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Life Cycle Analysis: A Step by Step Approach

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What It Is

Because the term “life cycle analysis” is becoming a more frequently used phrase in multiple industries, it is important to understand the process. Life cycle analysis (LCA) is the systematic approach of looking at a product’s complete life cycle, from raw materials to final disposal of the product [1]. It offers a “cradle to grave” look at a product or process, considering environmental aspects and potential impacts [2]. When LCAs were first developed in the 1960s, they were motivated by the economic struggles of the time. Through the 1970s and 80s, this analytical process became less popular due to the lack of standardization. The LCA concept has once again become important to industry and academia [3]. *Life Cycle Assessment: Principles and Practice*, published by the U.S. Environmental Protection Agency (US EPA) in 2006 [3], provides a detailed guideline for a systematic LCA approach. The EPA report, as well as other reports from the *International Journal of Life Cycle Analysis* and reports written by the European Commission regarding life cycle analyses, were used as sources for this description of basic life cycle concepts. Good examples of life cycle assessments can be found in Choi et al. [4] and Lu et al. [5]. In addition, Appendix 4 contains a list of other useful life cycle reports on electronic devices.

How LCA Works

Life cycle analysis examines the environmental impacts of a product by considering the major stages of a product’s life, which are:

- Raw material acquisition, which includes material harvesting and transportation to manufacturing sites;
- Processing, which involves materials processing and transportation to production sites;
- Manufacturing, which includes product manufacture and assembly, packaging, and transportation to final distribution;
- Product life, which includes energy and emissions during normal product life, required maintenance, and product reuse (refurbishing, material reuse); and
- Waste management/end of life, which includes recycling, landfills, liquid waste, gas emissions, etc.

The LCA technique can be narrowed down to four main steps which address one or more of the product’s life stages at a time:

1. The definition and scope is determined along with information needs, data specificity, collection methods and data presentation.
2. The life cycle inventory (LCI) is completed through process diagrams, data collection, and evaluation of the data.
3. The life cycle impact assessment (LCIA) is determined with impact categories and their weights, as well as any subsequent results.
4. The final report should include significant data, data evaluation and interpretation, final conclusions, and recommendations.

Figure 1 shows that the first three steps of a life cycle analysis are related to one another. More importantly, however, data interpretation is an integral part of all three steps and should be done after each of the sub-analyses is completed.

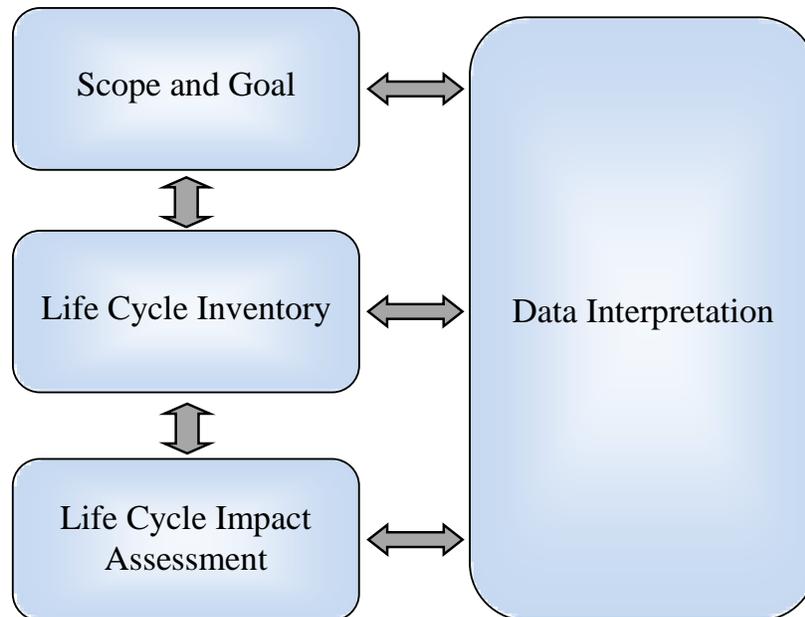


Figure 1: Phases of a Life Cycle Analysis [3]

Why Use LCA?

An effective LCA allows analysts to:

- Calculate a product's environmental impact
- Identify the positive or negative environmental impact of a process or product
- Find opportunities for process and product improvement
- Compare and analyze several processes based on their environmental impacts
- Quantitatively justify a change in a process or product

The LCA method provides researchers or companies with quantitative data for their current products. By looking at a product's life from the raw material extraction to its disposal, the environmental impact of each process and material can be analyzed. The LCA allows analysts to determine and analyze the technological, economical, environmental, and social aspects of a product or process necessary to manage the complete life cycle. With this quantitative data, desired changes can be justified with respect to the cost and environmental impacts of a product or process.

Definitions

- Anomaly assessment: An analysis which examines surprising or unexpected results based on previous results.
- Completeness check: A test that ensures that all relevant information and data which is needed for the interpretation of results is available and complete. The completeness check should follow a checklist of significant areas to be checked.
- Consistency check: An analysis that determines if the assumptions, methods, and data used in the LCA follow the goal, definition, and scope determined at the beginning of the LCA.
- Co-product (or Byproduct): Any stream of product which is neither the primary product of manufacture or waste. It may be resold or remanufactured for another purpose.
- Contribution analysis: An analysis that determines the contribution of the individual life cycle stages in comparison with the total result.
- Data quality indicators: Benchmarks created to test the fulfillment of the data quality requirements. They depend on the type of information obtained and the sources which are evaluated.
- Dominance analysis: An analysis that determines which statistical tools and techniques can identify significant contributions.
- Industrial scrap: Waste that is created during standard production (e.g. trim scraps). It is sometimes reworked into the production system. Industrial scrap is also a co-product.
- Sensitivity analysis: An analysis which observes how sensitive the results are to any changes in assumptions.
- Sensitivity check: A test which evaluates the reliability of the LCA results by determining if the uncertainty in data affects the level of confidence in conclusions.
- Uncertainty analysis: An analysis of the LCIA data variability in order to determine the significance of the impact indicator results.

