Life Cycle Assessment Support for California EPA's Green Chemistry Initiative

Project: Green Chemistry Initiative Life Cycle Thinking (Award 08-T3620)

Report Prepared in April 2011

Developed by:

Arpad Horvath, Ph.D. †
Professor

Mikhail Chester, Ph.D. †
Post-doctoral Scholar

† University of California, Berkeley
Department of Civil and Environmental Engineering

Contract Manager:

Bob Boughton
California Environmental Protection Agency
Department of Toxic Substances Control
Office of Pollution Prevention and Green Technology

Green Chemistry Initiative image source: California Department of Toxic Substances Control.

Table of Contents

1 Background 3
2 Review of Regulations and Other Documents 3
3 Tools for Life Cycle Assessment 4
3.1 Background on General Tools 4
3.2 Background on Transportation Tools 4
3.3 Background on Buildings Tools 5
3.4 Background on End-of-Life Tools 5
3.5 Background on Impact Assessment Tools 5
3.6 Background on Water Tools 5
3.7 Tools Matrix 6
3.8 Tools by Life Cycle Assessment Stages 11
4 Existing Guidelines Review 14
4.1 Existing Guidelines Summary 14
4.2 Incorporating Existing Guidelines for General Life Cycle Assessment 16
4.3 Incorporating Existing Guidelines for Life Cycle Impact Assessment 17
5 Case Studies 18
5.1 Case Study for System Boundary Selection 18
5.2 Case Study for Functional Unit Selection 21
5.3 Case Study for Life Cycle Inventorying 23
5.4 Case Study for Life Cycle Impact Assessment 25
5.5 Case Study for Data Quality, Uncertainty, and Sensitivity Assessment 27
6 Recommendations for Future Work 29

1 Background

The California Department of Toxic Substance Control (DTSC) established the Green Chemistry Initiative in 2007 to provide a framework for understanding and reducing the impacts of products containing toxic chemicals in the state. California's Assembly Bill 1879 gives the DTSC authority to regulate chemicals of concern in consumer products. However, changing product design or switching out problem chemicals may have environmental and human health implications. Alternative assessments should employ a life-cycle perspective when evaluating products, processes, and decisions that influence the use of chemicals in products to avoid regretful substitutions or unintended consequences.

Life cycle assessment (LCA) is the preeminent framework for understanding the cradle-to-cradle environmental impacts of products, processes, services, policies, and decisions. The LCA framework provides a structure for capturing ancillary (indirect) and supply chain effects in addition to the direct effects of immediate interest. LCAs of many different systems have shown that it is often the case that the bulk of impacts occur in ancillary and supply chain processes.

To provide a consistent LCA lens in drafting of regulations and support for green chemistry practitioners, Professor Arpad Horvath and Dr. Mikhail Chester (University of California, Berkeley, further referred to as UC Berkeley) assisted DTSC in the review of draft regulations and preparation of supporting information. This included development of a tools matrix, preparation of a literature summary of existing guidelines, and preparation of relevant case studies. The focus of the supporting information items is to provide documentation and support to green chemistry LCA practitioners. This report consolidates project deliverables into a document for DTSC to provide guidance to LCA practitioners.

2 Review of Regulations and Other Documents

As DTSC developed regulations, review was provided for intermediary drafts. DTSC released a regulation draft outline (April 15, 2010) and draft regulations (June 23, 2010), as intermediate working documents for the proposed regulations (September 2010). UC Berkeley reviewed the April 15 and June 23, 2010 documents to aid DTSC in appropriate LCA scoping for potential future practitioners. Feedback was given on drafts of these documents. The commenting was focused on clarifying language and identifying for DTSC any potential uncertainties that may lead to questions by readers and LCA practitioners. UC Berkeley also participated in public workshops held on October 21, 2009 and July 7-8, 2010.

3 Tools for Life Cycle Assessment

LCA tools take many different forms and are developed for specific or general purposes for any life cycle stage. While some tools are explicitly marketed for LCAs, others are not but can be used for similar ends. For the purposes of green chemistry alternatives assessment, several LCA relevant tools exist for use in analysis of direct, indirect, and supply chain impacts relevant to the production or use of a chemical of interest and its interdependent processes. The tools identified will give LCA practitioners a data and analysis starting point towards comprehensive evaluation of system-wide impacts.

