TOXICS USE
REDUCTION
INSTITUTE

THE MASSACHUSETTS
TOXICS USE REDUCTION INSTITUTE

A BACKGROUND DOCUMENT ON LIFECYCLE ANALYSIS:

BIODEGRADABLE POLYMERS

Methods/Policy Report No. 4 1993

University of Massachusetts Lowell

A Background Document on Lifecycle Analysis:

Phase I of a Study of Biodegradable Polymers

Frances Eagle
Doctor of Engineering Candidate, Plastics Engineering

Dr. Stephen McCarthy
Plastics Engineering Department

University of Massachusetts Lowell

The Toxics Use Reduction Institute Research Fellows Program

June 1993

The Toxics Use Reduction Institute
University of Massachusetts Lowell

TOXICS USE REDUCTION INSTITUTE

The Toxics Use Reduction Institute is a multi-disciplinary research, education, and policy center established by the Massachusetts Toxics Use Reduction Act of 1989. The Institute sponsors and conducts research, organizes education and training programs, and provides technical support to governments to promote the reduction in the use of toxic chemicals or the generation of toxic chemical byproducts in industry and commerce. Further information can be obtained by writing the Toxics Use Reduction Institute, University of Massachusetts Lowell, One University Avenue, Lowell, Massachusetts 01854.

Toxics Use Reduction Institute
Research Fellows Program

In 1991 the Toxics Use Reduction Institute established the Research Fellows Program at the University of Massachusetts Lowell (UML). The Research Fellows Program funds toxics use reduction research projects performed by graduate students and their advisors. The goals of the program are:

- to develop technologies, materials, processes and methods for implementing toxics use reduction techniques,
- to develop an understanding of toxics use reduction among UML graduate students and faculty,
- to facilitate the integration of the concept of toxics use reduction into UML research projects, and
- to provide UML faculty with "incubator" funding for toxics use reduction related research.

The types of projects funded through the Research Fellows Program are technology, methods and policy research projects. Each final report is published by the Institute. The opinions and conclusions expressed in this report are those of the authors and not necessarily those of the Toxics Use Reduction Institute.

Report #1

Table of Contents

The 'Greening' of America

The realization of the effect of technology on the U.S. environment first began in the early 1950's when scientists in Troy, New York noticed a higher than usual amount of local radioactivity.[1] The U.S. government by 1951 had tested sixteen atomic bombs and assured the public that the effects of the testing would be localized. However, scientists began to notice strontium 90 in areas far from the atomic bomb test sites, and later traced the source of the isotope to the nuclear tests. Understanding the potential health threat of radioactive exposure, U.S. scientists began to publicly disseminate information to the general public and urge citizens to contact their representatives to voice their concern. The result of public action resulted in the signing of the 1963 Nuclear Test Ban Treaty between the United States and the U.S.S.R. This treaty was the first milestone in the struggle for environmental protection within the United States.

The 1960's was a period of public awakening of the potential threat technology posed to human health and environmental quality. The concern over and investigation of air quality in California cities lead to regulations on the automobile industry.[2] Unanticipated water pollution found in rural areas was traced to the use of fertilizers.[3] The decrease in the commercial fish catch of Lake Erie was linked to industrial phosphorous and nitrate effluent.[4]

The 1962 publication of "Silent Spring"[5] further awakened the public to the realization that technology is a two-sided coin. In addition to the many and diverse benefits technology bestows upon America's standard of living, technology also creates instances of public concern as technological by-products adversely affect regional air, water and land quality, as well at pose a threat to people's health. The down-side effect of technology became well known to Americans as they watched televised accounts of Love Canal and other superfund cites.

