8% of the total demand of standard plastics (Brooks, 2012). In 2005, about 65% of PET production was used to fabricate fiber and 30% was used for bottles (Shen et al., 2010). This trend might change in the near future since the soft drink sector has been growing more rapidly than any other PET application (Sinha et al., 2008). PET experienced the biggest growth in the developing markets of Asia Pacific, Latin America and Eastern Europe. Nevertheless, the largest consumer of PET is still the United States, followed by Mexico and China.

The rising production of PET has raised a major environmental challenge as it is produced from fossil fuels (crude oil or gasoline) and takes a long time to biodegrade or photo degrade; around 1-3% in 100 years (Perugini et al., 2003). This dramatically increases the packaging waste in the already crowded disposal sites.

However, it is important to point out that PET, once produced, does not pose a direct risk to the environment by itself but it does significantly increase the amount of waste volume piled up in landfills, clog sewages, and provide incubation for various pests (Foolmaun and Ramjeawon, 2012).

To address this situation, different technologies have been developed in order to recycle the material or to recover its energy content. In this regard, the major advantage of PET is that it can be 100% recycled; either in a closed loop recycling route or in an open one, and by doing so the solid waste problem is reduced and the efficient use of raw petrochemical materials is promoted. In some countries like Germany, Sweden, Japan and Denmark, the recycling industry is reasonably consolidated. However, it is widely accepted that further actions must be implemented in order to truly obtain an advantageous management of the waste (Perugini et al., 2003).

The PET open loop recycling route is much more mature than the closed loop route. In the former, PET bottles are recycled into fibers or other items while in the latter, one they are reconverted into bottles. The technology to recycle PET for use in food packaging applications is relatively new because there were several safety concerns preventing its use in the past. However, this is no longer the case and recycled PET has proven to have the quality required for use in the food industry. In 2007, around 4.5 Mt of PET bottles were recycled into 3.6 Mt of flakes (Shen et al., 2010) of which around 72% were transformed into fibers, 18% into sheets and strapping tapes, and just 10% into recycled bottles. It is expected that in the near future more and more post-consumer PET bottles will be recycled back into new bottles (Shen et al., 2011).

Formerly, many studies have been conducted concerning the utilization of PET. Most of these studies used the Life Cycle Assessment (LCA) methodology; although with different purposes. While some studies aimed at identifying environmental performance indicators or comparing different goods or materials; others sought to establish a benchmark for various product policies or to provide relevant information to support the decision making process. In fact, the different applications of LCAs are quite vast and diverse. Regardless of the specificities of the different PET LCAs, all of them concluded that recyclying PET is an environmentally friendly practice that reduces the negative burden of the material production. However, the degree to which the burden is reduced varies from case to case (Gironi and Piemonte, 2011; Nakatani et al., 2010; Shen et al., 2011;Foolmaun and Ramjeeawon, 2012;

Pasqualino et al., 2011; Romero-Hernández et al., 2008; Schwanse, 2011;Coelho et al., 2011).

For this thesis, Mexico has been selected as a case study due to the enormous amount of PET bottles used and disposed of in the country. Mexico is the leading consumer of soft drinks in the world with a per capita consumption of approximately 163 liters per year (Fox News, 2011). Mexico is also the leader in consumption per capita of bottled water since the government has failed to provide clean drinking water from the pipes (Malkin, 2012a). The lack of PET bottles recycling represents a serious environmental and social problem but also a missed business opportunity. Therefore, it is crucial to find an adequate waste management solution that is in line with the principles of sustainable development.

Considering the forementioned information, this thesis has three main objectives. The first is to gain further knowledge regarding LCA methodology. The second objective is to analyze PET flows in Mexico and finally, the third objective is to determine which parameters need to be considered in order to carry out an LCA for PET recycling in Mexico. A complete LCA will not be performed due to the lack of available information; nevertheless, it does establish the required system to carry it out. The results of this thesis will hopefully assist in the development of PET recycling programmes in Mexico that are economically advantageous, environmentally friendly, and socially accepted.

In order to attain these three objectives, this thesis will be divided into six different sections. The first section will provide a broad and detailed description of the requirements for LCA studies according to the most prominent international standards, as a detailed understanding of LCA form the basis for its proper application. The second section will outline some general features of PET and it's impact on a global scale; the third will describe the waste generation and management in Mexico while the forth will analyze the issues regarding PET in the country. The fifth section will determine the necessary parameters that must be included in the LCA system and finally, the sixth section will draw some policy recommendations and conclude the study.

2. Life Cycle Assessment

Due to rapid environmental degradation and a growing awareness of this issue, a transition to greener production methods is already taking place. However, there is still a long way to go in order to truly regard the world economy as a "green one". An increasing amount of producers, consumers, governments, and the society in general seek to know and better understand the production chain of the products they are either consuming or producing. The idea behind it is to lead their activities towards sustainability. It is a well know fact that sustainable development comprises many different components even though its definition is still vague and highly conceptual[1]. For Hoffman et al. (1997), sustainable development requires several circumstances to be met but mostly, it requires urgent improvements in the way we use energy and natural resources and in the way in which we dispose of the waste generated from those resources; i.e. eco-efficiency.

The collection and generation of consistent data is one of the bases for a successful transition to a low carbon economy. It allows the proper quantification and comprehension of the environmental impacts and resource and energy consumption that are involved in the life cycle of various products. With the appropriate information, it is possible to develop solutions to reduce negative environmental impacts while maintaining the living standards of a society.

One of the most recognized tools that have been developed with the aforementioned purposes is the LCA. Its principal objective is to reform the unsustainable consumption and production by transforming processes and products into more environmentally friendly versions of themsleves. An LCA has been defined as "a structured, comprehensive and internationally standardized method; [since] it quantifies all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues that are associated with any goods or services (EC/IES, 2010)." In an LCA, the entire product's life cycle is taken into consideration: from the extraction of the raw materials, passing through

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[1] "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts: the concept of needs, in particular the essential needs of the world's poor, to which overriding priority should be given; and the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needsWorld Commission on Environment and Development, 1987."

the production line, the use phase, the reuse and recycling of it up to the final disposal of the generated waste.

Hence, LCA is an influential decision support tool, that when used in combination with other methodologies, can assist in the transition to a truly sustainable development given that it identifies environmental impacts that might not have otherwise been recognized (Nakatani and Hirao, 2011). In order to fully understand what an LCA is, its benefits and how it has been applied up to this point, this section will describe in detail the history and the methodological framework of this tool.

2.1 History and Development of Life Cycle Assessment

During the 1960s, there was a growing social concern about the availability of natural resources; which is considered the "first environmental wave". These concerns initiated a scientific effort to find the real energy used in different products and processes in order to determine the future availability of supplies and the time it would take to deplete them. In 1963 during the World Energy Conference, Harold Smith, the pioneer in this field, calculated the energy requirements for the production of chemical intermediates and products. However, the most transcendent study of the time was "The Limits to Growth" which showed how a growing population and economy interact with limited resources. Its conclusions served as an inspiration for the development of further research. In fact, following the publication of the study, several new studies have been conducted to examine the environmental and economic implications of various energy sources (SAIC, 2006).

In 1969, the foundation for the contemporary methodology used to conduct an LCA was developed. The Coca Cola Company carried out an internal study to determine which beverage container had the lowest environmental impacts and consumed the least natural resources. In this study, the raw materials and energy requirements were calculated for each package made out of different material. However, Coca Cola was not the only company with this idea; as several other companies in developed countries began performing similar studies. These studies had different names in the United States and in Europe. In the former they were referred to as Resource and Environmental Profile Analyses (REPA) while in the latter they were called Ecobalances. The main problem that these early LCAs faced was a lack of information due to the fact that their only sources were government documents and technical papers which were rarely available for the general public (SAIC, 2006).

Throughout this period, the initial assumptions and methodologies were revised by different experts in the field and industry which lead to reasonable improvements.

During the early 1970s, the main public concern was the availability and use of fossil fuels since the world was in the middle of the first oil crisis. In accordance with the spirit of the time, Ian Boustead calculated the amount of energy required for the production of various beverages containers with the intention of determining which material (glass, plastic, steel and aluminium) should be preferred in terms of energy efficiency. Over the years the author sophisticated its methodology and by 1979, the first *Handbook of Industrial Energy Analysis* was published (Hoffman et al., 1997).

After the oil crisis and throughout the 1980s, the environmental concerns around the scarcity of fossil fuels shifted to issues concerning waste management. Furthermore, when hazardous waste became a global problem in the late 1980s, an LCA was the preferred tool to evaluate the situation. Once again the LCA methodology had to be improved upon in order to address environmental problems of a different nature (SAIC, 2006). Finally, during the early 1990s a real interest for the LCA methodology permeated a large range of industries. It was even considered by the UN Earth Summit to be the most promising tool to support environmental management (Hoffman et al., 1997).

The use of LCAs grew so much that they were even improperly used as advertisement tools. To avoid this situation, different stakeholders successfully campaigned for the standardization of the LCA methodology and as a consequence the International Standards Organization (ISO) began the standarization process. ISO is not the only organization taking on this task, as several other international institutions and organizations have joined the cause of standardizing the LCA methodology. In 2002, the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) initiated the Life Cycle Initiative with the purpose of improving this methodological tool with enhanced statistics and indicators (UNEP, 2000). In the next section the state of the art of LCA methodology is described by outlining guidelines, principles, and models.

2.2 LCA Methodological Framework

According to ISO 14040, an LCA is a "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle (Guinée et al., 2001)." Therefore, it can be considered as an analytical tool that depicts the environmental footprint caused by a product or process from cradle to grave. This term means that an LCA will consider all production stages; from the extraction of raw materials to its final disposal. As is the case with most scientific tools, LCAs should, first and foremost, be quantitative in nature and only when the specific circumstances do not allow it, qualitative aspects should be considered.

LCAs can be used for diverse applications by a vast range of stakeholders. Eco-labeling is one common example of their application. In this case, an LCA is used to compare different products with the same function in order to assign a green label to the products that show better environmental performances. The Green Swan eco-labeling programme in Nordic countries and the Blue Angel programme in Germany are considered to be quite successful. Another application of LCAs is eco-design, which aims at designing and producing new products that are in line with the environmental concerns. Most of these studies are performed for internal use in private companies. The use of an LCA is not limited to its direct application in specific products. Actually, it can be used in a much broader sense such as in investment development, business strategies or governmental policies (Guinée et al., 2001).

However, it must be clearly understood that LCAs do have limitations and risks. For example, they cannot verify which product is more cost effective or which one provides more satisfaction to clients, as these tasks are out of the scope of the methodology. Since carrying out an LCA can be time and resource consuming, the objective must be established in advance in order to determine if an LCA is the proper tool to reach it (SAIC, 2006). In any case, the results of an LCA must be considered in combination with other decision making tools.

> As such, it provides information for decision support [yet] LCA cannot replace the decision making process itself. One cannot say: 'The LCA has proved that this decision must be made,' but rather 'Based on an LCA study and other evidence, the following decision has been made'(Guinée et al., 2001).

The structured framework established by ISO must be followed in order to perform an appropriate LCA. This is not a sequential process but an iterative technique, which means that some elements of the study may have to be redefined over and over again as the study progresses and the data availability increases or decreases. The ISO framework, which is supported by wide international consensus, divides the LCA methodology in four steps: goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and interpretation (ISO 14040, 2006). However, it only serves as a basis for LCA because each individual study should design a suitable process that is attuned to fulfill its particular objective. In the following sections the four methodological steps are described in greater detail.

2.2.1Goal and Scope Definition

The definition of the goal is the first step in every LCA and is crucial for the design of the subsequent steps. Therefore, a clear goal is indispensable to design and interpret an LCA correctly. In order to achieve an appropriate goal some basic aspects must be defined:

- Intended application of the results→ the purpose of the LCA should be stated in an accurate and explicit way. It is also possible that a single LCA has distinct intended applications. Depending on these applications, the requirements and methodological approaches stated by ISO 14040 can slightly change.
- Limitations due to the method, assumptions, and impact coverage→ once the goal is defined, the limitations resulting from the applied methodology and assumptions should be clearly stated as to avoid inappropriate comparability or transferability of results.
- Reasons for carrying out the study→ the goal must include a justification that explains the author's rationale for Given this rationale, it is possible to determined the type and quality of data required to perform the study.
- Decision context→ the definition of this aspect is of great importance because it directly influences the modelling framework (attributional versus consequential) and the LCI method approach (allocation versus substitution) that will be used. The decision context can be divided into Situations A, B and C, which will be explained in further detail later in this section.
- Target audience of the results→ the audience must be considered so as to establish the appropriate structure and languageto be used in the delivery of the results and if any critical review is necessary. There are many different types of audiences: internal, external, public, private, technical, non-technical, etc.
- Commissioner of the study and other influential actors→ the goal must clearly state who commissioned or supported financially the study (ISO 14040, 2006).

From all of the various aspects that must be considered, it is necessary to provide furhter details regarding the decision context. As mentioned before, the decision context can be classified into 3 categories, situations A, B or C. The differentiation arises from two variables. The first is whether a study explores the consequences of certain decision or not and the second considers the extent of change that a decision might produce. Therefore, if a study examines the potential consequences of a decision, the LCA should reflect these consequences. Otherwise, the study should simply describe the selected system without considering any aspects of the decision making process. Regarding the second variable, studies can be classified by the size of the consequences in the background system.[2] Small scale changes mean that it does not require the installation of further infrastructure. On the other hand, large scale changes, which are not so common, describe a situation where the decision transforms part of the economy and the installed equipment. It is important to point out that these are only changes for the background system since the foreground system has to be modelled explicitly in both cases (EC/IES, 2010).

