Application of Life Cycle Assessment to Cleaner Production

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ABSTRACT

The application of the concept of cleaner production (CP) to practice requires a suitable tool. Life cycle assessment (LCA) is one such tool for assessing the overall environmental burdens and resource consumption associated with products, processes and services throughout their life cycle – from cradle to grave. Case studies are presented, mainly from the Asia-Pacific region, where LCA has been applied for product comparison, product improvement as well as comparing alternative waste management scenarios. The results of these studies indicate how LCA can help selecting as well as developing new products and services with less overall environmental burdens thus demonstrating the utility of LCA for CP.

1. INTRODUCTION

The first generation of environmental technologies developed in the 1970's were the end-of-pipe type treating the air, water and solid emissions from industries. Though these technologies "treated" the emissions, the result was the transfer of pollutants from one form to another or one medium to another. This transformation was achieved at the cost of raw materials and energy consumption, but contributed little to the overall reduction of waste. The second generation of environmental technologies were the preventative, Cleaner Production (CP) systems which attempted to reduce the generation of waste at source through reduction in consumption of raw materials and energy resulting in increased productivity.

At first, CP efforts tended to focus on individual production processes, specific products or individual hazardous materials. The definition of CP evolved over time and has now been extended to include a systems approach leading to the current (third) generation of environmental technologies. During the period of development of the concept of CP, it has had a variety of names such as eco-efficiency, pollution prevention, green productivity, etc. UNEP defines CP as "*the continuous application of an **integrated** preventive environmental strategy to processes, products, and services to increase overall efficiency, and reduce risks to humans and the environment*" [emphasis by author]. The application of the concept of CP to practice requires a suitable environmental strategy.

A number of tools, such as Environmental Impact Assessment (EIA), Environmental Risk Assessment (EnRA) and Life Cycle Assessment (LCA), have been developed for decision support in environmental management. Each tool has its own specific area of application and is complementary to the others [1, 2]. EIA and EnRA are tools for site-specific environmental analysis. In LCA, the system boundaries are broadened to include all burdens and impacts in the life cycle of a product, process or service, and not focusing on the emissions and wastes generated by the plant or manufacturing site alone [3]. This integrated, systems approach makes it a suitable tool for achieving CP.

2. LIFE CYCLE ASSESSMENT

LCA has been defined by the Society of Environmental Toxicology and Chemistry (SETAC) as "*an objective process to evaluate the environmental burdens associated with a product, process or activity, by identifying and quantifying energy and materials used and waste released to the environment, and to evaluate and implement opportunities to effect environmental improvements*" [4]. The origins of the LCA methodology can be traced back to as early as the 1960s where the work focused mainly on calculating energy requirements [5]. However, the current methodology started being developed since 1990. Now, LCAs are far more comprehensive and yield much more environmental information than merely energy characteristics. Resource consumption as well as various environmental impacts such as global warming, stratospheric ozone depletion, acidification, nutrient enrichment, photochemical ozone formation, toxicity, etc. are considered in the assessment. Application of LCA even to products which are energy-intensive during their operation reveal, in addition to the predominant impacts due to energy, the importance of material and resource use, recycling and impacts such as toxicity [6].

LCA studies the environmental aspects and potential impacts throughout a product's life from raw material acquisition through production, use and disposal (Fig. 1). It is thus a holistic, systems approach that reduces the risk of problem displacement from one system to another or from one medium to another [7]. For example, it is important to know that while fluorescent bulbs require less power than incandescent ones and so contribute to less pollution, they contain toxic mercury. On the other hand, it is also important to know that when a refrigerant with high ozone depleting potential (ODP) is replaced with another with low ODP but lower heat transfer efficiency resulting in increased electricity consumption of an air-conditioner, the overall environmental effect of the replacement may not necessarily be positive [8, 9]. LCAs highlight such trade-offs which are important for decision making.

