CHAPTER II
LITERATURE REVIEW

2.1 Today's Environmental Problems and Rising Global Awareness

The world is presently encountering inevitable aftermaths resulting from global industrial expansion which was once unilaterally regarded as a phenomenal achievement of human high-civilization. Climate changing, resource scarcity, ozone layer depletion, urban pollution..., all are perceptible and critical warnings of nature to mankind's short-sighted and extravagant development. Redressing the given situation, sustainable development has been introduced as the only possible and acceptable way, if human civilization is to avoid collapsing in the near future. Playing the critical role as policy-makers, governments have been forced to act to improve the effectiveness of environmental controls and standards. Government action is most obvious and most advanced in Europe, although many of the European approaches have some counterpart in the USA, Canada, Japan, Korea and Taiwan. Environmental regulations cover a range of targets and address a number of issues. Some are focused on eliminating harmful substances or practices: restricting the levels of emission of pollutants; banning the use of certain materials (such as ozone-depleting substances); protecting sensitive environments or habitats; prohibiting the transport of toxic substances; and so on. Other regulations aim at altering the economic or social framework so that harmful activities are discouraged while better practice – or improved practice – is encouraged. For instance, EPR (Extended Producer Responsibility) and product stewardship are two names for a principle increasingly being adopted around the world as a basis for government policy and program to reduce waste and environmental impacts from the end-of-life disposal of goods. The Organization for Economic Co-operation and Development (OECD, 1997) defines EPR as:

"The principle that manufacturers and importers of products should bear a significant degree of responsibility for the environmental impacts of their products throughout the product life-cycle, including impacts [from] the selection of materials, the production process, and from the use and disposal of the products."

Besides, other environmental regulations – in the EU the WEEE (Waste from Electrical and Electronic Equipment) directive, the RoHS (Restriction of Hazardous Substances) directive, and the EuP (Energy-using Product) directive – also have directly or indirectly helped to build up the manufacturers' as well as the public attentiveness; and the existence or threat of those stringent environmental regulation has had, and continue to have, a considerable influence over the industry.

Companies are now being forced to implement strategies to reduce the environmental burdens of their products and services, in order to remain competent and competitive in today's global market, under such pressure from both the authority and the public. In established industrialized markets such as Europe, the USA, Canada and Japan, the demand for low-impact products, and the investment to create them, is growing at an astonishing rate, driven by increasingly rigorous standards and regulations. In the rapidly developing economies of Asia, demand is growing because of resource constraint in those regions that would otherwise limit the rate of development. Demand for 'cleaner and greener' products is also growing because investment in research, design and innovation is delivering new competitive products with greatly improved environmental efficiencies. In addition, companies can see that growing consumers' awareness about environmental degradation will continue to mature and gather momentum, as today's well-informed and eco-oriented youths will become more affluent consumers in the years to come.

Overall the message is clear: environmental issues no longer relate solely to compliance, clean-ups and other end-of-pipe scenarios. In fact, environmental management is not a "necessary evil"; it provides invaluable benefits to our habitat, as well as to a company's bottom line if properly executed. The days of companies acting on environmental issues simply because they are required to by government are gone, especially among OECD nations.

In that context, moreover, the recent strategy of implementing 'cleaner production' or pollution prevention as a way of saving money (and protecting the environment) has also been acknowledged as an incomplete solution to minimizing environmental impacts. Thus the advent of the life-cycle approaches has won the support and acknowledgement of progressive governments and corporations, of the global environmental movement, and of an ever-growing list of influential designers. Life-cycle approaches applied for a product or service involve looking towards the past, or upstream processes of that product or service (raw material extraction, manufacturing, transport, and so on), looking to the future use and possible disposal options, or downstream processes (energy and materials consumed by the product in use, reuse, recycling or disposal option for the product) and taking into account the roles of all stakeholders (government, designer, manufacturer, supplier, and consumer). A life cycle approach identifies both opportunities and risks of a product or technology, all the way from raw materials to disposal, from cradle-to-grave.

2.2 State-of-The-Art Life Cycle Approach

2.2.1 Introduction to Life Cycle Approach

Just like living organisms, products have a life cycle as well. Whereas living organisms originate, reproduce, and eventually die, products are produced from raw materials, used by consumers, and eventually disposed. A product's life cycle is generally broken into stages. The number of stages can vary; six stages are often distinguished (Figure 2.1).

- Product design (not shown in Figure 2.1);
- Raw material extraction and processing;
- Manufacturing of the product;
- Packaging and distribution to the consumer;
- Product use and maintenance;
- End-of-life management: reuse, recycling and disposal.

In every stage of its life cycle, product interacts with other systems: life cycles are therefore called open cycles. In order to make a product, substances, energy, labor, technology and money are required, while other substances are emitted to the environment. Products can interact with environmental (extraction or addition of substances, land use), economic (the cost to produce a product, implement technology, the profit to sell) and social domain (employment, workers rights). The relations between the environmental, economic and social domains are quite dynamic. The implementation of cleaner technology will decrease the pollution of the environment, for instance, but might increase the cost to make that product, at least in short term. A life cycle approach is a way of thinking which helps us recognize how our selections – simply as buying electricity or a new laptop – are one part of a whole system of events, so we can balance trade-offs and positively impact the economy, the environment, and society.

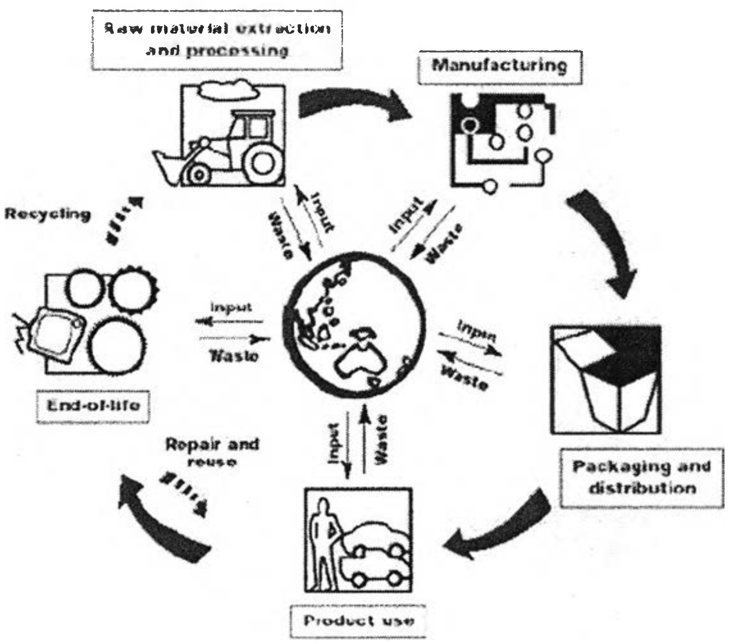

Figure 2.1 Stages of a product life cycle (Source: *Australian Government: Department of the environment and heritage*).

A life cycle approach helps promote:

- Awareness that our selections are not isolated, but influence a larger system. Buying office paper is a good example: if we know it takes 24 trees to create 50,000 sheets of office paper and 2.3 cubic meters of landfill space to dispose of it, we might choose paper made from recycled material and elect to support paper producers that source from sustainably managed forests.

- Making choices for the longer term and considering all environmental and social issues associated with those. Life cycle thinking helps us avoid short term decisions that lead to environmental degradation – such as over-fishing or polluting our air with mercury.

- Improving entire systems, not single parts of systems, by avoiding decisions that fix one environmental problem but cause another unexpected or costly environmental problem (like mitigating air pollution yet increasing water pollution like the case of using MTBE in gasoline). Life cycle thinking helps avoid shifting problems from one life cycle stage to another, from one geographic region to another and from one environmental medium (air, water or soil) to another.