Decision support?		Kind of process-changes in background system / other systems	
		None or small-scale	Large-scale
	Yes	Situation A "Micro-level decision support"	Situation B "Meso/macro-level decision support"
	No	Situation C "Accounting" (with C1: including interactions with other systems, C2: excluding interactions with other systems)	

Figure 1 Combination of two main aspects of the decision-context (EC/IES, 2010)

As seen in Figure 1, situation A accounts for studies that are carried out to inform consumers about products that are already on the market or ones that will be entering it soon. It should be noted that the term product is used for goods and services. In this situation, the life cycle of a product, either leads to no or very few changes in the background system. For example, the use of the installed capacity may be changed, but without the installation of new facilities.

On the other hand, situation B covers circumstances where the consequences of a certain decision have a large impact on the background system; the consequences are so far-reaching that extra capacity must be installed. This type of decision

[2] Background system is defined as a system that "comprises those processes that are operated as part of the system but that are not under direct control or decisive influence of the producer of the good (or operator of the service, or user of the good)(EC/IES, 2010)."

context is mainly applied for policy information and development. Finally, situation C is used when the objective of the study is a mere description of the product without the involvement of any decision making that could create changes in the system. This decision context has two subcategories: C1 and C2. The first describes a system and its external interactions while the second provides an illustration of the system in itself (EC/IES, 2010).

These situational concepts can be further classified into two categories: an attributional life cycle assessment (ALCA) or a consequential life cycle assessment (CLCA). ALCA, which includes situations C1 and C2, has the objective of describing the significant environmental input and output flows within the life cycle and its interactions. On the other hand, CLCA, which includes situations A and B, has the objective of describing how the same input and output flows will be affected in response to changes introduced into the life cycle. Decision theorists recognize that CLCA information is essential in order to make rational decisions (Ekvall and Weidema, 2004). Some scholars consider a CLCA to be superior to an ALCA (Earles and Halog, 2011); however, it must be pointed out that it is not about superiority but appropriateness. Whether the ALCA or the CLCA are “superior” will depend on the goal of the study in question.

Once the goal has been set, the scope must be defined too. The scope determines the most important characteristics of an LCA. It covers such matters as “temporal, geographical and technology coverage; the mode of analysis employed; and the overall level of sophistication of the study (Guinée et al., 2001).” The scope must be defined in great detail in order to facilitate the achievement of the LCA goal. While establishing the scope, some key items must be determined: the functional unit, the reference flows and the system boundaries and functions.

The functional unit shows the principal function fulfilled by the product’s system and qualitatively and quantitatively defines the features of the unit by using the questions what, how, how well, and how long (EC/IES, 2010). International System (SI) units should be used for the functional unit and reference flows and can be determined randomly or derived from a standardized measure; however, in each case a justification must be provided. When making comparisons, it is necessary to choose a functional unit that can be used equivalently in alternative products systems and to determine the reference flows for each of them. Reference flows are defined as the “measure[s] of the outputs from processes in a given product system which are required to fulfill the function expressed by the functional unit (Guinée et al., 2001).”

While comparing functional units and reference flows the LCA practitioners must make sure that they are indeed equivalent. One of the most common mistakes is to make a comparison between diverse materials considering their mass (EC/IES, 2010). However, this comparison will be inadequate since 1 kg of gold is not comparable with the functional unit of 1 kg of silver. In this case it would be more accurate to use the function of the metals to compare them; 1 gold necklace against 1 silver necklace.

Regarding system boundaries, they determine which stages and processes of the life cycle belong to the system which is being analyzed. In fact, this boundary separates the system from the rest of the technosphere. In some cases it is difficult to draw the line between ecosphere and technosphere; therefore,

> [t]he boundary technosphere / ecosphere can hence be more suitably be defined by determining the elementary flow as single substance or energy entering the system being studied that has been drawn from the ecosphere without previous human transformation, or single substance or energy leaving the system being studied that is released into the ecosphere without subsequent human transformation (EC/IES, 2010).

It is very important to accurately define the system boundaries so as to ensure that all processes and potential environmental impacts are included in them. All economic activities are interconnected in to certain extent and consequently, in theory, all should be included in the system. However, not all of these activities have the same relevance for the analyzed product. Therefore, all flows that are not especially relevant for the system can be “cut-off”, which means that they can be excluded. It should be mentioned that only normal and abnormal processes are covered by the LCA methodology; accidents or similar situations must not be included (ISO 14044, 2006).

As was previously mentioned, the system boundaries determine which stages and flows are included and therefore analyzed. This selection of stages and flows is comprised of a qualitative and a quantitative aspect. The qualitative aspect determines which phases of the life cycle must be included to guarantee a proper data set and valid comparison. In attributional LCAs, the life cycle is considered to be a generic supply chain, while in consequential LCAs, the phases in the background system that are affected by the decisions made in the foreground system must be considered. This means that elements which are not part of the analyzed system should be included in the system boundary. The quantitative aspect ranks the processes and flows in order of relevance. For those that are least relevant, low quality data can be used with the intention of focusing on the collection of high class quality data for those that are more relevant. As for the irrelevant ones, they can be cut-off entirely. These cut-offs must be stated in relation to the approximate excluded environmental impacts; e.g. 75% shows the cut-off of 15% of the total environmental impacts (EC/IES, 2010).

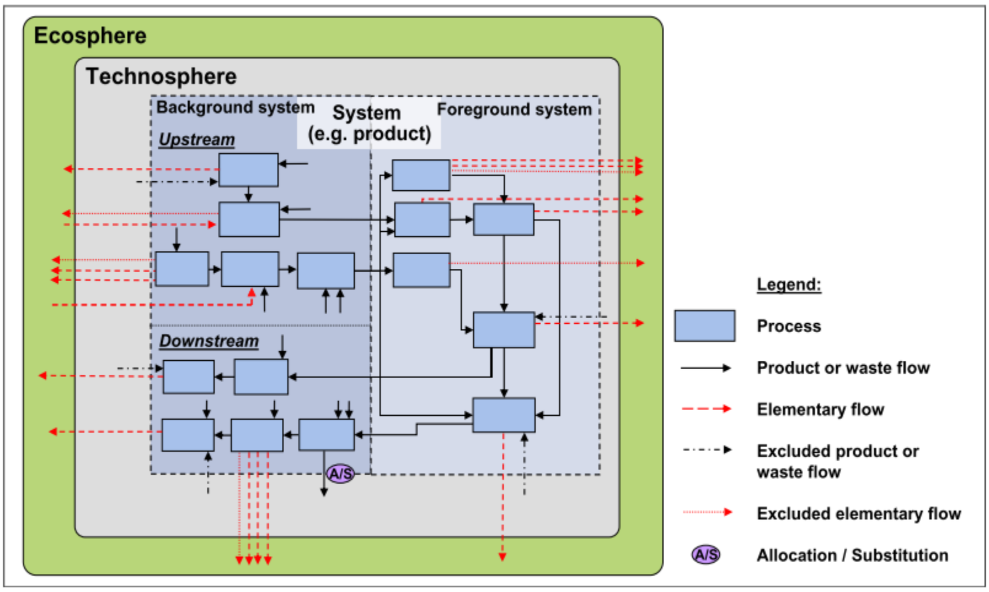

Figure 2 Ecosphere, Technosphere and the System Boundary (EC/IES, 2010)

Figure 2 shows a standard system flow diagram with its boundaries, flows and interactions between the technosphere and the ecosphere. It is strongly recommended to depict the analyzed system in this way in order to facilitate an understanding of the product system. Boxes are used to illustrate unit processes while arrows are used for linking flows; the direction of the arrow indicates the direction of the flow. In the system flow diagram three types of boundaries can be distinguished: boundaries between the product and the environmental system, boundaries between the relevant, and irrelevant system and boundaries between the analyzed system and other systems (Guinée et al., 2001).

After the determination of all the above mentioned elements, the outcome can be used to start the LCIA step which is described in greater detail in the next section.

2.2.2 Life Cycle Inventory

The second step in an LCA is the LCI. During this phase, all the input (energy and resources requirements) and output data (solid, liquid and gas emissions) are collected and organized. Without further analysis, the LCI can be used on its own to assist in the decision making process. For example, it could be used by the government to develop emissions limits or natural resources regulations. Basically, an LCI is a list that contains the energy and materials used in the production of the analyzed system plus the contaminants that are released to the environment due to this activity (Pålsson and Riise, 2013). In order to perform an LCI four steps must be followed: “[d]evelop a flow diagram of the processes being evaluated, [d]evelop a data collection plan, [c]ollect data [and e]valuate and report results (SAIC, 2006).”

Firstly, it is necessary to develop a flow diagram; what needs to be included in this diagram is determined by using the goal and scope information. The flow diagram illustrates the inputs and outputs from the process units. In order to get more accurate results, the flow diagram should be designed in a more complex way. However, the more complex it is the more time and resources must be devoted to data collection and analysis (ISO 14044, 2006). Figure 3 shows a generic flow diagram.

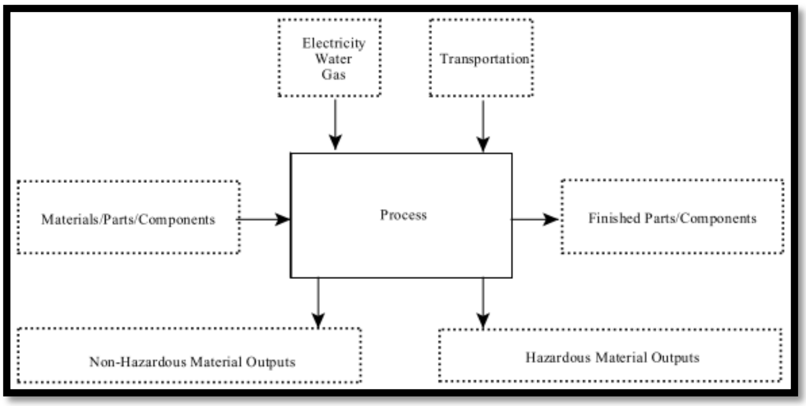

Figure 3 Generic Unit Flow Diagram (SAIC, 2006)

In order to facilitate the collection of data, it is recommended to divide the analyzed system into subsystems. Subsystems are individual steps that, when put together, form a complete system. For each one of the subsystems, input, output, and transportation data must be collected and specified as much as possible. The performed activities should also be described.

> Data should be gathered for the amounts and kinds of material inputs and the types and quantities of energy inputs. The environmental releases to air, water, and land should be quantified by type of pollutant […]Transportation [should be] quantified in terms of distance and weight shipped, and identified by the mode of transport used (SAIC, 2006).

If a process produces more than one product, all co-products should be quantified. Output products that have no value should be considered as waste; but if they have a market value they should be treated as co-products. In a multi-input/output system it is necessary to allocate the burdens between the different co-products. The allocation can be done by using different methods i.e. allocation based on indicators of economic value. The inclination towards the preferred allocation method should be clearly justified (Guinée et al., 2001). The collection of data should be measured using the formal data quality indicators (DQIs); which are completeness, accuracy, precision and representativeness. However, it is also recommended to include an explanation of how the data were generated.

Secondly, a data collection plan should be developed. To start with it, a quality goal should be determined to use as a benchmark during the collection of data. The level of accuracy needed for the decision making process will serve as guidance for the quality goal since there is not a predefined value that fits all LCAs. The decision of which DQI to use depends on the particular characteristics of the analyzed system (SAIC, 2006).

In order to maximize time and resources, it is recommended to define which data sources and types will be used for the LCI in advance; some data sources are government documents, industry data reports, academic journals, patent reference books, etc. Data types can be classified into three groups: specific, average, and generic data. However, in practice the data available is a mixture of three. Specific data refers to data that has been measured for a specific technology in a specific site; average data refers to data that combine and average a set of specific data and generic data refers to data that have been calculated using only a certain amount of specific data. The types and sources of data that are more suitable for an LCI depend on the defined goal and scope. Usually, when an LCA is designed to be publicly available, average or generic data are used, and when the LCA is for the internal use of an industry it uses specific data (EC/IES, 2010).

As a part of the data collection plan a spreadsheet should be designed to facilitate the construction of an electronic database. It should include: “system boundaries, type of data used, data collection procedure and data quality measures (SAIC, 2006)." Nonetheless, it can include other categories that seem appropriate for the case. Each subsystem and element should be included and linked in the spreadsheet in order to avoid omissions and double counting.

Thirdly, data must be collected. This stage includes the collection of data from different sources which range from industrial visits to academic publications. Since this can be very time and resource consuming, many LCA practitioners use commercial LCA software as a cost effective option even though there is the risk of losing a certain degree of transparency (Guinée et al., 2001).

Finally, the data must be evaluated and reported. In the final report, all previous stages should be clearly described and the assumptions explained. An LCI will contain a great amount of information that is sometimes very different in nature. Therefore, it is necessary to select a model to consistently aggregate all of it. In addition, the temporal, geographical and technological representativeness of the data inventory must be verified. The modelling of a system involves the transformation of all data from the systems' processes into a proper scale. This scale is determined in relation to the processes' participation in the whole system and functional unit. To scale all inputs and outputs, the data must be multiplied by the unit process. The resultant units show the amount of each input needed to produce one functional unit and the amount of output that is generated after its production (Pålsson and Riise, 2013). While performing the LCI calculations, it is indispensable to apply the same calculation procedure throughout. The final LCI results should only represent the functional unit and the elementary flows that cross the system's boundaries (SAIC, 2006).