Sustainable Economy Theory [6]

The 1960's was a decade that brought about the realization of the interrelationship between man and the environment. The 1970's brought about the awareness and concern of the finite limitation of the earth, and the concept that environment and technology development are interdependent. The 1972 publication of The Limited Growth hypothesized that the predicted future growth of the world's population would place a high demand for material goods on industry, which in turn would deplete renewable energy and mineral resources. From this hypothesis evolved the sustainable development theory, an idea recognized and endorsed by 113 nations attending the 1972 Stockholm UN Conference on the Environment. A sustainable economy emphasizes energy conservation, material recycling and production of only essential material goods, thereby minimizing raw material depletion and energy use.

As the sustainable development concept evolved it brought out a hidden flaw in business accounting practices. Traditional profitability is defined in terms of raw material costs, processing costs, labor costs and administrative overhead. However, an entire segment of costs related to product disposal and pollution clean up had been omitted.

It is estimated that from 1946 - 1960 levels of various pollutants generated by the American population increased anywhere from 200% - 2000%.[7] The cost of dealing with technology's by products initially became the responsibility of state and federal governments. As toxic waste pollution and solid waste pollution levels continued to grow and become more prevalent the public began to demand that industry be accountable for its developed technology.

By the end of the 1970's people began to realize the potential threat of technology developed to solely maximize business profits. The public had learned that by becoming actively involved in the political system it could alter the actions of government and industry.

Stakeholder Philosophy [8]

During the 1980's a new philosophy emerged regarding the role of the company to society. Although the obligation of the Board of Directors continues to be to maximize company profits many grass root movements began to pressure corporations to conduct business within the framework of the local society and global environment. This **stakeholder** philosophy expands the Board of Directors fiduciary responsibility past company boundaries to include the concerns of environmental groups, local communities, government agencies and public interest groups. The stakeholder philosophy views Corporations as "servants of the larger society"[9] and blends company specific goals with society and environmental concerns.

The Changing U.S. Economic Business Model

It can be speculated that the 21st century model for conducting business will be broad-based in many aspects. The micromanagement philosophy of optimizing the efficiency of isolated business departments is being replaced with a macromanagement philosophy that focuses on the efficiency of the company as a whole.[10,11] Traditional numerical standards for measuring productivity are being reviewed, revised and replaced with more meaningful standards.[10,12] The once familiar large business hierarchy is being scaled down to a smaller size, less hindered by multi-level management. Vertical integration is yielding to a lean production style philosophy.[12,13] Traditional research and development projects are being scaled back and replaced with market focused R&D projects.[14,15]

Another business factor once overlooked but now being considered in this new American business model is the environment.[15,16,17] Business is beginning to accept the sustainable development philosophy that a healthy environment leads to economic stability.

The Russian Ecocide Example

In the past industry has argued that environmental concerns have been exaggerated and that it is being unfairly burdened by unnecessary environmental regulations. However, it appears that the warnings of economic and environmental disaster predicted by the American environmental movement during the 1960's has occurred - in the former U.S.S.R.

A recent publication entitled "Ecocide in the U.S.S.R." [18] sites several examples of environmental mismanagement and its effect on the people, land, waters and air of the former U.S.S.R. This account of the country's current status points out the delicate balance between the environment and technology. It cites statistics of how current environmental decay resulting from decades of environmental neglect is seriously impacting agricultural and fishing industries, as well as the health of the population and business in general. The data in this book reinforces the concept of the sustainable economy philosophy: economies that minimize environmental decay maintain a long-term economic base, while economies that neglect the environment have short-lived prosperity.

Industry's Response to the Environment in the 1990's

Due to the environmental awareness efforts of the previous decades some of the larger corporations in the United States now actively design products and manufacturing processes to minimize their impact on the environment. Companies have found that designing a product to be environmentally friendly can also be profitable.[17] Companies such as AlliedSignal, 3M and Dow have adopted corporate strategies of "Environmentally Conscious Manufacturing", citing slogans of "Pollution Prevention Pays" (3M) and "Waste Reduction Always Pays" (Dow).