3.1 Background on General Tools

Several datasets and tools exist to provide general LCA of systems. These tools either provide data on specific life cycle processes or allow the practitioner to build a process-flow diagram for systems of interest. The NREL U.S. Life-cycle Inventory is a public repository of results from studies commissioned and performed by government agencies and contractors. The dataset is still under development and is limited in scope but yield useful information about specific processes. The Economic Input-Output Life-cycle Assessment (EIO-LCA) tool evaluates the supply chain effects of economic activity in sectors from cradle-to gate. Users can enter a dollar value worth of economic purchases for a particular sector (e.g., steel production) and EIO-LCA will estimate the supply chain energy and emissions associated with that production. Due to its nature of linking transactions between sectors of the economy, EIO-LCA offers one of the best options for understanding how activity in one process will result in supply chain ripple effects elsewhere. The preeminent tools for constructing custom-made life cycle processes within systems are Gabi and SimaPro. These tools have traditionally been developed with European datasets but have more recently expanded to other geographic regions. Gabi and SimaPro (both requiring purchase) allow the user to construct life cycle assessments by building the processes and related interconnectedness of indirect processes. They offer the potential to evaluate specific conditions and scenarios that most other tools do not. Users can specify end-of-life processes in both tools ultimately producing cradle-to-grave assessments and can evaluate a broad spectrum of human health and environmental impacts.

3.2 Background on Transportation Tools

Transportation LCA tools typically focus on fuel production effects but may also capture vehicle operation and manufacturing. The E3 Database, GHGenius, and GREET tools all focus on energy and emissions intensity of fuel feedstock processing. The tools typically are joined with vehicle operation (fuel combustion, evaporative losses, tire wear, and brake ware) factors as well. For the tools mentioned, E3 Database focuses on Europe, GHGenius on Canada, and GREET on the U.S.. GREET stands as one of the most comprehensive transportation life cycle tools evaluating fuel production and vehicle operation as well as vehicle manufacturing (in their version 2 series). Currently, GREET 1.8c evaluates fuel production and vehicle operation for U.S. conditions and CA GREET 1.8b has been developed to load the model with California-specific conditions. As a stand-alone tool, GREET 2.7 evaluates the manufacturing of conventional, hybrid, and fuel cell light-duty vehicle manufacturing. While GREET has been purposed as a fuel production analysis tool, it offers a rich repository of process data that can be useful to LCA practitioners. Easily extractable from the GREET model are data points on many different physical process that appear in non-fuel production systems. All of the tools mentioned consider well-to-wheels as their primary scope.

3.3 Background on Buildings Tools

BEES and Athena are the preeminent LCA tools for evaluating buildings through impact assessment. BEES is a publicly available tool developed by the U.S. National Institute of Standards and Technology while the Athena Institute has developed free and fee-based versions of their tool. Both tools include some assessment of materials, transportation, construction activities, building operation, maintenance, demolition, and disposal. Both tools capture material and energy requirements as well as emissions. The BEES tool also includes first and operating cost assessments. The environmental indicators are carried through to impact assessment.

3.4 Background on End-of-Life Tools

The end-of-life life cycle-related tools primarily evaluate waste management processes. While general recycling and remanufacturing information exists from Gabi and SimaPro, the end-of-life tools presented focus explicitly on the transport and management of waste. Depending on the tool, this can include recycling, landfilling, combustion, and composting. Within landfilling, the management of landfill methane gas is critical to the environmental balance of the system. Several of the tools consider the possibilities of no recovery of this gas, capture and flaring, and capture and energy production. These end-of-life tools offer the possibility to evaluate waste processing as a potential balance-changing life cycle process. Furthermore, the EPA's WaRM tool provides an energy and greenhouse gas assessment of waste avoidance. There are many end-of-life tools offering a wide set of potentials for analysis of this component,.

3.5 Background on Impact Assessment Tools

Impact assessment metrics are broad and the tools that address this life cycle stage encompass a wide-array of purposes. Here, the identification of impact-assessment tools focuses on those that evaluate beyond global warming potential. After constructing a process flow in Gabi and SimaPro, these tools will analyze the direct and indirect effects of the system creating a LCI and then linking it to human health and environmental damage categories. Developed by the U.S. EPA, TRACI is a tool for evaluating impacts given an inventory of stressors and particular geography of the US. APEEP computes county-level human health and environmental damage costs from the release of particular emissions. In evaluating life cycle effects of buildings, BEES and Athena compute impact assessment metrics. The waste LCA tools ORWARE, WISARD, WRATE, EASEWASTE perform impact assessment. The challenge of constructing an impact assessment from a LCI lies in the ability to combine data and multiple tool scopes. While one tool may provide a means for estimating a LCI of a particular process of interest, another dataset or tool may be needed to execute the impact assessment. This combination should be considered by the practitioner when identifying the scope of the assessment and the need to accurately quantify impacts for a process in a particular region.