In order to report the results of the LCI, different formats can be used. The two main formats are graphical and tabular. It is also useful to divide the results into different categories. For example, the energy data could be further divided in total energy process and total energy from the material resource; waste can be divided into industrial and post-consumer waste; environmental emissions can be divided into atmospheric and water emissions, etc. By doing so, it is possible to better understand, handle and report the data. It is recommended to use a combination of tabular and graphical formats. The inventory itself is better presented in a tabular way; however, the contents of the tables vary from study to study and depend on the goal and scope they have. The graphical presentation should assist in the interpretation and reporting of the tables. The objective is to ensure clarity, especially when the target audience is not comprised by experts in the field (EC/IES, 2010).

Direction	Group	Receiving environment	Name	Amount	Unit
Input	Natural resource	Ground	Bauxite	0,00024	kg
Input	Natural resource	Ground	Crude oil	0,43	kg
Input	Natural resource	Ground	Dolomite ore	0,22	kg
Input	Natural resource	Ground	Hard coal	0,72	kg
Input	Natural resource	Ground	Lignite	0,81	kg
Input	Natural resource	Ground	Natural gas	0,45	Nm3
Input	Natural resource	Ground	Uranium in ore	4,3E-05	kg
Input	Natural resource	Ground	Wood	0,051	kg
Input	Natural resource	Ocean	Mineral, oil and gas extraction area	1,31E-10	km2
Input	Refined resource	Technosphere	Fuel gas	3,54E-03	m3
Input	Refined resource	Technosphere	Steel	5,61E-05	kg
Output	**Product**	**Technosphere**	**Nitrogen fertiliser**	**1**	**kg**
Output	By-product	Technosphere	District heat	2,1	MJ
Output	Emission	Air	Ammonia (NH3)	0,21	g
Output	Emission	Air	CFC-11	1,4E-08	kg
Output	Emission	Air	CFC-114	3,6E-07	kg
Output	Emission	Air	CFC-12	2,9E-09	kg
Output	Emission	Air	Carbon monixide (CO)	0,72	g
Output	Emission	Air	Carbon dioxide (CO2)	2,61	kg
Output	Emission	Air	Dichloromethane	1,8E-09	kg
Output	Emission	Air	Hydrocarbons (HC)	0,0075	g
Output	Emission	Air	HCFC-22	3,20E-09	kg
Output	Emission	Air	Methane	0,0049	kg
Output	Emission	Air	Nitrous oxide (N2O)	4,58	g
Output	Emission	Air	Non-Methane Hydrocarbons (NMHC)	68,6	mg

Figure 4 Fictitious Example of an LCI (Pålsson and Riise, 2013)

Once the four steps have been realized, the LCI is complete. Figure 4 shows an example of an LCI in a tabular format. With the LCI information, an LCIA can be performed. The LCIA is explained in the next section.

2.2.3 Life Cycle Impact Assessment

An LCIA is performed with the intention of evaluating the possible environmental impacts of the analyzed system; i.e. its goal is to link the product or process with potential environmental negative consequences. Nevertheless, it does not intend to find out specific impacts associated with the analyzed system. LCI only determines stressors, which are a series of circumstances that can lead to a determined impact. The results of LCIAs should not be considered as predictions of actual environmental effects but only as impact potential indicators (EC/IES, 2010).

To execute an LCIA, it is necessary to have the data previously collected in the LCI. However, some other elements, mandatory and optional, should be considered. The mandatory elements are the selection, classification and characterization of the impact categories, while the optional elements are the normalization, grouping and weighting of them (ISO 14044, 2006). Each element is explained below in further detail.

The selection of the impact categories must be in accordance with the goal and scope of the analyzed system. The impacts are the consequences on the environment that the analyzed system will most likely produce. The impacts are typically divided into three areas of protection: human health, natural environment, and natural resources (SAIC, 2006). While performing an LCIA, two types of practice can be followed: the midpoint or the endpoint. The midpoint, also known as the problem oriented practice, classifies the flows into a few environmental areas which facilitate the evaluation of a large number of flows and therefore, it reduces the complexity of the model. The endpoint, also known as the damage oriented practice, classifies the flows into different environmental categories, and also classifies the damage according to human health, natural environment and damage to natural resources (Pålsson and Riise, 2013). Figure 5 illustrates how the data from the LCI is used and transformed into an LCIA and the difference between mid-points and end-points.

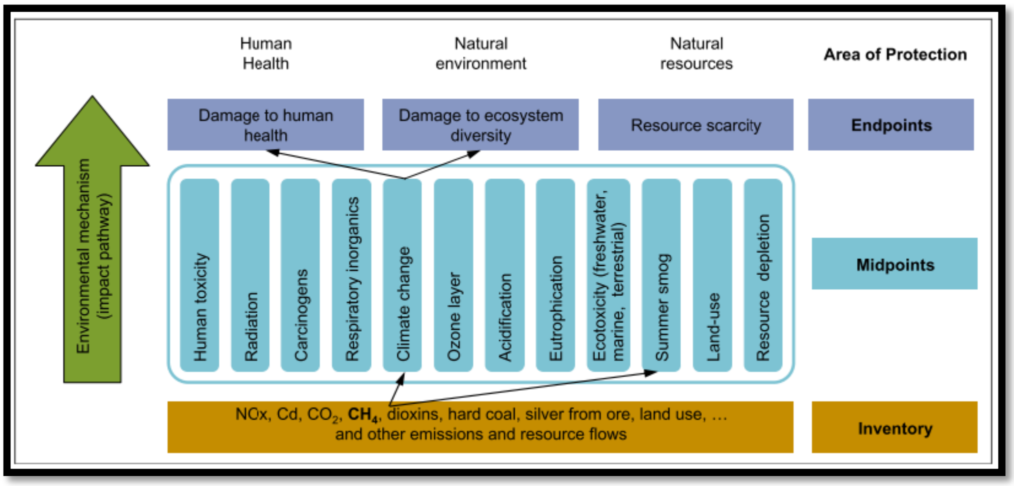

Figure 5 LCIA Schematic Steps from Inventory to Category Endpoints (EC/IES, 2010)

In order to decide which impact categories should be included in an LCA, some features have to be considered. The largest number of relevant impact categories should be included in the impact assessment so as to fulfill the defined goal and scope. The impact categories should be considered as independent entities in order to avoid double counting but they should be kept down to a practical number. Finally, they should be based on the scientific method (Pålsson and Riise, 2013).

On the subject of classification, the input and output data from the LCI is divided and grouped according to their environmental impact. The goal is to organize all the data information from the databases into particular impact categories. For the data that have an impact on only one category, the classification is not problematic; however, if an indicator can be placed into two categories a classification rule should be established. According to the ISO (2006), there are two methods of classification. The first one is applied when the effects are dependent on one another. In that case, the indicator is divided and proportionally placed in different categories according to its contribution to each one. On the other hand, the second one is used when the effects are independent of each other. In such cases, the indicator is placed into all categories where it fits.

As for characterization, it describes and quantifies the contribution that LCI data have on the category indicator. First it converts all the different units of an impact category into a single one and then it adds them all together in order to determine the total contribution of the analyzed system.

> For example, the category indicator Global warming potential is measured in CO_2 equivalents. In this case the characterization involves:
>
> 1. Converting all emissions to air from the product system that contribute to global warming (CO_2, methane, nitrous oxides, freons etc.) into CO_2 equivalents, and;
>
> 2. Adding up the contribution from each emission into the total CO_2 equivalents for the product system (Pålsson and Riise, 2013).

In order to achieve a successful characterization, it is necessary to utilize the proper characterization factor. For some categories such as global warming there is an international consensus concerning its appropriateness; however, for some others such as resource depletion it is still under debate (SAIC, 2006). It is important to point out that since the impact categories use different characterization factors, it is not possible to sum them up or to compare them.

At this point, all the mandatory elements have been fulfilled; however, three more optional steps can be performed. The first is normalization. The objective of normalization is to improve the level of interpretation of the results. Sometimes due to the usage of different units it is difficult to correctly understand the results, especially for a non technical target group. Normalization compares the results with a reference value, which can be chosen *ad hoc* e.g. total emissions per capita in a country, average consumption of certain product, a baseline scenario, etc. Therefore by showing the normalized results, it is possible to clearly identify and compare the contribution of the different impact categories on the system. Nevertheless, this comparison only reflects the contribution to a category but not the severity or relevance of it (EC/IES, 2010).

The second optional step is grouping, and it intends to divide the results into different categories according to the goal and scope of the analyzed system. The categories can be also ranked; although this ranking always involves value choices. The third and final optional step is weighting, which aims to calculate an environmental value that describes the entire system. To do this, all the impact categories are multiplied by a weighting factor, which finally allows all the categories to be summed up.[3] The problem with this method is the high level of subjectivity involved because the weighting factor is not derived scientifically and it is only based on social sciences. It shows the preferences of the author at a particular place and time. Consequently, its use cannot be extended any further; its preferences are not considered to be stable. It is not possible to develop an objective set of weights to apply to every LCIA, though some weighting methods do exist e.g. Modified Delphi Technique. This step is considered to be the least developed element of an LCIA (Pålsson and Riise, 2013).

2.2.4 Interpretation

Once all the previously mentioned steps are fulfilled, their different results can be interpreted together by considering their levels of accuracy, completeness, and precision. Also, the assumptions taken throughout the study should be revised. The interpretation phase has two objectives. First, it analyzes the conclusions, clarifies the study limitations, and recommends certain strategies that are deduced from the LCA and second, it should report and present the results in a complete and clear manner in order to transmit them to the target audience. The presentation should be in line with the goal and scope of the LCA. The interpretation of the results is not a straightforward method, can typically directly settle the best alternative. However, there are some cases where it is not possible to determine the best alternative due to the high level of uncertainty in the results. Even in these cases, the LCA is still useful as it provides information to the decision makers in terms of pros and cons of each alternative (Guinée et al., 2001).

In order to fulfil the interpretation step, three activities must be completed: identification of significant issues; completeness, sensitivity, and consistency of data

[3] Under ISO 14044 (2006) weighting shall not be used in comparative intended for the general public.

evaluation and finally, deduction of recommendations and conclusions (EC/IES, 2010). The process involved in each of these activities is described below.

The first activity is the identification of significant issues from all the data collected in the previous LCA steps. The significant issues can be elementary flows, parameters, assumptions, processes, products, etc that have had the biggest impact throughout the LCA. To determine which issues are indeed significant, the data collected should be evaluated in a broad manner. Due to the large amount of data collected throughout the entire process, it is necessary to identify the aspects that contribute the most in order to complete the next steps. The selection of significant issues can turn into a complex problem from time to time. In order to facilitate the process, different analyses can be applied. The contribution analysis compares the contribution of the data results. The dominance analysis ranks the results qualitatively or quantitatively and the anomaly assessment points out atypical deviations from the “usual” results. All of them define the relevance of the different results components (ISO 14044, 2006).

The second activity is the evaluation of the completeness, sensitivity, and consistency of the results. The objective of this activity is to create confidence in the results. The completeness check warrants that all the data that are needed are readily available and complete. A checklist can be developed in order to show that each relevant area is included in the system boundaries. If relevant data are missing, measures must be taken in order to remediate the gaps. On the other hand, the sensitivity check determines the precision and reliability of the results. Previous studies or the opinion of an expert can be part of this analysis. This type of analysis is not obligatory; however, it is recommended. Lastly, the consistency check verifies if the methods, assumptions, models and data are in compliance with the defined goal and scope. In the event of inconsistencies, it is necessary to justify them with the purpose of assuring the study’s validity (SAIC, 2006).

The third activity is the deduction of the conclusion and recommendations for the LCA. The objective is to integrate the LCA limitations, the conclusions derived from it and the recommendations for the decision makers (Guinée et al., 2001). With the intention of increasing transparency, it is better to clearly separate the facts from the judgement. It is advised to present final conclusions separately from recommendations. The conclusions state if the goal defined at the beginning of the LCA was reached; if the goal was accomplished the conclusions can be considered as final, but if that is not the case the conclusions must be reformulated and verified once more. The conclusions must clearly indicate any limitations of the study and should be as straight forward as possible in order to avoid misinterpretations. Finally, the recommendations are strategies that should be followed considering the final results. They should be logical, feasible, and practical and made in a conservative way based in the LCA findings (SAIC, 2006). In figure 6 a schematic version of the interpretation step and its interaction with the other phases is shown.

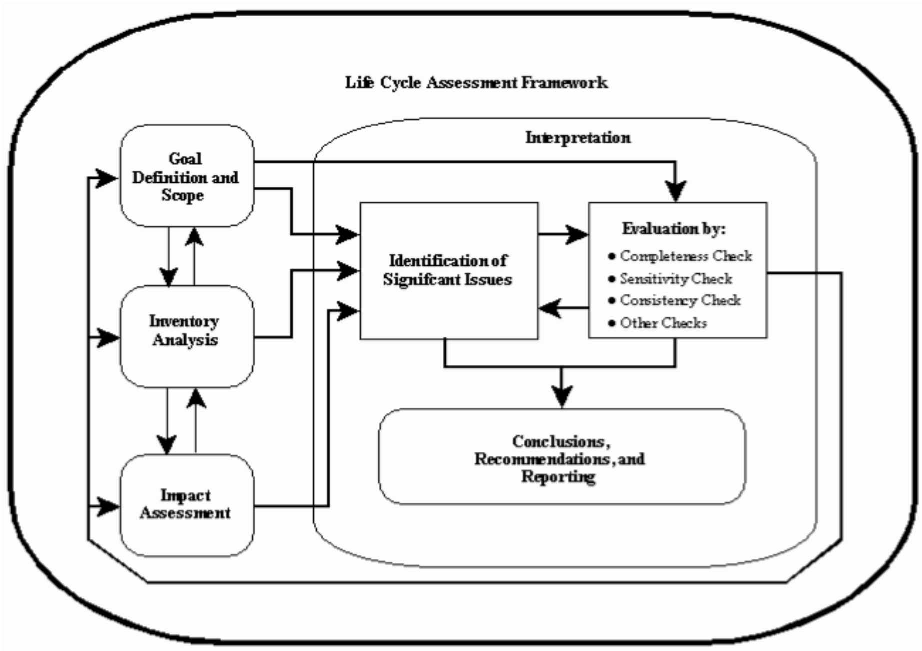

Figure 6 Interpretation Step with other Phases of the LCA (SAIC, 2006)

The final conclusions and recommendations must be reported in a tailored fashion in order to be perfectly understandable for the target audience. The content of the final report must be clear enough so the decision makers to misinterpret the information given or analyze it in an improper context. Upon the delivery of results to the stakeholders, the LCA is completed.