- Informed selections, but not necessarily 'right' or 'wrong' ones. Life cycle thinking simply helps us put our decisions in context with facts from all parts of the system or life cycle. It means we look for unintentional impacts of our actions (such as damaging a natural eco-system or inadvertently supporting unfair labor conditions and wages) and take some action to prevent those impacts (such as purchasing office paper from sustainably managed forests or coffee certified "fair trade").

Life cycle approaches are getting increased attention over the last ten years. This increase is not odd considering the advantages a life cycle approach has over the focus on a single process (like production or consumption of a product). Life cycle approach is commonly referred to as the product of a general evolution in strategies to deal with pollution, waste and other environmental issues. Concerns over pollution and waste initially led to end-of-pipe approaches aimed at 'blocking' pollution (with targets and controls on factory emissions, higher costs for waste disposal, etc.). This end-of-pipe approach was soon complemented by a more sophisticated interest in waste prevention and pollution minimization. Internationally, this latter approach became known as 'cleaner production'. The interest has shifted to redesigning or reconfiguring production processes to minimize resource consumption and waste. However, the environmental performance of a product doesn't stop at the gate of the factory, so it also needs to take into consideration other components of the product system, beyond the factory and thus the advent of life-cycle approaches has been recognized as the satisfactory answer to this problem.

2.2.2 Life Cycle Approach Potentials: from Government's, Producer's and Consumer's Perspectives

For society as a whole, life cycle approaches can bring considerable benefits, especially in decision making procedure. More and more people are basing their decisions on life cycle information, in effort to gain the most from their actions without unintentionally jeopardizing their ability to thrive in the future.

Applying life cycle approaches implies that everyone in the whole chain of a product's life cycle, from cradle to grave, has a responsibility and a role to play, taking into account all the relevant impacts on the economy, the environment and the society. These impacts from all life cycle stages need to be considered comprehensively by the citizens, the companies and the governments, when they make decisions on consumption and production patterns, policies and management strategies, avoiding the commonly encounter 'problem shifting'. A well-known example of problem shifting concerns the use of an aluminum car frame instead of regular steel one in order to decrease the energy consumption during use. However, the production of aluminum requires a higher energy input than steel production does. Studies that analyze the life cycle of steel and aluminum car frames from an environmental point of view show that the advantage of the lighter aluminum car frame is dependent on the amount of its future use: only after a certain number of kilometers, the change will pay off. By taking the whole life cycle into account, the danger of problem shifting can in principle be assessed and prevented.

From different stakeholders' point of view, life cycle approaches are of diverse interests:

❖ For Governments

Governmental initiatives will not only secure and strengthen the position of industrial and service sectors in regional and global markets, but also ensure overall environmental benefits to society (balanced with economic and social aspects). By engaging in supportive programs and initiatives to promote the implementation of life-cycle approaches, governments can show global responsibility and governance by sharing and disseminating sustainability options world- wide.

In addition, measuring potential life cycle impacts of decisions can help governments to:

- Inform government programs and help priorities these programs, based on life cycle information.

- Make policies more consistent among consumers, producers, material suppliers, retailers, and waste managers and also among different policy instruments (such as harmonizing regulations, voluntary agreements, taxes, and subsidies).

- Purchase products and services which are "environmentally preferable", reduce the impact government operations have on the environment and support regional and global markets for "preferable" products and services.

- Promote pricing products and services to accurately reflect the costs of environmental degradation, health problems, erosion of social welfare, and impacts at other life cycle stages. Such "price signals" can send messages to consumers and provide incentives for businesses to continuously improve the environmental and social performance of products or services, across each stage of the life cycle.

- Introduce take-back systems to establish a recycling-based economy according to the hierarchy reduce, reuse and recycle.

A further benefit of the life cycle methodology is that it also provides a sense of magnitude. For example, policy tends to focus almost predominantly on end of life issues (i.e. waste management). Yet when one considers directives such as those focusing on End of Life Vehicles (ELVs) or Waste from Electrical and Electronic Equipment (WEEE), by adopting a life cycle approach it becomes apparent that all our efforts are actually concentrating on approximately 1% of the total environmental impacts of the whole life of a car or an item of electrical equipment only. Respecting that in these instances, 80 to 90% of the environmental impacts are associated with the use phase, then this demonstrates that targeting the use phase is where improvements in environmental performance are most likely to yield the greatest

A typical example of life cycle initiative from government was found in France, where ADEME, France's Environment and Energy Management Agency, gathered results from life cycle studies that had been conducted on 11 different products and types of packaging, such as paper, aluminum, and plastic packaging. ADEME compared the environmental impacts from recycling the product or packaging with impacts from incinerating it, land filling it, or otherwise disposing of it. ADEME's comparison showed that recycling plastic is environmentally beneficial if the recycled plastic is used in a product in place of virgin plastic. However, if the recycled plastic is used in place of wood, it would have been more environmentally beneficial to incinerate that plastic and recover the energy from the incinerator (i.e., recycling is not favorable). The French government has used this life cycle information to inform their laws on recycling, waste prevention, and responsible "end-of-life" management for products and packaging. In France, it may soon "... become the responsibility of producers, importers and distributors of products (and materials in those products) to manage or contribute to eliminating waste from those products..." (translated from ART L541-10 du Code de l'Environnement) (UNEP 1st edition, 2004).

❖ For Consumers

Life cycle approaches will help orient consumption in a more sustainable direction by offering better information for purchasing, transport systems, energy sources - to guide consumers. For their part, consumers can look for life cycle information about the products and services they buy – do they entail the excessive use of energy, illegal labor conditions, the production of hazardous waste, the destruction of an endangered ecosystem, or the pollution of air and water? Consumers can try to find out if the businesses they regularly buy from have initiatives to address these issues and look for ways to support that work.

For some products and services, eco-labels and other types of environmental and social information demonstrate the awareness of the manufacturers. Consumers can also look for information that tells how they should use, care for, recycle or discard products effectively. All of this information is becoming increasingly available for products, and services ranging from foods such as fish and other meats to washing powder, hotels, cars, paper products and computers, among many others. Sometimes a simple label can tell us - the consumers - whether the refrigerator we are buying or the golf course we are using has fewer environmental impacts than certain alternatives.

For example in Thai Green Labels project, life cycle consideration was explicitly promoted. Thailand's Ministry of Industry, the Thailand Business Council for Sustainable Development, the Thai Industrial Standards Institute, and the Thailand Environmental Institute wanted to encourage businesses to improve the environmental quality of their products and services by stimulating consumer demand for such products. In October 1993, the group initiated the Green Label Scheme – a scheme to establish product criteria and certify products with less impact on the environment, compared to other products serving the same function. The product criteria are based on the significant impacts a product may have on the environment during its life cycle (referred to as life cycle consideration), as well as how easily businesses could meet criteria with reasonable process changes or improvements.

❖ For Industries

A company and its employees in design, sales, and finance make many choices to balance customer satisfaction, quality, innovation, safety, costs, and more. Thinking in terms of the life cycle, companies recognize that each choice sets the stage for not only how the product will look and function, but also for how it will impact the environment and the community as it is manufactured, used, disposed, or re-used and recycled. It is also recognized that no matter where in the life-cycle the impact lies, most of the impact is 'locked' into the product at the design stage when materials are selected and product performance is largely determined. For example, washing machines, refrigerators, and other appliances can be made from recycled materials, be free of harmful substances, use minimal water and energy, and be designed to have a long life. Furthermore, making adjustments in that part of the life cycle where intervening is relatively cheap, the costs of environmental improvements would be minimized. For example, redesigning a product to make it better fit for recycling maybe cheaper than investing in the improvement of recycling methods. In this way, better design for recycling will reduce both the environmental and economical costs of recycling. Trying to implement environmental protection strategies once the design is resolved or settled generally reflects an 'end-of-pipe' orientation and represents 'yesterday's thinking'. Obviously, the designer cannot bear responsibility for all negative effects of the product; yet, the designer can have a significant influence over the environmental impacts that may arise upstream or downstream of his or her own interaction.