An LCA includes four phases [10]:

- Goal and scope definition – the objectives of the study, the system boundaries of the study and assumptions are defined. The functional unit quantifying the function of the product, process or service under consideration, which will be used for normalizing the data in the inventory and impact analysis steps, is also defined as part of the scope.
- Inventory analysis – resource use, energy use, and emissions to air, water and soil are compiled and quantified.
- Life-cycle impact assessment – potential environmental impacts of a system are calculated based

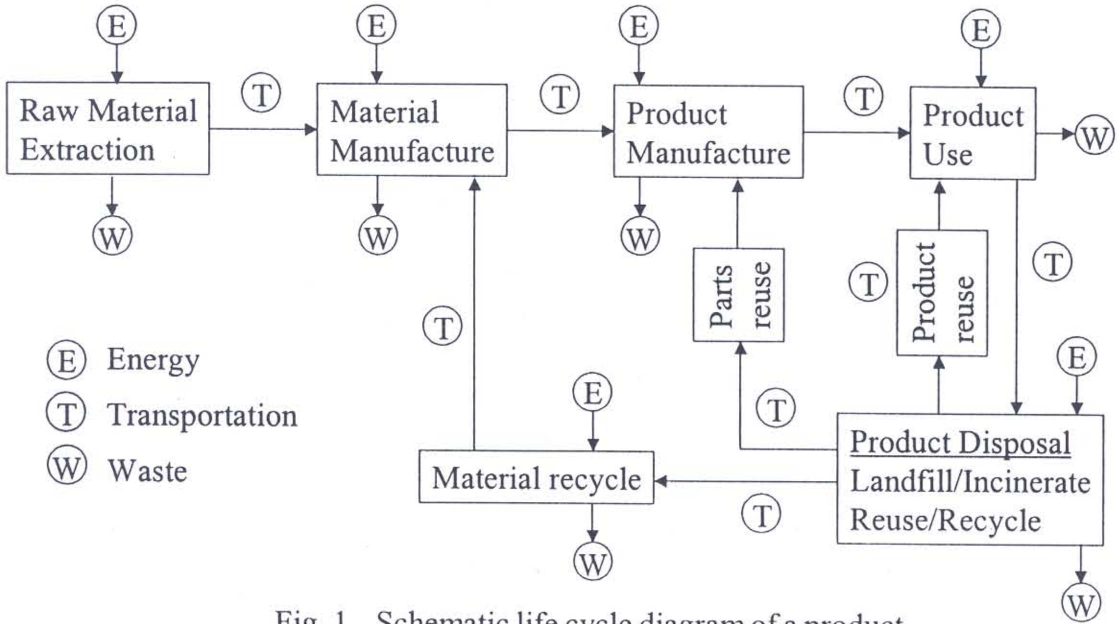

Fig. 1. Schematic life cycle diagram of a product

on the data collected during inventory analysis, in accordance with the goal and scope definition. This phase includes classification (assigning of inventory data to impact categories), characterization (calculation of environmental impact potentials) and normalization (conversion of all environmental impact potentials to the same unit). Weighting (or valuation), which assigns relative importance to the different environmental impact categories, may also be done.

- Interpretation – the findings of the inventory analysis and impact assessment are interpreted in accordance with the goal and scope definition. This step also includes sensitivity analyses of the key parameters of the assessment. Environmental "hotspots" are identified at this stage and improvements suggested.

The framework of LCA as per ISO (1997) [10] is shown in Fig. 2. The double arrows indicate that LCA is an iterative process. This implies that earlier steps in the LCA may be adjusted based on information made available in the later phases as the study progresses.