Data Acquisition

Obtaining necessary data for a life cycle analysis can be a difficult task. Sometimes companies are willing to provide available data in order to assist with a life cycle analysis. However, long-standing confidentiality agreements often present unforeseen difficulties in obtaining necessary and required data. To obtain needed data, several extensive databases and software applications are available and may be used. They include data based on observations, quantitative research, and manufacturer information to calculate national averages. Using a software package can be a convenient way to obtain data for a life cycle analysis, but software packages can also introduce errors into the process. For example, if the LCA observes a national trend, then the available software programs will provide sufficient data. Conversely, if the LCA is specific to a manufacturer or region, then the averaged data used in a software program will most likely not be detailed enough. Because data acquired during this process may include gaps due to lack of information, it is necessary to explain these gaps in the final report.

It is important to not only consider the data source, but also consider its validity. The data used in a LCA should be current. Because many manufacturing processes change frequently, the data must reflect the current process. It may be necessary to complete additional research to fill data gaps. Surveys sometimes provide enough information to fill the current data gaps. Some examples of common data gaps that might be filled by conducting a survey include:

product turnover rates; maintenance frequency and need; changes in manufacturing processes; and using a product for something other than its intended purpose.

Data availability also varies by region, country, and continent. In general, the United States, Canada, Western Europe, and Japan have the most readily available and accurate current statistical information. In regions and countries where data is unavailable, it may be acceptable to draw a comparison in data between similar countries that are not on the same continent. However, it is very important to make the assumptions reasonable. For example, just because there is a lack of data on Chinese manufacturing and a wealth of data from European manufacturing, one cannot conclude that industries in China and Europe are comparable or even similar to each other. Each location has drastically different attitudes toward and laws governing the manufacture and disposal of materials, which makes such a substitution unrealistic.

When comparing two or more sets of data, it is important that the sets are equivalent to one another. If the available data is not equivalent to one another, it cannot be correctly compared and analyzed. When evaluating data equivalency, it is necessary to consider the data source, age, and type. If there is detailed quantitative data for one process or product, but there is minimal data on another process which will be used for comparison, the analyst has to decide whether to omit data from the first data set in order to ensure data quality equivalence for both sets. The analyst can also report all of the data available, but only use equivalent data to make a quantitative comparison.

Table 1 provides examples of possible data inconsistencies when comparing two or more sets of data. The inconsistencies should be noted in the final LCA report. If possible, additional research can be completed in order to decrease the inconsistencies and increase the accuracy of test results and comparisons.

Category	Example of Inconsistencies in Life Cycle Inventories (LCI)
Data Source	A is based on literature; B is based on measurements
Data Accuracy	A uses a detailed process flow to create an LCI; B uses general data with little detail to create LCI
Data Age	A uses manufacturing data over an extensive period of time; B uses a one-year-study
Technological Representation	A uses a scaled laboratory model data; B uses production plant information
Temporal Representation	A uses data of a new technology; B uses a mix of old and new technological data
Geographical Representation	A uses US-regulated technology; B uses EU-regulated technology
System Boundaries, Assumptions, and Models	A uses a model based on a 500-year timeline; B uses a model based on a 100-year timeline

Table 1: Examples of Checklist Categories for Potential Inconsistencies between Alternatives A and B for Life Cycle Inventories (LCI) [3]

Types of data LCIs can include:

- Measurements
- Models
- Samples
- Averaged data
- Site or manufacturer specific data
- Vendor or manufacturer data
- LCA and non-LCA intended data

Data sources for LCIs can include:

- Equipment meter readings
- Operating logs and journals
- Industry and manufacturer reports and databases
- Test results
- Government reports, databases, and documents
- Publically available data and reports
- Published documents (journals, articles, books, references, encyclopedia, patents)
- Related previous tests and LCAs
- Government, process, and equipment specifications and requirements
- Previous experience
- Surveys and audits

Some available databases and software that can be used to obtain national and some regional statistics are listed in Appendices 1 and 2.

Input and Output Considerations

When designing a life cycle analysis, it is important to clearly define the inputs and outputs of a process or product. Inputs include energy and raw materials. Outputs include various types of products and wastes. This section will detail the input and outputs which should be considered when performing a LCA. Input and output data can be found in available databases and software (listed in Appendices 1 and 2).

Figure 2 shows the life cycle stages of a general process. Creating a similar process list/diagram at the beginning of a LCA helps an analyst to identify the major input and output materials.

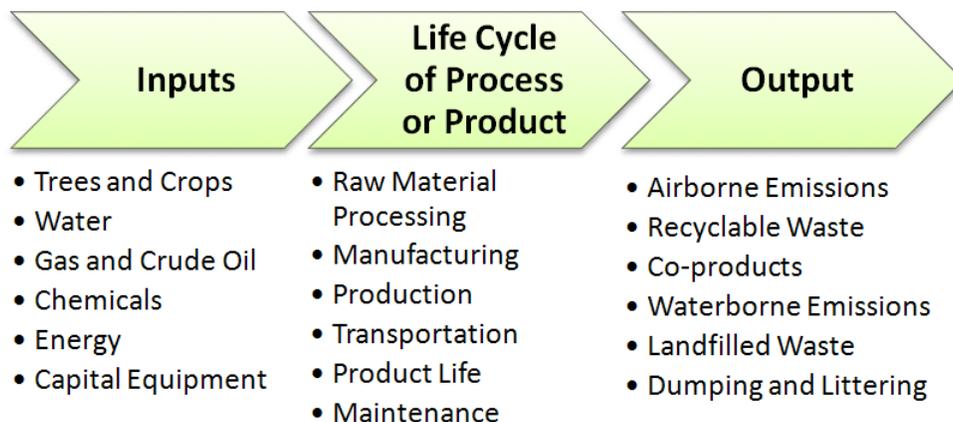


Figure 2: Sample Life Cycle Stages

Some of the following elements to consider regarding input/output are:

- Energy (Input and Output)
 - Process energy: Energy to operate subsystems (pumps, reactors, heat exchangers, blowers, boilers, etc.)
 - Transportation energy: Energy for trucks, trains, boats, etc.
 - Energy of material subsystems: Energy which is inherently in a system.
 - Energy combustion: Energy for combustion during a process or manufacture.
 - Energy pre-combustion: Energy used to deliver a useable fuel for combustion.
 - Energy sources
 - Electricity
 - Complicated to relate electricity use to a specific source of the electricity (coal, nuclear, hydro, etc.)
 - Computer models for electricity may be applicable
 - Coal
 - Nuclear power
 - Usually measured in its fossil fuel equivalency
 - Natural gas
 - Wind
 - Solar
 - Biomass
 - Hydropower
 - Theoretical energy equivalence of 3.61 MJ per kWh with no pre-combustion impacts
 - Associated ecosystem disruption is not considered in the inventory
 - Oil
 - Petroleum
- Water (Input and Output)
 - Only water unavailable for beneficial uses is included in the inventory
 - Beneficial uses include navigation, drinking water, aquatic habitat, etc.
 - Withdrawn, used, treated, and replaced water is not included in the inventory
- Environmental impacts (Output)
 - Atmospheric emissions
 - Reported by unit of weight of input and output
 - Usually only regulated materials required by the government are monitored
 - Common air emissions: particulates, nitrogen oxides, volatile organic compounds, sulfur oxides, carbon monoxide, aldehydes, ammonia, and lead
 - Water vapor and carbon monoxide are generally not included
 - Waterborne waste
 - Reported by unit of weight
 - Includes emissions from fuel combustion and processes
 - Common waterborne wastes includes biological oxygen demand (BOD), chemical oxygen demand (COD), suspended solids, dissolved solids, oil, grease, sulfides, iron, chromium, tin, metal ions, cyanide, fluorides, phenol, phosphates, and ammonia

- Solid waste
 - Includes all solid material disposed within sources of the system
 - Reported by unit of weight
 - Types of solid waste:
 - Industrial: Waste generated during production
 - Process: Waste generated within a process and not recycled
 - Fuel-related: Waste produced from combustion and product production (includes transportation and operating processes)
 - Post-consumer: Product and packaging waste which is discarded purchase
- Hazardous vs. non-hazardous
- Hazard classification of waste depends on governing laws and regulations
- Fugitive/accidental releases
 - May not be recorded, but estimates and discrepancies should be reported
 - Include low-frequency, high magnitude events (major oil spills) and more frequent, lower magnitude events
- Special cases (input or output)
 - Capital equipment
 - Resources and energy required for constructing buildings and process equipment should be included
 - Capital expenditures are complicated making the process specification difficult
 - Personnel issues
 - Waste generated and energy used by employees is not included
 - Consider personnel issues if they correspond with less efficient manufacturing processes
 - Improper waste disposal
 - It is generally assumed that all waste is disposed of properly and lawfully. Illegal dumping, littering, and other waste disposal methods are usually not considered in the LCI as a means of waste disposal
 - If it is clearly known that products are dumped and/or recycled illegally, the associated health and environmental hazards should be included in the final report

Data Quality Indicators

In the life cycle impact assessment (LCIA) of the life cycle assessment (LCA), characterization factors for chemicals and materials are determined in order to calculate the total environmental and health impacts for each material and process used. The impact indicator calculation is

$$Inventory\ Data \times Characterization\ Factor = Impact\ Indicator$$

For example, the Intergovernmental Panel on Climate Change (IPCC) determined that the factor value of chloroform is 9 [3]. Therefore, if a process produces 20 pounds of chloroform, the impact indicator for the chloroform in that process is 180.

Characterization factors should be applied with caution because most are based on European data. In order to apply the factors in the United States, the characterization factors should be based on U.S. data, rather than on available data of another country.

Impact Categories

When performing a LCIA, it is important to consider how the results of the life cycle inventory affect the world around us. Below are several categories along with their associated impacts. In addition, available impact assessment databases are listed in Appendix 3.

- Global impacts
 - Global warming
 - Polar melt, soil moisture loss, longer seasons, forest loss/change, wind and ocean pattern changes
 - Ozone depletion
 - Increased ultraviolet radiation
 - Resource depletion
 - Decreased resources for future generations
- Regional impacts
 - Photochemical smog
 - Smog, decreased visibility, eye irritation, respiratory tract and lung irritation, and vegetation damage
 - Acidification
 - Building corrosion, water body acidification, vegetation and soil effects
- Local impacts
 - Human health
 - Increased morbidity and mortality
 - Terrestrial toxicity
 - Decreased production and biodiversity, decreased wildlife populations
 - Aquatic toxicity
 - Decreased aquatic plant and insect production, decreased biodiversity, decreased fish populations

Completing a Life Cycle Analysis

In order to complete a successful LCA, detailed steps should be followed. The following checklist of information needs is useful when completing a LCA, since it helps an analyst know what type of information to look for and include. The list is not all-inclusive, but it does offer a starting point and is meant to inspire more detailed questions in order to complete a successful and thorough LCA.