To make decisions during product design, companies research where the raw materials might come from, which manufacturing processes may be needed, who will use the product, what type of maintenance and cleaning might be required, what types of waste will be created, and where the product will go when it is discarded. To find this out, designers conduct life cycle studies and measure the potential impacts of various options.

Companies also request such information from their suppliers. There are international standards for these business-to-business communications or "environmental product declarations". Each declaration must be based on a life cycle study and tell the business customer about the life cycle environmental impacts of the component or product being purchased. Declarations exist for building and construction products, refrigerators and other appliances, chemicals, train cars, dairy products, and circuit breakers, to name a few.

Life cycle thinking that influence product design, strategic planning, procurement, and sales helps companies:

- Enhance their image and the value of their brands – businesses can avoid criticism and participate in issues abroad or beyond their direct sphere of influence. Financial indices such as the Dow Jones Sustainability Indexes (DJSI) track and report the financial performance of leading sustainability driven businesses, worldwide. In addition, it helps to avoid criticism that a company is only interested in shareholder value and possible impacts in the direct sphere of influence, and that it does not bother about impacts abroad or in the future.

- Find new ways for marketing and sales departments to communicate and interact with customers – some fifty percent of businesses say they are interested in learning about sustainability. This means a company can promote its products and services by talking about its social and environmental attributes.

- Share life cycle information with suppliers, customers, and waste handlers to identify risks and opportunities for improvement – the risks might relate to the environment, human health, safety, and finance, while opportunities could include growing market share, brand image, effective use of materials, and innovation. Together, businesses can find new ways to improve output while optimizing their use of time, money, labor, and material input

Overall, life cycle thinking can promote a more sustainable rate of production and consumption. Experts from government, industry, and other organizations agree that implementing life cycle approaches during decision-making phases will help to halt and possibly reverse some of the damaging trends in our communities and environment. It certainly won't solve all the current environmental problems, but it can help find sustainable ways to tackle many of them.

2.2.3 Tools and Technique Under Life Cycle Approaches

An overview of all major tools, programs and procedures under life cycle approaches is given in Figure 2.2.

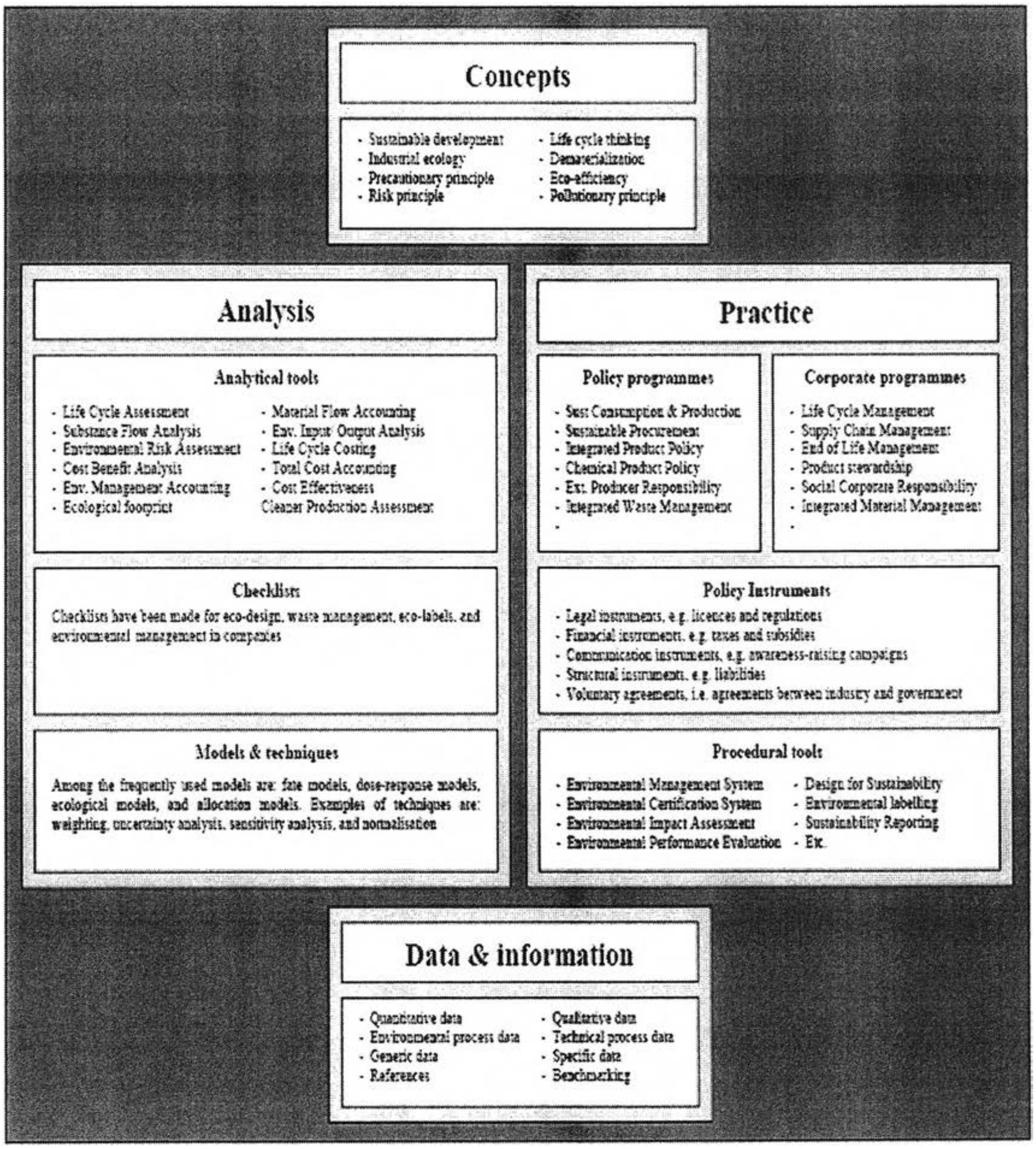

Figure 2.2 Life cycle approaches, consisting of analysis and practice, are directed by concepts and supported by data and information (Haes *et al.*, 2005).

Basically, life cycle approaches can be split into analytical and practical approaches.

- Analytical approaches are modeling the systems in a quantitative way, aiming at providing scientifically sound information for learning about the system under consideration and ultimately better decision-making. The focus of analytical approaches is on computational algorithms and thus requires quantitative data. These approaches include analytical tools such as Life Cycle Assessment (LCA) or Life Cycle Costing, checklists consisting of pass-fail criteria, and a number of models and techniques (like pollutant fate or allocation models) (Haes *et al.*, 2005).

- The practical life cycle approaches are meant to translate theory and lessons learnt from the use of analytical tools into practice. Practice consists of (governmental) policy programs, corporate programs, policy instruments, and procedural tools. Noted that these contributions to practice are not exclusive. Although some overlap exists, there are differences between policy programs and corporate programs. Examples of policy programs are the Integrated Product Policy (IPP) program of the European Union, or the Chemical Product Policy of the OECD. Typical corporate programs include Supply Chain Management and End of Life Management. Policy instruments are tools to support mainly the interventions of governments, for example taxes, laws, or communication. Procedural tools are procedures and guides helping to motivate and implement environmental decisions, like Environmental Performance Evaluation and Design for the Environment (DfE) (Haes *et al.*, 2005).

All life cycle approaches are steered by concepts, which are guiding principles (e.g. ideas, ideals) on how to achieve a life cycle economy. Examples of concepts are "sustainability" and "life cycle thinking". Both analysis and practice are supported by data and information. Examples of data and information are databases with specifications of resource use and emissions (like life cycle inventory process data) and toxic substances (like life cycle impact assessment characterization factors), or statistical data on a country's demography.

The current trend in LCA development is that analysis has to become more practice-oriented, and practice more science-based, responding to many criticisms exerting on both analytical and practical approaches. Analytical approaches, which are generally developed by the scientific community, are said to be too much science driven. They are said to be too complicated, and not sufficiently made for easy use. On the other hand, current practical approaches, which generally consist of programs developed by governmental and corporate organizations, are criticized for lacking sufficient scientific support. These programs and also the underlying procedures and policy instruments are criticized of being based on qualitative concepts and guidelines, rather than on science and lessons learnt from the use of analytical tools.