As seen in Fig. 2, LCA finds application in a variety of areas such as product development and improvement, strategic planning, public policy making, marketing, etc. LCAs can be valuable from a variety of perspectives. They can help identify processes, components, materials, and systems that are major contributors to environmental impacts, and can be used to compare options for minimizing these impacts [11]. Although the LCA methodology developed first in the US and Europe, it is finding increasing application in the Asia-Pacific region. Japan has been one of the forerunners in the development of LCA in Asia and established the Japan LCA forum as early as 1991 [12]. The government, research institutions, industry and academia have all been involved in the development of the databases required for Life Cycle Inventory (LCI), a difficult and time consuming part of any LCA. Japan has developed its own LCA software, NIRE-LCA. Further information about Japan's LCA activities can be found in [13, 14]. Australia too started developing LCA in the 1990's [15]. Their national project on LCI database was started in 1997. Currently, LCA activity in Australia extends to a wide range of areas including waste management, transport and fuels, packaging, buildings, raw materials, food and agriculture, process engineering and product design. The Korean government started building the LCI databases since 1998 [16]. LCA is being used in environmental labelling as well as product and process development. Other countries like India, Taiwan and Thailand are also making rapid progress [17-19]. This article considers several case studies, mostly from the Asia-Pacific region, to illustrate the utility of LCA for CP.

2.1 Application of LCA to Product Comparison

This section provides some examples of the application of LCA to selection of cleaner products. This area has been the subject of much controversy and has generated skepticism about the value of

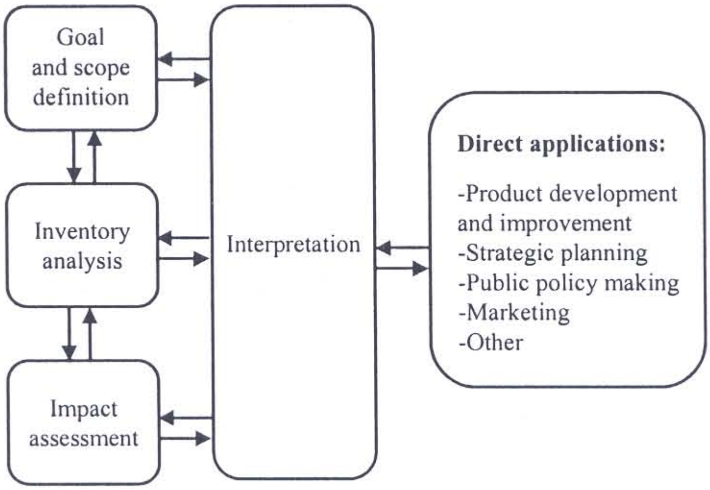

Fig. 2 LCA framework [10]

LCA due to the possibility of misuse by interested parties. However, the objective here is to demonstrate how it can be a valuable tool for comparing the overall environmental burdens of different product categories providing similar services. In the process of this analysis, important information may be revealed which could lead to further improvement of the existing products.

Light Bulbs

It was mentioned earlier in this article that while fluorescent bulbs require less power than incandescent lamps and so contribute to less pollution, they contain toxic mercury. Which option is more "eco-efficient"? At first glance the solution to this trade-off seems to depend on the relative priority given to energy consumption and ecotoxicity. However, an LCA study carried out in Japan yielded a surprisingly unambiguous result. This study compared the overall environmental burdens from incandescent, fluorescent and high intensity discharge (HID) lamps [20]. The types of lamps considered in this study are shown in Table 1. The basis of comparison (functional unit) was the provision of a certain level of illuminance for one year in residential usage by each type of lamp. The environmental parameters used for the evaluation were global warming and mercury emission. The evaluation stages included raw material production, packing material production, lamp manufacture, transport of lamps, usage and disposal. For global warming, CO_2, CH_4 and N_2O were considered. For mercury emissions, the entire amount of mercury included in the product was considered emitted to the environment at the time of disposal and emissions at the electric power stations were included.

It was observed that global warming effects were highly sensitive to CO_2 emissions from the electric power stations and mercury emissions were highly sensitive to mercury emissions from the electric power stations. Thus, even though the incandescent lamps did not contain mercury *per se*, their LCA showed mercury emissions due to electricity consumption from the use phase. Eco-efficiency values calculated to include both global warming and mercury emissions revealed that fluorescent and HID lamps performed better than incandescent lamps. Replacement of incandescent lamps with fluorescent or HID lamps would result in reduction of overall environmental burden.

