LIFE CYCLE ASSESSMENT STUDENT HANDBOOK

Mary Ann Curran, Editor

Scrivener Publishing

WILEY

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Contents

Preface

This student handbook was created to serve as a companion to the 2012 *Life Cycle Assessment Handbook*[1], a compilation of writings by eminent leaders in the field of LCA and related methodology. The LCA Handbook was designed to be as comprehensive as possible, covering every facet of LCA methodology and presenting a variety of applications. This was quite a challenge given the ever-growing scope and acceptance of LCA over the years as an environmental management tool. The final product far exceeded my initial expectation. The chapter authors provided clear insight into the various aspects of LCA methodology and practice, and they openly shared their invaluable wisdom, experience and knowledge. However, the LCA Handbook does not attempt to explain in step-wise fashion how the various phases of an LCA can be completed. Other similar books and documents have also been published on LCA reflecting the ISO-standard[2] approach. But, again, few "how-to" guides exist. This student handbook is intended to fill that gap by addressing the individual steps of conducting, interpreting, and reporting an LCA.

For the sake of consistency, and maintaining a uniform "voice," the student handbook repeats much of the text prepared by the experts who contributed to the LCA Handbook. Because of the way in which the LCA Handbook was compiled, the chapters reproduce much of the same background introductory descriptions and the discussions on key issues scattered throughout the book. The student handbook brings these parts together in the appropriate sequence so that the chapters and sections present procedural guidance for conducting an LCA.

The student handbook then builds upon the various aspects of LCA practice with pertinent exercises for the reader to complete in order to help reinforce the messages within the sections. These exercises intend to help students gain a better understanding of the details involved in conducting an LCA by putting them in the position of both commissioner and practitioner of an assessment. In most cases, the exercises are thought problems, rather than ones requiring calculations or precise solutions. The aim is to encourage readers to look closer at certain methodological issues and check their understanding of them.

After presenting a brief overview (Chapter 1), the student handbook delves into the details of the stages that comprise LCA methodology: goal and scope definition (Chapter 2), life cycle inventory (Chapter 3), life cycle impact assessment (Chapter 4), normalization, grouping, and weighting (Chapter 5), and interpretation (Chapter 6). Chapter 7 addresses forward thinking applications of LCA in Life Cycle Sustainability Assessment (LCSA)

[1] Life Cycle Assessment Handbook: A Guide for Environmentally Sustainable Products (2012) MA Curran (ed) Scrivener-Wiley Publishing; ISBN 9778-1-118-09972-8; 640 pages.

[2] ISO 14040:2006 Environmental Management – Life Cycle Assessment – Principles and Framework, International Standard, International Organization for Standardization, Geneva, Switzerland.

including the role of modeling social impacts. The final chapter (8) provides additional resources readers might find useful.

The handbook aims to focus on LCA methodology and not extend into related, yet tangential, topics such as the life cycle of buildings, or life-cycle (eco)design. Also, the student handbook does not address the application of exergy analysis to LCA. There are many other textbooks that the reader can refer to that cover this topic in detail. As mentioned, Chapter 7 does address the topic of Life Cycle Sustainability Assessment (LCSA), including Social LCA, which the LCA Handbook also covers. Although not in detail, the chapter introduces the topic in order to give readers an idea of the future direction that is expected for LCA as its application moves toward meeting sustainability goals.

My sincere thanks go to the authors of the chapters in the LCA Handbook, which form the basis of the student handbook. Readers are encouraged to refer to the LCA Handbook as needed. Each chapter of the student handbook begins with page references to the LCA Handbook to make this easier for the reader.

1. *Life Cycle Assessment Handbook* Chapters and Authors:

"If I have seen further it is by standing on the shoulders of Giants."
Isaac Newton, Letter to Robert Hooke, February 5, 1675

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Cincinnati, Ohio, USA
March 2015

1

Introduction to Life Cycle Assessment

Abstract
Life Cycle Assessment (LCA) is a holistic, cradle-to-grave environmental approach which provides a comprehensive view of the environmental aspects of a product or process throughout its life cycle. A properly conducted LCA identifies and quantifies the potential impacts of an industrial system (aiming to assess products, processes and activities). But more importantly, LCA identifies the potential transfer of environmental impacts from one media to another and/or from one life cycle stage to another. If an LCA were not performed, these trade-offs might not be recognized and properly included in the analysis because it is outside of the typical scope or focus of the decision making process.

This chapter explores why it is important to use a life cycle perspective in environmental management. It outlines the advancement of pollution strategies over the years, moving from end-of-pipe to pollution prevention (cleaner production) strategies and later to life cycle based approaches to meet sustainability goals. The key benefit of LCA, to identify potential transfer of environmental impacts, is demonstrated in a few brief examples. The chapter also presents the basic LCA methodology as described in a series of standards and technical reports produced by the International Standards Organization (ISO).

References from the LCA Handbook

Aims of the Chapter

1. Place life cycle thinking in proper context with environmental strategies as they have evolved over the years.
2. Help users understand the basic characteristics of the ISO standard for LCA, from scoping to interpretation.
3. Provide real world examples of LCA applications and how life cycle has been used in industry and government.