Even though LCAs all have to follow the same general methodology, they can be modified according to the needs of the study. Since this thesis is addressing post consumer PET recycling, the next section will describe the methodology that has been developed to better model recycling scenarios.

2.3 LCA Recycling Methodology

In a world where recycling is perceived as one of the most optimal options for the End-of-Life of most products, LCA scholars were required to develop appropriate ways to measure and prove the various benefits of recycling. This task raised specific challenges such as the correct placement of the system boundaries and product allocation.

In order to properly place the system boundaries of a recycling system, it is necessary to define the kind of recycling route that the product follows. Theoretically, recycling routes can be classified into 3 different categories: closed-loop recycling, open-loop recycling and semi-closed-loop recycling. Closed-loop recycling takes place when the recycled materials are introduced again into the same manufacturing process. This is possible because the recycled material has the same properties as the virgin material. In contrast, open loop recycling occurs when the recycled materials are used in a different manufacturing process since its properties vary significantly from the properties of the virgin material. Finally, semi-closed-loop recycling takes place when the recycled materials, albeit conserving the characteristics of the virgin material, is used in diverse production processes (Guinée et al., 2001). Closed loop and semi-closed loop are regarded as one category by most scholars.

The main challenge regarding the allocation of post-consumer products is how to divide the impacts of the system. Several allocation methods have been developed thus far. The most utilized ones are: cut-off, system expansion, economic allocation, input oriented, substitution, value-corrected substitution and multiple recycling. In all of these, the inputs and outputs can be allocated differently; therefore, in each case, the allocation method must be clearly explained and documented. If many allocation methods can be applied to a specific case, a sensitivity analysis can be carried out to select the method that is most appropriate (ISO 14044, 2006). In the next few paragraphs each allocation method is explained in greater detail.

1) The Cut-off Method is one of the simplest methods to apply as there is no need to collect data from other processes that are outside the system boundaries. The environmental burdens caused directly by a product in the different stages of its life cycle are assigned to that product. The first life includes the environmental burdens of the virgin material production while the second life comprises the burdens of the refurbishing process and the recycled material. The environmental burden of waste disposal will not be counted until the materials are finally disposed of in sinks (Link et al., 2009). This method is seen as a promoter of products that contain a high amount of

recycled materials.

2) The System Expansion Method is used to avoid allocation problems. All the processes involved with a product are placed inside the system boundaries. Actually, ISO 14044 (2006) greatly encourages the use of system expansion. However, the inclusion of new processes witin the system boundaries can greatly increase the level of complexity and could even lead to new allocation problems (Guinée et al., 2001).
3) The Economic Allocation Method is based on the monetary value of the inputs and outputs of the system, and its goal is to find the economic equilibrium of the different flows. It assumes that since the system is part of the economy, it is possible to base allocation decisions on economic data. Nevertheless, this method is complicated as market prices oscillate with supply and demand (Franklin Associates, 2009).
4) The Input Oriented Method is based on the cut-off approach. It only considers the system inputs including collection, recycling and waste disposal. However, the output of the system in not placed inside the system boundaries (Ligthart and Ansems, 2002).
5) The Substitution or Avoided Burden Method is based on the assumption that recycled material is substituted for virgin material. It is especially useful when the recycling route is a closed loop since virgin and recycled materials share the same properties. ISO 14044 (2006) states that for the closed- loop route, allocation is not necessary due to the complete substitution of the virgin material. This method also includes the refurbishing of new material since some of the virgin material is disposed of without recycling. It promotes the benefits of recycling as an increase in the recycle rate leads to a reduction of environmental impacts (EC/IES, 2010).
6) The Value-corrected Substitution Method takes into account the difference in quality between the virgen material and the recycled one. It uses the material to price ratio to determine the quality loss in the recycled material. This ratio will then determine the amount of recycled material that can be substituted for the virgin one, i.e. the market prices are considered as a proxy for material quality. It is necessary to have a constant price relation between both materials otherwise, as in the economic allocation method, this method becomes quite complicated due to the price volatility. Environmental burdens change in relation to the price variation, even if the rest of the system remains the same (Ligthart and Ansems, 2002).

7) The Multiple Recycling Method is used for open-loop and semi-closed -loop recycling routes where the recycled material slightly changes its characteristics. It is used for recycling processes that have more than one life cycle. Several parameters are needed in order to determine the cumulative amount of product for the number of cyles and the environmental impact of the system. The parameters are: recovery rate, yield of the recovery process, impact of the primary production, impact of the secondary production, and the number of life cycles (Ligthart and Ansems, 2002).

3. PET Problematic

In the last few decades, due to rapid economic development and high rates of urbanization, the disposal of garbage started to become a genuine and ever-growing global problem. In urban areas most of the world's rubbish is generated; however in general, they have better waste management than their rural counterparts. In 2012, cities all around the world "generate[d] around 1.3 billion tonnes of MSW a year, or 1.2kg per city-dweller per day, nearly half of which comes from OECD countries (The Economist Online, 2012)." It must be emphasized that these averages are broad estimations since the garbage generation greatly diverges from one place to another. Also the composition of waste varies and is shaped by a number of different factors like income level, culture, weather, natural resources, among several others. For example developing countries have a larger proportion of organic waste than developed countries which present high amounts of plastic and paper (Hoornweg and Bhada-Tata, 2012).

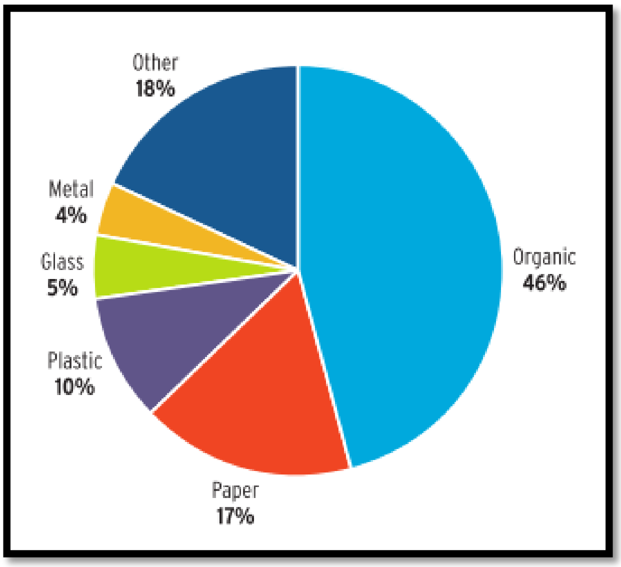

Figure 7 Global Solid Waste Composition (Hoornweg and Bhada-Tata, 2012)

As seen in Figure 7, plastic represents 10% of the global MSW, which is a considerable percentage; especially if it is compared to other inorganic materials like glass or metal. Since its invention, plastic has been used to substitute other materials and it is considered as the engineering material of our time. It is the "most intelligent application of crude oil, since more than 80% of this valuable source is still used for the direct production of energy (Perugini et al., 2003)." PET is a variety of plastic that has experienced an exponential growth due to its numerous convenient properties. This material has been so successful because it presents several economic and environmental advantages over similar materials. Its production is cheaper and less energy consuming than other material, and it is easier to transport given that it is significantly lighter. Furthermore, it fulfills the same quality requirements as other materials in order to be used in food packaging (Coelho et al., 2011).

According to a study from Smithers Pira, the global consumption of PET will be around 19.1 million tonnes by 2017(Brooks, 2012). The United States is the leading consumer of PET packaging followed by China and Mexico. This increase is mainly due to the massive consumption of beverages that are packaged in PET bottles. In 2007, the global consumption of PET bottles was 15 million tonnes, which accounted for 8% of the world plastic production (Shen et al., 2010). The increasing consumption of PET has lead to a serious environmental problem. Due to its chemical composition, PET biodegrade in an extreme low pace which means that PET bottles occupy an important fraction of landfill space that is already crowded and scarce (Perugini et al., 2003). Furthermore, it is possible that this disposal technique will not be accepted anymore since it contributes to ground water pollution, gaseous emissions and health problems.

As a consequence, proper waste disposal of PET has become a relevant issue. PET non returnable beverage bottles entered gradually into different recycling schemes. Today, the recycling of post consumer bottles can be seen as an industry under consolidation in most developed countries. The most successful case of PET bottle recycling is that of Japan, which in 1997 introduced national legislation in order to promote PET recycling. In a decade, the collection rate increased to 88.4% (Nakatani and Hirao, 2011). However, around the world the collection rate is much lower than in Japan even for developed countries.

Environmental awareness and strategies are no longer considered to be a temporary tendency but they have become a central part of the plastic industrial philosophy. The business environmental approach, once implemented due to stringent legislation is now implemented as a market strategy and company guideline. The idea of sustainable packaging; where all stakeholders prosper, has genuinely permeated the PET industry. The main idea behind it is to decouple the economic development from the environmentally negative consequences that it produces (Welle, 2011). The analysis of the production and disposal chain is necessary to determine the environmental impacts of a product. Therefore, in the next section, PET bottle production and recycling is explained in greater detail with the intention of better understanding the dynamics of the industry.

3.1 PET Bottles Production

PET is produced from non renewable resources such as crude oil or natural gas. It is “made through a polycondensation of [Purified Terephthalic Acid] (PTA) with ethylene glycol (EG)(HITACHI, 2013).” In Figure 8, the PET production process is depicted.

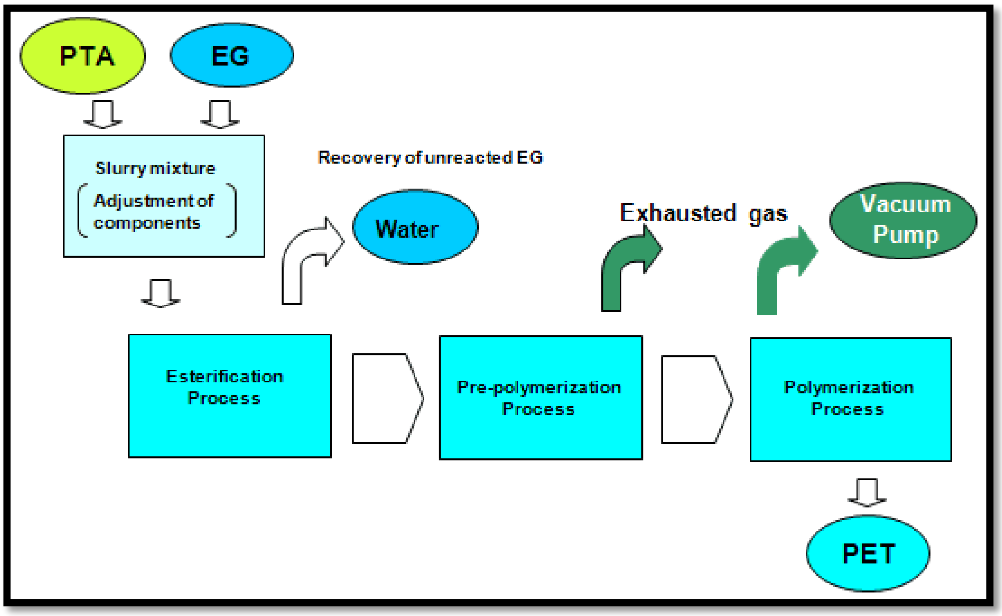

Figure 8 PET Production Process (HITACHI, 2013)

Once PET is produced, it is transformed into different products by diverse processes. In the case of PET bottles, the production consists of mainly three stages.

> First, the polymer is synthesized from crude oil usually using antimony trioxide as a catalyst and pure PET flakes are produced. Then, small and dense test-tube like pre-forms which weigh the same as the final bottle are injection moulded from the PET flakes. Finally, the bottles are formed by stretch-blow moulding of these pre-forms(Best Food Forward, 2008).

Once the bottles are formed, they are ready to be filled up and distributed to the consumers. When consumers finish using PET bottles, they can be disposed of in different ways; recycling is one of them. In the next section PET recycling is explained.

3.2 PET Recycling

Many developed countries operate municipal waste incinerators as a solution for crowded landfills and to produce energy from waste. However, this solution has not satisfied some important stakeholders and has created long lasting conflicts with environmentalist groups and the waste recovery industry. Regarding the plastic portion of waste, the main problem is that during simple incineration toxic gases are produced. Hence, complementary solutions needed to be established and waste recycling was one of the most popular solutions proposed to reduce garbage.

Recycling comprises the reintroduction into the system of used material and energy that was previously considered merely as disposable waste. Besides, it extends the lifetime of material since once it is consumed and disposed of, it can be processed into new raw material (Coelho et al., 2011).