Table 1 List of lamp types [20]

Group	Product		Contains mercury
Incandescent lamps	Silica light bulb		No
	Tungsten halogen lamp		No
Fluorescent lamps	Compact fluorescent lamp		Yes
	Tubular fluorescent lamp	Round	Yes
		Straight	Yes
High intensity discharge lamps	High pressure mercury vapour lamp		Yes
	Metal halide lamp		Yes

Air-conditioning

The idea of product comparison can be extended to comparing similar functions provided by different product systems, which is underlined by defining the functional unit in the scope definition of an LCA. This concept was used to compare cooling provided by two different types of air-conditioning systems – individual (split) and central systems – instead of just air-conditioners of the same type from different companies. The area to be cooled was 1000 rooms distributed over 40 ha at an average cooling load of 3.5 kW (1 ton) each, at the Asian Institute of Technology, Thailand [21]. The existing system, a central chiller plant used for generating cool and chilled water used for transferring the cool, was compared with providing each of the rooms with cool using individual units. The basis of comparison (functional unit) was providing 3.5 MW (1000 tons) of cool, 10 hours per day for 10 years. The environmental impacts considered in the analysis were global warming, acidification, stratospheric ozone depletion, photochemical ozone formation, nutrient enrichment and resource use.

The LCA revealed that central systems were superior to individual systems on all the environmental counts considered (Fig. 3). The central system also consumed lesser energy carriers than individual systems whereas it consumed more water. Some metal consumptions (Cr, Ni, Zn) were higher for central systems due to the galvanized iron in water piping network and stainless steel in pumps. However this result would change if the area over which the cool were being provided was smaller (for instance, a single multi-storeyed building). On the whole however, central systems used lesser resources. Since many of the impacts were dependent on the electricity consumption during use phase, sensitivity analyses were performed on the electricity mix. These studies revealed that the results are valid even if 80% of the electricity is from hydropower which contributes very little to the environmental impact categories considered.

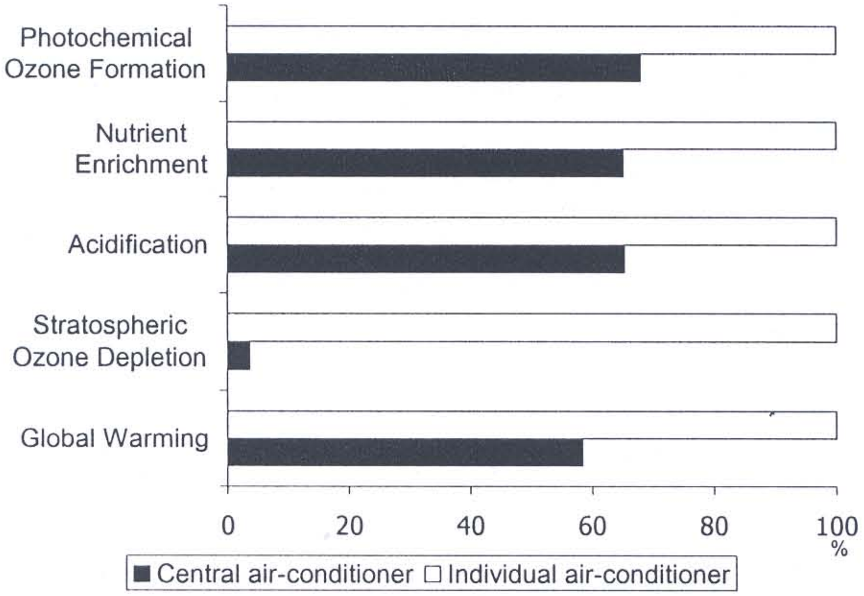

Fig. 3. Comparison of environmental impacts between central and split systems [21]

2.2 Application of LCA to Product Improvement

In the environmental design of products, LCA of a reference product can be used to identify environmental "hotspots" which can lead to development of cleaner products [22]. A number of companies in the Asia-Pacific region have used this concept for improving the environmental profiles of their products. Examples include reduction in usage of toxic materials (lead, hexavalent chromium, cadmium, mercury, volatile organic compounds, etc.), reduction in energy usage, designing products for easy disassembly and recycling. However, many of the reports remain unpublished due to confidentiality. The final results of their achievements are highlighted in their environmental sustainability reports, which are accessible to the public. But these do not contain the detailed procedures of how LCA was used in product improvement and are not used for illustration here.