Similarly, long time environmental advocates are altering their approach to controlling pollution by recognizing that pollutants cannot be eliminated from an offending technology in an economical manner. Studies indicate that decreasing the amount of a pollutant with control devices has been successful but "as controls are made more efficient, their costs will necessarily escalate until, becoming prohibitive, any further environmental improvement is blocked"[19]. For example:

> "If an adsorbent column can remove 90% of the entering pollutant, doubling its length will remove 99%, tripling it will remove 99.9%, and so on. In practice this relationship leads to an exponential increase in the cost of a control system as its efficiency rises. . . . The net result is that the degree of environmental improvement that a control device can achieve is sharply limited by cost." [19]

Current systems in place for the control of sulfur dioxide, ozone and automobile exhaust emissions follow this exponential expense curve.

It is now suggested that a more successful route to minimizing pollutants in the environment is to choose a technology that never generates the pollutant during its manufacturing process or during its use; a prevention strategy rather than a control strategy. Choosing alternate technologies that are less harmful to humans and the environment and which still accomplish the intended objective in an economical manner has been successfully achieved. Examples of technologies that have been redesigned to eliminate targeted pollutants include: alternative octane boosters to replace lead in gasoline; the introduction of semi-permeable membrane technology to replace the use of mercury in the production of chlorinated alkali; less harmful insecticides replaced DDT; water replaced chlorinated solvents in some processes of the semiconductor industry; sodium bicarbonate replaced toxic solvents in paint strippers.

The concept of retiring mature, polluting technologies and replacing these technologies with non-polluting alternates that accomplish the same end objective is now the proposed scheme of environmental advocates and industry.[17,19]

A question still remains regarding the analysis of existing technologies: How does one assess any given technology in a qualitative and quantitative manner to determine its use of resources and its generation of pollutants as well as assign some rank of toxicity to these pollutants? The United States Environmental Protection Agency (EPA) has a guideline for conducting such an analysis. The technique being suggested by the EPA for adoption by both industry and environmental advocates is a Life Cycle Analysis.

II. Life Cycle Analysis [20]

Background

The Environmental Protection Agency is legislated by Congress to define, measure and suggest solutions to the pollution problems of the nations land, air and water. One means of defining manufacturing parameters that pollute the environment is through the use a Life Cycle Analysis. Life Cycle Analysis had its beginnings in the 1960's when groups within the U. S. society realized that the world's raw material resources were limited, that its population would continue to increase and that industry would expand globally. It was readily predicted that these three factors would overwhelm nature's ability to effectively handle the anticipated level of emitted pollution and energy demands of the coming decades. Organizations tried to identify and quantify the many effluents, emissions, solid waste and energy usage generated by industry. Case studies were performed on industrial processes or products deemed to be negatively affecting the environment.

During the 1970's a standard method for analyzing pollutant generation and its effects on the environment began to emerge and become accepted by government and industry. However, during the later part of the 1970's a new U.S. environmental concern - hazardous waste - became a national crisis due to its toxicity, its immediate potential threat to human life and its widespread occurrence. The focus and efforts of government, environmental and industrial groups turned to solving this critical issue. Life Cycle Analysis (LCA) studies of identifying and reducing emissions or minimizing energy resource demands for industry were no longer a priority and the evolution of the methodology was stalled until the late 1980's.

The decade of the 1980's ushered in a worldwide concern over solid waste disposal. LCA studies were again used to ascertain environmental impact. It was soon realized that the identification of pollutants was only the first step in actually solving the problem of reducing or eliminating pollutants. A complete Life Cycle Analysis included the additional steps of quantifying each pollutant's effect on the environment and offering alternative ways of eliminating, replacing or minimizing the pollutant with a benign technology.

The impact of LCA studies was greatly diminished during the 1980's because the analysis became a tactic for verifying the opinions of specific groups. When industry and environmental groups assessed a technology assumptions were incorporated into the analysis skewing its conclusions. As a consequence LCA were conducted without using an accepted methodology and without peer review. Published LCA were criticized and considered bias resulting in heated controversy between industrial, government and industrial groups.

