CHAPTER 2

THEORIES

2.1 Overview of Life Cycle Assessment

Life Cycle Assessment (LCA) has its roots in the 1960s, when scientists were concerned about the rapid depletion of fossil fuels, LCA was developed as an approach to understanding the impacts of energy consumption. A few years later, global-modeling studies predicted the effects of the world's changing population on the demand for finite raw materials and energy resource supplies. In 1969, the Midwest Research Institute initiated a study of the Coca-Cola Company to determine which type of beverage container had the lowest releases to the environment and made the fewest demands for raw materials and energy. In the 1970s, the U.S. Environmental Protection Agency (EPA) refined this methodology, creating an approach known as Resource and Environmental Profile Analysis (REPA). In the late 1970s and early 1980s, environmental concern shifted to issues of hazardous waste management. As a result, life cycle logic was incorporated into the emerging method of risk assessment, which was used with increasing frequency in the public policy community to develop environmental protection standards.

When solid waste became a worldwide issue in the late 1980s, the life cycle analysis method developed in the REPA studies again became a tool for analyzing the problem. In 1990, for example, a life cycle assessment was completed for the Council for Solid Waste Solutions, which compared the energy and environmental impacts of paper to that of plastic grocery bags (CSWS, 1990). Thereafter, environmental groups around the world have also adopted life cycle analysis. Initially, it was limited to the public sector, and then LCA has been adopted by increasing numbers of corporations and nonprofit organizations as an aid to understanding the environmental impacts of their actions (Svoboda, 1995). In 1999, the International Organization for Standardization (ISO) developed the standard ISO 14040 series on Environmental Management – Life Cycle Assessment.

According to ISO 14040, LCA is "a technique for assessing the environmental aspects and potential impacts associated with a product, service or function by compiling an inventory of relevant inputs and outputs of a product system" (McDougall et al., 2001). Rebitzer et al., (2004) has defined LCA as a methodological framework for estimating and assessing the environmental impacts attributable to the life cycle of a product, such as climate change, stratospheric ozone depletion, tropospheric ozone (smog) creation, eutrophication, acidification, toxicological stress on human health and ecosystems, the depletion of resources, water use, land use, and noise and others.

Every product has a "life" starting with the design/development of the product, followed by resource extraction, production (production of materials, as well as manufacturing/provision of the product), use/consumption, and finally end-of-life activities (collection/sorting, reuse, recycling, waste disposal). All activities, or processes, in a product's life from "cradle to grave" result in environmental impacts due to consumption of resources, emissions of substances into the natural environment, and other environmental exchanges (Rebitzer et al., 2004) see Figure 2.1.

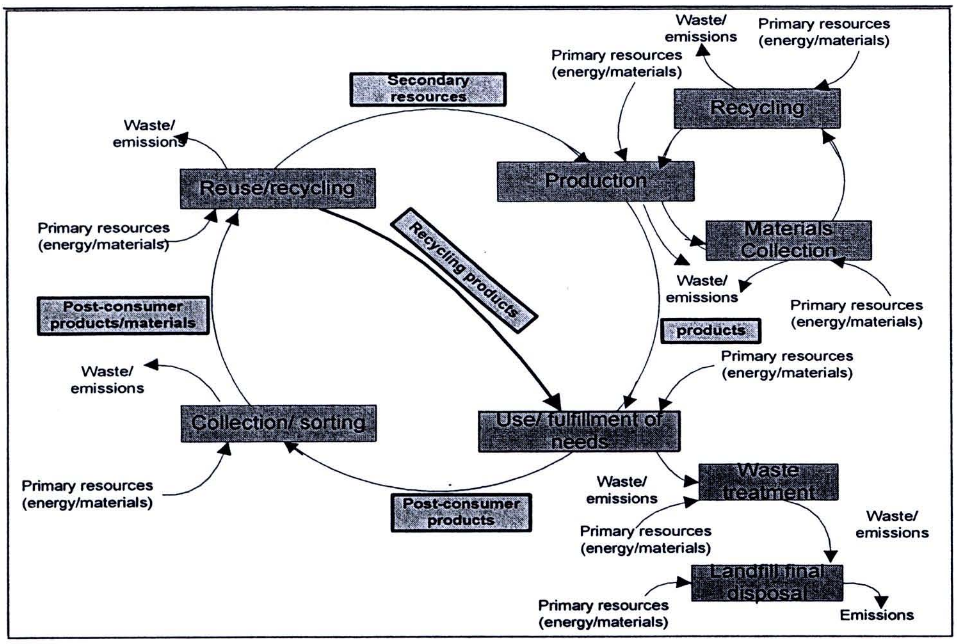

Figure 2.1: Schematic representation of a generic life cycle of a product (source: Rebitzer, et al., 2004)

To evaluate the sustainability of MSW management systems in a systematic way, LCA would be an appropriate tool (Liamsanguan and Gheewala, 2008a; Shekdar, 2008) since it facilitates compilation and evaluation of all the inputs, outputs and the potential environmental impacts of a product system in a systematic way for its entire life cycle (McDougall et al., 2001; Finnveden, 1999).