High Pressure Cleaners

For the purpose of step-by-step illustration of the application of LCA to product improvement, a Danish study of high pressure cleaners has been chosen [23]. The LCA of the high pressure cleaner revealed that ecotoxicity due to the chemicals used during cleaning was the most important environmental impact. The other important impacts arose from the electricity consumption during the use phase and resource consumption of metals. On the basis of these results, several product alterations were introduced by the manufacturers, resulting in the improvement of the environmental profile of the high pressure cleaner. Some of the product improvements are listed as follows:

- To address the ecotoxicity issue, foaming of the chemicals before use was introduced by mixing of chemicals and water in the nozzle with addition of air. This resulted in a reduction in chemical usage, and hence ecotoxicity potential, by 50%.
- Introduction of automatic start/stop by means of hydraulic remote control reduced the energy consumption during use phase by 10%. A new nozzle was designed which improved the cleaning effect and also reduced the energy consumption in the use phase. The improved cleaning effect further reduced the use of chemicals. Nozzle life was also increased.
- New design using more homogeneous material composition saved material in the range of 25% and made disassembly easier which in turn facilitated recycling.

In addition to the environmental benefits, all the mentioned modifications resulted in reduced capital and operating cost of the product.

2.3 Application of LCA to Services

When planning for waste management systems, it is imperative to consider the environmental implications of the various options. A waste hierarchy is often used in policy making – reduce, reuse, recycle, incinerate with energy recovery, incinerate without energy recovery, landfill. The priority to reduce waste is of course, desirable. However, over-reliance on the hierarchy in decision-making for the remaining options, irrespective of impacts up and down the chain of extraction, use and disposal may be too simplistic [24, 25]. For example, the environmental benefits of recycling paper have been questioned in the light of studies that have shown increased fuel consumption and greater emissions of greenhouse gases and acidifying gases [26]. LCA has been successfully used as a tool for assessment of waste management systems [27, 29].

MSW Incineration

An application of this methodology for evaluation of an appropriate solid waste management technique is illustrated in the following case study from Japan [30]. If all the municipal solid waste (MSW) in Japan were to be deposited in landfills, the available disposal sites would be saturated in a matter of years. In order to reduce the volume of final waste going to landfill, recycling is being actively promoted by the government. Incineration offers an easy way to volume reduction, but has problems of toxic emissions such as dioxins associated with it. On the other hand, it produces high temperatures which can be used to generate electricity. The amount of electricity generation is limited by the production of hydrogen chloride and other substances which corrode the superheater pipes.

One way to increase the generating efficiency is repowering which involves addition of a gas turbine to MSW incinerators to raise steam temperature and pressure. The other technique, reburning, entails injecting natural gas into incinerators to reduce NO_x and dioxins, while at the same time recovering the energy of that natural gas as steam. Utilizing energy from MSW incineration requires installation of power generating equipment. Also, adding repowering and reburning requires additional generating equipment. Manufacturing and operation of these equipment require additional energy inputs. Thus energy inputs and CO_2 emissions over the whole life cycle were considered. Figure 4 shows the energy balance of MSW power generation. The same approach was used for CO_2 balance.

Three scenarios were considered – (a) energy generation only, (b) energy generation with repowering, (c) energy generation with reburning and repowering – to assess which scheme would yield the maximum environmental benefits. Gas turbines of 6, 15 and 40 MW capacities were considered for the analysis. The results showed that more energy recovery was possible from scenarios (b) and (c) than from (a) for all the three gas turbine capacities. Scenarios (b) and (c) also performed better in terms of CO_2 emissions.