Recognizing the importance of a Life Cycle Analysis as a tool for obtaining constructive information regarding an industrial process or product, the U.S. Environmental Protection Agency (EPA) awarded a 1988 contract to Battelle and Franklin Associates to provide a standard LCA guideline. Findings would be reported in a consistent manner and format. Peer review would be added to ensure a balanced presentation.

By adopting a standard LCA format with peer review, newly generated LCA studies would contain accurate data that allowed assessment of generated pollutant levels

Objectives

The objectives of the LCA developed for the EPA include:

1. Establish a template methodology for studies conducted throughout the world in order to obtain meaningful comparative data.

2. Establish a quantitative baseline for comparing technologies to assess the improvement or merit of one technology over another.

3. Prioritize pollutant activity.

4. Relay information in an accurate manner to industry, government and the public so that informed decisions may be made regarding the technology's impact on the environment.

Life Cycle Analysis Definition

A fully developed Life Cycle Analysis is an analytical methodology that considers the inputs and outputs of each step of a process leading to a manufactured end product. In general, the method quantitatively describes the effects a process has on the environment, including the energy required for production. The results of the study target and prioritize pollutants. This information can then be the basis for industrial and federal guidelines or incentives to implement or invent ways of removing, reducing or eliminating the pollutant from the manufacturing process. A complete LCA consists of three segments: 1) inventory analysis, 2) impact analysis and 3) improvement analysis.

The **inventory analysis** segment of the LCA usually quantifies or qualifies the amount of energy used and the pollutant emissions for each process leading to the end product . This analysis includes the processes of raw material acquisition, product manufacturing, fabrication, distribution, market use and disposal.

Depending on the product or process under consideration, the inventory analysis segment of the LCA can be extensive. **Raw material acquisition** includes effects of removing the raw material from the earth, its transportation and its refining processes. **Product manufacturing** includes each individual manufacturing process and its associated transportation and energy costs of each pre-manufacturing segment leading to the end product. **Product fabrication** is the final process resulting in the actual end product. **Distribution** includes all processes related to the filling, packaging, distribution and storage of the end product prior to its sale to the consumer. **Consumer use** includes all emissions and energy requirements associated with the products use. The final step of **disposal** encompasses energy and pollutants generated via collection and landfilling, recycling, degradation and/or incineration of the product.

The **impact analysis** segment of the LCA reviews each of the pollutants and the energy requirements identified in the inventory analysis from an ecological and human health point of view. In addition to toxicity issues, ecological aspects may also include habitat effects, as well as noise and heat generation issues.

The **improvement analysis** segment of a LCA reviews existing technologies. Suitable technologies are offered to reduce, remove or eliminate existing pollutants and reduce energy requirements. The suggested replacement technologies should also be subject to a LCA in order to ensure that the replacement technology does not introduce new pollutants equally damaging to the environment. This review of existing technologies is expected to generate new ideas for future areas of research.

Parameters common to each LCA segment include energy consumption, transportation costs, atmospheric emissions, waterborne wastes, solid wastes and disposal techniques. As such, the results of each stage are cumulative and are added together to obtain a total value by standardizing the report data. For instance, energy consumption would consistently be reported in Btu, solid waste would be reported in pounds or by volume, etc. Standardizing data units allows for cross comparison with other LCA studies.

Limitations of Life Cycle Analysis Studies

Accurate data for energy consumption and pollutant level generation may not be readily available. Some sources for obtaining data include industry and government reports, open literature, product specifications, professional associations and laboratory data. Most data available to the public is generalized and represents an industry average that may be skewed since it originated from that specific industry. Plant specific data is rarely available. The source of the data should always be reported.

Past LCA studies were criticized as bias because peer review was not included as part of the LCA process. A complete LCA includes a peer review.