2.3 Life-cycle assessment (LCA)

2.3.1 LCA Origin and Its Applications

Life Cycle Assessment (LCA), as an analytical tool under life cycle approach, aims at specifying the environmental consequences of products or services from cradle-to-grave. In other words, LCA attempts to attribute the environmental loads from all stages of the life-cycle of a product or a product system back to the 'functional unit' of the product. In ISO 14040, LCA is defined as the "compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life-cycle". LCA methodology has developed steadily over the past two decades, since the early '90s, predominantly in Europe, but also in the USA and more recently in Asia.

LCA is a powerful tool for the analysis and optimization of a product by offering a holistic view of the environmental impacts of products or technologies by considering impacts throughout the value chain under study; and is effective in broadly implementing life cycle thinking. The value of LCA is in its ability to map a product's environmental impact across its whole life-cycle, including:

- Extraction and processing of raw materials.
- Manufacture of the product (and any associated packaging and consumables)
- Use or operation of product
- End-of-life option (e.g. re-use, remanufacture, recycling, treatment and disposal).

LCA is internationally accepted, recognized and endorsed by the European Commission's work on Integrated Product Policy and the United Nations in proceedings of the World Summit in Johannesburg. The EU Commission concludes for Integrated Product Policy (IPP):

"*...LCAs provide the best framework for assessing the potential environmental impacts of products currently available. They are therefore an important support tool for IPP*" (IPP 2003)

Many initially thought that LCA would be a very good tool to support environmental claims that could directly be used in marketing. Over the years, it has become clear that this is not the best application for LCA, although it is clearly important to communicate the LCA results in a careful and well-balanced way. A survey on how LCA is used shows that the most common reasons for the application of LCA are for internal purposes:

- Product improvement
- Support for strategic choices
- Benchmarking
- External communication

As it can be seen, the core application of LCA concerns product related decisions support. Employing LCA allows the product designer to consider and design around the broader environmental implication of the product. It can also be used for hotspot identification in product systems, product development, product comparison, green procurement and market claims. Furthermore, LCA is, next to other tools, important for technology choices, setting technologies into a product related chain perspective. LCA is increasingly used at a strategic level for business development, policy development, and education as well.

Finally, as Udo de Haes (1993) explains, LCA differs from environmental impact assessment (EIA) and risk assessment (RA). Firstly, because LCA studies the whole life cycle of an economic system, resources may come from different countries and waste products may be globally distributed. Therefore, a non-site-specific approach to environmental impacts is required, which in this respect differs from EIA. Secondly, LCA is concerned with factual inputs and outputs of the system under study. The intrinsic risks of the processes themselves, however, are not addressed as they are in risk assessment studies.

2.3.2 LCA Methodology

In its early period, LCA studies were simple and generally restricted to calculating energy requirements and solid wastes, with little attention given to evaluating potential environmental effects. During the oil crisis of the early 1970s, extensive energy studies based on life cycle inventories were performed for a range of industrial systems. By the end of the 1980s, numerous studies using LCA had been performed, mainly by private companies in Sweden, Switzerland and the USA (Udo de Haes, 1993). However, many of these studies were performed using different methods and without a common theoretical framework. Consequently, the results between studies with the same goals often differed considerably, preventing LCA from becoming a more accepted analytical technique (Udo de Haes, 1993).

The general framework for the LCA methodology has changed over the years, just as the motives for performing LCAs have changed. Since 1990, attempts have been made to develop and standardize the LCA methodology under the coordination of the Society of Environmental Toxicology and Chemistry (SETAC) (Udo de Haes, 1993). In 1993, SETAC published a "Code of Practice", which presents general principles and a framework for the conduct, review, presentation and use of LCA findings. An international standard for LCA put together by the International Standardisation Organisation (ISO) has recently emerged and was documented in four environmental management system standards (the ISO 14040 series). The methodology framework for ISO is similar to that for SETAC with some differences for the interpretation phase, where ISO has included further analysis and sensitivity studies. (*Note*: the ISO standards used to define LCA, namely ISO 14040:1997, ISO 14041:1999, ISO 14042:2000 and ISO 14043:2000, have been replaced by new published standards ISO 14040:2006 and 14044:2006. The new editions have been updated to improve the readability, while leaving the requirements and technical content unaffected, except for errors and inconsistencies. In this study, old numbers of the ISO standards are still referred to for consistency reason with other papers).

According to ISO, the methodology is generally broken up into four stages:

- Definition of the goal and scope (ISO 14041)
- Life-cycle inventory analysis (ISO 14041)

- Life-cycle impact assessment (ISO 14042)
- Life-cycle interpretation (ISO 14043)

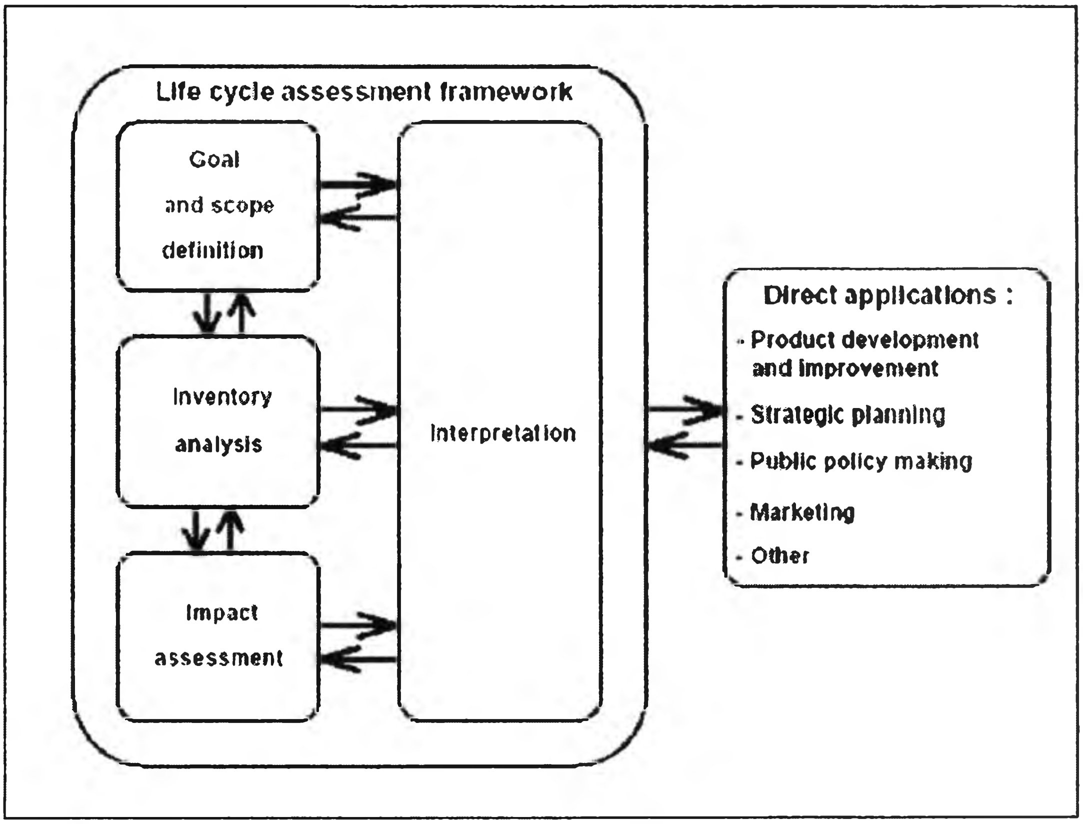

Figure 2.3 Phases of an LCA (ISO 14040).