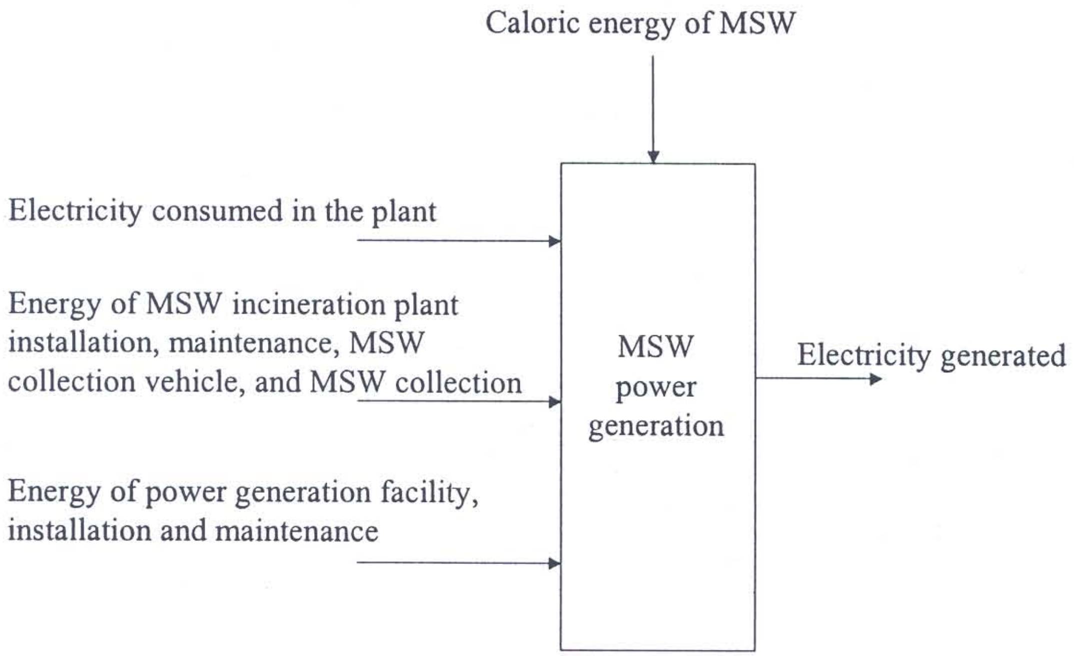

Fig. 4 Energy balance of MSW power generation [30]

Packaging

An Australian study used LCA to examine whether a reuse and recycle strategy for a plastic-based packaging system that substantially reduces the quantity of waste to landfill would also reduce the overall environmental burden [31]. The company conducting the study produced refrigerators in the range 140 L to 650 L. The packaging consisted of expanded polystyrene (EPS) top, bottom and side pieces, all enclosed in a polyethylene (PE) bag. To reduce the burden on the landfill, it was necessary to include recycling and reuse. However, the EPS components suffered enough damage during the transportation process to preclude reuse. Hence, the packaging was made more impact resistant by bonding a layer of high-impact polystyrene (HIPS) onto the outside of the polystyrene foam top, bottom and side pieces before shrink-wrapping in PE. This additional packaging would reduce the burden on the landfill because of some recycling and reuse of materials. But how would it affect the overall environmental burdens?