1.1 Purpose of the Student Handbook

In recent years, Life Cycle Assessment (LCA) practice has evolved from a specialty field practiced by a handful of practitioners with closely guarded databases, to a widely used tool with emphasis on transparency and data sharing. Although LCA practice still requires a high degree of expertise and knowledge, the availability of sophisticated LCA software, such as SimaPro and GaBi, have made LCA-accessible to a much wider user base. The use of computer software for conducting LCA continues to grow. Since 2006, an open source software called openLCA has been available for conducting professional level LCA. The software and its source code is freely available. The software is fully transparent and can be modified by anyone.

It is important for users to fully comprehend what these various products offer. This handbook is not intended to teach any one particular software program. Instead, the basic characteristics of the different LCA software products are covered so that students have a better understanding of what they are and how they operate. This is presented in Chapter 2 along with discussion on life cycle inventory and in Chapter 3 on life cycle impact assessment models.

1.2 Why LCA?

Before jumping into discussing how to conduct an LCA, it is important to first understand the "why." The following section provides a brief description of the evolution of environmental management and how it has moved from an end-of-pipe focus toward the broader goal of sustainability, of which LCA is an important part. The chapter then presents the stages of LCA as constituted by the International Standards Organization (ISO). This structure lays the foundation for the following chapters in the handbook.

1.3 Evolution of Environmental toward Life Cycle Thinking

Environmental management strategies have evolved through the development of laws and regulations that limit pollutant releases to the environment. For example, since its inception in 1970, the US Environmental Protection Agency (US EPA) has made important progress toward improving the environment in every major category of environmental impact caused by pollutant releases. Levels of emissions across the nation have stayed constant or declined; hundreds of primary and secondary wastewater treatment facilities have been built; land disposal of untreated hazardous waste has largely stopped; hundreds of hazardous waste sites have been identified and targeted for cleanup; and the use of many toxic substances has been banned. Together, these actions have had a positive effect on the nation's environmental quality and have set an example for other nations. However, despite the combined achievements of the federal government, States and industry in controlling waste emissions which have resulted in a healthier environment, the further improvement of the environment has slowed.

Worldwide, the advancement of environmental protection strategies moving from end-of-pipe to pollution prevention and beyond has been steady. This evolution can be summarized by the following chronology:

Evolution of Environmental Protection	
Chronology	**Strategy**
1970's to 1980's	End-of-Pipe Treatment
Mid 1980's	Waste Minimization/Reduction
Early 1990's	Pollution Prevention/Cleaner Production
Mid 1990's	ISO Certification/Life Cycle Assessment
2000 and Beyond	Sustainable Development/Life Cycle Sustainability Assessment

This evolution follows a pattern of ever-broadening scope when thinking about environmental management. In the 1980's, the term "waste minimization", or "waste reduction," was defined as "Measures or techniques that reduce the amount of wastes generated during industrial production processes; term is also applied to recycling and other efforts to reduce the amount of waste going into the waste stream." However, much of the focus remained on recycling and other end-of-life activities. In 1990, it was replaced by the term "pollution prevention" (or "cleaner production" outside the US) in order to give equal emphasis to activities that reduce potential environmental releases at the source of generation (Pollution Prevention Act 1990):

"The term "source reduction" means any practice which –

i. reduces the amount of any hazardous substance, pollutant, or contaminant entering any waste stream or otherwise released into the environment (including fugitive emissions) prior to recycling, treatment, or disposal; and
ii. reduces the hazards to public health and the environment associated with the release of such substances, pollutants, or contaminants. The term includes equipment or technology modifications, process or procedure modifications, reformulation or redesign of products, substitution of raw materials, and improvements in housekeeping, maintenance, training, or inventory control."

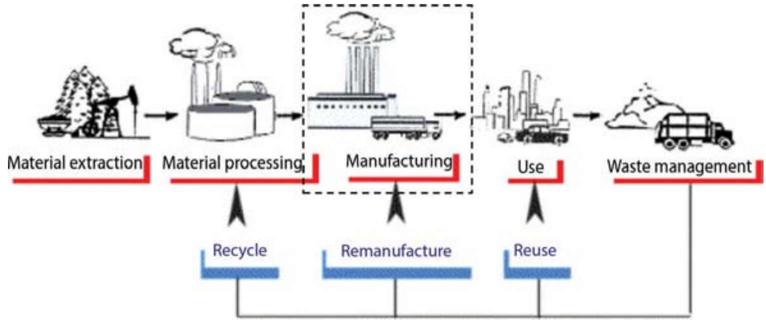


Figure 1.1 The boundaries of a pollution prevention (cleaner production) assessment are typically drawn around a single facility (dotted lines) omitting activities that may occur elsewhere in the product system.

However, the boundaries of a pollution prevention assessment[1] are drawn tightly around the facility or the plant (figure 1.1). This narrow, "gate-to-gate" focus does not allow for the identification of impacts that may occur in the manufacture and supply of materials going into the facility (i.e. the supply chain) or during the use and end-of-life stages of products coming out of the production facility.