It should also be marked that the ISO standards are defined in a quite vague language, which makes it difficult to see if an LCA has been made in line with the standard. Unlike the 14000 standard, it is not possible to get an official accreditation that states that an LCA, an LCA methodology or LCA software such as SimaPro has been made in accordance with the ISO standard. It is completely up to the practitioner to conform to these standards or to deviate. If one deviates, it is clear that he cannot claim that his LCA has been made according to the international standards, and it will be more difficult to convince others of the reliability of his results.

The most important consequences of aiming adhere to an ISO standard is the need for careful documentation of goal and scope and interpretation issues. As an LCA practitioner, one has a rather wide choice of alternative ways to perform his LCA, as long as he carefully documents what he does. A second consequence of complying with the standards that one might need to include a peer review by independent experts, as described in ISO 14040.

➢ Definition of the goal and scope

This first stage is very important, as it defines the questions being asked in the LCA (who the audience is and the reason for carrying out the study) and the scope of the activities that will be undertaken to answer those questions. The goal and scope also define the boundaries of the system that will be included in the assessment as well as allocation and cut-off rules. The goal and scope can be revisited later in the project in light of new information or in light of a lack of available information.

The functional unit is established in this step, with the necessary data and information needed for the inventory and impact assessment also identified. The selection of functional unit is straightforward for processes (usually 1 kg of product), but more debatable for products where product effectiveness (as a surface coating, an insulating material, a detergent) rather than mass or volume becomes of key importance.

➢ Life-cycle inventory (LCI) analysis

The inventory analysis component of an LCA quantifies the inputs (using mass and energy balances) and outputs (products and releases to air, water and land) of all processes included in the system boundary. The first task in the inventory analysis is to specify all the processes involved in the product life cycle in the form of a process flow chart. The next step is to collect data on each process, by consulting scientific literature, published data (e.g. databases) or directly from involved sources. Collecting the data is the most time consuming and perhaps the most difficult part of an LCA. Two types of data are usually distinguished:

- Foreground data
- Background data

Foreground data refers to very specific data you need to model your system. It is typically data that describes a particular product system and particular specialized production system. Background data is data for generic materials, energy, transport and waste management systems. This is data that can be found in databases and literature. The distinction between these data types is not sharp and depends on the subject of an LCA. In a case one would consider truck's emissions as background data (transportation), in another case the truck becomes foreground data if it is the main subject of that LCA study.

The outcome of this analysis is a long list of resources used, and emissions to the environment (air, water, soil, etc.). On its own, this data may contain some useful information, such as total carbon dioxide (CO_2) emissions, or the total emissions of a controlled substance. Many life cycle studies have stopped at the inventory stage, often basing conclusions and recommendations on how the inventory interventions can be minimized. However, the major drawback with this approach is that information on whether some categories in the inventory analysis are more hazardous than others is not considered. That is why the next phase is needed for better understanding the potential environmental impacts of these LCI results.

➢ Life-cycle impact assessment (LCIA)

LCIA aims to connect, as far as possible, each LCI result to its potential environmental damages, on the basis of impact pathways (impact pathways are composed of environmental processes like a product system consists of economic processes).

This stage takes the list of items provided by the inventory analysis and classifies them into different environmental impact categories (classification step). These categories are defined in the goal and scope and usually include common impacts such as global warming, energy use, solid waste and toxic emission (see more in Appendix A). A summary of the prioritization of impact category results is included in Table 2.1. Relevant inventory results are attributed to different impact categories. Once the impact categories are defined and the LCI results are assigned to these impact categories, it is necessary to define characterization factors (characterization step). These factors should reflect the relative contribution of an LCI result to an impact category compared to a reference substance. For example, the reference substance for global warming is carbon dioxide; the global warming contribution by other substances is then expressed in terms of the equivalent amount of carbon dioxide that would have the same global warming effect (methane has the characterization factor of 22 kg CO_2 equivalent, for instance). However, for many impacts this information is not available or reliable (e.g. in the case of toxic emissions).

Table 2.1 Significance of impact categories (Jolliet and Brent, 2003)

Required	Nice to know	Low priority
• Climate Change • Ozone Depletion • Habitat loss as result of deliberate actions • Human toxicity • Eco-toxicity • Acidification and Eutrophication • Photo-oxidants • Extraction of Minerals • Energy from Fossil Fuels • Nuclear Radiation • ***Water usage	• *Salinisation • *Erosion • *Soil Depletion • Habitat loss as a result of indirect actions • Noise • Use of GMOs	• *Health of workers • **Safety • Landscape • Extraction of biotic resources

Note:

* Classified as "required" if only answers from non-traditional LCA countries are considered

** Classified as "nice to know" if only answers from non-traditional LCA countries are considered

*** Not in the initial list, but explicitly asked for by a number of respondents.

This classification and characterization procedure is at the basis of most LCIA methods. The ISO 14042 standard defines LCIA; it considers these steps as the obligatory steps. If such procedures are not applied, one may only refer to the study as a life cycle inventory (LCI).

The result after this step is a number of impact category indicator results. Impact categories can be ‘normalized’ to determine equivalent contributions within each category compared with a national or global reference value, making it easier to understand the relative magnitude of each environmental impact score (normalization). The categories can then be weighed based on their environmental significance by multiplying with corresponding weighting factors. These weighting factors may be established in a panel, either on the national, regional or global level, with the general idea being to directly investigate the preferences of society for reduction of environmental impacts. Weighting factor may also be defined on political or ecological goals or standards, often referred to as distance-to-target approaches. The weighted impacts subsequently can be summed to determine a single score or 'eco-indicator'. These two steps (optional) require many subjective judgments and are an area of significant debate within LCA community. However, for users with little time and environmental knowledge, single scores based on impact weighting represent useful information that can readily be used in the decision-making process.

An important distinction is made between internal and external applications. If results are intended to compare (competing) products and they are to be presented to the public, weighting may not be used due to its subjective characteristic.

Furthermore, also according to ISO, LCI results are classified in impact categories and the category indicators can be located at *any* place between the LCI-results (interventions) and the category endpoints. So based on this format, two main schools of assessment methods have been developed:

- Classical impact assessment methods (e.g. CML 2002, EDIP 97) which stop quantitative modeling relatively early in the cause-effect chain to limit uncertainties and group LCI results in what we call here midpoint categories, according to common themes: i.e. common mechanisms (e.g. climate change-global warming) or commonly accepted grouping (ecotoxicity).

- Damage oriented methods such as Ecoindicator 99 or EPS, which try to enhance relevance by modeling (sometimes with high uncertainties) the cause-effect chain up to the endpoint or damage.

The term 'midpoint' expresses that this point lies somewhere on the impact pathway as an intermediate point between the LCI results and the damage or end of the pathways. In consequence, a further step may allocate these midpoint categories to one or several damage categories, the latter representing quality changes of the environment being the ultimate objects of human societies concern (Figure 2.4). A damage indicator is the quantified representation of this quality change. In practice, a damage indicator is always a simplified model of a very complex reality, giving only a coarse approximation to the quality status of the item.