Recycling strategies and technologies have been implemented for a long time in most of the developed world and lately, it has turned out to be much more common practice in developing and transition countries as well. In Europe, member states first introduced these practices in order to comply with the European Council Directive 94/62/EC on packaging and its waste (Sevigné et al., 2011). Nevertheless, the packaging industry embraced the idea of producing sustainable packaging options and set recovery and recycling rates for their products. Evian, a producer of mineral water, is aiming to use 50% of recycled PET in all its products and the Coca Cola Company (TCCC) is aiming for 25% (Schwanse, 2011). Figure 9 illustrates the post-consumer recycling rate of some developed and developing countries. One interesting fact is that some developing countries have higher rates of PET recycling than developed countries. Brazil has a higher recycling rate than Europe and Argentina has a higher one than the United States.

Countries	Post-consumer PET recycling rate (%)
Japan (2007)	69.2
Brazil (2008)	54.8
Europe (2008)	46.0
Australia (2007)	42.3
Argentina (2008)	34.0
United States (2008)	27.0
Mexico (2008)	12.6

Figure 9 Post- Consumer PET Recycling Rate (Coelho et al., 2011)

Even though, the recycling of PET has become a well founded industry around the world PET recycling rates are still very low. Since most of the PET garbage is comprised of PET bottles, their recycling can be considered to be a good approximation of PET garbage recycling as a whole. In 2007, only 30% of the post consumer PET bottles were collected and reprocessed into flakes, which can be used as raw material in the manufacturing of new PET products (Shen et al., 2010). Even if there is real determination and willpower from several stakeholders to increase the PET recycling rates several difficulties are still in the way. The main two obstacles are the process costs and the lack of a guarantee in the supply (Brooks, 2012). However, it is expected that with the proper strategies, these difficulties will be overcome.

As seen in Figure 10, from the PET that was recycled, 72% was transformed into fibers, 10% into new bottles and the rest into different applications. This proportion might change in the near future since it is expected that PET bottles will be recycled mainly into new bottles.

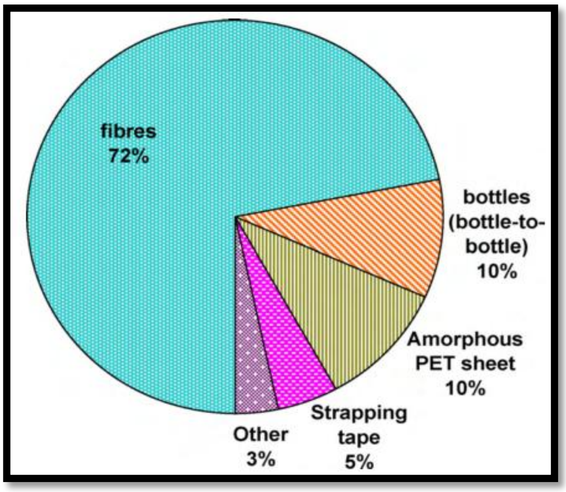

Figure 10 Worldwide Applications of Recycled PET in 2007 (Shen et al., 2010)

As noted, PET bottles can be recycled into different final products. The recycling routes for PET can be broadly divided in two categories: open loop recycling and closed- loop recycling (Nakatani et al., 2010).

Open-loop recycling, also called mechanical recycling, refers to a process where a product that is composed of one type of material is transformed by recycling techniques into another product (Coelho et al., 2011). This kind of recycling can be further classified into open-loop with the same primary route and open-loop with a different primary route. The first one refers to recycling that does not change the intrinsic characteristics of the product, and the second one describes one that changes them (ISO 14044, 2006). In the case of PET bottles, these are transformed into polyester fibres, sheets, strapping tape, bristles of brooms and brushes, shower stalls, film, etc. Mechanical recycling converts PET flakes into a diversity of products by melt-extrusion. In fact there are two ways to produce recycled fibres. One is to extrude directly the PET flakes into fibres and the other is to transform the PET flakes into PET pellets and then extrude them into fibres. During this process around

1% of the PET flakes cannot be reused and are discarded as PET scrap (Shen et al., 2010). Even if recycled PET fibres have a wide range of applications, it does not replace 100% the virgin PET fibres since this one is used to produce some products that cannot be produced using recycled PET as raw material. While virgin PET fibres can be used in technical applications, high performance applications and apparel; recycled PET fibres can only be used in technical ones due to its limited dyeing ability and lack of capacity to produce microfiber (Shen et al., 2011).

On the other hand closed-loop recycling, also called chemical recycling, refers to a process where the waste or by-product of a product is used to manufacture the same product once again. Theoretically, closed-loop recycling could be used in the creation of new products without having to use virgin materials (Coelho et al., 2011). During the chemical recycling process the PET bottles are transformed by depolymerisation techniques into monomers or oligomers. Nowadays, there are several common depolymerisation technologies like "glycolysis, methanolysis and alkaline hydrolysis (Shen et al., 2010)." By applying substantial cleaning and processing, the recycled PET obtains the same quality as the virgin one.

However, this was not always regarded as true and a major concern has always been the decontamination of the PET pellets for their reintroduction into food packaging. The most problematic contaminants are adhesives (Coelho et al., 2011) However, with the development of new technology, closed- loop recycling is a reality. The downside is that it is significantly more expensive than open-loop recycling due to quality requirements. In order to determine the quality of the recycled PET, the intrinsic viscosity, color, visible unwanted materials, and invisible unwanted materials (Nakatani and Hirao, 2011) are checked out and ensured. Therefore, chemical recycling usually needs to be performed in a large scale so as to become profitable.

4. Waste Current Situation in Mexico

In Mexico, the industrialization process created a higher demand for raw materials in order to satisfy the consumers increasing consumption of goods and services. Moreover, the economic development led to an enhancement of the purchasing power of the population, which consumed more and therefore increased waste production. Consequently, environmental problems arose causing negative impacts in the population and ecosystems' wellbeing.

Even if Mexico is a middle income country, its waste management system lags way behind its level of development. Actually, the Mexican waste management system could be categorized as a pre-modern one due to the fact that is mainly based on a single disposal technology i.e. landfilling (Aparcana and Salhofer, 2013). Furthermore, it uses equipment that is essentially out of date or inadequate and infrastructure which is managed by local governments. The involvement of private stakeholders is quite limited and is predominantly present in the recycling sector where informal and uncontrolled activities take place. Therefore, nowadays, one of the most pressing matters in the country is the collection, treatment, and disposal of waste. “These aspects have not only environmental and sanitary implications, but economical, commercial, technological, social and political ones as well; these implications can spread even beyond the country’s borders turning it into a global issue which can affect other countries as well (Armijo de la Vega et al., 2006).”

In Mexico, environmental awareness started around the 1970s when environmental degradation reached a very high level. In 1976, the national authorities finally recognized this pressing matter with the creation of the *Subsecretaría de Mejoramiento Ambiental* (SMA). During the next few decades, the SMA implemented several projects in major cities with the intention of developing a standard MSW management (Armijo de la Vega et al., 2006). However, due to the lack of real political will and public investment, the installed infrastructure was neither sufficient nor effective. There is a significant lack of correspondence between the growth rate of the waste generated and the new infrastructure that is introduced.

Regarding legislation, Mexico introduced federal waste related laws rather late. The General Law for Waste Prevention and Waste Integral Management entered into force in 2003. It was designed to fill in many regulation gaps concerning MSW management. In this law, waste has two different connotations. The first one is as a pollutant that should be avoided, reduced and handled in a sustainable way and should apply the polluter pays principle. The second one is as a valuable material that can be reused, recycled or incinerated in order to recover the energy contained in it.

Also, it classifies the waste in three different groups according to its characteristics and origin: MSW, special treatment waste and hazardous waste. With this law as a guideline, new regulations have been issued to facilitate waste prevention, generation, management and disposal. However, the complexity of the geographic, economic, social and political situation is often an obstacle that hinders the development of reforms in order to improve the Mexican MSW management (Schwanse, 2011).

In the next sections, the different steps of the MSW generation and management are described so as to provide a better understanding of the current waste situation in Mexico. This information will be useful to develop recommendations concerning management strategies for PET waste.

4.1 MSW Generation

MSW is defined as the waste that is generated by private homes, schools, hospitals and businesses and it is the result of the everyday items that are used and then discarded. MSW includes packaging, furniture, clothes, food scrap, newspaper, appliances, and batteries, among others (EPA, 2012).

In Mexico, the MSW has shown a steady growth due to industrialization, urbanization, introduction of new technologies and changes in consumption patterns. In 1992, the MSW generated was around 21,967 thousand tons and by 2011, that amount nearly doubled. In 2011, Mexico had 112,336,538 inhabitants that produced around 41, 062 thousand tons of waste, which means that 112 tons were generated each day nationwide (SEMARNAT, 2012). This amount of garbage places Mexico as the 10th biggest MSW producer worldwide (Gasnier and Portales Derbez, 2008). The *per capita* waste generation was 0.870 kg per day (Armijo de la Vega et al., 2006). If compared with the rest of the OECD countries, the Mexican per capita waste generation is one of the lowest; just surpassed by Slovakia and Poland (OECD, 2007).

Nevertheless, it presents important variations within the country; it ranges from 0.680 kg in the Southern part of the country to 1.40 kg in Mexico City (SEMARNAT, 2012). It has been suggested that more economic development leads to higher rates of waste generation and as a whole, this trend is accurate for the Mexican case. The states that generated more waste *per capita* were the ones which had a larger contribution to the GDP. In fact, positive lineal relation was found between contribution to the GDP and the MSW generation. From 32 states, only two were regarded as outsiders: Mexico City and the State of Mexico. For the first one, the contribution to the GDP is higher than the one of its waste generation and for the State of Mexico the opposite is true (SEMARNAT, 2012).

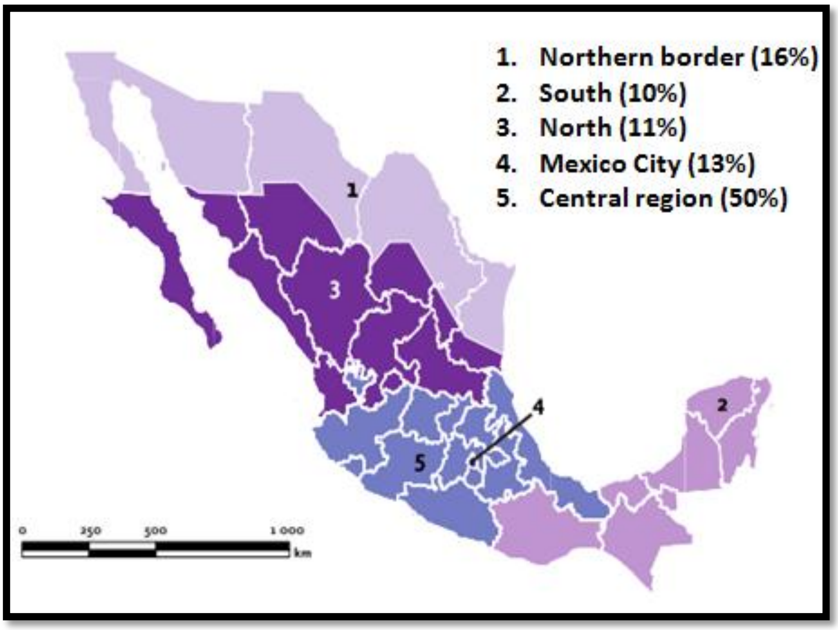

Figure 11 MSW Generation by Region (SEMARNAT, 2012)

As seen in Figure 9, half of the national waste is generated in the central region of the country while the south contributes the least to waste generation. If instead of classifying waste generation by region, it is classified by state, then only seven states account for 53.7% of the national waste generation. These states are Mexico City, State of Mexico, Jalisco, Veracruz, Guanajuato, Tamaulipas and Nuevo Leon. Alternatively, if it is classified by locality size, then the cities that have more than one million inhabitants contribute to 44.9% of the total waste generated. Furthermore, the waste generation rate of these cities increased by around 48% in the last decade while the small cities and rural areas showed a smaller increase of only 15% (SEMARNAT, 2012).

In terms of waste composition, half of it is comprised of organic waste while the other half is divided into potentially recycled materials (32.3%) and others. Nonetheless, these shares have changed following the economic situation. During the 1950s, the percentage of organic waste was around 70% while nowadays it only accounts for 50.4% (SEMARNAT, 2012).

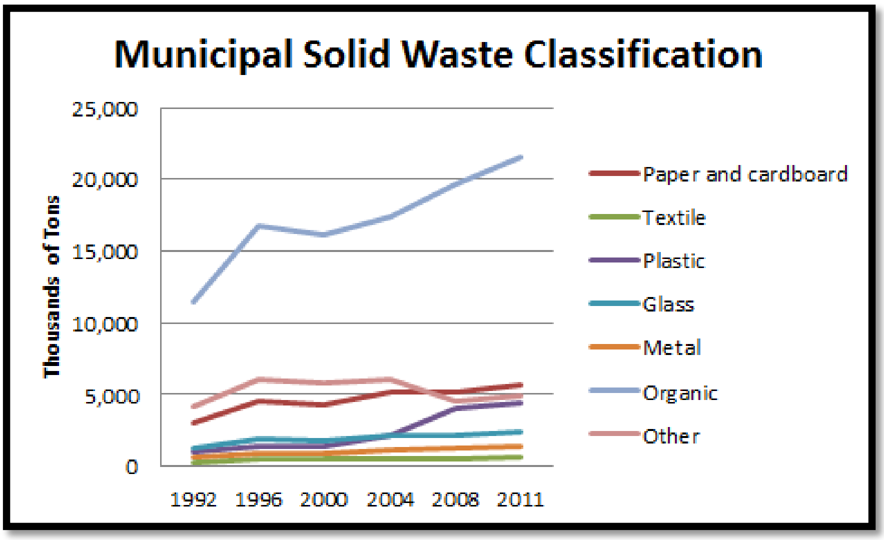

Figure 12 Evolution of MSW Composition (SEDESOL, 2012)

As seen in Figure 12, all components besides "others", presented an increase in terms of quantity. Since 2000, the plastic share increased far more than the rest of the MSW components and it is expected to keep growing at a high rate. Nevertheless, it accounted for merely 10.9% of the MSW while paper and cardboard represented 13.8%, textile 1.4%, glass 5.9%, metal 3.4% and other residues 12.1% (Mascott Sánchez et al., 2012)

In order to dispose of all the waste that is generated in the country, several different steps are involved. In Mexico, MSW management involves four activities which are collection, transfer and transportation, treatment and final disposal. In the next sections each is described in greater detail.