3.6 Background on Water Tools

Water-specific LCA tools were not found but several initiatives are underway that may be valuable to practitioners. General LCA tools like Gabi and SimaPro include incomplete water inventories. These tools are currently at the forefront for providing water data for processes and allowing the practitioner to build a customized LCA system for chemical production and use. Additionally, there are a few qualitative water tools that may help practitioners think about high-impact processes for facilities or corporate operations. The WBCSD Global Water Tool and the GEMI Water Sustainability Planner may be valuable to practitioners in scoping the system boundary for the water assessment. According to the publisher, the Water Footprint Assessment Manual details the Water

Footprint Network's standards for assessing processes, products, consumers, geographic areas, countries, catchments and river basins, municipalities, and businesses.

3.7 Tools Matrix

Table 1 shows identified tools which may be of use to LCA practitioners as described above. For each tool, a link to its URL (), assessment stage, focus, cost (free or access fee), applicable life cycle phases, processes, indicators, geography, and timeframe are shown and described below. The LCA *stage* identifies if the tool is useful in evaluating inventorying, impact assessment, or costing. The *focus* identifies the tool's intended system of analysis (e.g., transportation, buildings, end-of-life, etc.). The *phases* and *processes* categories present the direct, indirect, and supply chain processes that are included in the tool's scope. The *Indicators* column shows the energy inputs, emission outputs, costs, and impacts evaluated by the tool. Finally, *geography* and *timeframe* identify the geographic and temporal scope of the tool. For general LCA practitioners, a list of tools is available from the European Commission's Joint Research Centre . The focus of the matrix below is consumer product development and relevant chemical production or use so a narrower scope of tools is presented. Practitioners may wish to browse the ECJRC's list for additional LCA resources.

Table 1 – Tools Matrix

Name	LCA Stage	LCA Focus	Free/ Fee	Life Cycle Phases	Processes	Indicators Evaluated	Geography	Relevant Analysis Time Period
EIO-LCA	LCI	General Cradle-to-gate	Free	Material production through use including supply chains.	Material production through use including supply chains.	Inputs: Energy. Outputs: economic value, GHGs, CAP, Hazardous Waste, and Toxic Releases.	Databases for the US, Canada, Germany, Spain, and China.	For the US, 1992 and 1997 are free while 2002 can be accessed for a fee.
NREL U.S. Life-cycle Inventory	LCI	General	Free	Various. Repository of government life cycle reports of various processes.	178 processes.	Various.	US	Most recent data set is 2008.
TRACI	LCIA	Emissions impacts	Free	Life cycle Impact Assessment.		Ozone depletion, smog formation, GWP, AcP, EuP, human health cancer, human health noncancer, human health criteria pollutants, eco-toxicity, fossil fuel depletion, land use, water use.	US	
BEES	LCI, LCIA, LCCA	Buildings Cradle through use	Free	Materials-based LCA for buildings.	Material production through end-of-life	Inputs: Energy and water. Outputs: Many other emissions to air, water, and land	US	
Gabi	LCI, LCIA	General Cradle-to-grave	Fee	Ability to build LCA and include any phase. Professional dataset includes 1,000 processes.	Ability to build LCA and include any process	Energy, many other emissions	Several databases which include Europe, US, and Japan	Most recent Gabi update (v4.4) is 2010.
SimaPro	LCI, LCIA	General Cradle-to-grave	Fee	Ability to build LCA and include any phase. Ecoinvent dataset includes 4,000 processes.	Ability to build LCA and include any process	Energy, many other emissions	Several databases which include Europe, US, and Japan	Most recent Ecoinvent Update (v2.2) is 2010.
CCaLC	Carbon Inventorying, LCIA, LCCA	General Cradle-to-grave and Supply Chain	Free and Fee Tools	Raw material acquisition, processing, transportation, storage, use, and waste management.	Material production through end-of-life.	Free version captures GHG emissions. Fee version does impact assessment.	UK	

Athena	LCI, LCIA	Buildings Cradle-to-grave	Free and Fee Tools	Material production, construction, transportation activities, maintenance and replacement, demolition for buildings.	Material production through end-of-life (excluding use phase)	Free version captures GHG emissions. Fee version does impact assessment including energy, air emissions, water emissions, land emissions, and resource use.	US and Canada	
APEEP	LCIA, LCCA	Emissions impacts	Free	Evaluate PM, VOC, NO_X, NH_3, and SO_2 emissions externalities at county resolution.	Morbidity, mortality, and environmental cost assessment.	Costs.	US	
E3 Database	LCI, LCIA, LCCA	Transportation Well-to-wheel	Fee	Fuel Production. Vehicle Operation.	Transportation fuels. Vehicle Operation.	Energy, GHG, NO_X, SO_2, CO, NMVOC, Dust/PM, Costs.	Europe	
GREET 1.8c	LCI	Transportation Well-to-wheel	Free	Fuel Production. Vehicle Operation Vehicle. Manufacturing.	Transportation fuels (Including petroleum-based, biofuels, hydrogen, and electricity). Light duty auto and truck vehicle operation and manufacturing.	Energy, GHG, VOC, CO, NO_X, PM, SOX.	US	1990 to 2020
CA GREET 1.8b	LCI	Transportation Well-to-wheel	Free	Fuel Production. Vehicle Operation. Vehicle Manufacturing.	Transportation Fuels (Including petroleum-based, biofuels, hydrogen, and electricity). Light duty auto and truck vehicle operation and manufacturing.	Energy, GHG, VOC, CO, NO_X, PM, SOX.	California	1990 to 2020