A comprehensive LCA includes comments from industry, government, consumer, environmental and academic groups. The collective comments from these groups minimizes criticism of the LCA and enhances the likelihood that the recommendations will be implemented.

III. The Inventory Analysis Segment of a LCA[20, 21]

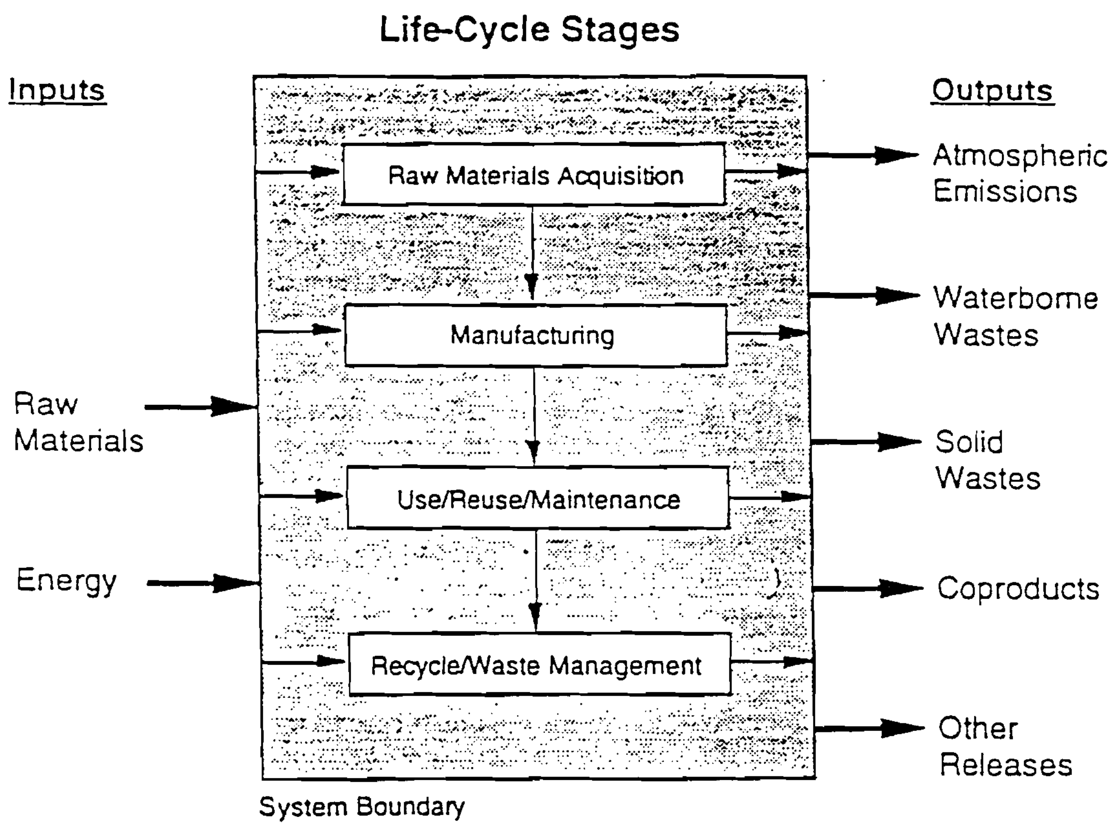
General Issues

The general steps in conducting an inventory analysis are: 1) define the purpose of the LCA; 2) define the system boundaries; 3) compile a checklist of data required for the study; 4) gather, standardize and tabulate the data; 5) construct a flow diagram of the LCA studied; 6) interpret the results; 7) conduct a peer review; and, 8) incorporate the peer review into the final LCA.

The various stages of product production that should be considered when conducting the inventory segment of a LCA are found in Figure 1. These stages include: means of acquiring the raw materials, manufacturing operations, product fabrication processes, filling/packaging/distribution operations, consumer use and product disposal. A fictitious process flow diagram for the production of product 'A' is found in Figure 2. The process flow diagram is used as a tool to consistently collect similar information on each processing segment of each product under consideration.. The purpose of the template is to record all process requirements (inputs) used to obtain a given product and record all process products and by-products (outputs) generated during each stage of the inventory analysis.