Life cycle methodology would be very useful to make the appropriate choices and to develop indicators based on key sustainability aspects of life cycle such as energy resources, environmental impact and financial and environmental costs (Eriksson et al., 2005). By applying the life-cycle approach, priorities can be identified more easily since it helps with a thorough assessment of every stage of the life cycle, from collection/ transportation, processing, reuse/ recycling and then final disposal and also to quantify the potential impacts from different phases (Buttol et al., 2007). In addition, every operation of unit processes can be clearly examined via life cycle perspective, including all inputs (raw material, resources and energy) and output (emissions to air, water and soil) (McDougall et al., 2001) .

2.2 LCA Methodology

LCA methodology is normally considered to involve four phases such as goal and scope definition, inventory analysis, impact assessment and interpretation (McDougall et al., 2001). According ISO 14040, the life cycle assessment framework is shown in Figure 2.1.

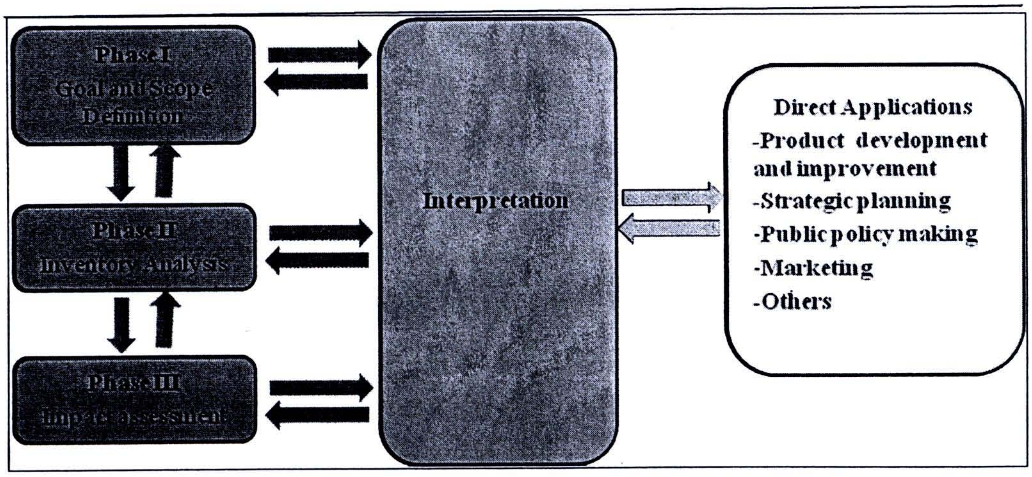

Figure 2.2: Life cycle assessment framework according to ISO 14040

2.2.1 Goal and scope definition

First step of LCA is the goal and scope definition, in which the initial choices that determine the working plan of the entire LCA are made (Guinée et al., 2001). The goal of a LCA study shall unambiguously state the intended application, the reason for carrying out the study and the intended audience (McDougall et al., 2001). When the LCA is presented, objective of the study should be described very clearly, which provides appropriate guideline to the use of the results.

According to ISO 14040, the scope of the study should cover the function of the product system(s), functional unit, the product system to be studied, the product system boundaries, allocation procedures, the type of indicators and methodology of LCA and subsequent life cycle interpretation to be used, data requirements, assumptions, limitations, initial data quality requirements, type of critical review (if any) and the type and format of the report (McDougall et al., 2001; Guinée et al., 2001).

The functional unit is an important basis in LCA, that enables alternative goods, or services to be compared and analyzed. Basically, the functional unit describes the primary function(s) fulfilled by a product system, and indicates how much of this function is to be considered in the intended LCA study. It is used as a basis for selecting one or more alternative product systems that might provide these function(s). The functional unit enables different systems to be treated as functionally equivalent to allow reference flows to be determined for each of them (Guinée et al., 2001). In relation to MSW management, "quantity" based functional unit would be more appropriate and it could be "one tonne of MSW treatment" under different technologies.