GHGenius 3.15	LCI, LCCA	Transportation Well-to-wheel	Free	Fuel Production. Vehicle Operation. Vehicle Manufacturing.	Transportation fuels (including petroleum-based, biofuels, hydrogen, and electricity). Light and heavy duty vehicle operation and manufacturing.	Energy, GHG, CO, NO_X, NMOC, SO_2, PM.	Canada, US, Mexico, India	
IWM	LCI	End-of-life	Free	Waste collection, material recovery facility, composting, anaerobic digestion, energy recovery, landfilling, reprocessing, and gas recovery.	Waste collection and processing.	Energy, GHG emissions, NO_X, SOX, HCl, PM, VOCs, Pb, Hg, Cd, Dioxins, BOD.	Canada	
ORWARE	LCI, LCIA, LCCA	End-of-life	Free	Waste transport, incineration, sewage plant, anaerobic digestion, composting, and landfilling.	Waste collection and processing.	Energy, materials, heavy metals, NOX, SO2, HCl, PCB, dioxins, PAH, AOX, CH4, CO, CHX, CO2, BOD, COD, NH3/NH4, P, NO2-/NO3-	Sweden	Released in 2002
IWM-2 ISBN 978-0-632-05889-1	LCI	End-of-life	Free	Waste collection, MRF and RDF sorting, biological treatments, thermal treatments, landfilling, and recycling.	Waste collection and processing.	Inputs: Waste and energy. Outputs: recovered materials, compost, air emissions, water emissions, and residual solid waste.	Various countries.	
WASTED	LCI	End-of-life	Free	Waste collection, material recovery and recycling, composting, landfilling, and incineration and gasification.	Waste collection and processing.	Inputs: Waste and Energy. Outputs: air and water emissions.	Default factors from various countries (including the US and Denmark). Ability to customize defaults.	Released in 2006

EASEWASTE	LCI, LCIA	End-of-life	Free	Waste generation, collection, treatment, disposal, and transport.	Waste collection and processing.	Resource, energy, and land inputs. GHG, AcP, nutrient enrichment, O_3 depletion, O_3 formation, ecotoxicity, HTP, stored toxicity, and spoiled groundwater.	Europe	Released in 2008
WRATE	LCI, LCIA	End-of-life	Fee	Waste collection, transport, treatment and disposal activities.	Waste collection and processing.	Abiotic resource depletion, freshwater AqEco, AcP, EuP, GWP, HTP.	UK and Ireland	
WISARD	LCI, LCIA	End-of-life	Fee	Waste collection, transport, treatment and disposal activities.	Waste collection and processing.	Energy, GHG, CAP, others.	UK	
WaRM	LCI	End-of-life	Free	Waste disposal options. Can evaluate material extraction and production by evaluating recycling and material reuse assessments.	Landfilling with no recovery, flaring, and LFGE. Material reuse, recycling, composting, and incineration.	GHG emissions.	US	
MSW-DST	LCI	End-of-life	Free	Raw material acquisition through use for waste material remanufacturing considerations.	Waste management options.	Energy, GHG, criteria pollutants, and +30 other pollutants.	US	
AWAST	LCI, LCCA	End-of-life	Free	Collection/transport, biological treatment, incineration, and landfilling.	Waste management options.	Energy, atmospheric emissions, costs.	Europe	
TCAce	LCCA	General	Fee	User defined product or process	User defined product or process.	Facility compliance, contingent liabilities, pollutant external, federal statute penalties, accidents, settlement, and CERCLA costs.	Provides framework to implement costs for any geographic condition.	Data timeframe varies depending on databases implemented.

WBCSD Global Water Tool	Corporation or Facility Water Use	Corporation or Facility Water Use	Free	User enters water consumption information for corporation or facility processes. Maps consumption information to regional water stress data.	Water	International	Most recent updates in 2010.
GEMI Water Sustainability Planner	Corporation Water Use	Corporation Water Use	Free	Corporate questionnaire designed to aid large organizations in identifying their water stresses.	Water	International	
Water Footprint Assessment Manual	Processes, products, consumers, geographic areas, countries, catchments and river basins, municipalities, and businesses.	Processes, products, consumers, geographic areas, countries, catchments and river basins, municipalities, and businesses.	Fee	Manual lays out the Water Footprint Network's standards for water footprint assessment.	Water	International	