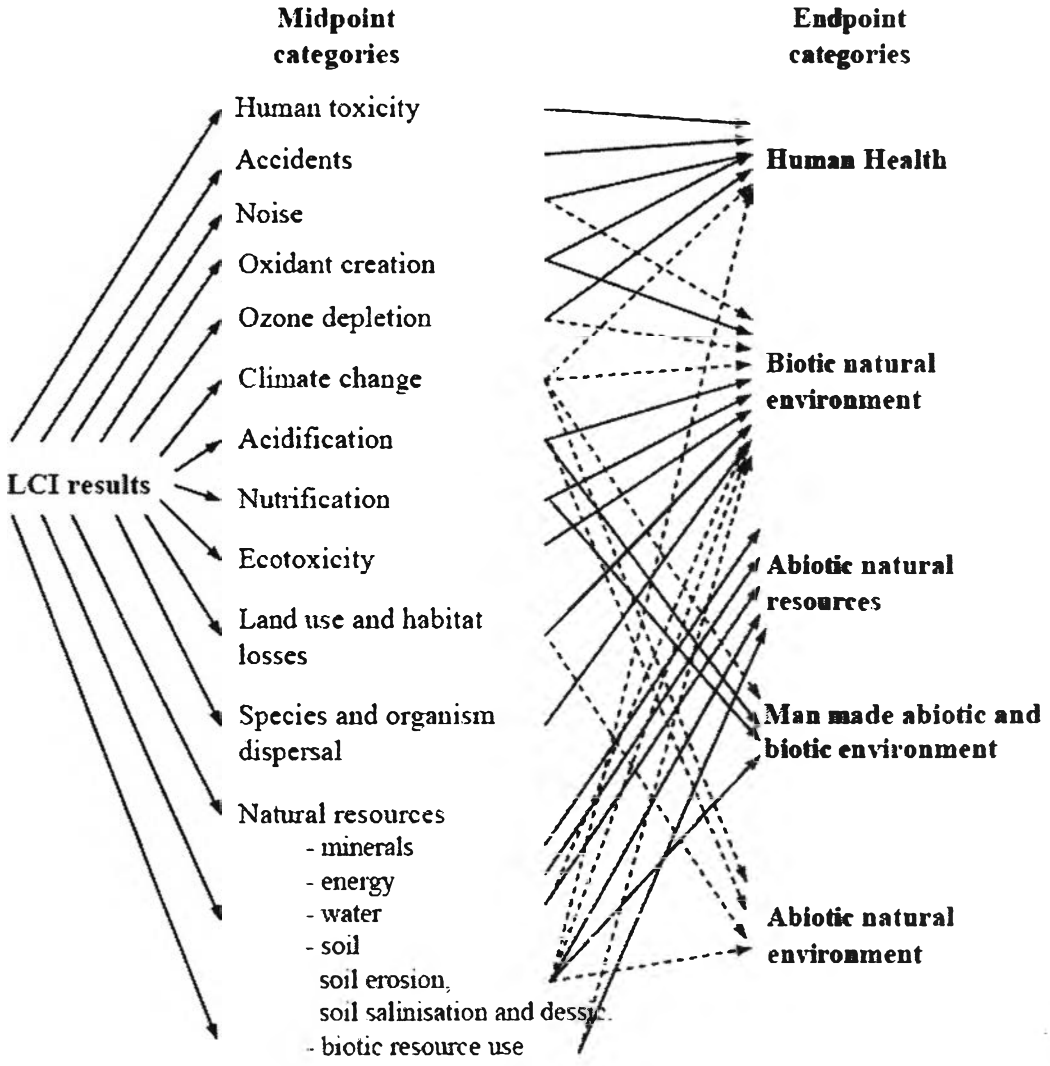

Figure 2.4 Pathways linking LCI results via midpoint categories to end-points. Dotted arrows: currently available information between midpoint and damage levels is particularly uncertain according to preliminary analyses. (Jollilet and Brent, 2003)

Adequate scientific information may often be unavailable for the links between midpoints and the damage categories: it is then desirable to provide information on the connection of these midpoint indicators to quality changes at damage level at least by supplying a verbal statement describing the expected relationships. When only semi-quantitative or verbal information is available, interpretation (and weighting, if any) is to be performed at the level of midpoint indicators.

➢ Life-cycle interpretation

In the life-cycle interpretation phase, significant results from the LCA are tested to check their validity before making and reporting the conclusions. This is an extremely important step, given that LCA conclusions are the result of many calculations and assumptions. Where significant results are based on data that are not reliable or on assumptions for which there is no verification, either more investigation is required or some form of qualification may need to be included when reporting the results.

It is also clear from those phases above that relevant Life Cycle Inventory (LCI) data are uncontrovertibly the prerequisite for any LCA study. However, this crucial information is not always available to LCA practitioners and its quality as well as reliability is sometimes questionable. Therefore building a reliable national database (supplying background data), which covers all the basic raw materials and is accessible to every LCA practitioner, would be a critical step for utilization of LCA as an effective tool supporting decision-making procedure.

2.4 Global Current Status of LCA Activities and Thailand's National Master Plan on Green Product Development

2.4.1 The General Picture

The LCA awareness initiatives have been taken tremendously well by many governmental agencies, research institutions, academia and industries around the world. Commonly, LCA has been used for evaluating the environmental performance of products and processes, and some regulations, such as the EuP directive, require an ecological profile of energy-using products (i.e. most EEEs) (award of an eco-label) based on LCA analysis. In most of the APEC Economies, LCA is in the development stages, apart from countries like Japan, Korea or Australia, which already have experience in LCA capacity building. With only a few exceptions, the focus of most industries is only on energy efficiency and some selected emissions (e.g. carbon dioxide, dust, etc.). Besides, the focus is usually not on the entire life-cycle, but is limited within the companies' system boundaries.

2.4.2 The Ultimate Need for a Common LCI Database

A few years back, several big companies in the chemical, electrical and electronics, and automotive sectors took LCA analysis. Although they have developed in-house LCI databases for their own purposes, they need more basic LCI databases in some specific areas such as energy, utility, transportation, raw material, etc. In addition, due to those new comprehensive and product-oriented policies mentioned previously, many companies, especially small- and medium-size enterprises (SMEs), want to conduct LCA analysis for improving the life-time environmental performance of their products and processes. However, in general, SMEs do not have enough financial resources and expertise for this task. As for them, LCA implementation as part of environmental management decision tools is a far cry from adaptation in the industry. Findings have shown that almost all local LCA research activities require a standard life cycle inventory (LCI) database in order to make LCA at all levels available. In other words, the need to establish a national LCI database is incontrovertible before conducting any reliable LCA analysis for every industry. Presently, it is known that the European countries have more than 2,700 databases, Japan has 476 databases, USA 429 databases and Korea 307, as of November 2004 (Hong Yong Kang *et al.*, 2005).

A number of existing LCI databases and projects are listed in Table 2.2.

Table 2.2 Rough overview of existing types of projects and databases with relationship towards LCI data issues (selection)

Established LCI databases widely used in LCA practice	GaBi, KCL-Eco, LCAit, SimaPro, SPINE, TEAM, Umberto, etc.
Actual national LCI database projects	Australia, Canada, Germany, Italy, Japan, Switzerland, USA, etc.
Multinational LCI database projects	Cost Action 530, eLCA, etc.
LCI databases that are made publicly available, but were developed within or for industry associations	APME database, etc.

2.4.3 The National LCI Database Development for Thailand Project

Acknowledging the importance of the issue, the Thailand Research

Fund, a governmental agency, together with the National Metal and Materials Technology Center (MTEC) and a number of organizations, have started developing a plan and framework to identify the mechanism which will support green products and services under the LCA concept. The National Master Plan on Green Product Development, with a vision of creating green products for sustainable development and increasing competitiveness of Thai industry, has been set up. Under that master plan, a hierarchy of relevant strategies was also clearly defined, at top of which was the intense need for establishing a national LCI database and employing a web-based central information network for easy access to and use of the database (Figure 2.5).