The resources and environmental effects for the conventional (EPS/PE) and modified (EPS-HIPS/PE) packaging were assessed over their entire life cycles including extraction of the original materials and energy resources, transformation of these into usable manufacturing inputs, the manufacturing process itself, transport and distribution of intermediate and end products, and the use and final disposal (Figs. 5 and 6). Construction energy for the main transport and processing equipment was also included. The categories considered for comparison were fossil fuel consumption, greenhouse gas emissions and photochemical oxidant precursors. The functional unit for the comparison was packaging assembly for a 500 L refrigerator. The EPS-HIPS/PE system produced less greenhouse gas emissions and used lesser fuel resources than the EPS/PE system. Though both systems contributed to photochemical oxidant precursors, the marginal impact of EPS/PE system was greater because for the EPS-HIPS/PE system the energy intensive processing steps responsible for most of the photochemical oxidant precursors were moved away from the city area. This highlights the environmental improvement that can be gained by changing the geographical location of certain steps. The study also showed that the energy consumed during transportation was negligible as compared to the overall energy consumption of the system. This is important because transport emissions are often cited as a reason for not pursuing recycling possibilities.

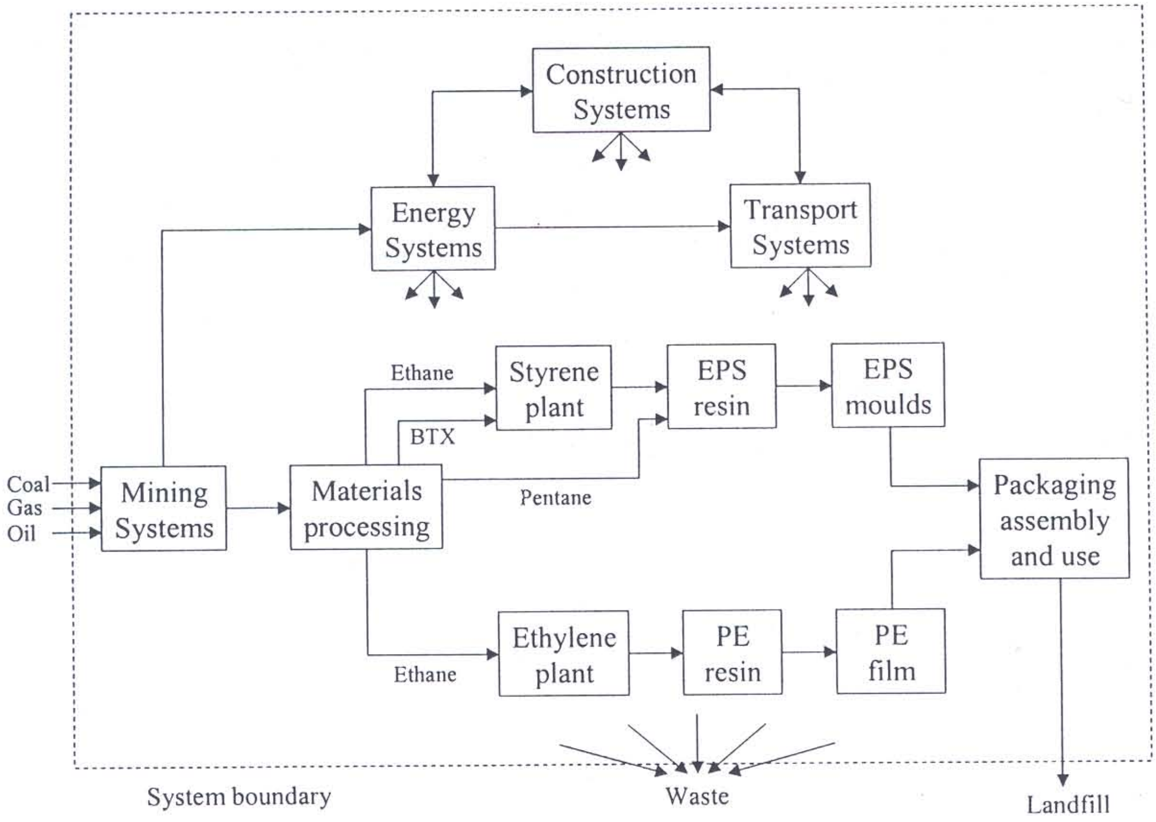

Fig. 5 Life-cycle of current EPS/PE packaging system [31]