Step 1: Create a definition and scope

When developing the scope and definition, consider the following topics:

- Goal of this life cycle analysis
 - Available data and possible data gaps
 - Current legislation
 - Currently available designs of the product/process
 - Environmental impacts of current processes and products
 - Product or process comparison options
- Audience
 - End consumer, stakeholders, policy makers, manufacturers, processors, recyclers, refurbishers

- Production and process information
 - Product usage
 - Product or process materials
 - Identifying the least environmentally damaging product/process
 - Inclusion of all necessary data
 - Possible result impacts (uncertainties, assumptions)
 - Possible process or product changes
- Data accuracy
 - Type of data
 - Specificity and required amount of data
 - System boundaries (regional, national, or global)
 - Availability of current data
 - Need for additional data collection
 - Data discrepancies
 - Data equivalency for comparisons
- Result interpretation and display
 - Data comparison of products and process steps
 - Units for comparison
 - Required data for accurate results
 - Data clarity
 - Amount of data to display
 - Data gaps
- Ground rules
 - Assumptions
 - Quality assurance
 - In line with goal and scope
 - Ground rule implementation during data collection

Figure 3 is an example flow chart which should be completed when beginning a LCI. To improve accuracy of the analysis, the flow chart should be as detailed as possible.

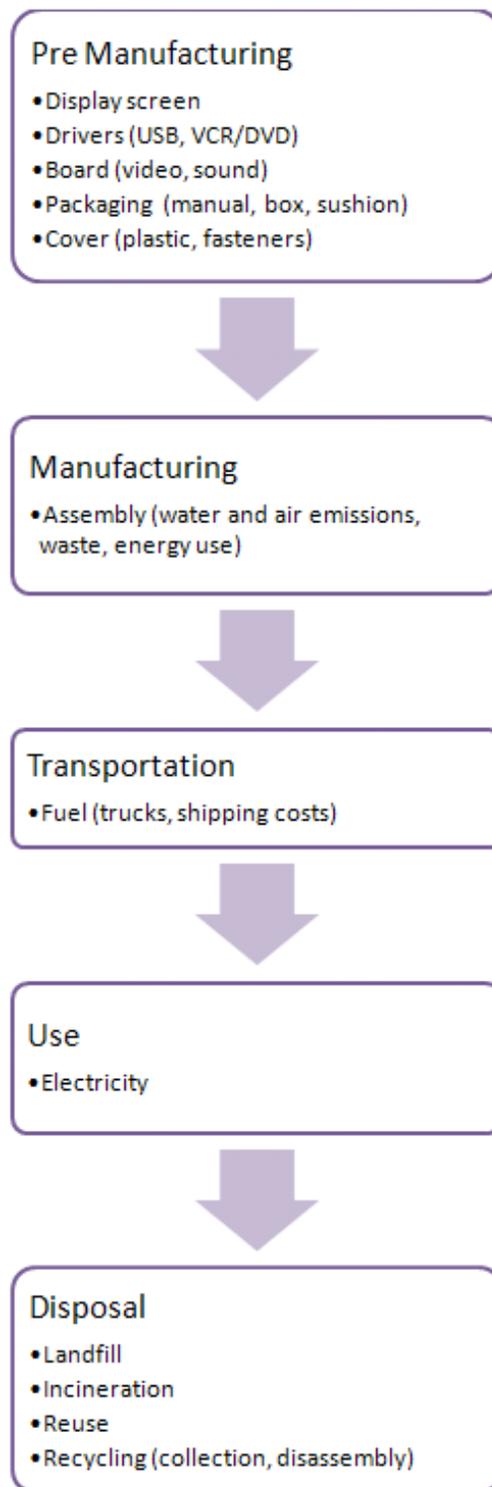


Figure 3: Television Life Cycle Assessment Flow Chart

Step 2: Complete a life cycle inventory (LCI)

LCI is a process which quantifies all inputs and outputs of a process or product. Consider inputs like energy and raw materials. The process outputs include any material emissions to the environment, such as water, air, and solid waste.

An LCI is also a way to develop a comparison of the environmental impacts and potential improvements of the process or product. LCIs can be useful for finding improvement opportunities, supporting design changes, and developing new regulations.

Consider the following when completing a LCI:

- Process flow
 - Energy inputs
 - Raw materials
 - Transportation (mode of transportation, weight, and distance of transport)
 - Production quantity
 - Final product and by-products
 - Industrial scrap
 - Production duration (includes plant shut downs, startup activities, fluctuations in production, etc.)
 - Environmental impacts of product use
 - Final product disposal
 - Environmental impacts of disposal
 - Energy and materials consumed from product use
- Data gathering
 - Data type and quality
 - Data quality indicators (DQIs)
 - Data generation and accuracy
 - Necessary spreadsheets
 - Decision areas
 - Purpose of the inventory
 - System boundaries
 - Geographic scope
 - Types of data used
 - Data collection procedures
 - Data quality measures
 - Computational spreadsheet construction
 - Presentation of results
 - Possible omissions or double-counting
 - Data sensitivity
 - Data collection methods (research, interviews, surveys, available data)
- Data inventory; options are:
 - Providing all data, no matter how minor
 - Excluding data which may be outside of the predetermined scope
 - Excluding data which may be negligible, as determined by the sensitivity analysis
 - Excluding certain types of input, such as capital equipment replacement
- Units of measure and their consistency
- Results
 - Boundaries
 - Environmental impacts
 - Basis of comparison
 - Relative process contributions
 - Result trends
 - Environmental impact recommendations
 - Geographical limitations
 - Environmental and health impacts
 - Clear result summary (table or graph)
 - Information organization (by life cycle stage, media, process, or a combination)

Step 3: Complete the life cycle impact assessment (LCIA)

The LCIA is a way to interpret how the processes and products in the LCA impact human health and the environment. The LCIA addresses concepts like the depletion of resources and possible health effects by analyzing the stressors found within the manufacturing process or product. Therefore, the LCIA considers the LCI data but gives it a more meaningful basis for comparison.