Over the years, other federal policies have been developed to address environmental concerns at the various points across the life cycle. Some of these activities include the following:

- US National Environmental Policy Act (NEPA[2]) for Mining Operations.
- US EPA's March 1995 Risk Characterization Policy for assessing risk to human and ecological health from exposure to chemicals.
- The Resource Conservation and Recovery Act (RCRA), enacted in 1976, is the principal federal law in the United States governing the disposal of solid waste and hazardous waste.
- Energy Production and Use, for example, the Energy Star program that rates energy consuming products in order to help consumers optimize energy efficiency.
- Vehicles and Transportation, for example, the Renewable Fuels Standard which aims to replace conventional fossil fuels with those derived from bio-feedstock, such as bioethanol.

These examples demonstrate policy actions that focus on specific aspects. Like the fable about the six blind men and the elephant (Figure 1.2).

The conceptual jump to the broader environmental LCAs was made through a series of small steps. The first studies that are now recognized as (partial) LCAs date from the late 1960s and early 1970s, a period in which environmental issues like resource and energy efficiency, pollution control and solid waste became issues of broad public concern (US EPA 1993). One of the first (unfortunately unpublished) studies quantifying

[1] Pollution Prevention Assessment – Systematic, periodic internal reviews of specific processes and operations designed to identify and provide information about opportunities to reduce the use, production, and generation of toxic and hazardous materials and waste (US EPA 1992).
[2] Signed into law by President Richard Nixon on January 1, 1970.

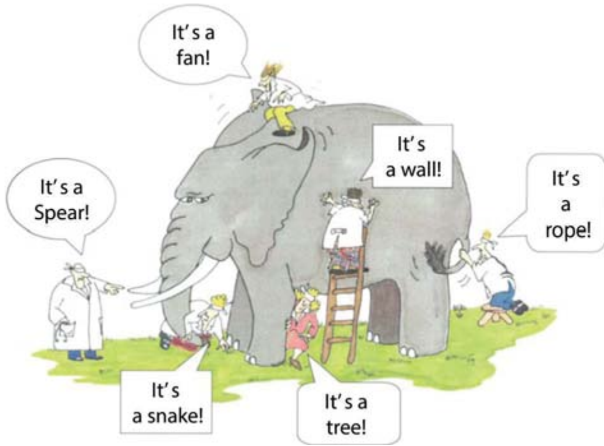


Figure 1.2 The Six Blind Men and the Elephant.

the resource requirements, emission loadings and waste flows of different beverage containers was conducted by Midwest Research Institute (MRI) for the Coca Cola Company in 1969 (see box).

A follow-up of this study conducted by the same institute for the US EPA in 1974 (Hunt *et al* 1974), and a similar study conducted by Basler & Hofman (1974) in Switzerland, marked the beginning of the development of LCA as we know it today. MRI used the term Resource and Environmental Profile Analysis (REPA) for this kind of study, which was based on a system analysis of the production chain of the investigated products "from cradle to grave." After a period of diminishing public interest in LCA and a number of unpublished studies, there has been rapidly growing interest in the subject from the early 1980s on.

Lesson Learned from Aluminum Beverage Cans

In the early 1970s, the Coca-Cola Company conducted a study of its beverage containers. The results showed that all of the containers had some type of environmental impact. What Coca-Cola decided to do (from what was told to me) was not to ban or deselect the poorest-performing material(s). Instead, they challenged the material and container companies to make adjustments to their products and processes which would result in reduced life cycle environmental impacts over previous design options. For one of the materials – aluminum – the sector worked with local governments to develop a recycling infrastructure for the used beverage containers, resulting in a reduction of more than 90% in the energy used throughout the life cycle of the aluminum beverage container. The other material groups made similar improvements.

What did we learn? Because Coca-Cola chose not to ban any of the materials but challenged its suppliers instead, they created an innovative atmosphere which allowed development and financing of a recycling infrastructure to recapture the inherent value in the aluminum.

James Fava
PE International & Five Winds Strategic Consulting (now thinkstep)

The period 1970-1990 comprised the decades of conception of LCA with widely diverging approaches, terminologies and results. There was a clear lack of international scientific discussion and exchange platforms for LCA. During the 1970s and the 1980s LCAs were performed using different methods and without a common theoretical framework. LCA was repeatedly applied by firms to substantiate market claims. The obtained results differed greatly, even when the objects of the study were the same, which prevented LCA from becoming a more generally accepted and applied analytical tool (Guinée *et al* 2011).

The 1990s saw a remarkable growth of scientific and coordination activities worldwide, which is reflected in the number of workshops and other forums that have been organized in this decade and in the number LCA guides and handbooks produced:[3]