Product system to be studied is to understand the environmentally significant unit processes within a boundary so that data collection can be carried out focusing on the most important processes. This, however, means that it must be possible to identify what is the most important processes within the system before data collection is undertaken. The scope definition of the product system therefore necessary involves an introductive rough assessment, which is used to design the data collection for the actual assessment. Time scale is also an important factor under the scope definition to make sure the period of time that LCA results to be valid.

The Allocation step is very important in the whole LCA as it has a strong influence on the final results. When more than one product enters or leaves a process, the emissions of this process have to be attributed to individual products. In order to allocate the input and undesirable outputs among the products and the co-products, it is necessary to know the type of products and the co-products, type of inputs and undesirable outputs to be allocated to among the products and co-products and the allocation rule (Schaltegger, 1996).

2.2.2 Inventory analysis

Inventory analysis involves data collection and calculation procedures to quantify the relevant inputs and outputs of a product system. Thus, all of the raw materials and energy input and outputs (releases to air, water and land associated with the system) over the whole life cycle (cradle to grave) of a product or service should be accounted for, as shown in Figure 2.3. At this stage, setting the system boundaries (between economy and environment, with other product systems and its relation to cut-off), designing the flow diagrams with unit processes, collecting data for each of these processes, performing allocation for multifunctional processes and completing the final calculations (Guinée et al., 2001) has to be done. The results of this phase generate an inventory of the environmental burdens associated with the functional unit. These burdens can be segregated by life cycle stage, by media (air, water, land) or by specific process.

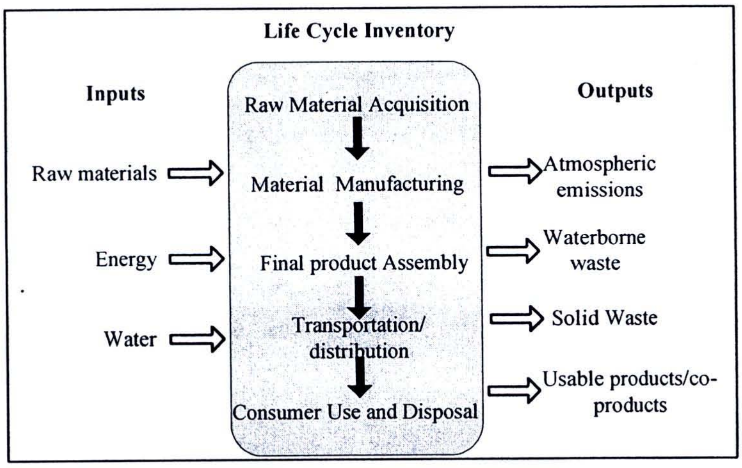

Figure 2.3: Defining the system boundary for life cycle inventory analysis

2.2.3 Life Cycle Impact Assessment (LCIA)

The impact assessment aims at a further interpretation of the LCI data and to analyze the environmental burdens associated with the material and energy flows determined in the inventory analysis. Impact categories, category indicators, characterization models, equivalency factors, and weighting values (McDougall et al., 2001) are the important components of LCIA to measure the potential impacts on human health and environment using. This phase includes the mandatory and optional elements (Pennington at al., 2004), see Figure 2.4.

Classification: Assignment of the inventory data to the chosen impact categories.
Characterization: Calculation of impact category indicators using characterization factors. The impact potentials for the product are the sums of the impact potentials for the emissions occurring throughout the product system.
The equation below provides an example of emissions data of how indicators for each impact category can be readily calculated from the inventory data of a product using generic characterization factors. These factors are typically the output of characterization models (Pennington at al., 2004)

$$\text{Impact Category Indicator}_i = \sum_s \text{Characterization factor (s) x Emission Inventory (s)};$$

where -s denote the emissions.

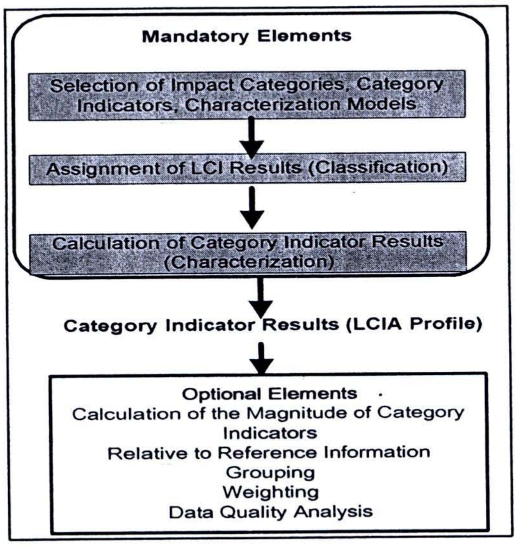

Figure 2.4: Elements of Life Cycle Impact Assessment

Even after the aggregation of inventory data to impact categories, it is not possible to conclude on the relative importance of these values. Thus, normalization (calculation of category indicator results relative to reference values) grouping and/or weighing (to conclude on the overall environmental preference of one or the other products or processes under investigation) steps have to be done, which are the optional elements in LCA.