In order to calculate the environmental and health impacts of a product or process, science-based characterization factors are utilized. According to ISO 14042 [3], impact category selection, classification, and characterization are required steps when performing an LCIA. In order to complete a life cycle impact assessment, the following should be taken into account:

- Impact categories
 - Global warming, acidification, terrestrial toxicity (“natural system effects”)
 - Input/output effects on human health, plants, animals, future availability of natural resources
- Result categorization (e.g. Carbon dioxide effects global warming)
 - LCI categorization
 - Conversion factors
 - Impact factors
- Impact comparisons
 - Single life cycle stage or whole life cycle comparison
 - Indicator grouping (By location, industry, process, product, and manufacturer)
 - Baseline comparison
- Important potential impacts
 - Sorting (By severity, characteristics)
 - Weighting (Determination, bias)
- Results
 - Accuracy
 - Conclusions
 - Recommendations
 - Limitations
 - Assumptions
 - Uncertainties

Figure 4 is an example pie chart for a life cycle analysis report, showing one way that data can be displayed in order to indicate which television components have the largest environmental impact.

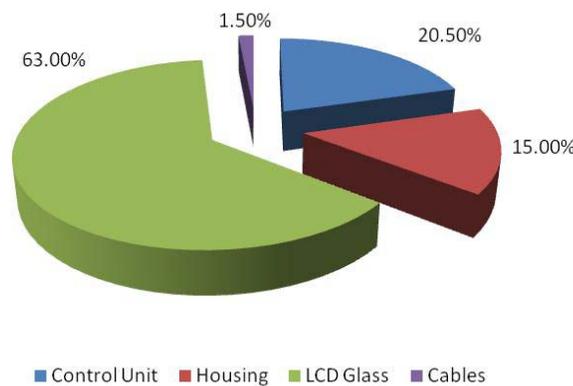


Figure 4: An Example Showing the Environmental Impact of Television Set Components

Step 4: Interpret the results and make recommendations

Life cycle assessments are performed in order to systematically examine a product's life cycle, from raw materials to the final disposal of products [1]. LCAs utilize information from LCI and LCIA to draw conclusions on processes and make appropriate recommendations from their results.

When interpreting LCA results, consider:

- Final results
 - Consistency check
 - Evaluate completeness, sensitivity and consistency of LCIA
 - Contribution or dominance
 - Result expectation
 - Result discrepancies
 - Anomaly check
 - Completeness check
 - Sensitivity check
- Conclusions
 - Most significant issues
 - Comparison data
 - Data differences
 - Environmental and health impacts
 - Impact magnitude
 - Boundary conditions
- Limitations
 - Assumptions and estimates
 - Data bias
 - Result specifications
 - Observations and recommendations
- Recommendations
 - Data availability
 - Product/process change
 - Maintain initial scope and goal
- Report information
 - Administration information
 - Goal and scope
 - Data collection methods and results
 - Results, assumptions, limitations, and conclusions
 - Peer review
 - Reviewer comments and recommendations

Figure 5 shows a sample quantitative comparison of the energy usage of products A and B. This identifies the process with the greatest environmental energy use.

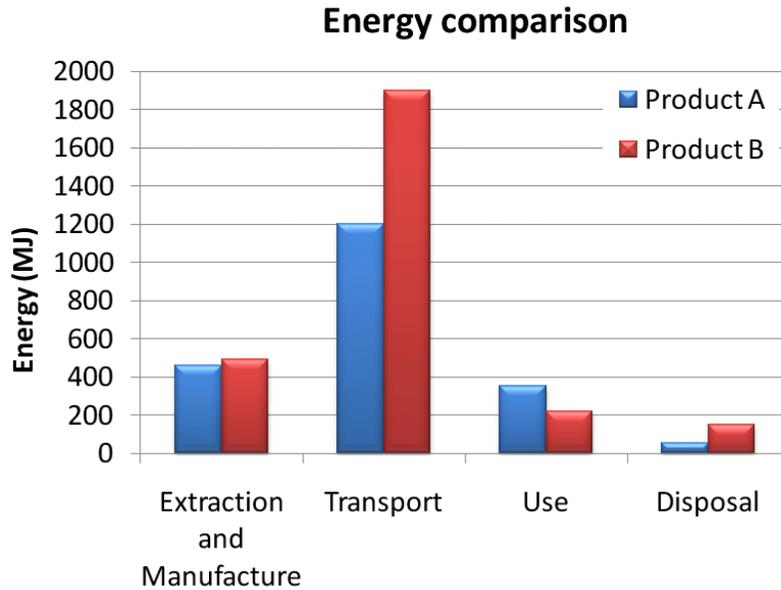


Figure 5: Energy Assessment Example

Conclusion

The four steps that comprise the life cycle assessment (LCA) allow one to examine the full extent of environmental and economic effects assignable to products and processes in order to make more informed decisions. In today's manufacturing world, life cycle assessments are becoming increasingly complicated, due to extensive globalization evidenced worldwide. Despite such difficulties, LCA is an invaluable tool when comparing the environmental impacts of various products and processes. By performing life cycle analyses, manufacturers around the globe are able to quantitatively see the environmental impacts (and associated money flow) of their products or processes. Companies can make necessary corrections to decrease economic costs and, more importantly, decrease the environmental impacts and find better ways to make their products.

References

- [1] Atlantic Consulting and IPU. 1998. *LCA Study of the Product Group Personal Computers in the EU Ecolabel Scheme*. European Commission.
- [2] Feng, C., and X.Q. Ma. 2009. The energy consumption and environmental impacts of a color TV set in China. *Journal of Cleaner Production* 17 (1): 13-25.
- [3] Scientific Applications International Corporation (SAIC). 2006. *Life cycle assessment: principles and practice*. Cincinnati: National Risk Management Research Laboratory, Office of Research and Development, US Environmental Protection Agency. [Availability: <http://www.epa.gov/NRMRL/lcaccess/pdfs/600r06060.pdf>]
- [4] Choi, B.C., H.S. Shin, S.Y. Lee, and T. Hur. 2006. Life cycle assessment of a personal computer and its effective recycling rate. *International Journal of Life Cycle Assessment* 11 (2): 122-8.
- [5] Lu, L.T., I.K. Wernick, T.Y. Hsiao, Y.H. Yu, Y.M. Yang, and H.W. Ma. 2006. Balancing the life cycle impacts of notebook computers: Taiwan's experience. *Resources, Conservation and Recycling* 48 (1): 13-25.