(Notes: AcP = Acidification Potential, AqEco = Aquatic Ecotoxicity, CAP = Criteria Air Pollutants, EuP = Eutrophication Potential, HTP = Human Toxicity Potential, GWP = Global Warming Potential)

3.8 Tools by Life Cycle Assessment Stages

The International Organization for Standardization's (ISO) 14040 series defines LCA to include 1) inventorying, 2) impact assessment, and 3) interpretation stages. Inventorying develops environmental indicators (e.g., quantities of emissions released from processes) for processes in the life cycle without linking them to impacts to human health or the environment. The impact assessment stage addresses the effects of energy use and emissions drawing linkages from activity emissions through exposure and its effects. The third stage, interpretation, is meant to provide a mechanism for data quality assessment, uncertainty analysis, and review of the life cycle study to understand the critical factors that appear and what can be done to improve them. Fitting with the inventory and impact assessment stages is life cycle costing. The economic considerations can be viewed as a cost inventory or impact depending on the analysis scope.

Using these ISO stages, the life cycle tools identified above are binned into their respective categories to aid LCA practitioners in data gathering and assessment. Table 2, Table 3, and Table 4 identify the tools that address in some functionality the inventorying, impact assessment, and costing life cycle stages. Additionally, the life cycle processes of focus are shown.

Table 2 – Life Cycle Inventorying Tools

Name	LCA Focus	Geography
APEEP	Emissions impacts	US
Athena	Buildings (Cradle-to-grave)	US and Canada
AWAST	End-of-life	Europe
BEES	Buildings (Cradle through use)	US
CA GREET 1.8b	Transportation (Well-to-wheel)	California
CCaLC	General (Cradle-to-grave and Supply Chain) for Carbon Footprints & Emissions Impacts	UK
E3 Database	Transportation (Well-to-wheel)	Europe
EASEWASTE	End-of-life	Europe
EIO-LCA	General (Cradle-to-gate)	US, Canada, Germany, Spain, and China
Gabi	General (Cradle-to-grave)	Europe, US, and Japan focus.
GHGenius 3.15	Transportation (Well-to-wheel)	Canada, US, Mexico, and India
GREET 1.8c	Transportation (Well-to-wheel)	US
IWM	End-of-life	Canada
IWM-2	End-of-life	Varies
MSW-DST	End-of-life	US
NREL U.S. Life-cycle Inventory	General	US
ORWARE	End-of-life	Sweden
SimaPro	General (Cradle -to-grave)	Europe, US, and Japan focus.
WaRM	End-of-life	US
WASTED	End-of-life	US and Denmark
WISARD	End-of-life	UK
WRATE	End-of-life	UK and Ireland

Table 3 – Life Cycle Impact Assessment Tools

Name	LCA Focus	Geography
APEEP	Emissions impacts	US
Athena	Buildings (Cradle-to-grave)	US and Canada
BEES	Buildings (Cradle through use)	US
CCaLC	General (Cradle-to-grave and Supply Chain) for Carbon Footprints & Emissions Impacts	UK
E3 Database	Transportation (Well-to-wheel)	Europe
EASEWASTE	End-of-life	Europe
Gabi	General (Cradle-to-grave)	Europe, US, and Japan focus.
ORWARE	End-of-life	Sweden
SimaPro	General (Cradle -to-grave)	Europe, US, and Japan focus.
TRACI	Emissions impacts	US
WISARD	End-of-life	UK
WRATE	End-of-life	UK and Ireland

Table 4 – Life Cycle Costing Tools

Name	LCA Focus	Geography
APEEP	Emissions impacts	US
AWAST	End-of-life	Europe
BEES	Buildings (Cradle through use)	US
CCaLC	General (Cradle-to-grave and Supply Chain) for Carbon Footprints & Emissions Impacts	UK
E3 Database	Transportation (Well-to-wheel)	Europe
GHGenius 3.15	Transportation (Well-to-wheel)	Canada, US, Mexico, and India
ORWARE	End-of-life	Sweden
TCAce	Process or Product Direct and Indirect Costs	Customizable

Table 5 – Water Tools

Name	Focus	Geography
WBCSD Global Water Tool	Water consumption information for corporation or facility processes. Maps consumption information to regional water stress data.	International
GEMI Water Sustainability Planner	Corporate questionnaire designed to aid large organizations in identifying their water stresses.	International
Water Footprint Assessment Manual	Manual lays out the Water Footprint Network's standards for water footprint assessment.	International

4 Existing Guidelines Review

The LCA methodology has been formalized (International Organization for Standardization 14040 series) and improved for several decades in Europe and the United States. From inventorying (LCI) to impact assessment (LCIA) to application of results in sustainability and management assessment, the LCA framework has been improved, refined, and updated for both general and specific assessment of products, processes, and services. Government environmental entities or non-governmental organizations including academic institutions have created specific guidelines for performing LCA. Existing LCA guideline documents were selected based on their establishment in the literature and availability to the general public. While some guidelines are general and provide overviews of the LCA framework, others are highly specific to particular aspects in the assessment. A review of some of these guidelines follows.

