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**LIFE CYCLE ASSESSMENT:**
**PRINCIPLES AND PRACTICE**

by

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## Notice

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## Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

**Sally Gutierrez, Director**
**National Risk Management Research Laboratory**

## Abstract

The following document provides an introductory overview of Life Cycle Assessment (LCA) and describes the general uses and major components of LCA. This document is an update and merger of two previous EPA documents on LCA ("Life Cycle Assessment: Inventory Guidelines and Principles," EPA/600/R-92/245, and "LCA101" from the *LCAccess*, website, http://www.epa.gov/ORD/NRMRL/lcaccess). It presents the four basic stages of conducting an LCA: goal and scope definition, inventory analysis, impact assessment, and improvement analysis. The major stages in an LCA study are raw material acquisition, materials manufacture, production, use/reuse/maintenance, and waste management. The system boundaries, assumptions, and conventions to be addressed in each stage are presented. This document is designed to be an educational tool for someone who wants to learn the basics of LCA, how to conduct an LCA, or how to manage someone conducting an LCA. Companies, federal facilities, industry organizations, or academia can benefit from learning how to incorporate environmental performance based on the life cycle concept into their decision-making processes. This report was submitted in fulfillment of contract 68-C02-067 by Scientific Applications International Corporation (SAIC) under the sponsorship of the United States Environmental Protection Agency. This report covers a period from December 2005 to May 2006, and work was completed as of May 30, 2006.

**Contents**

## Exhibits



## Tables

## Abbreviations

| | |
|---|---|
| BOD | biological oxygen demand |
| Btu | British thermal unit |
| CO | carbon monoxide |
| COD | chemical oxygen demand |
| $CO_2$ | carbon dioxide |
| DQIs | data quality indicators |
| EPA | United States Environmental Protection Agency |
| GWh | gigawatt-hour |
| ISO | International Standards Organization (International Organization of Standardization) |
| kWh | kilowatt-hour |
| LCA | life cycle assessment |
| LCI | life cycle inventory |
| LCIA | life cycle impact assessment |
| LCM | life cycle management |
| MJ | megajoule |
| $NO_2$ | nitrogen dioxide |
| NRMRL | National Risk Management Research Laboratory |
| REPA | Resource and Environmental Profile Analysis |
| SETAC | Society of Environmental Toxicology and Chemistry |
| $SO_2$ | sulfur dioxide |
| TRACI | Tool for the Reduction and Assessment of Chemical and other environmental Impacts |
| TRI | Toxics Release Inventory |
| VOCs | volatile organic compounds |

# Chapter 1
# Life Cycle Assessment

## What is Life Cycle Assessment (LCA)?

As environmental awareness increases, industries and businesses are assessing how their activities affect the environment. Society has become concerned about the issues of natural resource depletion and environmental degradation. Many businesses have responded to this awareness by providing "greener" products and using "greener" processes. The environmental performance of products and processes has become a key issue, which is why some companies are investigating ways to minimize their effects on the environment. Many companies have found it advantageous to explore ways of moving *beyond* compliance using pollution prevention strategies and environmental management systems to improve their environmental performance. One such tool is LCA. This concept considers the entire life cycle of a product (Curran 1996).

Life cycle assessment is a "cradle-to-grave" approach for assessing industrial systems. "Cradle-to-grave" begins with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth. LCA evaluates all stages of a product's life from the perspective that they are interdependent, meaning that one operation leads to the next. LCA enables the estimation of the cumulative environmental impacts resulting from all stages in the product life cycle, often including impacts not considered in more traditional analyses (e.g., raw material extraction, material transportation, ultimate product disposal, etc.). By including the impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in product and process selection.

The term "life cycle" refers to the major activities in the course of the product's life-span from its manufacture, use, and maintenance, to its final disposal, including the raw material acquisition required to manufacture the product. Exhibit 1-1 illustrates the possible life cycle stages that can be considered in an LCA and the typical inputs/outputs measured.