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Appendix 1: List of Several LCA/LCI Databases

Database Name	Sponsoring Organization	Available Data	Data Source	Access	Cost	Website
SP = Software Program; WA = Web Access; P = Purchase required; F = Free; FD = free demo; * = In development or update stages						
Australian Life Cycle Inventory Database Initiative*		Energy, Manufacturing, Plastics, Transport, Agriculture, Building & Construction	Australia	WA*	F*	http://www.auslci.com/
Canadian Raw Materials Database	University of Waterloo	Glass, Plastics, Steel, Wood	Canada	WA	F	http://crmd.uwaterloo.ca/
Center for Design	Royal Melbourne Institute of Technology	Raw materials and transportation	Australia	WA	F	http://simapro.rmit.edu.au/LCA/datadownloads.html
CLM-IA	Universiteit Leiden, Institute of Environmental Sciences	Data from Eco-Indicator 99, EPS, and others	Europe	WA	F	http://cml.leiden.edu/software/data-cmlia.html#features
CPM LCA Database	Industrial Environmental Informatics Chalmers	Transports, aggregated processes	Sweden; E.U.	WA	F	http://www.cpm.chalmers.se/CPMDatabase/Start.asp
CPM LCI Data Store	Industrial Environmental Informatics Chalmers	LCA data for various process, divided by country and region	Global	WA	P	http://databases.imi.chalmers.se/imiportal/
E3IOT	Universiteit Leiden, Institute of Environmental Sciences	High resolution, environmentally extended input/output table for Europe	Europe	WA	P	http://cml.leiden.edu/software/data-e3iot.html
Ecoinvent	Swiss Center for Life Cycle Inventories	Building products, chemicals, wood, metals, paper, detergents, waste treatment transportation; production, use and disposal of electric and electronic equipment; new CHP system, renewable materials, petrochemical solvents, metal processing	Global	WA	F/P	http://www.ecoinvent.org/database/
EIME Database	Bureau Veritas Codde	Data for raw materials, energy, and other processes	Global	SP	P	http://www.codde.fr/page.php?rubrique=20&ssRubrique=24
ESU LCI Database	ESU-Services	Energy (country specific), Food production, Household appliances	Global	SP	P	http://www.esu-services.ch/cms/index.php?id=104
European Reference Life Cycle Database	European Commission-Joint Research Center	End-of-life treatment, Energy carriers and technologies, Materials Production, Systems, Transport Services	Global, E.U.	WA	F	http://lca.jrc.ec.europa.eu/lcainfohub/datasetCategories.vm?topCategory=Transport+services
						http://lca.jrc.ec.europa.eu/lcainfohub/databaseList.vm

Appendix 1 (continued)

Database Name	Sponsoring Organization	Available Data	Data Source	Access	Cost	Website
SP = Software Program; WA = Web Access; P = Purchase required; F = Free; FD = free demo; * = In development or update stages						
International Reference Life Cycle Data System Data Network*	European Commission	Data sets can be submitted by for legitimate and verified industry, national projects, consultants, researchers, and others	Global	WA*	F/P*	http://lct.jrc.ec.europa.eu/eplca/deliverables/the-international-reference-life-cycle-data-system-ilcd-data-network
IVAM LCA Database	IVAM	1350 Processes for more than 350 materials	Global	SP	P	http://www.ivam.uva.nl/index.php?id=164&L=1
KNCPC LCI Database*	Korea Institute of Industrial Technology, Korea National Production Center	Energy, Chemicals, Metal, Paper, Electronic/Electric, Construction, Production Process, Delivery, Disposal, Utility	Korea			http://www.kncpc.re.kr/eng/topics/Lci.asp
NEEDS Life Cycle inventory Database	New Energy Externalities Development for Sustainability (NEEDS)	Research-provided energy data	E.U.	WA	F	http://www.isistest.com/needswebdb/search.php

Appendix 2: List of Several LCA/LCI Software Programs

Software Name	Production Company	Available Data	Data Source	Access	Cost	Website
SP = Software Program; WA = Web Access; P = Purchase required; F = Free; FD = free demo; * = In development or update stages						
Boustead Model	Boustead Consulting Lrd.	Processes, air and water emissions, solid wastes, and raw materials	Global	SP	P/FD	http://www.boustead-consulting.co.uk/products.htm
Chain Management by Life Cycle Assessment (CMLCA)	University of Leiden (Universiteit Leiden), Department of Industrial Ecology	No process or impact assessment data		WA/SP	P/FD	http://www.cmlca.eu/
Data for Environmental Analysis and Management (DEAM)	Ecobilan	Chemical and detailed material data	Europe, Global?	WA	F	https://www.ecobilan.com/uk_deam01_02.php
Earthster*	Sylvatica	Non-proprietary industry data	Global	WA	F	http://www.earthster.org/
EcoSpold*	Swiss Center for Life Cycle Inventories	Process, elementary flows, products and wastes, locations	Global	WA/SP	F/FD	http://www.ecoinvent.org/database/ecospold-data-format/ecospold-v2/
EIO-LCA Method	Carnegie Mellon	Database formed of publically available data	Global	WA	F	http://www.eiolca.net/index.html
GaBi Software	PE International	Lean and professional databases with ability to add extension databases	Global	SP	P/FD	http://www.gabi-software.com/gabi/gabi-4/
GLOBOX	Universiteit Leiden, Institute of Environmental Sciences	Eco-invent data	Global	WA	F	http://cml.leiden.edu/software/software-globox.html
Inventory of Greenhouse Gases Emissions (INES)	Ecobilan	Industry and research data	Global	WA	F/P	https://www.ecobilan.com/uk_ines.php
JEMAI-LCA Pro	Japan Environmental Management Association for Industry(JEMAI)	Inventory database, impact assessment, weighting	Japan, Global	SP	P	http://www.jemai.or.jp/CACHE/lca_details_lcaobj198.cfm