The existing guidelines should provide detailed background reference material for practitioners to understand the methodological steps in the purpose and practice of LCA. Practitioners can use existing guidelines to complement their understanding and improve their general background needed for specific evaluations related to the California Green Chemistry Initiative.

4.1 Existing Guidelines Summary

The guidelines selected are shown below grouped by their developer and with short descriptions of their relevance to Green Chemistry LCA practitioners. Each guideline has a link (🔗) to the document's online source as of May 2010.

European Environment Agency

Life Cycle Assessment: A Guide to Approaches, Experiences, and Information Sources 🔗 (August 1997)
General overview of what LCA is and what can be evaluated with the framework. Provides a discussion of the methodological background for performing LCAs. Has a comprehensive listing of informational sources including newsletters, journals, books, reports, conference proceedings, databases, standards, and software for LCA practitioners.

European Commission

International Reference Life Cycle Data System (ILCD) Handbook: General Guide for Life Cycle Assessment 🔗 (March 2010)
The document is not meant to serve as a training manual for beginners and has a focus on the decision aspects related to LCA. It is heavily focused on the methodological aspects of LCI and LCIA. The target audience is described as experts in the public and private sector dealing with environmental decision support related to products, resources, and waste management. Developed by the Joint Research Council and Institute for Environment and Sustainability. Overarching guidance for detailed LCA.

Environmental Impacts of Products (EIPRO): Analysis of the life cycle environmental impacts related to the final consumption of the EU-25 🔗 (May 2006)
This document focuses on the European Commission's development of an input-output model for product evaluation. The product categories are not specific to chemicals but capture the broad range

of items used throughout an economy. Developed by the Joint Research Council, European Science and Technology Observatory, and Institute for Prospective Technological Studies.

U.S. Environmental Protection Agency

Life Cycle Assessment: Principles and Practice (May 2006)
This document is meant to be an educational tool for those who want to learn the basics of LCA. It discusses the basic stages of LCA (goal and scope definition, LCIs, LCIAs, and improvement analysis) and the importance of evaluating processes from cradle-to-grave (raw material acquisition, materials manufacture, production, use/reuse/maintenance, and waste management).

European Union - Calcas: Coordination Action for Innovation in Life-Cycle Analysis for Sustainability

D20 Blue Paper on Life Cycle Sustainability Analysis (July 2009)
"Life Cycle Assessment, as standardized by ISO, is well recognized as the most suitable method for the environmental analysis of products. Nevertheless, the question of sustainability assessment, in particular of complex systems with extended and durable effects on the whole of society, requires a broadened scope of analysis and a deepening of modeling." Developed for the European Union by LCA researchers at l'Energiae l'Ambiente (ENEA), Leiden University (CML), and the Swedish Environmental Research Institute (IVL). Presents a roadmap for defining Life Cycle Sustainability Analysis (LCSA).

United Nations Environment Programme (UNEP)

Life Cycle Approaches: The Road from Analysis to Practice (2005)
This document presents the general background for LCA and Life Cycle Management (LCM) principles. It discusses the key steps in performing each analysis but does not provide step-by-step instructions for executing an LCA. Developed by the UNEP and the Society of Environmental Toxicology and Chemistry.

Evaluation of Environmental Impacts in Life Cycle Assessment (2003)
A qualitative overview of the LCIA framework good for those interested in understanding the importance of performing this stage. This document does not provide step-by-step instructions for performing an LCIA from a LCI. Developed by the UNEP Division of Technology, Industry and Economics, Product and Consumption Branch.

Life Cycle Assessment: What it is and how to do it (1996)
Written early in the development of LCA methodology, this document presents LCA, first, as what it is, and second, why we should use it. The first part discusses what LCA is, why it is used, how an LCA is performed (in general), and how the results can be used. The second part provides information on the basic steps of performing an LCA including goal and scope definition, collecting data, establishing system boundaries, processing data, classification, characterization, valuation, reporting, and improvement analysis. Developed by the UNEP in conjunction with the University of Leiden (CML) Centre of Environmental Studies, Netherlands Agency for Energy and the Environment (Novem), and the Netherlands National Institute for Public Health and the Environment (RIVM).