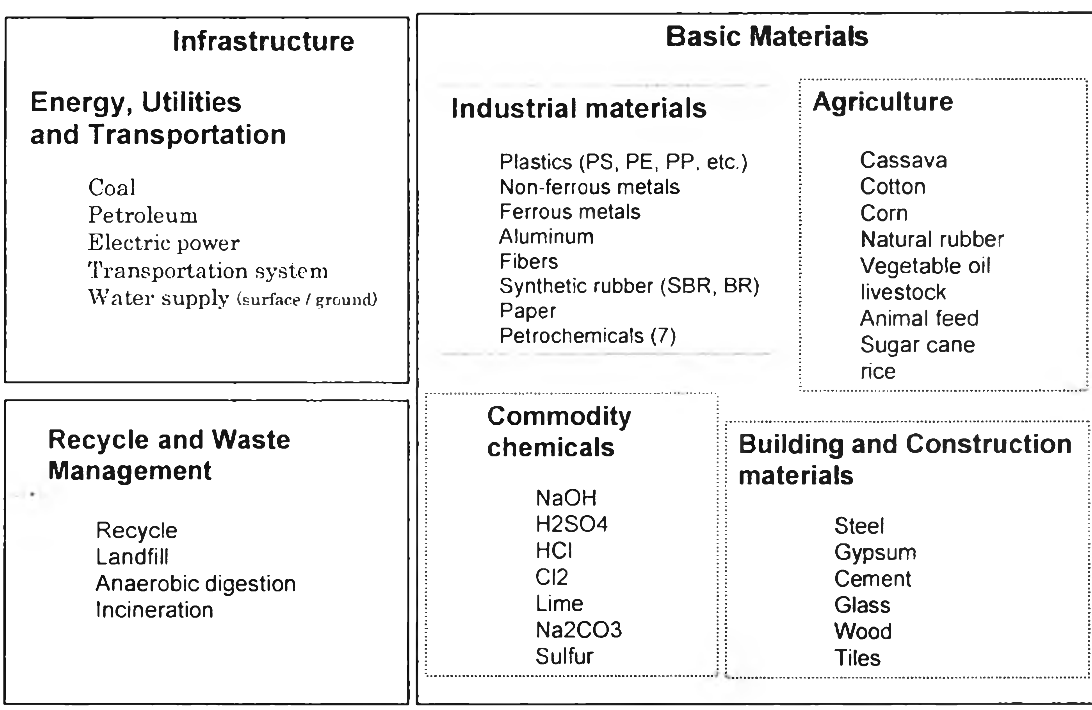

Figure 2.5 Thailand National LCI Database (Source MTEC & CU).

Actually, in comparison to other developed countries, Thailand's LCI database is still modest in quantity and quality at its preliminary stage; electricity, mining, cement, paper, etc., are a few with good completion. However, as the national databases expand, more and more sectors will be covered in the subsequent stages. Among the various categories the database is aiming at (such as infrastructure, basic materials, etc), natural gas, oil refining and petrochemical industries have been chosen as pilot projects due to their crucial priority. According to the MTEC plan, at the first stage, three working groups are going to investigate and collect data from natural gas, oil refining and petrochemical industries concurrently, following a "gate-to-gate" concept. Subsequently, all pieces of these building blocks will be assembled, rendering a full picture of Thailand's petroleum and petrochemical industry along with characteristic inventory data of its innumerable vital products.

2.4.4 LCI Database for Thailand's Petrochemical Industry

Figures 2.6-2.7 illustrate the importance of petrochemical products in other industries as well as the share of major chemicals in typical fields.

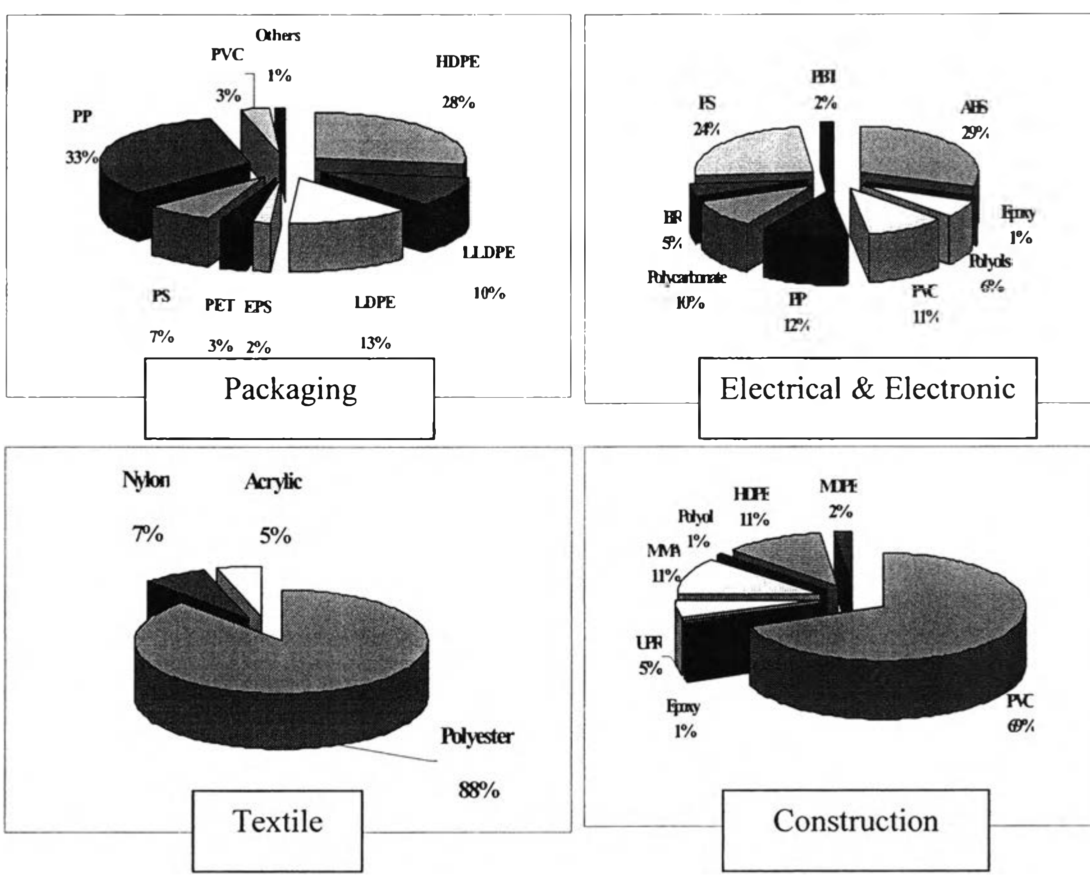

Figure 2.6 Major petrochemicals' contribution in typical industries. (Source PTIT)

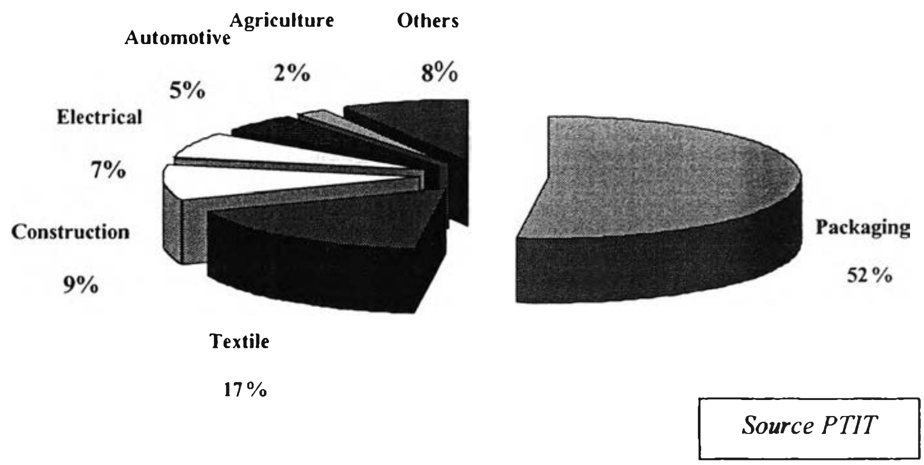

Figure 2.7 The use of petrochemical products in different industries.

Regarding LCA analysis, in the petrochemical sector, plenty of studies have been conducted during recent years, presenting invaluable insights about the life-cycle of HDPE, LLDPE, PS, etc. With the purpose of contributing to the progress, this research focused on the production line of PVC in petrochemical section, from ethylene to VCM and ended at the exit gate of PVC manufacture plant.

2.5 Polyvinylchloride (PVC) – Application and Production

2.5.1 Application of PVC

The most important applications of PVC are in the building and construction sector (windows/ shutters, sheets, flooring and pipes), the electric and electronic equipment sector (predominantly cables), the transport sector (plastisols, artificial leather, dashboards and structural parts) and the packaging sector (non-beverage packaging).