Appendix 2 (continued)

Software Name	Production Company	Available Data	Data Source	Access	Cost	Website
SP = Software Program; WA = Web Access; P = Purchase required; F = Free; FD = free demo; * = In development or update stages						
LCA@CPM	Industrial Environmental Informatics Chalmers	Inventory database, impact assessment	Global	WA	F	http://databases.imi.chalmers.se/imiportal/
Life Cycle Index Module (PIX); LCAPIX	KM Limited	Allows for addition of general databases	Varies	SP	P	http://www.kmlmtd.com/pas/index.html
Open LCA*	GreenDelta TC GmbH	Ecoinvent database	Global	SP	F	http://www.openlca.org/Idea-need.34.0.html
SimaPro	PRé: Product Ecology Consultants	Access to 13 databases	Global	SP	P	http://www.pre.nl/simapro/
Spider	Industrial Environmental Informatics Chalmers	Data from other completed LCAs; data sharing software	Global	SP	F	http://databases.imi.chalmers.se/imiportal/
TCAce	Sylvatica	Case studies, sensitivity/uncertainty risk, economic evaluation; industry data	Global	SP	P	http://www.earthshift.com/tcace.htm
Tool of Environmental Analysis and Management (TEAM)	Ecobilan	Ecobilan data and your own data	Varies	SP	P/FD	https://www.ecobilan.com/uk_team.php
Umberto	ifu Hamburg	Companies, consulting, academia	Global	SP	P	http://www.umberto.de/en/product/index.htm
Waste-Integrated Systems for Assessment of Recovery and Disposal(WISARD)	Ecobilan	Ecobilan data and your own data	Varies	SP	P/FD	https://www.ecobilan.com/uk_wisard.php

Appendix 3: List of Several Impact Assessment Databases

Name of Design/Database Project	Available Data	Data Source	Access	Cost	Website
SP = Software Program; WA = Web Access; P = Purchase required; F = Free; FD = free demo; * = In development or update stages					
Eco-Indicator/1999	Eco-indicator 99	Europe	WA	F	http://workshop.imi.chalmers.se/Workshop/static/static/map/index_ia_start.asp
EDIP default	EDIP 1997	Europe	WA	F	http://workshop.imi.chalmers.se/Workshop/static/static/map/index_ia_start.asp
EPS default	EPS/2000	Sweden, Europe	WA	F	http://workshop.imi.chalmers.se/Workshop/static/static/map/index_ia_start.asp
LCA-E (ECOI/EPD)	Eco-Indicator/1999, EDIP/1997, EPS/2000	Europe, Global	WA	F	http://workshop.imi.chalmers.se/Workshop/static/static/map/index_ia_start.asp
Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI)	US EPA Risk Assessment Guidance for Superfund and US EPA's Exposure Factors Handbook	US	WA/SP	F	http://www.epa.gov/ORD/NRMRL/std/sab/traci/index.html
New Energy Externalities Development for Sustainability (NEEDS) Life Cycle inventory Database	Research-provided energy data for the E.U.	E.U.	WA	F	http://www.isistest.com/needswebdb/search.php
CPM LCA Database	EPS/2000	Sweden, Global	WA	F	http://www.cpm.chalmers.se/CPMDatabase/IAM/index.asp?IAM=EPS+default&IAMVer=2000

Appendix 4: Further Reading

Ahluwalia, P.K., and A.K. Nema. 2007. A life cycle based multi-objective optimization model for the management of computer waste. *Resources, Conservation and Recycling*, 51 (4): 792-826.

Blazek, M., J. Carlson, and M. DeBartolo. 1998. Life cycle management of personal computers in a service company. In *Proceedings of the 1998 IEEE International Symposium on Electronics and the Environment*, 275-279. Oak Brook, IL.

Brinkley, A., J.R. Kirby, I.I. Wadehra, P.G. Watson, C. Chaffee, C.N. Cheung, S.P. Rhodes, and M. Wolf. 1994. Ecoprofile studies of fabrication methods for IBM computers: sheet metal computer cover. In *Proceedings of the 1994 IEEE International Symposium on Electronics and the Environment*, 299-306. San Francisco, CA.

Dawson, R.B., and S.D. Landry. 2003. Brominated flame retardants: Issues surrounding their use in electrical and electronic equipment. In *Proceedings of the 2003 IEEE International Symposium on Electronics and the Environment*, 1-6. Boston, MA.

Deubzer, O., H. Hamano, T. Suga, and H. Griese. 2001. Lead-free soldering - Toxicity, energy, and resource consumption. In *Proceedings of the 2001 IEEE International Symposium on Electronics and the Environment*, 290-295. Denver, CO.

Duan, H., M. Eugster, R. Hirschler, M. Streicher-Porte, and J. Li. 2009. Life cycle assessment study of a Chinese desktop personal computer. *Science of the Total Environment*, 407 (5): 1755-1764.

Dunnett, M., E. Grenchus, R. Keene, L. Yehle, M. Jacques, M. Karlsson, J.R. Kirby, and D. Pitts. 1999. Evaluation of IBM end of life products: Measuring DFE effectiveness. In *Proceedings of the 1999 IEEE International Symposium on Electronics and the Environment*, 98-103. Danvers, MA.

Hannemann, C.R., V.P. Carey, A.J. Shah, and C. Patel. 2008. Lifetime exergy consumption of an enterprise server. In *Proceedings of the 2008 IEEE International Symposium on Electronics and the Environment*, 1-5. San Francisco, CA.

Hatori, M. 2004. Peak-shift method for notebook computers: A power management approach for load leveling. In *Proceedings of the 2004 IEEE International Symposium on Electronics and the Environment*, 117-121. Phoenix, AR.