ReCiPe Impact Assessment Guidelines

ReCiPe 2008: A life cycle impact assessment method which comprises harmonized category indicators at the midpoint and the endpoint level (January 2009)
An extensive discussion of the different LCIA metrics and their evaluation. An excellent resource for those trying to bridge LCIs with LCIA. This document provides step-by-step instructions for performing and LCIA from a LCI including environmental and human health damage characterization factors that can be implemented in LCA software. Developed by life cycle impact assessment researchers in the Netherlands including PRé Consultants, University of Leiden (CML), Radboud University Nijmegen (RUN), and Bilthoven (RIVM).

GHG Protocol

Product Life Cycle Accounting and Reporting Standard (Draft) (November 2009)
Aims to develop GHG accounting and reporting standards for businesses, governments, NGOs, and academic institutions. Focuses on LCA methodology providing basic information for new LCA practitioners for GHG assessment. Developed by the World Business Council for Sustainable Development and the World Resources Institute.

4.2 Incorporating Existing Guidelines for General Life Cycle Assessment

The LCA framework is generally defined as goal and scope definition, inventorying, impact assessment, interpretation, and reporting, and are detailed by several of the existing guidelines listed above. This framework can be applied to large or small systems including products, processes, and services.

The guidelines relevant for general LCA background are:

- European Environment Agency – Life Cycle Assessment: A Guide to Approaches, Experiences, and Information Sources
- U.S. Environmental Protection Agency – Life Cycle Assessment: Principles and Practice
- GHG Protocol – Product Life Cycle Accounting and Reporting Standard (Draft)
- United Nations Environment Programme – Life Cycle Assessment: What it is and how to do it
- European Commission – International Reference Life Cycle Data System (ILCD) Handbook: General Guide for Life Cycle Assessment

These guidelines cover many facets of the general LCA framework providing a thorough background of the methodology for practitioners. This includes how to identify the system boundary, defining functional units, setting study goals, collecting data, data sources, processing data, connecting inventories to environmental and human health damages, valuing damages, interpreting results to improve the analysis and data quality, and reporting. Many of the guidelines provide step-by-step examples for new practitioners. For example, "Life Cycle Assessment: What it is and how to do it" walks the reader through an LCA of bean oil production, "International Reference Life Cycle Data System (ILCD) Handbook: General Guide for Life Cycle Assessment" presents a template for aiding in system boundary selection, and "Life Cycle Assessment: Principles and Practice" shows a hypothetical LCI for gasoline production.

Many of the existing general LCA guidelines present or mention literature which would also likely prove useful to practitioners. The literature will discuss the more rigorous steps and considerations that are made in performing an LCA and the interpretation of results.

4.3 Incorporating Existing Guidelines for Life Cycle Impact Assessment

Several existing guidelines discuss LCIA either exclusively or in the context of LCA. ReCiPe 2008, an LCIA guideline developed by LCA consultants and academics in the Netherlands, focuses explicitly on this step and provides detailed information on midpoint and endpoint environmental and human health damage assessments including characterization factors that can be applied to LCI results.

The most relevant LCIA guidelines are:

- European Commission – International Reference Life Cycle Data System (ILCD) Handbook: General Guide for Life Cycle Assessment
- ReCiPe Impact Assessment Guidelines – ReCiPe 2008: A life cycle impact assessment method which comprises harmonized category indicators at the midpoint and the endpoint level
- United Nations Environment Programme – Evaluation of Environmental Impacts in Life Cycle Assessment

The LCIA existing guidelines discuss the connection between LCI and LCIA and the multiple damage assessments that can be performed. This includes climate change, ozone depletion, acidification, eutrophication, toxicity, human health, ionizing radiation, land use, water depletion, mineral depletion, and fossil fuel depletion. The "Evaluation of Environmental Impacts in Life Cycle Assessment" guideline provides a qualitative background and understanding of LCIA while "ReCiPe 2008" details the quantitative steps that should be taken to generate data-driven results.

5 Case Studies

Case studies were developed by UC Berkeley to assist practitioners to apply LCA in alternatives assessments for safer products. The case studies are intended to guide LCA novices towards appropriate thinking and first analytical steps for 1) system boundary selection, 2) functional unit selection, 3) life cycle inventorying, 4) life cycle impact assessment, and 5) data quality, uncertainty, and sensitivity assessment. A common example of evaluating a chemical of concern in a product of interest is followed. The case studies are not meant to be comprehensive and explain the detailed steps for completing an LCA. Instead, they are meant to outline the basic principles that a practitioner should consider at each step. For additional detail and step-by-step analytical assistance, practitioners should refer to the *Existing Guidelines Review* section of this report.

5.1 Case Study for System Boundary Selection

The system boundary selection phase in LCA defines the scope of the analysis, the processes included, and the comprehensiveness of results. Performing an LCA with a truncated system boundary can exclude life cycle components that when considered would change conclusions and recommendations from the analysis. Selecting an appropriate system boundary that balances capturing enough processes to develop comprehensive results with the resource and time constraints in evaluating far into the product supply chain is the goal of practitioners. Ideally, the practitioner wants to capture the effects of a product, process, or system through the global supply chain, but in practicality this sophistication is very difficult and would need to be evaluated against the available resources for developing sound conclusions.