Figure 1 [21]

Life Cycle Stages
Inputs / Outputs

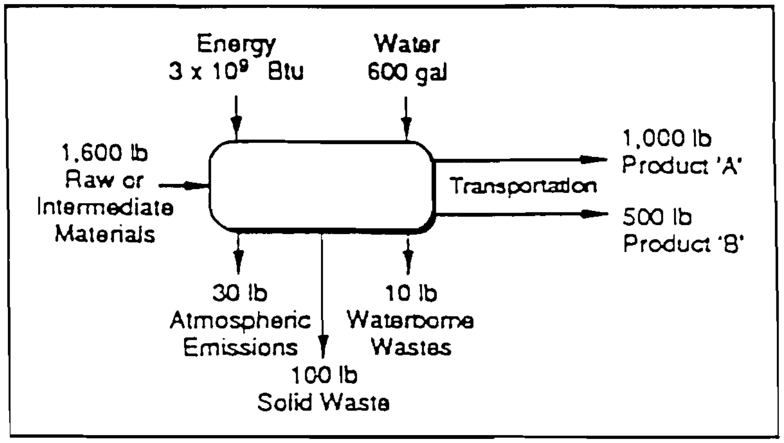


Defining system boundaries

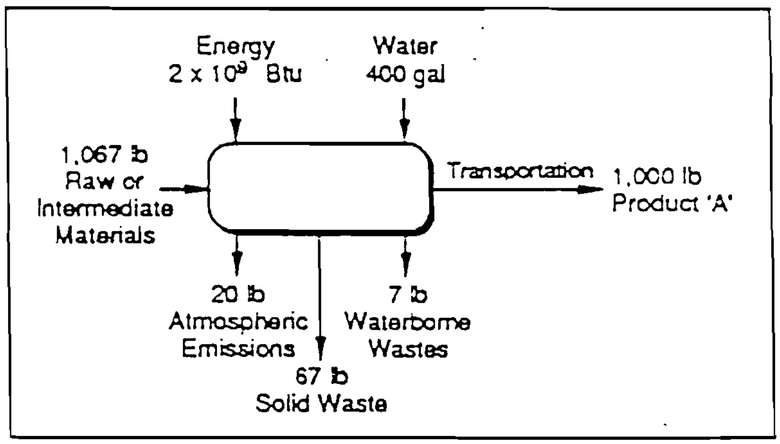
Figure 2[21]

Process Flow Diagrams
Using Input / Output Scheme

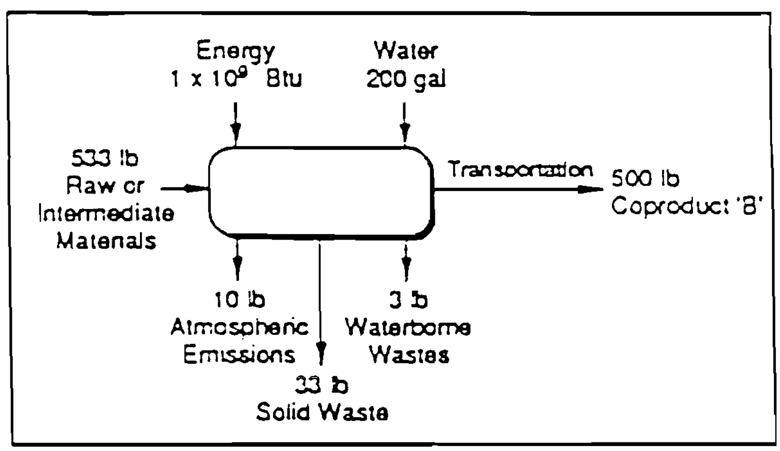
Actual process flow diagram for the production of Products 'A' and 'B'