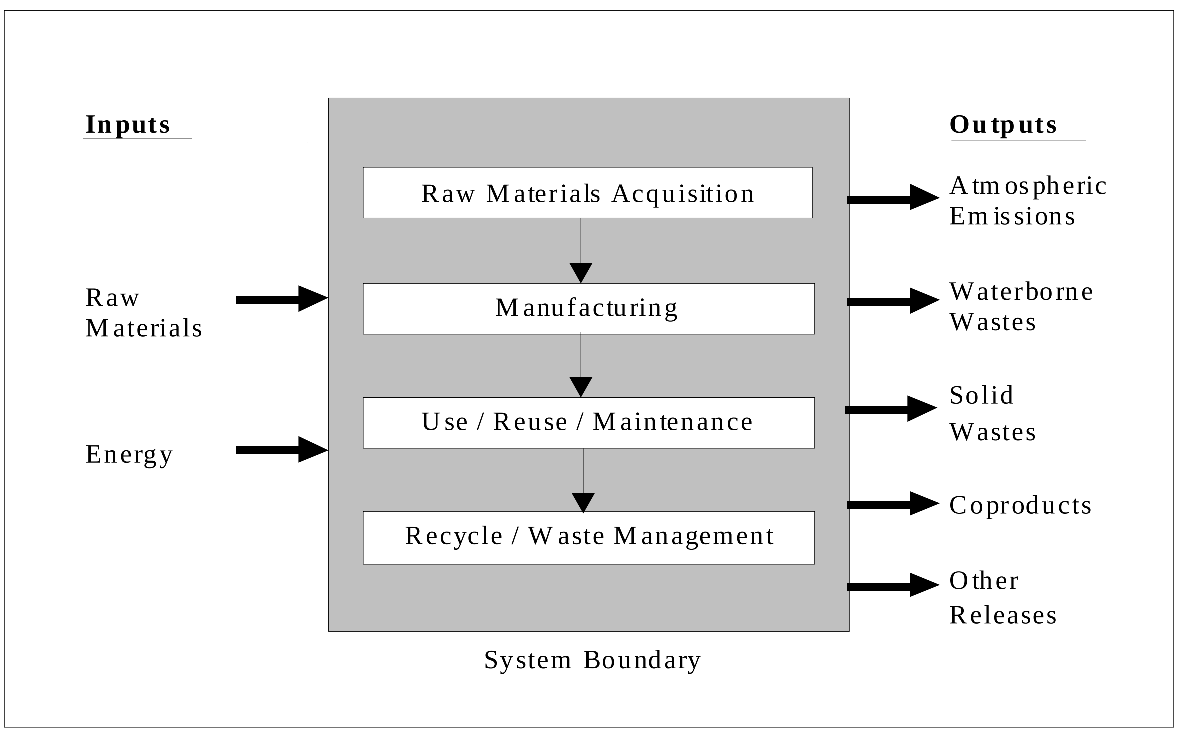


**Exhibit 1-1. Life Cycle Stages** (Source: EPA,1993)

Specifically, LCA is a technique to assess the environmental aspects and potential impacts associated with a product, process, or service, by:

- Compiling an inventory of relevant energy and material inputs and environmental releases
- Evaluating the potential environmental impacts associated with identified inputs and releases
- Interpreting the results to help decision-makers make a more informed decision.

The LCA process is a systematic, phased approach and consists of four components: goal definition and scoping, inventory analysis, impact assessment, and interpretation as illustrated in Exhibit 1-2:

1. *Goal Definition and Scoping* **-** Define and describe the product, process or activity. Establish the context in which the assessment is to be made and identify the boundaries and environmental effects to be reviewed for the assessment.

2. *Inventory Analysis* **-** Identify and quantify energy, water and materials usage and environmental releases (e.g., air emissions, solid waste disposal, waste water discharges).

3. *Impact Assessment* **-** Assess the potential human and ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis.

4. *Interpretation* **-** Evaluate the results of the inventory analysis and impact assessment to select the preferred product, process or service with a clear understanding of the uncertainty and the assumptions used to generate the results.