2.5.2 Overview of PVC Production and Its Compounds (European Commission, 2004)

2.5.2.1 Production process of PVC

PVC is produced from two primary raw materials, ethylene and chlorine. These react to form ethylene dichloride (EDC) which, upon cracking, yields vinyl chloride monomer (VCM). Free radical polymerization is used to produce the PVC polymer itself (Figure 2.8).

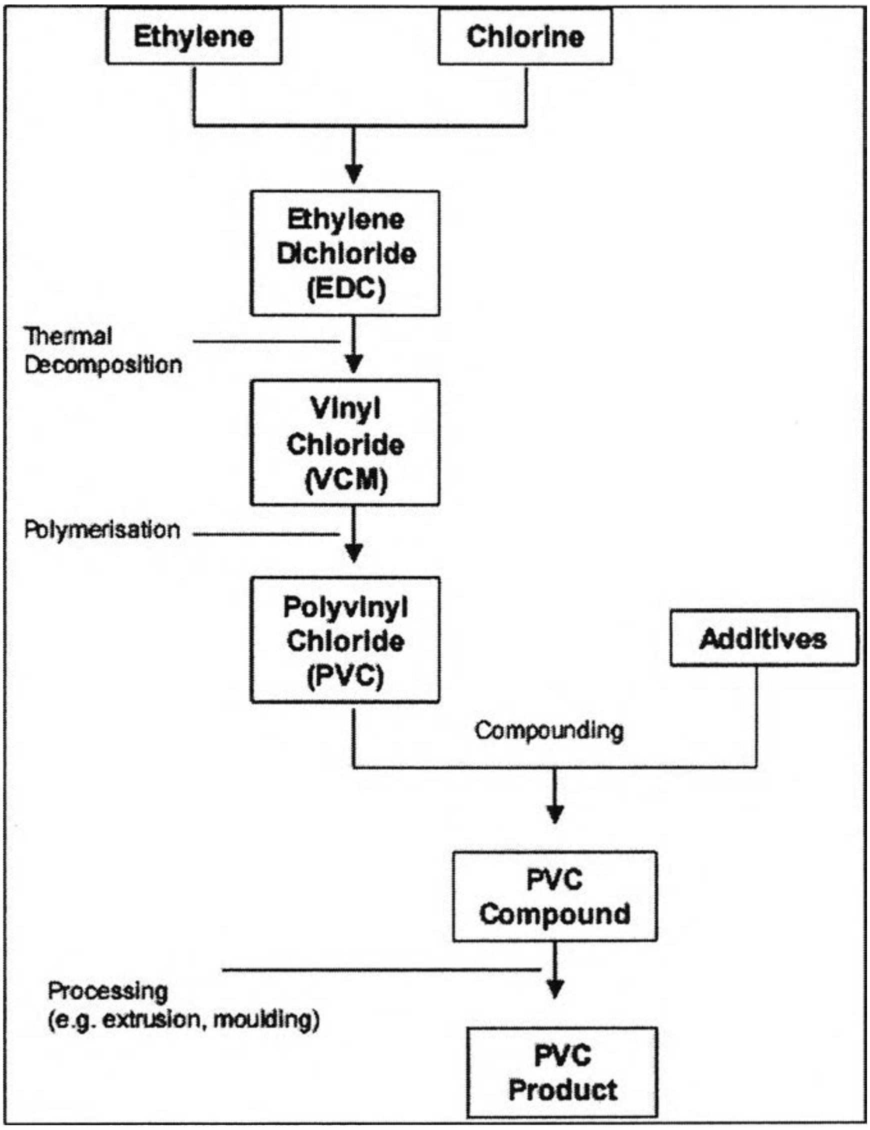

Figure 2.8 Typical integrated process for manufacturing PVC from ethylene and chlorine.

The two most important polymerization techniques are suspension polymerization and emulsion polymerization, leading to the production of S-PVC and E-PVC, respectively. These two types of PVC polymer have different properties and are used for distinct applications. The S-PVC process yields granules of polymer of 100 to 200 microns in diameter, which are used in processes such as injection molding, extrusion and PVC film manufacture. The difference between S- and E-PVC is rather small, as the type of polymerization has a low impact on the overall performance of the PVC over its life cycle. Thus, in this study, data collected from industrial associations for S-PVC and E-PVC were mixed and used as average data for PVC production in Thailand.

2.5.2.2 PVC compounds

Pure PVC is a hard, brittle material which degrades at around 100°C and is sensitive to deterioration under the influence of light and heat. Pure PVC is therefore supplemented with additives which improve its service life properties and allow it to be processed more easily. With the right combination of additives, it is possible to tailor the material for various applications (Table 2.3).

Table 2.3 Typical composition of PVC compounds

	Component Share (weight - %)				
Application	**PVC polymer**	**Plasticiser**	**Stabiliser**	**Filler**	**Others**
Rigid PVC applications					
Pipes	98	-	1 - 2	-	-
Window profiles (lead stabilised)	85	-	3	4	8
Other profiles	90	-	3	6	1
Rigid films	95	-	-	-	5
Flexible PVC applications					
Cable insulation	42	23	2	33	-
Flooring (Calender)	42	15	2	41	0
Flooring (paste, upper layer)	65	32	1	-	2
Flooring (paste, inside material)	35	25	1	40	-
Synthetic leather	53	40	1	5	1

There are many types of additives, such as:

- plasticizers (especially phthalic acid esters or phthalates)

- pigments (titanium white, lead chromates)

- heat and light stabilizers (usually organic compounds based on lead, tin, zinc, barium, a number of organic antioxidants and co-stabilizers)

- lubricants (wax, fatty alcohols, fatty acid esters)
- fillers (chalk, china clay, talcum, magnesium oxide)
- flame retardants (antimony trioxide, aluminum hydroxide, magnesium oxide, chloroparaffins), these are rarely used since PVC itself is relatively flame retardant
- impact modifiers, etc.

All PVC is stabilized through the addition of stabilizers. The most important group of stabilizers are presented in Table 2.4.

Table 2.4 List of stabilizers for different PVC applications

Stabiliser Type	Main Use
Lead stabiliser	Pipes, cables, profiles for construction.
Tin organic stabiliser	Mainly rigid products (>95%), including food-contact use.
Ba/Zn or Ca/Zn liquid systems are used in flexible PVC, whilst solid systems are used in rigid PVC as lead replacements in addition to their traditional use in medical and food-contact applications.	Wide range flexible PVC application, calendered sheet, flooring, etc. Ca/Zn penetration in pipes and profiles is increasing. Ba/Zn is the dominant type of stabiliser in flooring in 1996 in Sweden (IPU.0019). Ca/Zn to a minor extent.

Plasticizers are organic compounds, which separate polymer chains, allowing them to move in relation to one other and thereby improve elasticity. The most common plasticizers are presented in Table 2.5.

Table 2.5 List of main plasticizers and their product applications

Plasticiser Type	Main Use
Phthalates	Flooring, cable, wire, films and sheets
Adipates	Flooring, cable, cling film
Trimellitates	Products which are exposed to high temperatures, e.g. cables in engine rooms

Fillers are mainly inert materials such as calcium carbonate (chalk), talc, kaoline, magnesium oxide, etc., used to improve some mechanical properties of PVC as well as to reduce costs.

Pigments are insoluble compounds that are used to color products. A variety of colors are obtained by mixing different pigments. One of the most important pigments is titanium dioxide

However, in this study, the environmental impacts due to the use of these additives were ignored. The primary reason was because of confidentiality concerns of participated industrial associations. Yet, according to the Final Report of Life Cycle Assessment of PVC and of Principal Competing Materials (European Commission, 2004), the production of additives has less negative impacts on the environment than the production of PVC and in most cases, harmful substances used in additives (such as lead) are recycled. Therefore skipping the contribution of additives will not underestimate the loads associated with the production of PVC resin.