Flow diagrams showing the normalized resources and environmental releases for each coproduct



Coproduct Allocation for Product 'A'



Coproduct Allocation for Product 'B'

Typical Input Information for each manufacturing step may consist of the following:

Raw Materials:	solids, liquids, catalysts, water
Intermediate materials:	solids, liquids, catalysts, water
Process energy:	reactors, heat exchangers, stirrers, pumps, boilers
Transportation energy:	truck, barge, rail carrier, ocean ship, pipeline
Precombustion energy:	energy expended to acquire the useable base fuels
Energy Sources:	coal, natural gas, petroleum, hydropower, nuclear, electricity
Capital Equipment:	Description, cost, energy requirements
Market Share:	General Information

Typical Output Information may consist of the following:

Regulated atmospheric emissions:	CO, NH3, Pb, SO, NO, particulate per pound of end product
Regulated waterborne waste:	BOD, COD, suspended/dissolved solids, oils, Cr, Sn, sulfides, CN, Fl, phenol, phosphates, NH3
Solid waste:	packaging, scrap, trim, sludges, emission solids
Coproducts:	useful cogenerated products
Transportation energy:	truck, barge, rail carrier, ocean ship, pipeline

Any of the above data included in the study should be as detailed as possible as defined by the level of personnel, finances and time allocated to complete the study. In addition, the source and age of all data should be clearly delineated. Reviewers are then aware of the accuracy of the published data.

The various aspects of the inventory segment of the LCA are now reviewed.

a. Define the purpose and scope of the study

An explanation of the need to conduct a Life Cycle Inventory Analysis is presented in order to familiarize the reader with the importance of the study. Background information regarding any controversy surrounding the area of study should be clearly presented with references.

b. Define the system boundaries

It may not be feasible to conduct a thorough and complete LCA inventory analysis on complicated manufacturing systems due to personnel, finance or time constraints. In such an instance an attempt should be made to outline an entire LCA noting that the system boundaries chosen for the study are a subset of the entire process. When dealing with many variables in a processing system one should assess those parameters that are most critical to the process. Materials that account for less than one percent of the system input/output may be neglected with a written justification explaining its omission.

c. Begin the inventory analysis

The checklist of all the data required for an accurate inventory analysis for your particular study may not be readily apparent. Review the types of data used in the template of Figure 2 and the data suggested on page XX as a starting point of the study. As the study proceeds, the information initially gathered may be expanded at a later date as a better understanding of the process and the important input/output parameters is learned.

Raw Material and Energy Acquisition

The starting point of any LCA begins with the current raw materials used to make the product. Each raw or intermediate material is traced back to its original origins on the earth ie) extraction from drilling wells or mines, planting/harvesting requirements, etc. The inputs and outputs of the process are tabulated for each processing step for each raw material, including transportation costs. The effect of the extraction process on the ecosystem may be attempted. The most recent data available should be cited. References should be clearly stated when industry or government estimates are used in the study.

Material Manufacture

This stage of the inventory analysis includes all the manufacturing processes to refine the raw materials, create intermediates and produce the product. The inputs and outputs are tabulated for each manufacturing step. When useful coproducts are generated from the same manufacturing process the inputs and outputs are scaled down according to the ratio reflecting the percentage of the product being studied to its coproduct(s). Reused industrial scrap is not recorded as an input or output since it stays within its manufacturing subsegment. Scrap that is sold to another company or division and used as input to another manufacturing process is recorded and considered a coproduct.

Product Fabrication

Many times this stage of the inventory analysis consists of a single fabrication process. It is the process that converts the raw materials and/or intermediates to the final end product prior to customer use. Inputs and outputs are recorded.

Filling / Packaging / Distribution

This stage of the inventory analysis includes all the processes that act upon the product prior to customer consumption, including transportation costs. Inputs and outputs are recorded. The analysis usually does not include the product itself but rather just the packaging surrounding the product and the associated distribution costs.