- *Product Life Assessments: Policy issues and implications*; Summary of a Forum on May 14, 1990; World Wildlife Fund and The Conservation Foundation: Washington, DC, 1990.
- Fava, J.A., Denison, R., Jones, B., Curran, M.A., Vigon, B., Selke, S., Barnum, J., Eds. *A Technical Framework for Life-Cycle Assessments*; Workshop Report Society of Environmental Toxicology and Chemistry; SETAC: Washington, DC, 1991.
- Smet, B. de, Ed. *Life-cycle analysis for packaging environmental assessment*; Proceedings of the specialised workshop, 24-25 September 1990, Leuven. Procter & Gamble Technical Center: Strombeek-Bever, Belgium, 1990.
- *Life-Cycle Assessment*; Proceedings of a SETAC-Europe workshop on Environmental Life Cycle Assessment of Products December 2-3 1991, Leiden; SETAC-Europe: Brussels, Belgium, 1992.
- Fava, J.A., Consoli, F., Denison, R., Dickson, K., Mohin, T., Vigon, B., Eds. *A Conceptual Framework for Life-Cycle Impact Assessment*; Society of Environmental Toxicology and Chemistry and SETAC Foundation for Environmental Education, Inc. Workshop Report; SETAC: Pensacola, Florida, 1993.
- Huppes, G., Schneider, F., Eds. Proceedings of the European Workshop on Allocation in LCA under the Auspices of SETAC-Europe, February 24-25, 1994, Leiden; SETAC-Europe: Brussels, Belgium, 1994.
- *Umweltprofile von Packstoffen und Packmitteln: Methode*; Fraunhofer-Institut für Lebensmitteltechnologie und Verackung: München; Gesellschaft für Verpackungsmarktforschung Wiesbaden und Institut für Energie- und Umweltforschung Heidelberg: Germany, 1991.
- Grieshammer, R., Schmincke, E., Fendler, R., Geiler, N., Lütge, E. Entwicklung eines Verfahrens zur ökologischen Beurteilung und zum Vergleich verschiedener Wasch- und Reinigungsmittel; Band 1 und 2. Umweltbundesamt: Berlin, Germany, 1991.
- *Product Life Cycle Assessment - Principles and Methodology*; Nord 1992:9, Nordic Council of Ministers: Copenhagen, Denmark, 1992.

[3] See also Chapter 8 Resources for Conducting Life Cycle Assessment

- Heijungs, R., Guinée, J.B., Huppes, G., Lankreijer, R.M., Udo de Haes, H.A., Wegener Sleeswijk, A., Ansems, A.M.M., Eggels, P.G., Duin, R. van, Goede, H.P. de. *Environmental life cycle assessment of products. Guide & Backgrounds – October 1992*; Centre of Environmental Science, Leiden University: Leiden, The Netherlands, 1992.
- Vigon, B.W., Tolle, D.A., Cornaby, B.W., Latham, H.C., Harrison, C.L., Boguski, T.L., Hunt, R.G., Sellers, J.D. *Life-Cycle Assessment: Inventory Guidelines and Principles*; EPA/600/R-92/245; Environmental Protection Agency: Washington, DC, 1993.
- Lindfors, L.-G., Christiansen, K., Hoffman, L., Virtanen, Y., Juntilla, V., Hanssen, O.J., Rønning, A., Ekvall, T., Finnveden, G. *Nordic Guidelines on Life-Cycle Assessment, Nord 1995:20*; Nordic Council of Ministers: Copenhagen, Denmark, 1995.
- Curran, M.A. *Environmental Life-Cycle Assessment*; McGraw-Hill: New York, 1996.
- Hauschild, M., Wenzel, H. Environmental Assessment of products. Volume 1: Methodology, tools and case studies in product development - Volume 2: Scientific background; Chapman & Hall: London, U.K., 1998.

Also, the first scientific journal papers started to appear in the *Journal of Cleaner Production*, *Resources, Conservation and Recycling*, *the International Journal of Life cycle Assessment*, *Environmental Science & Technology*, *the Journal of Industrial Ecology*, and other journals.

Through its North American and European branches, the Society of Environmental Toxicology and Chemistry (SETAC) started playing a leading and coordinating role in bringing LCA practitioners, users and scientists together to collaborate on the continuous improvement and harmonization of the LCA framework, terminology and methodology. The SETAC "Code of Practice" (Consoli *et al* 1993) was one of the key results of this coordination process. Next to SETAC, the International Standards Organization (ISO) has been involved in LCA since 1994. Whereas SETAC working groups focused at development and harmonization of methods, ISO adopted the formal task of standardizing methods and procedures.

The period of 1990-2000 can, therefore, be characterized as a period of *convergence* through SETAC's coordination and ISO's standardization activities, providing a standardized framework and terminology, and platform for debate and harmonization of LCA methods. In other words, the 1990s was a decade of standardization. Note, however, that ISO never aimed to standardize LCA methods in detail: "there is no single method for conducting LCA." During this period, LCA also became part of policy documents and legislation, with the main focus on packaging legislation, for example, in the European Union (EC 1994) and the 1995 Packaging Law in Japan (Hunkeler *et al* 1998).

1.4 Examples of Environmental Impact Trade-Offs

LCA identifies the potential transfer of environmental impacts from one medium 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 stage). 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. By broadening the study boundaries, LCA can help decision-makers select the product or process that causes the least impact to the environment. This information can be used with other factors, such as cost and performance data, in the selection process.

In connecting the different parts of the system, many LCAs lead to unexpected and non-intuitive results. For example, in the US in the 1980s, there was a perceived landfill crisis with many predicting the country running out of landfill space in the near future (NY Times 1986). Disposable (also called single-use) diapers (nappies) were caught up in the scare and perceived as a bad environmental choice because they end up in landfills by the millions, taking up valuable space, and take an estimated 500 years to decompose. Additionally, they are made using valuable non-renewable and renewable resources including wood pulp and plastic during their manufacture. But consumers often prefer the convenience and ease of disposable diapers.