4.2 Collection and Transportation

In Mexico, one of the main challenges of collection is the lack of proper storage facilities in private households, schools, hospitals and businesses. "Temporary waste storage is perhaps the one element of the cleaning system that has received the least technical and professional attention (Armijo de la Vega et al., 2006)." The major problem is that most of the time, the places used for temporary storage for the waste were not designed for this purpose, and therefore, they are typically highly inadequate and risky.

One common difficulty that arises is that storage facilities of poor quality ofetn break apart while being carried to the collection trucks. However, the majority of households place their garbage outside their houses in plastic bags. Therefore, kerbside collection is inefficient because it has to be done manually house by house (Armijo de la Vega et al., 2006). Waste collection is the most expensive MSW management stage, and it uses around 60 to 70% of the total budget. Nevertheless, the collection costs strongly vary from $30 to $640 per ton depending on the population density, the amount of waste collected, the filling efficiency of the truck, the condition of the vehicles and the routes' designs (Gutiérrez Avedoy, 2006). From all the collection costs, the salaries of the employees represent around 60% of the overall collection. An increase in the labor force productivity could reduce a significant fraction of the total MSW management costs (DEFRA/Embajada Británica en México, 2009).

Regarding the MSW collection rate, it has improved in the last decades. In 1996, it was around 70% nationwide; however, it reached 88.4% by the year 2007. As for waste generation, the collection rate highly depends on the location's income level, urbanization and size; the bigger and richer the cities, the higher collection rate they have. For example Mexico City collects 98% of the volume that is generated while the state of Oaxaca collects 78.9 % (SEMARNAT, 2012).

With reference to collection routes, Mexico is quite underdeveloped. The most common method used for the design of collection routes is based on the experience and judgment of the cleaning chief or of the truck drivers (DEFRA/Embajada Británica en México, 2009). In the entire country just 26.67% of the routes can be considered efficient since they were designed by technical methods. The local governments, which are in charge of the collection routes' designs, do not have enough resources to develop adequate collection strategies, and therefore, the majority of cities are provided with ineffective and insufficient collection routes.

Even though in recent years several stakeholders have actively promoted the garbage separation, it is still quite low. In the majority of the country, waste is disposed of without any distinction between organic and inorganic. Sometimes even if it is separated at the source, it is mixed during the collection process since the trucks do not have separated spaces for each type. In 2010, only 11% of the collection was selective while the rest was mixed (SEDESOL, 2012).

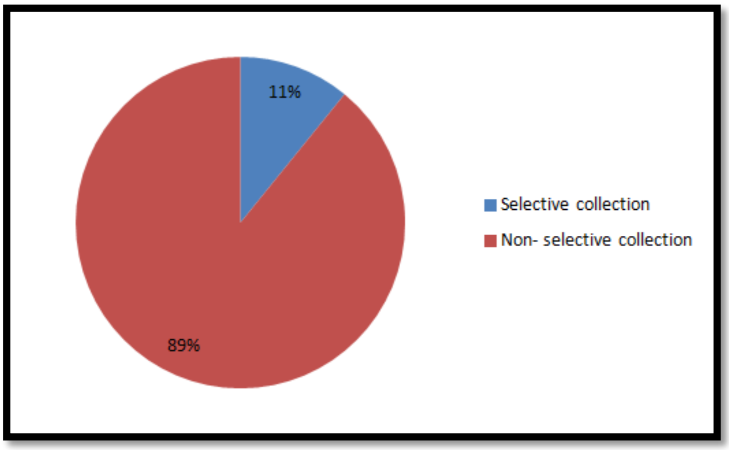

Figure 13 MSW by Collection Type (SEMARNAT, 2012)

The collected waste is transported in different types of vehicles. The national vehicle fleet consists of 14,300 units. Compactor trucks make up to 64% of the fleet, vehicles with open boxes make up 34% and the last 4% are classified as "others". The most common ones, the compactors trucks, have a capacity that ranges from $10m^3$ to $15m^3$; the ones with a 10 m^3 capacity can transport a maximum of 4 tons and the ones with $15m^3$ a maximum of 8 tons (INEGI, 2011).

4.3 Transfer Stations

Once the waste is collected, it can be transported to three different places. It can either be carried directly to transference sites, to treatment facilities or to final disposal sites. Transference sites are defined as a group of facilities and equipment where the waste collected by collection trucks is deposited in trailers of larger capacity with the intention of transporting them to the final disposal site. Generally, the transfer trailers can hold around 20 to 25 tons of MSW which represent in average the waste collected by 5 collection trucks. The intention of using them is to increase the efficiency and reduce the costs of the MSW since the transportation time, use of the equipment and the required work force are reduced. Transfer stations are definitely required for cities that have one million inhabitants or more although it is also recommended to have them even in smaller ones(Ramos Cortéz et al., 1996).

In Mexico there are 86 transfer stations from which 62 serve only as temporal storage and 24 have further equipment to treat the waste. This equipment includes separation, compaction, and crushing machinery. Mexico City with its 8 million inhabitants utilizes 13 transfer stations in total (INEGI, 2011). The costs of the transfer stations vary greatly but in general they account for around 22% of the MSW management budget. The cost ranges from $22 to $145 per ton (Gutiérrez Avedoy, 2006).

4.4 Waste Treatment

In Mexico, waste treatment has not shown the desired results, and its application is still rather low. From the 2,456 municipalities only 6% utilized any type of waste treatment facility. In the case of organic waste, it is necessary to install composting plants in order to treat it. In Mexico, the composting market is not fully developed and the compost produced presents serious quality problems. The capacity of these plants varies significantly. For example, the composting plant with the biggest capacity is located inside the main landfill of Mexico City and receives around 10 tons of organic waste per day. Nevertheless, there are others that only receive 1 or 2 tons per month (INE, 2006).

Regarding inorganic waste, different processes are necessary to recycle a variety of materials. Even though serious efforts have been made nationwide to increase the volume of waste that is recycled, the recycling rate is extremely low. In 1998, 2.4% of the total waste was recycled and a decade later the rate only increased to 3.9% (SEMARNAT, 2011). One of the governmental strategies to improve the recycling process was the establishment of collection centers around the country. In 2010 there were 241 collection centers that received around 103 tons of waste per day (INEGI, 2011). In Figure 14, the distribution of the collected materials in these collection centers can be seen. The most collected materials are paper and cardboard while cooper, bronze and lead are the least collected.

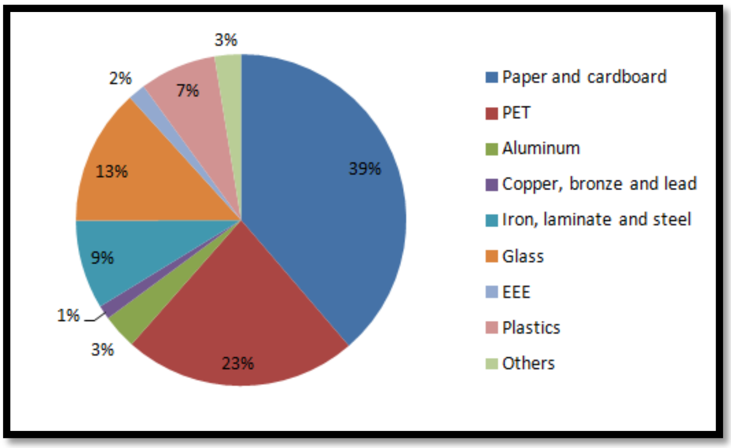

Figure 14 Distribution of the Acquired Materials in Collection Centers (SEDESOL, 2012)

In 2007, the materials which had the highest recycling rates according to their consumption were metals at 24.1% recycled followed by glass at 17.8%, and paper at 8.5%. The lowest ones were plastics and textiles at 0.3% each. However, the recycling rates change if they are measured according to the total volume of MSW. In that case, the highest recycling rate corresponds to paper at 38.7% followed by glass at 34.7% and metals at 26%. The lowest ones were once again plastics and textiles at 0.5% and 0.2%, respectively (INEGI, 2011). The overall recycling rate ranges between 5-8%; a low rate compared to other countries with the same level of development (Schwansee, 2007).

4.5 Final Disposal

The final disposal refers to the permanent placement of MSW in a certain location (Mascott Sánchez et al., 2012). As mentioned before, the majority of the waste is not treated and goes directly to its final disposal in landfills. It is estimated that the 41,062 thousand tons produced in the country require around 115,123 m^3 of space for disposal (SEDESOL, 2012). It is necessary to find new strategies to reduce the MSW as land has become a scarce and valuable resource. In Mexico, landfills are regarded as an adequate disposal method of MSW; however only 13% of all waste is disposed of in controlled landfills. Nowadays, there are 1,882 registered final disposal sites from which 1,644 are considered open air dumps since they do not comply with the minimum legal requirements (Armijo de la Vega et al., 2006). However, it must be taken into account that the volume capacity of the landfills is much higher than into open air dumps. In fact, 67% of the total municipal solid waste goes to landfills. Furthermore, there has been a significant improvement in the amount of landfills constructed in the country. In 1995, there were as few as 30 landfills but by 2011 the number reached 238 (SEMARNAT, 2011).

5. PET Situation in Mexico

The extended use of PET products in the world has produced serious environmental concerns, and efforts have been made to try and reduce these concerns in the last past few decades. In this section the PET situation in Mexico is analyzed as to show the extent of the issue on a national level.

Plastics account for 10.9% of the MSW in Mexico; and even though this may seem to be a small fraction, the plastic share has increased far more than the other shares since 2000. From the plastic share of waste, 10% consists of PET products (Conde

Ortiz, 2012). Most of the PET consumed is produced locally; there are 90 PET bottle industries that produce between 700 and 800 tons of bottles per year. This amount is likely to increase due to the 13% annual demand growth (Diaz Dosamante, 2010).

This trend is mainly attributed to two factors. The first is that the water coming from the pipes in Mexico is not potable, even when there have been important public investments to remediate the situation. Hence, most water consumption comes from purchasing and drinking bottled water. According to the Inter-American Development Bank, each Mexican consumes around 450 liters of bottled water per year, which places the country in first place for bottled water consumption per capita in the world (Malkin, 2012a). The second factor is that Mexico is also the biggest soft drink consumer per capita in the world. Each Mexican consumes 163 liters of soft drinks per year (Fox News, 2011) and discards about 365 bottles or 8.7 kg of PET annually (Schwanse, 2011). A typical Mexican household spends a large portion of their food expenses on soft drinks; in fact, the only food expenditures that surpass this portion are tortillas and milk (Medina and Smith, 2013). As a consequence of the enormous consumption, the lack of recycling awareness among the population and PET non biodegradability, PET bottles have turned into a national environmental curse.

Millions of bottles are inappropriately disposed of in public places, roads, etc. creating visual contamination. Moreover when PET bottles end up in water bodies, they endanger the wildlife, damage the fishing nets, and ruin the coastal areas. It is estimated that over 80% of all marine debris is composed of plastic waste, principally plastic bags and bottles (UNEP, 2009). When they do not reach water bodies, PET bottles highly contribute to the clogging of sewage systems causing floods. In landfills, they represent 2-5% of the total MSW and 7-10% of the total volume (Schwansee, 2007). These high percentages are due to the fact that the PET recycling industry in Mexico is quite young and that the amount of recovered material is extremely low compared to the total production. The current national PET recycling rate is around 6.7%.

5.1 PET Collection in Mexico

In order to promote the recycling industry, first it was necessary to guarantee the supply of post-consumer material. In Mexico as stated in the previous section, the collection of recyclable materials varies from municipality to municipality, and it is mainly uncontrolled. The collection is essentially done by the informal sector because separated MSW collection programmes and government collection centers are quite limited. The informal sector consists of scavengers, street sweepers and employees of the MSW cleaning department (Armijo de la Vega et al., 2006). In 2003, it was estimated that there were 25,000 to 30,000 scavengers only in Mexico City (Velasco Pérez Alonso, 2011). There are no official figures but the number is expected to be higher by now.

The majority of these people work directly in open dumps and landfills without any protection gear thus they face high health risks due to their constant contact with waste. In addition, they do not have any kind of social security and they have to work long hours for a very low amount of money. "Each scavenger earns \$39 to \$62 a week (Malkin, 2012b)." As with other marginalized groups, scavengers often suffer from different types of addiction and domestic violence; besides, half of the adults are women and many of them are single mothers. In many cases entire families, which have in average 6 children, work in the landfills. "A survey [conducted] in seven cities showed that 40% of [them] had no formal education, 10% had been educated for 2 years and only 4% had completed elementary education (OECD, 2003)." Since children are more vulnerable, the constant and direct contact with the polluted environment leads to a high rate of gastrointestinal, respiratory and skin diseases as well as psychological damage (Medina and Smith, 2013). This unfavorable situation can perpetrate their poverty, and keep them in the landfills or trucks for the rest of their lives.