Consumer Use / Disposal

This is the last stage of the inventory analysis. It typically includes the inputs/outputs of using the product as well and the inputs/outputs of disposing the product and its packaging. The disposal process includes landfilling, incineration, recycling, composting or other technologies commonly used.

d. Peer Review

Once the data has been tabulated and standardized a peer review should be conducted. Send the compiled study to various individuals in government, academia, industry and environmental groups for review. Comments may be directly integrated into the final content of completed report or attached as an appendix with comments. Once the peer review comments have been included the study is disseminated to the public.

Literature Cited

1. B. Commoner, *The Closing Circle*, Bantam Books, New York, 1971. Chapter 3.

2. B. Commoner, *The Closing Circle*, Bantam Books, New York, 1971. Chapter 4.

3. B. Commoner, *The Closing Circle*, Bantam Books, New York, 1971. Chapter 5.

4. B. Commoner, *The Closing Circle*, Bantam Books, New York, 1971. Chapter 6.

5. R. Carson, *Silent Spring*, Houghton Mifflin, Boston, 1987.

6. *The Sustainable Society: Implications for Limited Growth,* D. Pirages, Ed., Praeger, New York, 1977.

7. B. Commoner, *The Closing Circle*, Bantam Books, New York, 1971. p. 138.

8. J. Bowditch, A. Buono, *A Primer on Organizational Behavior*, John-Wiley & Sons, New York, 1989. Chapter 8. .

9. J. Bowditch, A. Buono, *A Primer on Organizational Behavior*, John-Wiley & Sons, New York, 1989. p. 191.

10. E. Goldratt, J. Cox, *The Goal*, North River Press, Hudson, New York, 1992.

11. Garvin, *Operation Strategy* , Prentice Hall, Englewood Cliffs, N. J., 1992. p.22.

12. B.W.Chew, "No nonsense guide to measuring productivity", Harvard Business Review, Jan/Feb, 1988.

13. J. Womack, D. Jones, D. Roos, *The Machine that Changed the World* , Macmillion Publishing, New York 1990.

14. V.Franchetti, Director of Technology, Monsanto Chemical Group, "The Challenges of the '90's for Research and Development Management: Developing the Competitive Edge", Guest Lecturer, Center for Industrial Competitiveness, University of Massachusetts Lowell, September 1992.

15. J. Wirth, Sr. Vice President, Raychem Corporation, "Leadership of Technology in the 90's", Guest Lecturer, Center for Industrial Competitiveness, University of Massachusetts Lowell, January 1993.

16. H. Petrauskas, Vice President, Ford Motor Company, "Total Quality Management: Path to Environmental Protection", Guest Lecturer, Center for Industrial Competitiveness, University of Massachusetts Lowell, January 1993.

17. M. Good, Vice President, AlliedSignal, Inc., "Environmentally 'Friendly' Manufacturing", Conference Presentation, National Center for Manufacturing Sciences, Washington, D.C. May 1993.

18. M. Feshbach, A. Friendly, *Ecocide in the USSR* , BasicBooks, New York, 1992.

19. B. Commoner, "Pollution Prevention: Putting Comparative Risk Assessment in its Place", Conference Presentation: Resources for the Future: The EPA Risk-Based Paradigm and Its Alternatives, Annapolis, MD, November 1992. Sponsored by the Center for the Biology of Natural Systems.

20. "Life-Cycle Assessment: Inventory Guidelines and Principles" Environmental Protection Agency, Washington D.C. EPA/600/R-92/245 or NTIS PB#93-139681

21. M. Curran, V.Vigon, "Life Cycle Inventory Methodology: a Residential Carpeting Case Study", Conference Presentation: Environment & Waste Management , Arlington Virginia, June 1993. Sponsored by the Association of the Nonwoven Fabrics Industry.