Cloth diapers differ from disposables in that they are intended to be reused, thus cloth diapers are viewed as the more environmentally conscious alternative. While made of a renewable, natural material (cotton), cloth diapers require hot water (energy use) and detergents for washing. In order to determine the environmental superiority of cloth diapers, if any, multiple LCAs of disposable and cloth diapers were developed by P&G, the trade association EDANA, the UK Environment Agency, and others. However, when additional studies showed that cloth diapers also have meaningful environmental impacts due to use and heating water for washing, it became unclear which product was actually better.These studies found that most environmental impacts are linked to the energy, water, and detergents needed for cleaning cloth diapers, while the largest impacts, in addition to postconsumer waste, were related to raw material production for disposable diapers (Fava *et al* 1991, Krause *et al* 2009).

We learned that, depending upon the impact in question and where it occurs, different and equally valid interpretations can result. What these early studies revealed was that all products have impacts on the environment and that LCA tools enable decision makers to use new and additional information to make better-informed decisions.

Over the years, the instances in which one problem was solved but caused another are numerous. Compact fluorescent bulbs reduce electricity consumption by 75% but

Figure 1.3 Dueling diaper (nappy) LCA studies raised awareness of the diversity of environmental impacts that products can create.

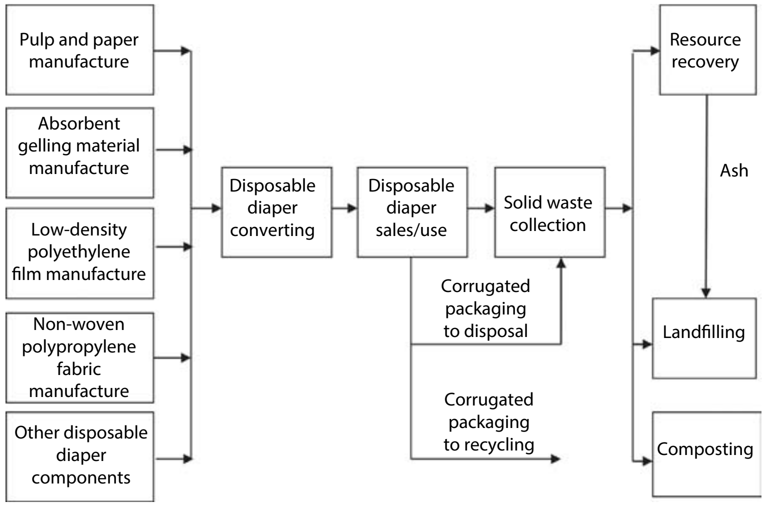


Figure 1.4 Disposable Diaper (Nappy) Life Cycle.

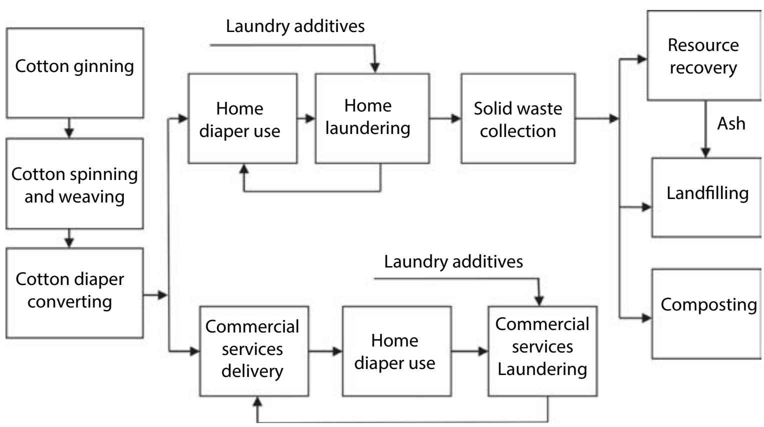


Figure 1.5 A Reusable Diaper (Nappy) Life Cycle.

come with a dash of mercury. Biobased fuels reduce greenhouse gas emissions but contribute to air, water and soil quality impacts in the agricultural stage.

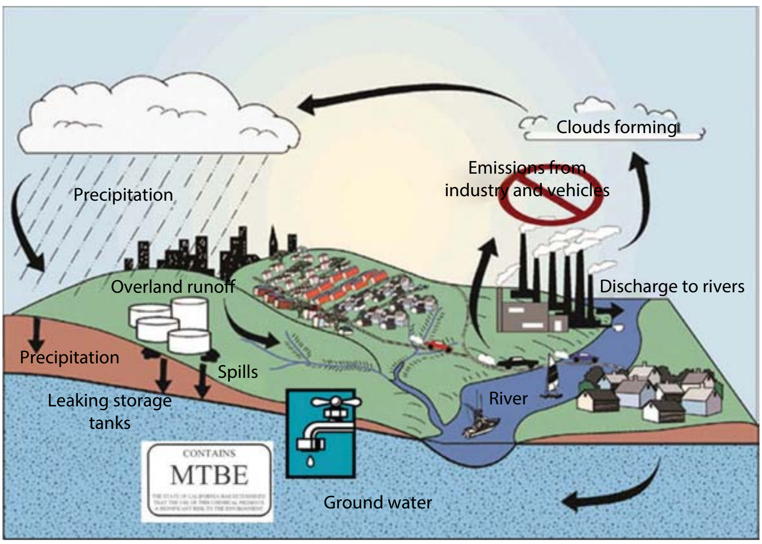
Tools are needed that can help us to evaluate the comparative potential cradle-to-grave impacts of our actions in order to help us to prevent such wide-ranging effects. While LCA can provide assistance in the decision-making process, it has limited applicability in that it can only help us to evaluate the data that are available at the time. That is, it is not a predictive tool but can only model activities for which data are available. However, it has become increasingly evident that we must look much more holistically at our actions in order to more effectively protect human health and the environment in the short and long-term and to therefore, contribute to the development of more sustainable societies.