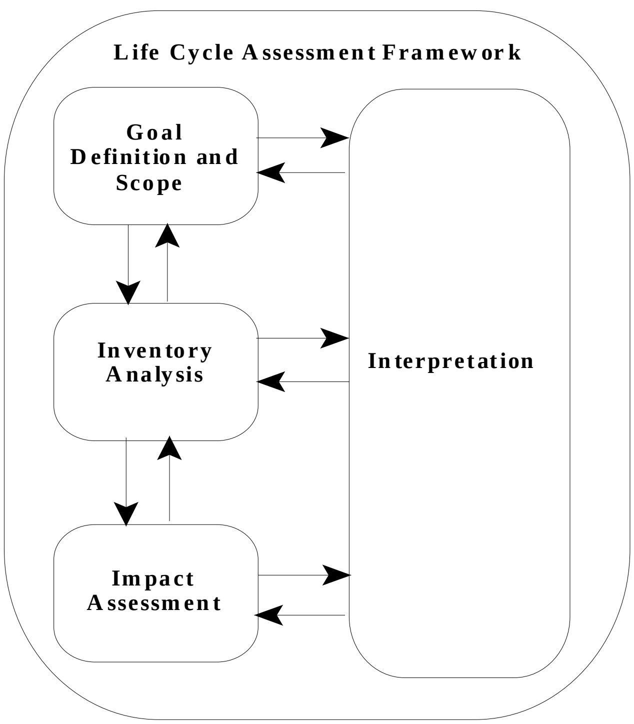


**Exhibit 1-2. Phases of an LCA** (Source: ISO, 1997)

Life cycle assessment is unique because it encompasses all processes and environmental releases beginning with the extraction of raw materials and the production of energy used to create the product through the use and final disposition of the product. When deciding between two or more alternatives, LCA can help decision-makers compare all major environmental impacts caused by products, processes, or services.

**What Are the Benefits of Conducting an LCA?**

An LCA can help decision-makers select the product or process that results in the least impact to the environment. This information can be used with other factors, such as cost and performance data to select a product or process. LCA data identifies the transfer of environmental impacts from one media to another (e.g., eliminating air emissions by creating a wastewater effluent instead) and/or from one life cycle stage to another (e.g., from use and reuse of the product to the raw material acquisition phase). If an LCA were not performed, the transfer might not be recognized and properly included in the analysis because it is outside of the typical scope or focus of product selection processes.

**LCA Helps to Avoid Shifting Environmental Problems from One Place to Another**

An LCA allows a decision maker to study an entire product system hence avoiding the sub-optimization that could result if only a single process were the focus of the study. For example, when selecting between two rival products, it may appear that Option 1 is better for the environment because it generates less solid waste than Option 2. However, after performing an LCA it might be determined that the first option actually creates larger cradle-to-grave environmental impacts when measured across all three media (air, water, land) (e.g., it may cause more chemical emissions during the manufacturing stage). Therefore, the second product (that produces solid waste) may be viewed as producing less cradle-to-grave environmental harm or impact than the first technology because of its lower chemical emissions.

This ability to track and document shifts in environmental impacts can help decision makers and managers fully characterize the environmental trade-offs associated with product or process alternatives. By performing an LCA, analysts can:

- Develop a systematic evaluation of the environmental consequences associated with a given product.
- Analyze the environmental trade-offs associated with one or more specific products/processes to help gain stakeholder (state, community, etc.) acceptance for a planned action.
- Quantify environmental releases to air, water, and land in relation to each life cycle stage and/or major contributing process.
- Assist in identifying significant shifts in environmental impacts between life cycle stages and environmental media.
- Assess the human and ecological effects of material consumption and environmental releases to the local community, region, and world.
- Compare the health and ecological impacts between two or more rival products/processes or identify the impacts of a specific product or process.
- Identify impacts to one or more specific environmental areas of concern.

**A Brief History of Life-Cycle Assessment**

Life Cycle Assessment (LCA) had its beginnings in the 1960's. Concerns over the limitations of raw materials and energy resources sparked interest in finding ways to cumulatively account for energy use and to project future resource supplies and use. In one of the first publications of its kind, Harold Smith reported his calculation of cumulative energy requirements for the production of chemical intermediates and products at the World Energy Conference in 1963.

Later in the 1960's, global modeling studies published in *The Limits to Growth* (Meadows *et al* 1972) and *A Blueprint for Survival* (Goldsmith *et al* 1972) resulted in predictions of the effects of the world's changing populations on the demand for finite raw materials and energy resources. The predictions for rapid depletion of fossil fuels and climatological changes resulting from excess waste heat stimulated more detailed calculations of energy use and output in industrial processes. During this period, about a dozen studies were performed to estimate costs and environmental implications of alternative sources of energy.

In 1969, researchers initiated an internal study for The Coca-Cola Company that laid the foundation for the current methods of life cycle inventory analysis in the United States. In a comparison of different beverage containers to determine which container had the lowest releases to the environment and least affected the supply of natural resources, this study quantified the raw materials and fuels used and the environmental loadings from the manufacturing processes for each container. Other companies in both the United States and Europe performed similar comparative life cycle inventory analyses in the early 1970's. At that time, many of the available sources were derived from publicly-available sources such as government documents or technical papers, as specific industrial data were not available.