Hickey, S., and C. Fitzpatrick. 2008. Using feedback to enhance use phase efficiency of personal computers. In *Proceedings of the 2008 IEEE International Symposium on Electronics and the Environment*, 1-6. Phoenix, AR.

Horikoshi, Y., I. Watanabe, K. Kimura, T. Hashitani, and K. Nishii. 2003. Life cycle assessment for recycled magnesium alloy and polymer resin housings for notebook computers. In *Proceedings of the 2003 International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, 269-270. Tokyo, Japan.

Appendix 4: Further Reading (continued)

- Kahhat, R., and E. Williams. 2009. Product or Waste? Importation and End-of-Life Processing of Computers in Peru. *Environmental Science & Technology*, 43 (15): 6010-6016.
- Khanna, V., B.R. Bakshi, and L.J. Lee. 2007. Life cycle energy analysis and environmental life cycle assessment of carbon nanofibers production. In *Proceedings of the 2007 IEEE International Symposium on Electronics and the Environment*, 128-133. Orlando, FL.
- Kim, S., T. Hwang, and M. Overcash. 2001. Life cycle assessment study of color computer monitor. *The International Journal of Life Cycle Assessment*, 6(1): 35-43.
- Kimura, K., Y. Horikoshi, T. Hashitani, and K. Nihsii. 2005. The Development of Bio-based Polymers for Notebook PC. In *Proceedings of the 2005 International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, 114-115. Tokyo, Japan.
- Landry, S.D., and R.B. Dawson. 2002. Life-cycle environmental impact of flame retarded electrical and electronic equipment. In *Proceedings of the 2002 IEEE International Symposium on Electronics and the Environment*, 163-168. San Francisco, CA.
- Masanet, E., and A. Horvath. 2006. Enterprise strategies for reducing the life-cycle energy use and greenhouse gas emissions of personal computers. In *Proceedings of the 2006 IEEE International Symposium on Electronics and the Environment*, 21-26. San Francisco, CA.
- Mohite, S., and H. Zhang. 2005. Disassembly analysis, material composition analysis and environmental impact analysis for computer drives. In *Proceedings of the 2005 IEEE International Symposium on Electronics and the Environment*, 215-220. New Orleans, LA.
- Murphy, C.F., and G.E. Pitts. 2001. Survey of alternatives to tin-lead solder and brominated flame retardants. In *Proceedings of the 2001 IEEE International Symposium on Electronics and the Environment*, 309-315. Denver, CO.
- Murphy, C.F., J.-. Laurent, and D.T. Allen. 2003. Life cycle inventory development for wafer fabrication in semiconductor manufacturing. In *Proceedings of the 2003 IEEE International Symposium on Electronics and the Environment*, 276-281. Boston, MA.
- Plepys, A. 2004 . The environmental impacts of electronics. Going beyond the walls of semiconductor fabs. In *Proceedings of the 2004 IEEE International Symposium on Electronics and the Environment*, 159-163. Phoenix, AR.
- Schut, J.H. 2007. Recycling E-plastics new material stream brings its own set of problems. *Plastics Technology*, 53 (8): 48-53.
- Sharpe, M. 2005. Climbing the e-waste mountain. *Journal of Environmental Monitoring*, 7 (10): 933-936.

Appendix 4: Further Reading (continued)

Socolof, M.L., J.R. Geibig, and M.B. Swanson. 2003. Cradle to gate toxic impacts of solders: A comparison of impact assessment methods. In *Proceedings of the 2003 IEEE International Symposium on Electronics and the Environment*, 66-71. Boston, MA.

Socolof, M.L., J.G. Overly, L.E. Kincaid, R. Dhingra, D. Singh, and K.M. Hart. 1999. Life-cycle environmental impacts of CRT and LCD desktop monitors. In *Proceedings of the 1999 IEEE International Symposium on Electronics and the Environment*, 232-237. Danvers, MA.

Somani, A., P. Gschwend, S.J. White, D. Boning, and R. Reif. 2006. Environmental impact evaluation methodology for emerging silicon-based technologies. In *Proceedings of the 2006 IEEE International Symposium on Electronics and the Environment*, 258-263. San Francisco, CA.

Taiariol, F., P. Fea, C. Papuzza, R. Casalino, E. Galbiati, and S. Zappa. 2001. Life cycle assessment of an integrated circuit product. In *Proceedings of the 2001 IEEE International Symposium on Electronics and the Environment*, 128-133. Denver, CO.

Tekawa, M., S. Miyamoto, and A. Inaba. 1997. Life cycle assessment; an approach to environmentally friendly PCs. In *Proceedings of the 1997 IEEE International Symposium on Electronics and the Environment*, 125-130. San Francisco, CA.

Williams, E.D. 2004. Revisiting energy used to manufacture a desktop computer: Hybrid analysis combining process and economic input-output methods. In *Proceedings of the 2004 IEEE International Symposium on Electronics and the Environment*, 80-85. Phoenix, AR.

Williams, E., and T. Hatanaka. 2005. Residential computer usage patterns in Japan and associated life cycle energy use. In *Proceedings of the 2005 IEEE International Symposium on Electronics and the Environment*, 177-182. New Orleans, LA.

Yan, Y., and E. Williams. 2008. Forecasting sales and generation of obsolete computers in the U.S. In *Proceedings of the 2008 IEEE International Symposium on Electronics and the Environment*, 1-6. San Francisco, CA.

Yang, X., P. Moore, and S.K. Chong. 2009. Intelligent products: From lifecycle data acquisition to enabling product-related services. *Computers in Industry*, 60(3): 184-194.

Yoshida, A., T. Tasaki, and A. Terazono. 2009. Material flow analysis of used personal computers in Japan. *Waste Management*, 29(5): 1602-1614.

Zhang, H., and S.Y. Yu. 1997. Environmentally conscious evaluation/design support tool for personal computers. In *Proceedings of the 1997 IEEE International Symposium on Electronics and the Environment*, 131-136. San Francisco, CA.