The Life Cycle of Methyl Tertiary-Butyl Ether (MTBE) as a Fuel Additive

MTBE is added to automotive fuel (gasoline/petrol) to increase octane levels and enhance combustion. It also provides the following environmental benefits:

- Reducing ozone precursors by 15%
- Reducing benzene emissions by 50%
- Reducing carbon monoxide emissions by 11%

But after it was commercialized, and the environmental benefits from reducing the emissions from vehicles were being realized, it became evident that there were measured amounts of MTBE in the environment. It could have leaked from storage tanks. MTBE in potable water supplies (e.g., lakes, reservoirs, and groundwater) is the greatest concern. Measured MTBE concentrations in some cases exceeded standard indicators for potable water, including "taste and odor" and "human health." There was insufficient information on its long-term toxicity.



This graphic shows a system view of MTBE movement (modified from US Geologic Survey (http://sd.water.usgs.gov/nawqa/pubs/factsheet/fs114.95/fact.html)

While the use of MTBE reduced air emissions in the cities – an excellent outcome – it also created unexpected releases of MTBE into groundwater. Drinking water sources were contaminated as a result of an action that was designed to reduce air pollution.

As manufacturing operations become increasingly diverse, both technically and geographically, producers and the service industry are realizing the need to be fully aware of the potential environmental impacts in the sourcing of resources, manufacturing and assembly operations, usage, and final disposal. 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

Figure 1.6 LCA is a "cradle-to-grave" assessment which spans the gathering of raw materials from the earth, manufacturing and use, on through to the return of materials to the earth. The arrows represent transportation.

performance. Society, in general, is becoming increasingly more aware of the fact that human activity can have far reaching impact.

This expanded view of interactions between human activity and the environment is prompting environmental managers and policy makers to look at products and services from cradle to grave. Out of this need came Life Cycle Assessment (LCA). What started as an approach to compare the environmental goodness (greenness) of products has developed into a standardized method for providing a sound scientific basis for environmental sustainability in industry and government. LCA provides a comprehensive view of the environmental aspects of product or process alteration or selection and presents an accurate picture of potential environmental trade-offs. LCA is useful in addressing cross-media problems and avoiding the transfer of a problem from one medium to another or from one place to another. Figure 1.6 presents a cradle- to-grave system of a generic product to depict the broad scope covered by LCA.

1.5 LCA Methodology

The LCA framework has evolved over time. In 1990, SETAC held the first in a series of LCA-related Pellston style workshops[4]. Although LCAs had been performed previously in one form or another, it was during this workshop when the name was coined and the resulting document presented the name of the method (SETAC 1990). As seen in Figure 1.7, the original LCA framework consisted only of three components with goal definition obviously missing. This omission was corrected in 1993 in a following SETAC

[4] Pellston workshops, named for the location of the first workshop of this type (Pellston, Michigan), aim to advance cutting edge technical and policy issues in environmental science by assembling scientists, engineers, and managers from government, private business, academia, and public interest groups to share current information on a given topic. At the end of the intense 4-5 day workshop, a document is produced that describes this knowledge with recommendations for enhancing the current state of the science.

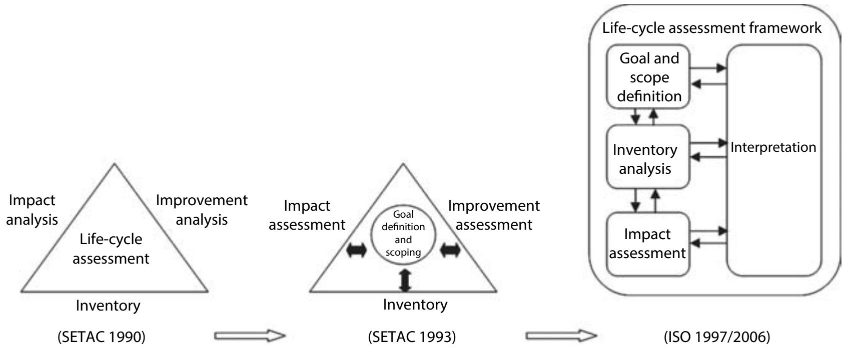


Figure 1.7 The Evolution of the Life Cycle Assessment Framework.

workshop, held in Sesimbra, Portugal. A new component called "Goal Definition and Scoping" was inserted in the middle of the SETAC triangle with arrows connecting it to Inventory, Impact Analysis, and Improvement Analysis, to depict the interconnections. By 1996, the triangle was replaced by a flow diagram with "Goal and Scope Definition" clearly shown as a first step (although the four interrelated phases of LCA are not necessarily conducted in 1, 2, 3, 4 order, GS&D should be addresses as a first step[5]).