2.2.4 Interpretation

This phase of LCA is to combine the findings from the inventory analysis and the impact assessment, consistent with the goal and scope in order to reach the conclusions and the recommendations. The phase may involve the iterative process of reviewing/revising the scope of the LCA, as well as the nature and the quality of the data collected consistent with the defined goal. In addition, the phase should reflect the results of any sensitivity analysis that was performed (McDougall et al., 2001).

2.3 Application of LCA Concept for Economic Assessment

LCA provides a useful tool for environmental analysis of municipal waste management. Apart from environmental issues, the economy is also a very important decisive factor for sustainable MSW management. Thus, it is important to analyze this aspect as systematically as the environment analysis with LCA (Aye and Widjaya, 2006; Finnveden et al., 2009). Moreover, it is a great advantage if the systems studied with the economic analysis and the LCA have the same system boundaries, so that two analyses may supplement each other in the decision making process.

Even though there are economic methods like cost benefit analysis to assess the financial feasibility, there are several characteristics with these methods that make them less suitable for a combination with LCA (Reich, 2005). Thus, to quantify all the overall cost for the entire life cycle and revenues, life cycle economic performances analysis is needed. "Life Cycle Cost" (LCC) assessment can be done considering the same LCA framework for a particular system which covers all the costs incurred by the extended waste management system. For example, if a financial LCC is done for a LCA system, all the costs for fulfilling the functional unit (or units) should be included. Moreover, to match the economic calculations to the LCA calculations, using the same time frame becomes necessary. In order to be able to allocate costs accordingly, the use of standard economic tools are necessary, such as the time value of money (interest rate, discounting, present value), and annuity calculations (allocation of investments over time). For instance, in order to calculate present value of all the cost components (p), the following formula can be used (Heredia, 1996).

$$P = \left[1 - \frac{(1+r)^n}{(1+i)^n}\right]\left[\frac{1+r}{1-r}\right]a$$

Where, r: inflation rate, i: prevailing interest rate, n: number of years, a: initial cost. Therefore, the financial LCC becomes a parallel analysis tool to a LCA since they analyze the same problem, but from different aspects.

2.4 Application of LCA Concept for Social Assessment

In relation to sustainable development and policy making arena, there has been an increasing interest for the inclusion of social aspects into the environmental LCA of products or systems in the recent years (Craighill and Powell, 1996). This task has been commenced in the development of the so-called Social Life Cycle Assessment (SLCA) (Jørgensen at al., 2008; Finnveden et al., 2009). The SLCA can in many regards be seen as a parallel to the environmental life cycle assessment, but rather than focusing on environmental impacts, the SLCA focuses on social impacts of products, processes, services or systems in principle throughout their life cycle (Jørgensen at al., 2008).

A goal for SLCA should be to assess the social conditions of the different level of stakeholders on which impacts are assessed in the SLCA perspective. However, the ultimate objective of conducting a SLCA would be to promote improvement of social conditions and overall socio-economic performance of a product throughout its life cycle for all of its stakeholders.

Generally, however, the inventory is restricted in scope to quantitative environmental emissions. Scope should be redefined for including a measure of social factors at the inventory stage. In this section, the origin of social impacts, allocation, system boundary setting and social indicators have to be discussed. As reported, the SLCA inventory analysis should focus on the companies involved in the product system. Then, SLCA can be used to assess the impacts, ranging from direct impacts on workers like employment opportunities, damage to human health etc to broader societal consequences. The impacts can be calculated under same system boundary conditions for the same functional unit of LCA.

As discussed by some authors, a share of the total amount of impacts created by the company/project involved in the product system should be allocated to the assessed product or service, and that the share should be determined by the weight that the company/project is given in the product's or service's total product chain. Thus the share factor or allocation principle could be based on value creation, number of labour hours spent, etc. In addition to the employment opportunities, consideration and quantification of the potential health impacts on the worker/ stakeholders would be an important aspect under the SLCA.