The process of quantifying the resource use and environmental releases of products became known as a Resource and Environmental Profile Analysis (REPA), as practiced in the United States. In Europe, it was called an Ecobalance. With the formation of public interest groups encouraging industry to ensure the accuracy of information in the public domain, and with the oil shortages in the early 1970's, approximately 15 REPAs were performed between 1970 and 1975. Through this period, a protocol or standard research methodology for conducting these studies was developed. This multi-step methodology involves a number of assumptions. During these years, the assumptions and techniques used underwent considerable review by EPA and major industry representatives, with the result that reasonable methodologies were evolved.

From 1975 through the early 1980's, as interest in these comprehensive studies waned because of the fading influence of the oil crisis, environmental concerns shifted to issues of hazardous and household waste management. However, throughout this time, life cycle inventory analysis continued to be conducted and the methodology improved through a slow stream of about two studies per year, most of which focused on energy requirements. During this time, European interest grew with the establishment of an Environment Directorate (DG X1) by the European Commission. European LCA practitioners developed approaches parallel to those being used in the USA. Besides working to standardize pollution regulations throughout Europe, DG X1 issued the Liquid Food Container Directive in 1985, which charged member companies with monitoring the energy and raw materials consumption and solid waste generation of liquid food containers.

When solid waste became a worldwide issue in 1988, LCA again emerged as a tool for analyzing environmental problems. As interest in all areas affecting resources and the environment grows, the methodology for LCA is again being improved. A broad base of consultants and researchers across the globe has been further refining and expanding the methodology. The need to move beyond the inventory to impact assessment has brought LCA methodology to another point of evolution (SETAC 1991; SETAC 1993; SETAC 1997).

In 1991, concerns over the inappropriate use of LCAs to make broad marketing claims made by product manufacturers resulted in a statement issued by eleven State Attorneys General in the USA denouncing the use of LCA results to promote products until uniform methods for conducting such assessments are developed and a consensus reached on how this type of environmental comparison can be advertised non-deceptively. This action, along with pressure from other environmental organizations to standardize LCA methodology, led to the development of the LCA standards in the International Standards Organization (ISO) 14000 series (1997 through 2002).

In 2002, the United Nations Environment Programme (UNEP) joined forces with the Society of Environmental Toxicology and Chemistry (SETAC) to launch the Life Cycle Initiative, an international partnership. The three programs of the Initiative aim at putting life cycle thinking into practice and at improving the supporting tools through better data and indicators. The Life Cycle Management (LCM) program creates awareness and improves skills of decision-makers by producing information materials, establishing forums for sharing best practice, and carrying out training programs in all parts of the world. The Life Cycle Inventory (LCI) program improves global access to transparent, high quality life cycle data by hosting and facilitating expert groups whose work results in web-based information systems. The Life Cycle Impact Assessment (LCIA) program increases the quality and global reach of life cycle indicators by promoting the exchange of views among experts whose work results in a set of widely accepted recommendations.

**Limitations of Conducting an LCA**

Performing an LCA can be resource and time intensive. Depending upon how thorough an LCA the user wishes to conduct, gathering the data can be problematic, and the availability of data can greatly impact the accuracy of the final results. Therefore, it is important to weigh the availability of data, the time necessary to conduct the study, and the financial resources required against the projected benefits of the LCA.

LCA will not determine which product or process is the most cost effective or works the best. Therefore, the information developed in an LCA study should be used as one component of a more comprehensive decision process assessing the trade-offs with cost and performance, e.g., Life Cycle Management.

**Life Cycle Management**

Life Cycle Management (LCM) is the application of life cycle thinking to modern business practice, with the aim to manage the total life cycle of an organization's product and services toward more sustainable consumption and production (Jensen and Remmen 2004). It is an integrated framework of concepts and techniques to address environmental, economic, technological, and social aspects of products, services, and organizations. LCM, as any other management pattern, is applied on a voluntary basis and can be adapted to the specific needs and characteristics of individual organizations (SETAC 2004).

There are a number of ways to conduct Life Cycle Impact Assessment. While the methods are typically scientifically-based, the complexity of environmental systems has led to the development of alternative impact models. Chapter 4 expands on this.

As mentioned earlier, an LCA can help identify potential environmental tradeoffs. However, converting the impact results to a single score requires the use of value judgments, which must be applied by the commissioner of the study or the modeler. This can be done in different ways such as through the use of an expert panel, but it cannot be done based solely on natural science.