The current LCA methodology refers to the process of compiling and evaluating the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. LCA has come a long way, and it continues to improve. Since a decade or so ago, there has been a broadly accepted set of principles that can be claimed as the present-day LCA framework.

The International Standards Organization (ISO) produced a series of standards and technical reports for LCA. Referred to as the 14040 series, these standards include the documents listed in Table 1.1.

The standards are organized into the different phases of an LCA study. These are:

> Goal and Scope Definition - identifying the purpose for conducting the LCA, the boundaries of the study, assumptions and expected output;
> Life Cycle Inventory - quantifying the energy use and raw material inputs and environmental releases associated with each stage of the life cycle;
> Life Cycle Impact Assessment - assessing the impacts on human health and the environment associated with the life cycle inventory results; and
> Interpretation – analysis of the results of the inventory and impact modelling, and presentation of conclusions and findings in a transparent manner.

The quality of a life-cycle inventory depends on an accurate description of the system to be analyzed. The necessary data collection and interpretation is contingent upon

[5] This was also when the component "Improvement Analysis" was renamed "Interpretation."

Table 1.1 ISO Documents on Life Cycle Assessment (LCA).

Number	Type	Title	Year
14040	International standard	Principles and framework	1996, 2006
14041	International standard	Goal and scope definition and inventory analysis	1998[1]
14042	International standard	Life cycle impact assessment	2000[1]
14043	International standard	Life cycle interpretations	2000[1]
14044	International standard	Requirements and guidelines	2006[2]
14047	Technical report	Examples of application of ISO 14042	2003
14048	Technical report	Data documentation format	2001
14049	Technical report	Examples of application of ISO 14041	2000

[1] Updated in 2006 and merged into 14044.

[2] Replaces 14041, 14042, and 14043.

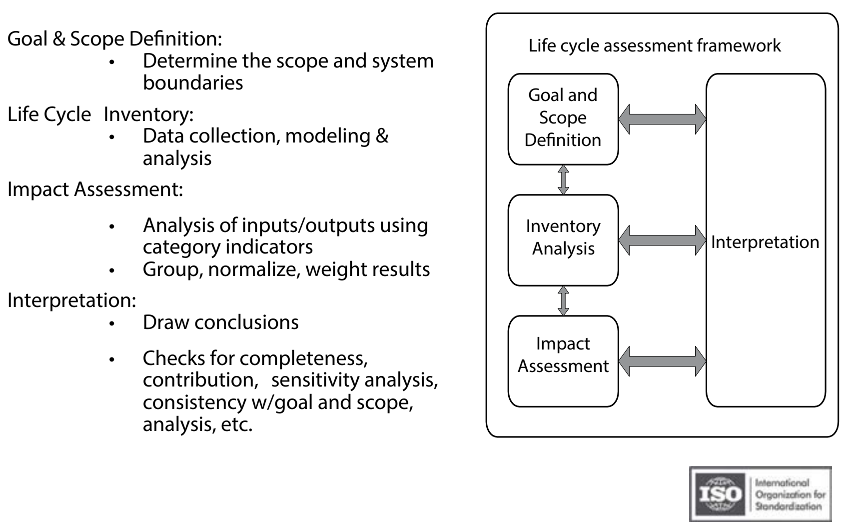


Figure 1.8 ISO Life Cycle Assessment Framework. This excerpt is adapted from ISO 14040:2006, Figure 1, page 8 with the permission of ANSI on behalf of ISO. © ISO 2015 - All rights reserved.

proper understanding of where each stage life-cycle begins and ends. The general scope of each stage can be described as follows:

Raw Materials Acquisition. This stage of the life cycle of a product includes the removal of raw materials and energy sources from the earth, such as the harvesting of trees or the extraction of crude oil. Land disturbance as well as transport of the raw materials from the point of acquisition to the point of raw materials processing are considered part of this stage.

Manufacturing. The manufacturing stage produces the product from the raw materials and delivers it to consumers. Three substages or steps are involved in this transformation: materials manufacture, product fabrication, and filling/packaging/distribution.

Materials Manufacture. This step involves converting raw material into a form that can be used to fabricate a finished product. For example, several manufacturing activities are required to produce a polyethylene resin from crude oil: The crude oil must be refined; ethylene must be produced in an olefins plant and then polymerized to produce polyethylene. Transportation between manufacturing activities and to the point of product fabrication should also be accounted for in the inventory, either as part of materials manufacture or separately.

Product Fabrication. This step involves processing the manufactured material to create a product ready to be filled, or packaged, for example, blow molding a bottle, forming an aluminum can, or producing a cloth diaper.

Filling/Packaging/Distribution. This step includes all manufacturing processes and transportation required to fill, package, and distribute a finished product. Energy and environmental wastes caused by transporting the product to retail outlets or to the consumer are accounted for in this step of a product's life cycle.