Other scavengers work as "volunteers" for the government collection trucks, where they try to separate as much waste as possible before the truck gets to the landfill. These volunteers earn less than they would working in the landfills, but they prefer it because they aquire less infections and diseases this way (Malkin, 2012b).

In most landfills, scavenger associations and unions have been formed. Two examples of these associations are: *Asociación* de *Selectores* de *Desechos Sólidos* de *la Metrópoli* which works at the San Juan Aragón landfill and the *Unión de los Pepenadores del DF* of Rafael Gutiérrez Moreno which works at Santa Catarina (OECD, 2003). These Unions work as lobbying groups with a high level of political influence and control over all transactions made in their landfills. The money the scavengers receive as compensation is less than the market prices since the sorted products are collected by these leaders so as to sell them afterwards to middlemen and PET brokers. This last group sorts, washes and granulates the PET bottles

(Schwanse, 2011). On average a post consumer PET bottle goes through three to five stakeholders before it is actually recycled. In each step, the market value of the bottle increases since its quality increases as well. As seen in figure 15, the scavengers receive at least one Mexican (MXN) Peso for 1 kg of PET from their union leaders, which represents around 40 bottles. After that, the unions sell the collected material to the middlemen for 5 MXN Pesos per kg and finally after treatment, the middlemen receive 16 MXN Pesos for the same kg.[4] The money the middlemen receive depends on the method used to treat the collected material. The post-consumer PET price has been increasing since 2004 when 0.70 MXN pesos per kg was paid. By 2010, the price reached 4.50 MXN pesos from which 2.5 MXN Pesos were paid to the scavengers (Schwanse, 2011).

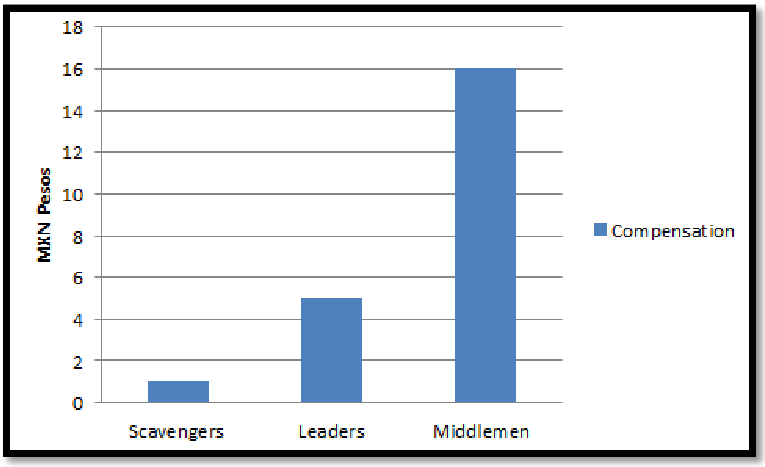

Figure 15 Post-consumer PET Bottle Value Chain (Gutiérrez, 2012)

Another challenge for the recycling industry is the legal background. At the end of the 1990s, the Mexican authorities exerted some pressure on the PET industries by warning them that if voluntary recycle and recovery programmes were not implemented, the government would establish mandatory compliance measures. As a consequence in Mexico there are no legal requirements for recycling or recovery as the packaging and bottling industries created the Ecology and Corporate Commitment (ECOCE) in 2002. This private non-profit organization financed by private funds has the objective of collecting post consumer PET bottles in order to assure the supply for the recycling industry. Also, it promotes environmental awareness through national recycling campaigns and actively participates in policy

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[4] 1 MXN Peso is around 0.08 US Dollars.

proposals in order to improve the legal environment for recycling activities. It is formed by 30 groups and more than 60 brands from the beverage and food industry that represent 61% of the total PET bottling and packaging market in Mexico. Some participant brands are Jumex, Nestlé, Coca Cola, Pepsi, La Costeña, among others (ECOCE, 2012).

In order to promote post-consumer PET collection, ECOCE has implemented three different programmes: one for the private industrial sector, one for schools and one for the general public. The industrial programme promotes the separation of PET bottles in the workplace by giving the employees cash or different items as incentives. Most of the time, the money accumulated by the employees is donated to charity. The school programme is called ECO RETO and it promotes the separation of PET bottles in educational institutions. Collection centers have been installed in 6,463 schools throughout the country, and involve the participation of around 1.8 million students. According to the number of PET bottles collected, schools receive prizes that can vary from soccer balls to computers for the IT labs. Finally, the programme for the general public involves the installation of 12 collecting centers around the main cities to facilitate the PET purchasing from the whole population (Medina and Smith, 2013). Most of the time, the collected material comes from scavenger leaders. ECOCE has tried to avoid this situation by buying the materials directly from scavengers in the landfills. However, this was not possible since the access to the landfills is granted by the leaders, who won't allow entrance to ECOCE trucks unless they purchase the material from them. As a consequence, ECOCE have had to work within the established structure, where the leaders receive the payment. Unfortunately, the way this money is distributed among the scavengers is not under the control of ECOCE (ECOCE, 2012).

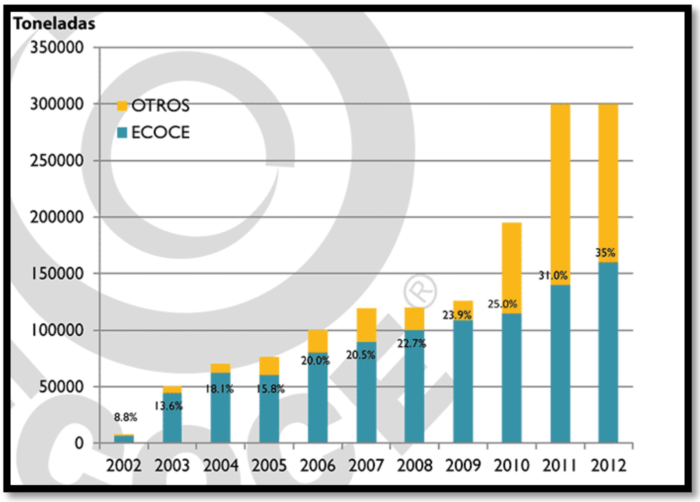

Figure 16 National Post-consumer PET Collection (ECOCE, 2012)

As seen in Figure 16, the collection of PET has grown exponentially since the foundation of ECOCE and by 2012, 300,000 tons were collected. The blue fraction of the bars represents the amount of PET collected by ECOCE while the yellow fraction is the collection achieved by other stakeholders. The percentage shown by each bar represents the amount of PET collected by ECOCE in comparison with the total production of its members, which accounts for 58% of the Mexican PET packaging and bottle industry (ECOCE, 2012). It must be pointed out that the collection done by other stakeholders has grown significantly more than ECOCE collection in the past few years.

5.2 PET Exports

From the 300,000 tons of PET that were collected in 2012, 244,700 tons were exported. This trade trend can be explained by legal and economic factors. First, foreign customers pay higher prices. In fact, the average price per kg paid by foreign customers can be up to 80% higher than the price paid locally. They can afford to pay more because the payment is made in cash avoiding the corresponding taxes and tariffs. This takes advantage of the containers that transport products to Mexico since then post-consumer PET is exported under a fraction tariff that is neither clear nor effectively controlled. Furthermore, they do not demand a high quality for the collected product (Gutiérrez, 2012). In Figure 17, the different destinations for the exported PET are showed.

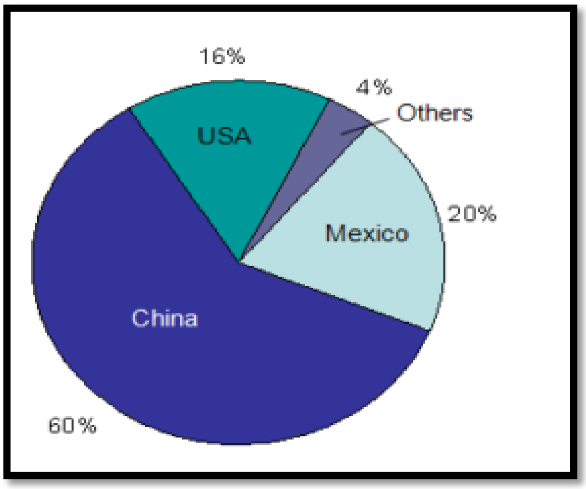

Figure 17 Destination of PET Collected in Mexico (Gasnier & Portales Derbez, 2008)

5.3 PET Recycling Industry in Mexico

Even if collection is promoted, the PET recycling industry cannot develop without the proper infrastructure. Until very recently, Mexico only used openloop recycling technology that transformed PET bottles into a variety of products. The situation changed in 2005 when the Industria Mexicana del Reciclaje (IMER) was founded. This recycling plant has the technology to convert used PET bottles into FDA (Food and Drugs Administration) grade PET pellets that can be used safely by the food and beverage industry. The PET pellets produced in this facility are already substituting virgin PET in Coca Cola bottles production (Schwanse, 2011).

In 2007, PETSTAR the second bottle to bottle (BTB) recycling plant was opened in Toluca, a city 56 km away from Mexico City. PETSTAR was partly funded by a US$33.48 million loan from the International Finance Corporation (IFC), a member of the World Bank Group. Its operation has been regarded as a success and in 2012, Coca Cola and its Mexican subsidiaries decided to invest $34 million more in order to double the plants recycling capacity (Medina and Smith, 2013). Finally in 2009, Centro de Procesado de Resinas (CPR) was funded by Brazilian investment in Celaya, a city in the central region of Mexico. These three recycling plants have the joint installed capacity to transform 72,000 tons of post-consumer PET (Schwanse, 2011). Figure 18 summarizes some important details of each recycling plant.

Recycling Plant	Location	Input Capacity (Tons)	Reprocessed
PETSTAR	Toluca	32,000	35,000
IMER	Toluca	20,000	16,000
CPR	Celaya	20,000	0
Total		72,000	51,000

Figure 18 Installed Recycling Capacity for FDA grade PET (Schwanse, 2011)

The market value of the Mexican PET recycling industry has already surpassed 4,000 million MXN Pesos, which represents around 10% of the national plastic industry. Nowadays, the PET recycling sector is estimated to include around 180 different companies (Gutiérrez, 2012).

6. Life Cycle Assessment of PET in Mexico

As mentioned before, in order to comprehensively analyze a system or a product, it is necessary to consider its overall performance in the different stages of its life cycle. LCA is an ideal tool to achieve this goal. Previously, many studies have been conducted around the utilization of PET. While some studies aimed to identify environmental performance indicators or to compare PET to different goods or materials: others sought to establish a benchmark for product policy or to provide relevant information to support the decision making process. Regardless of their specificities, all of them have concluded that to recycle PET is an environmentally friendly practice that reduces the negative burden of the material. However, the degree to which the burden is reduced varies from case to case. In this section the necessary parameters for an LCA for BTB PET recycled in Mexico is developed. Unfortunately, a complete LCA is not performed due to the lack of available information.

As described in section 1, all LCAs start with the goal and scope definition. The goal of this study is to assist in the development of PET recycling programmes in Mexico that are economically advantageous, environmentally friendly and socially accepted. Also, it intends to identify processes where improvements can be implemented so as to propose policy recommendations. Therefore, a consequential LCA should be carried out in order to determine the recycling rate and the collecting routes distances that would generate the best practicable environmental result.

The decision context for the study is regarded as situation B because the decisions made could have far reaching consequences that would require the installation of extra BTB recycling capacity. The target audience is considered to be the several private and governmental stakeholders that are involved in the MSW management and PET recycling industries. The results of the study intend to help these stakeholders in the decision making process. Finally, the main limitation of this LCA is that it only considers the environmental impacts of PET recycling. However, in Mexico an important percentage of the industry is built on the work of thousands of scavengers who work under terrible conditions. Therefore, the study might underestimate this social factor.

The system boundary is cradle to grave; thus, it must include all the processes that are involved from the extraction of the raw materials to their final disposition. The functional unit is 40 kg of PET, which can be in the form of resin, pellets or bottles. The latest was not defined by number of units since there are different bottles sizes that have specific weights. Nevertheless, the functional unit was not chosen randomly. This choice is justified because it represents the weight of 1000 units of 2L bottles, the most consumed size of soft drinks in the country (Ghirardelly, 2013). The geographic scope of the study covers the entire country and the technology analyzed is BTB recycling.

After examining several studies carried out in different contexts (Gironi & Piemonte, 2011; Nakatani et al., 2010; Shen et al., 2011; Foolmaun & Ramjeeawon, 2012; Pasqualino et al., 2011; Romero-Hernández et al., 2008; Schwanse, 2011; Coelho et al., 2011) several parameters were identified. However, not all the parameters found were applicable to the Mexican context; especially because MSW management is not highly developed like in most industrialized countries.

Figure 21 shows the case study system flow diagram. As seen in the figure, inside the system boundaries, 9 different processes are involved in BTB recycling in Mexico. These processes were considered as relevant and were thus included. They can be classified into 3 categories: production phase, consumption phase and disposal phase. Also, the transportation between processes was taken into consideration since it affects the overall benefits of recycling (Coelho et al., 2011). In fact, there is a limit for collection where the route distances overweigh the benefits of PET recycling. The maximum collection distance could be determined by carrying out the LCA. The disposal phase of the system has major discrepancies with the ones carried out in developed countries. In Mexico, there are very few mechanical treatment processes before the waste is deposited in landfills, and there is not a separated collection for each type of waste. The sorting activities, which are done mechanically in developed countries, are performed manually by the informal sector and therefore, they do not cause energy requirements. Therefore, they were cut off from the analysis and were regarded as insignificant.