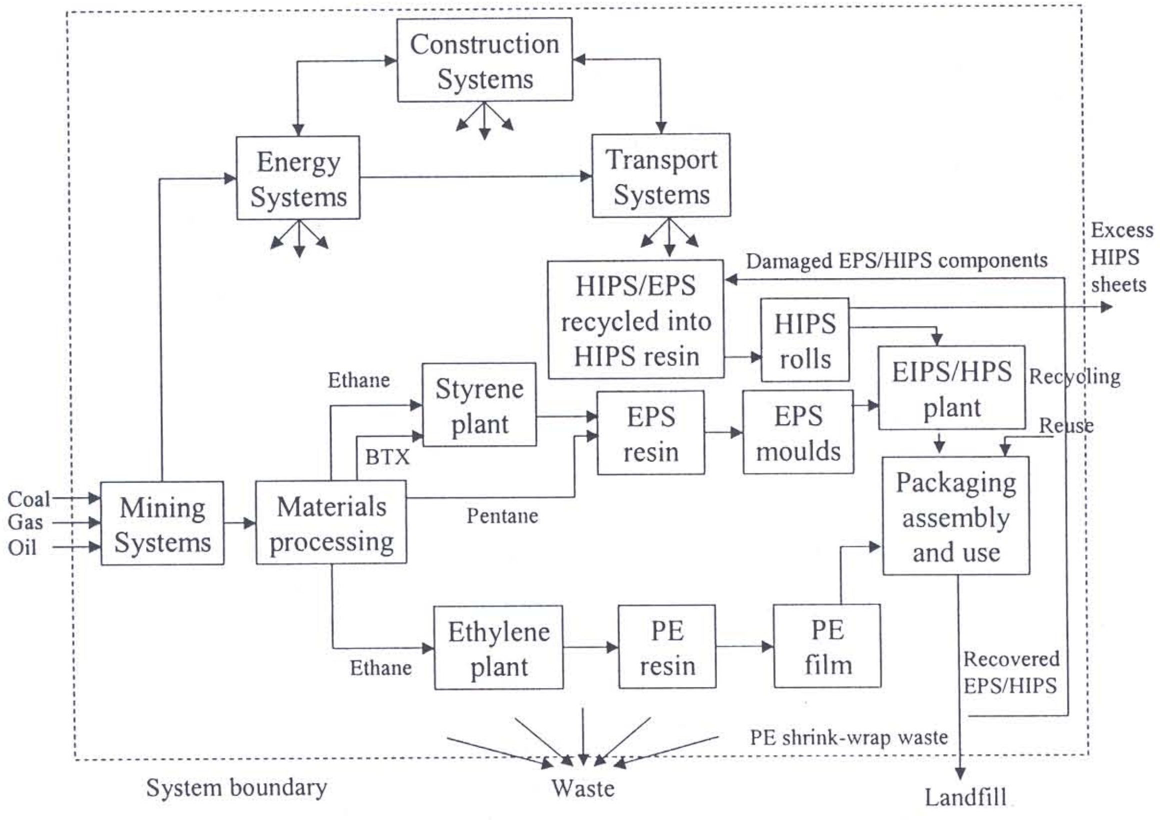

Fig. 6 Life-cycle of proposed EPS-HIPS/PE packaging system [31]

3. CONCLUSION

The application of LCA to CP in the Asia-Pacific region has been demonstrated using case studies. LCA is an environmental assessment tool considering resource use, energy use and emissions to air, water and soil throughout the life cycle of the product, process or service under consideration.

The examples of light bulbs and air-conditioning show how LCA can be used to compare different products categories providing the same service. A case study of high pressure cleaners demonstrates the systematic approach for identifying environmental hotspots leading to improvement in the environmental profile of products. Lastly, the application of LCA to waste management alternatives is illustrated using the case of MSW incineration and packaging. The examples have been chosen to illustrate the various areas of application of LCA to achieve CP and are only representative. Many big companies in the region are pursuing CP using LCA, results of which are presented annually in their environmental sustainability reports.

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