Use/Reuse/Maintenance. This is the stage consumers are most familiar with, the actual use, reuse, and maintenance of the product. Energy requirements and environmental wastes associated with product storage and consumption are included in this stage.

Recycle/Waste Management. Energy requirements and environmental wastes associated with product disposition are included in this stage, as well as postconsumer waste management options such as recycling, composting, and incineration.

The following general issues apply across all four life-cycle stages.

Energy and Transportation. Process and transportation energy requirements are determined for each stage of a product's life cycle. Some products are made from raw materials, such as crude oil, which are also used as sources for fuel. Use of these raw materials as inputs to products, represents a decision to forego their fuel value. The energy value of such raw materials that are incorporated into products typically is included as part of the energy requirements in an inventory. Energy required to acquire and process the fuels burned for process and transportation use is also included.

Environmental Waste Aspects. Three categories of environmental wastes are generated from each stage of a product's life cycle: atmospheric emissions, waterborne wastes, and solid wastes. These environmental wastes are generated by both the actual manufacturing processes and the use of fuels in transport vehicles or process operations.

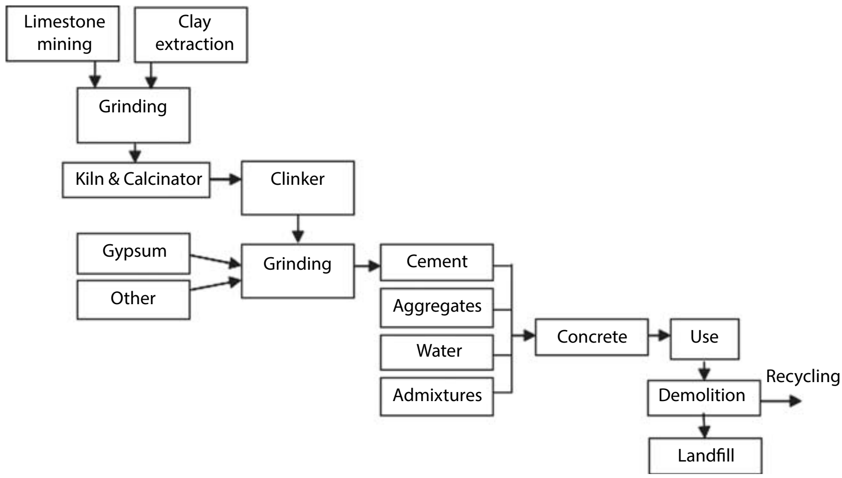


Figure 1.9 A Concrete Example of an LCA Flow Diagram (adapted from Sjunnesson 2005).

Waste Management Practices. Depending on the nature of the product, a variety of waste management alternatives may be considered: landfilling, incineration, recycling, and composting.

Allocation of Waste or Energy among Primary and Co-Products. Some processes in a product's life cycle may produce more than one product. In this event, energy and resources entering a particular process and all wastes resulting from it are allocated among the product and co-products. Allocation is described in more detail in Chapters 2 and 3.

1.6 Maintaining Transparency (Openness)

LCA involves various simplifying assumptions and value-based judgments throughout the process. LCAs can produce different results even if the same product seems to be the focus of the study. Differences can be caused by a number of factors, including:

- Different goal statements.
- Different functional units.
- Different boundaries.
- Different assumptions used to model the data.

The key is to keep these to a minimum and be explicit in the reporting phase about what assumptions and values were used. Readers of the study can then recognize the judgments and decide to accept, qualify, or reject them and the study as a whole.

It is very important to maintain transparency[6] in reporting an LCA study. The word transparent is used in the sense that it is easy to see what was done (versus the other

[6] ISO 14044 2006 defines transparency as the open, comprehensive and understandable presentation of information.

possible meaning of transparent which is to operate like a black box and be invisible to the user). This is necessary because it is not a single, prescriptive process. Rather, it involves multiple decision points that can greatly influence the outcome of the LCI and the LCIA. Although it would be best to achieve consensus on the methodology, thereby reducing or eliminating variations in the practice, at this time, the best solution is to maintain transparency and to fully document how the data were calculated. That way, even if others may not agree with the approach, at least, it is clear what was done.

1.7 Conclusions

If life cycle environmental information is to be integrated into product design and development to the same extent as price, quality, safety and performance, what are the changes that might need to occur? If we take a step back from these short case studies and critically examine what we have learned that might influence how we design and develop new products, technologies, and services for the 21st century, several breakthrough innovation principles and concepts surface are foundational to how we design and commercialize products.

1. Life cycle environmental performance will become as predominant as safety and quality are today in the design and development of products, technologies and services.
2. We have to create a marketplace which rewards greener companies, products, and brands.
3. We must move beyond examining a single impact or life cycle stage as the sole criteria for developing products that are more sustainable.
4. We already know much about life cycle hot spots and can direct innovation efforts by developing materials that incorporate the knowledge that exists in the life cycle community and in the thousands of LCA studies that have been completed over the last 20 years.
5. There is still significant additional information and knowledge to be learned, so we need to continue generating life cycle inventory data and conducting LCA studies. Moreover, there are questions that have not yet been formulated, let alone asked.

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