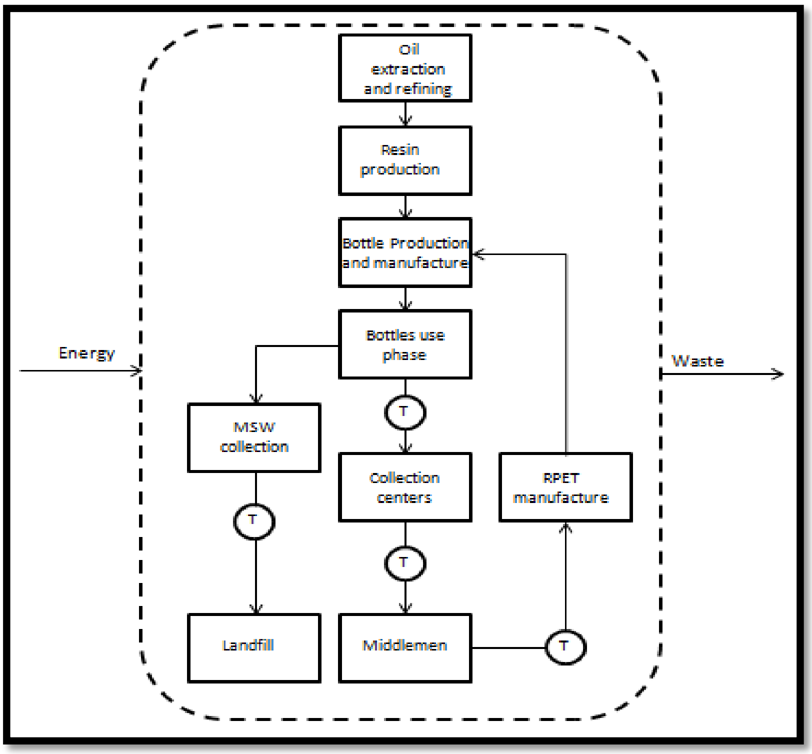

Figure 19 LCA System Flow Diagram

In order to determine the reference flows of the system and obtain a complete picture of the system metabolism, a Material Flow Analysis (MFA) was performed. It is based on the information acquired from a variety of sources including research papers, governmental reports and ECOCE statements. The figures shown in the MFA use two significant figures.

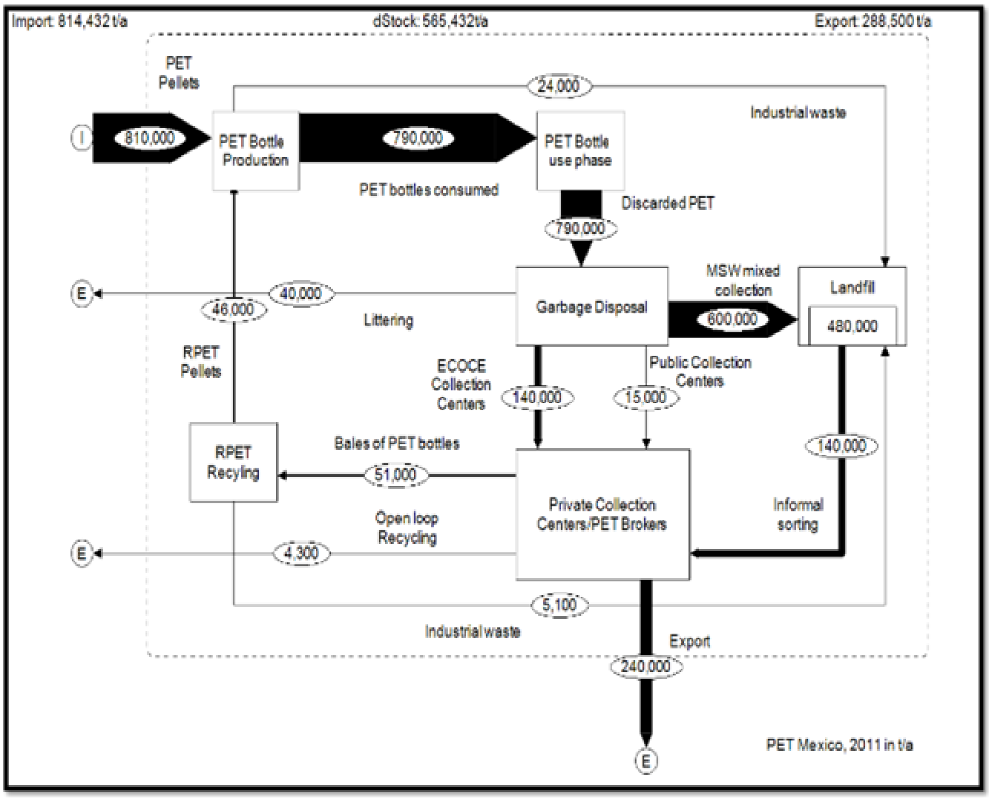

Figure 20 MFA of PET in Mexico, 2011

In 2011, the national production of PET bottles was 790,000 tons (Schwanse, 2011). In order to produce this amount, 810,000 tons were imported into the system. This amount was calculated considering that there is a 3% loss of material during the bottle manufacturing (Gironi and Piemonte, 2011). The industrial waste was disposed of directly in landfills. The other 97% of production was manufactured and filled with different kinds of beverages, which are ready to be sent to the market.

Once consumers have used the PET bottles, there were several routes to discard them. The first route was by littering. Schwanse (2011) estimates that approximately 5% of the bottles consumed are left in inappropriate public locations; where they create visual contamination, sewage clogging, and marine debris. Littering, which accounted for 40,000 tons, left the system as an export flow. This amount was calculated with the total production and the littering percentage.

The second route is by taking the bottles to different collection centers. These can be divided into ECOCE, government, and private centers. According to ECOCE (2012), 300,000 tons were collected in the different collection centers, which accounts for 38% of the total production. From all the PET collected, 47% was aquired through ECOCE and the rest through Government and private collection centers. The amount of PET collected by the Government centers was taken from the INEGI (2011) database. The last year reported was 2010; however, it had been assumed that this figure did not vary significantly from one year to the other and can still be valid for the year 2011. The ECOCE and governmental centers mainly receive bottles that were separated from the generation source while the private ones mainly buy bottles that have been sorted manually by scavengers in landfills. In Figure 20, the collection rates of the different centers are shown. These figures represent the percentage of collected tons from the total bottle production.

	ECOCE	Government	Private
PET	18%	2%	18%

Figure 21 Collection rate in different collection centers

The third route is by disposing of PET bottles with the rest of the MSW. Since there are so few separate collection programmes and sorting plants in Mexico, they can be considered as negligible (SEMARNAT, 2012). Therefore, it is assumed that all waste collected is mixed and that it goes directly to the landfills. With this route, 75% of the bottles consumed end up in the landfills without any treatment. This amount was calculated by substracting the ECOCE and Government collection and the littering from the total PET consumed. Once in the landfills, the waste is sorted manually by thousands of scavengers. The amount of PET collected by them was calculated by substracting the Government and ECOCE shares from the total PET collection reported by ECOCE (2012). From all the PET that reached the landfill, 140,000 tons were sorted by scavengers and sold to private collectors; which means that scavengers had a sorting efficiency of 24%. The share of PET that was not sorted in the landfills is considered as stock.

Once the PET was collected, it was either recycled in the country or sent abroad for the same purpose. In 2011, 81.5% of the collected material, which represents 30% of the total production, was exported. Therefore, 240,000 tonnes, left the system as an export flow. This amount was calculated by substracting the amount of PET recycled in the country from the total PET collected. The quantity of PET recycled was taken from Schwanse (2011). The material that remained in the country, around 55,000 tonnes, was recycled by mechanical and chemical treatments. Most of it was recycled in a closed-loop while the remaining 7.7% was used to produce a variety of products. Open-loop recycling is also considered as an export flow and therefore, 4,300 tonnes of PET left the system.

In order to recycle the PET bottles, it is necessary to produce FDA pellets. According to Gironi and Piemonte (2011), 10% of the input material is lost during this process. The industrial waste was sent to landfills. The remaining 90% was used as raw material to produce new bottles. The FMA shows that in 2011, only 5.8% of the produced bottles were recycled into new bottles in the entire country.

7. Conclusions and Policy Recommendations

The generation of waste is unavoidable since most human activities produce it. Due to rapid economic development and high rates of urbanization, its disposition has raised enormous challenges. One of the waste components that has produced a major environmental problem is PET. The global demand for it has increased in the few last decades and this trend is expected to continue given the convenience of its inherent characteristics. Among them durability, once considered as it major advantage, has become an environmental torment. Attributable to its chemical composition, PET neither biodegrades nor photo degrades or at least not in 1,000 years or less. Furthermore, its production is based on crude oil or gasoline which are non renewable resources.

For many years, post consumer PET bottles were placed in disposal sites without any previous treatment. However with its expanding production, landfilling has become an unpractical and irresponsible practice. In the last decades, developed countries have followed several strategies in order to reduce the amount of material that is sent to landfills. Since PET can be 100% recycled, different technologies have been developed in order to do so. By recycling PET, developed countries have reduced their solid waste stream and have promoted the efficient use of non renewable materials.

However, this is not the case for transitional and developing countries where the MSW is still placed, in the best case scenario, in controlled landfills. In Mexico, the economic development of the last few decades has derived in an increasing consumption of goods and services. In the case of PET bottles, Mexico is the second largest consumer in the world. This is mainly attributed to two factors: the lack of potable water from the pipes and the high soft drinks consumption. In fact, Mexico has the biggest consumption per capita of water bottles and soft drinks. This massive consumption combined with a lack of environmental awareness has lead to serious problems that have caused negative impacts among the population and the environment. Therefore, it is crucial to find an adequate waste management solution that is in line with the principles of sustainable development. Recycling has been regarded as the most promising option.

For decades many scholars have been conducting studies in order to measure and prove the real benefits of recycling. Most of them have used an LCA methodology for that purpose. In particular, in the case of PET, all of them have concluded that PET recycling is an environmentally friendly practice that reduces the negative burdens of the material production and disposal. Nonetheless, the degree to which the burden is reduced varies from case to case. Therefore, the principal objective of this thesis was to determine which parameters needed to be considered so as to carry out an LCA for PET recycling in Mexico. Unfortunately, a complete LCA was not performed due to the lack of available information.

In order to determine the parameters, the MSW and the post-consumer PET management were extensively analyzed. It was found that the MSW situation in Mexico can be regarded as pre-modern since it is mainly based on a single disposal technology i.e. landfilling. The lack of investment and political determination has lead to obsolete and inefficient collecting and disposal facilities. Regarding recycling activities, they are carried out mainly by private stakeholders who do not gain any fiscal incentives or benefits by doing so. Besides, the lack of a national recycling culture and proper collection trucks has made selective collection impossible. Therefore, the recycling material supply is mostly provided by thousands of scavengers who sort the waste manually. This marginalized group works informally in the landfills without any protective gear or social security. Furthermore, they work long hours for very little pay and they are under the “patronage” of leaders who have total control over the landfills.

From all PET bottles collected, around 80% are exported, mainly to China and the USA. The above is explained because foreign customers provide higher payments and require low quality standards. In fact, they can pay higher prices because they do not pay taxes and take advantage of a fraction tariff that is not clearly regulated. As for the 20% that remains in the country, it is recycled by locals either by mechanical or chemical recycling routes. The majority of it is recycled into new bottles. Yet in 2011, only 5.8% of the produced bottles were recycled into new bottles at a national level.

From the above analysis, the parameters necessary to perform a CLCA for the Mexican BTB recycling were determined. The system, which is defined as cradle to grave, is composed of 9 processes. They are: oil extraction and refining, resin production, bottle production and manufacture, bottles use phase, MSW collection, collection centers, landfill, middlemen and RPET manufacture. Also, the transportation between the processes was included in the system boundaries since it affects the overall benefits of recycling. An MFA was also conducted so as to analyze the reference flows and to obtain an enhanced picture of the system's metabolism. Considering the most important flows, a series of recommendations were derived. They address generation, collection and recycling issues.

Regarding generation, it is necessary to implement environmental awareness campaigns with the objective of promoting a recycling culture among the population. It is necessary to encourage waste separation in every household and to put an end to the Mexican antipathy towards waste separation. If waste is separated at its source, even if the government does not have the infrastructure to collect it separately, the labor of the scavengers would essened and would become more efficient. Thus, more PET bottles could be sorted out from the waste stream in the landfills.

As for collection, routes have to be designed according to technical elements and not based on the experience and judgment of the truck drivers. With proper planning, collection can become much more cost-efficient. The more efficient use of resources could help make funds for separated garbage trucks available in the future.

Concerning recycling, three recommendations arose. First, any effort towards the modernization of the sector must include the scavengers given that most of the sorted material is provided by them. Most importantly, thousands of families depend on the income generated by this activity for their survival and their exclusion could lead to severe social tensions. Moreover, the scavengers' unions are a strong lobbying group with heavy political influence. Their lack of inclusion will only create an unnecessary obstacle for the recycling industry.

Second, the government should promote recycling by granting tax reliefs and other economic incentives to recycling industries. By doing so, the Mexican stakeholders would be in a better position to compete with their foreign counterparts. Finally, the national authorities should close the loop-hole in the fraction tariff that has been used by foreigners in order to export the collected PET bottles at low cost. By doing so, the national recycling industry could guarantee its supply and expand its capacity.

This thesis revealed that PET BTB recycling in Mexico is the most suitable option to significantly decrease the amount of post consumer PET bottles piled up in landfills and to make more efficient use of non renewable resources. However, the scope of its benefits will be quantified only after the complete conduction of an LCA. The established parameters for the Mexican case should be used in order to develop recycling strategies that result in higher profits, social inclusion and enhanced environmental protection.

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