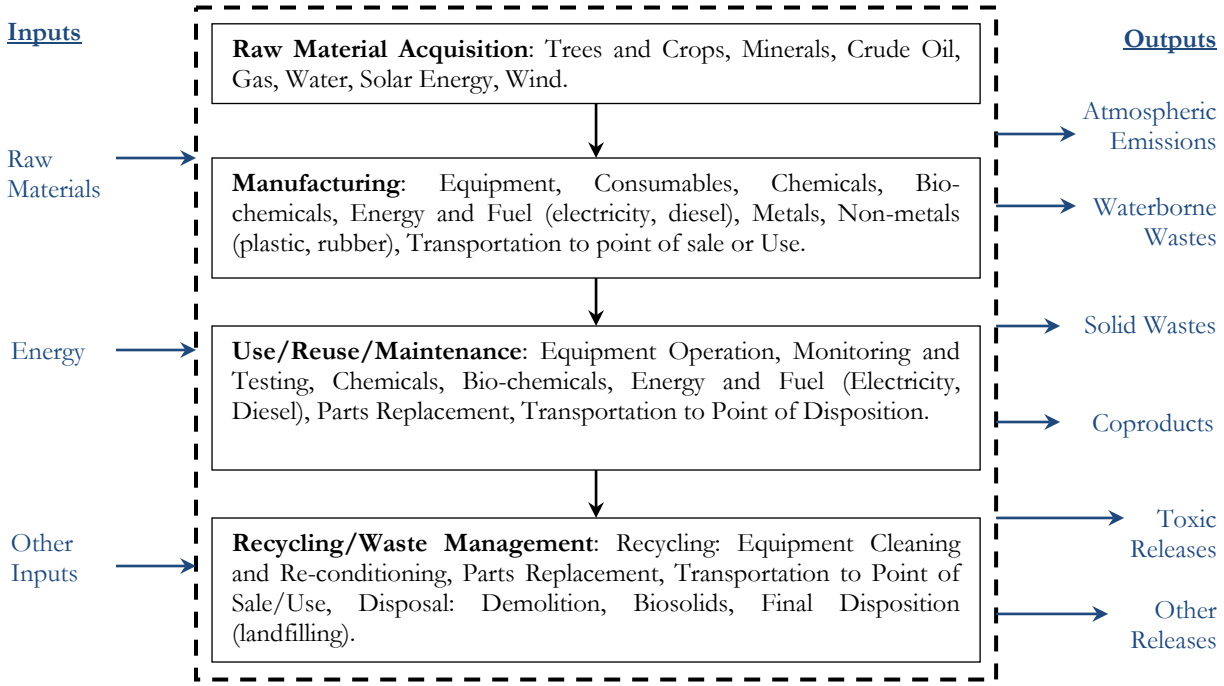
The ISO 14040 series recommends considering mass, energy, and environmental relevance when identifying significant inputs and outputs (and ultimately the corresponding life cycle components) in system boundary selection. However, the practitioner should also be cognizant that 1) there is no guarantee that small mass or energy contributions will result in negligible environmental impacts, 2) there are ancillary materials and processes that exist to support the production of the final product, and 3) that the accumulation of upstream components that have been excluded (which by themselves may be negligible) may be significant. When establishing the system boundary, encapsulating the following dimensions may be useful to the practitioner: (I) boundaries between the technological system and nature, (II) geographic area, (III) time horizon, (IV) production of capital goods, and (V) boundaries between the life cycle system of the studied product or service and the connected life cycle systems of other products.

In general, the practitioner will start by considering a system boundary with cradle-to-grave processes, that is, raw material extraction and processing through use and disposal or recycling, including intermediary effects (e.g., transportation). For chemical production, the system boundary would include cradle-to-gate (or raw material extraction, processing to intermediate materials, transportation, and final production) and gate-to-grave (use and disposal) components. Particular attention should be given to co-product allocation where certain production processes may produce more than one product of value and LCIs would need to be apportioned between.

The U.S. EPA presents guidelines for establishing appropriate system boundaries and offers a generic framework of what to consider within (Figure 1). For each life cycle component in each stage (raw material acquisition, manufacturing, use/reuse/maintenance, and recycling/waste management), inputs and outputs would be quantified and normalized to the functional unit. The arrows within the system would also be evaluated as, for example, transportation activities.

Components within the system should be evaluated as either primary or secondary. Primary components directly contribute to the making of the chemical or product while secondary components are the ancillary processes which exist in some capacity to support primary components.

Figure 1 – Generic System Boundary Including Life Cycle Phases, Inputs, and Outputs



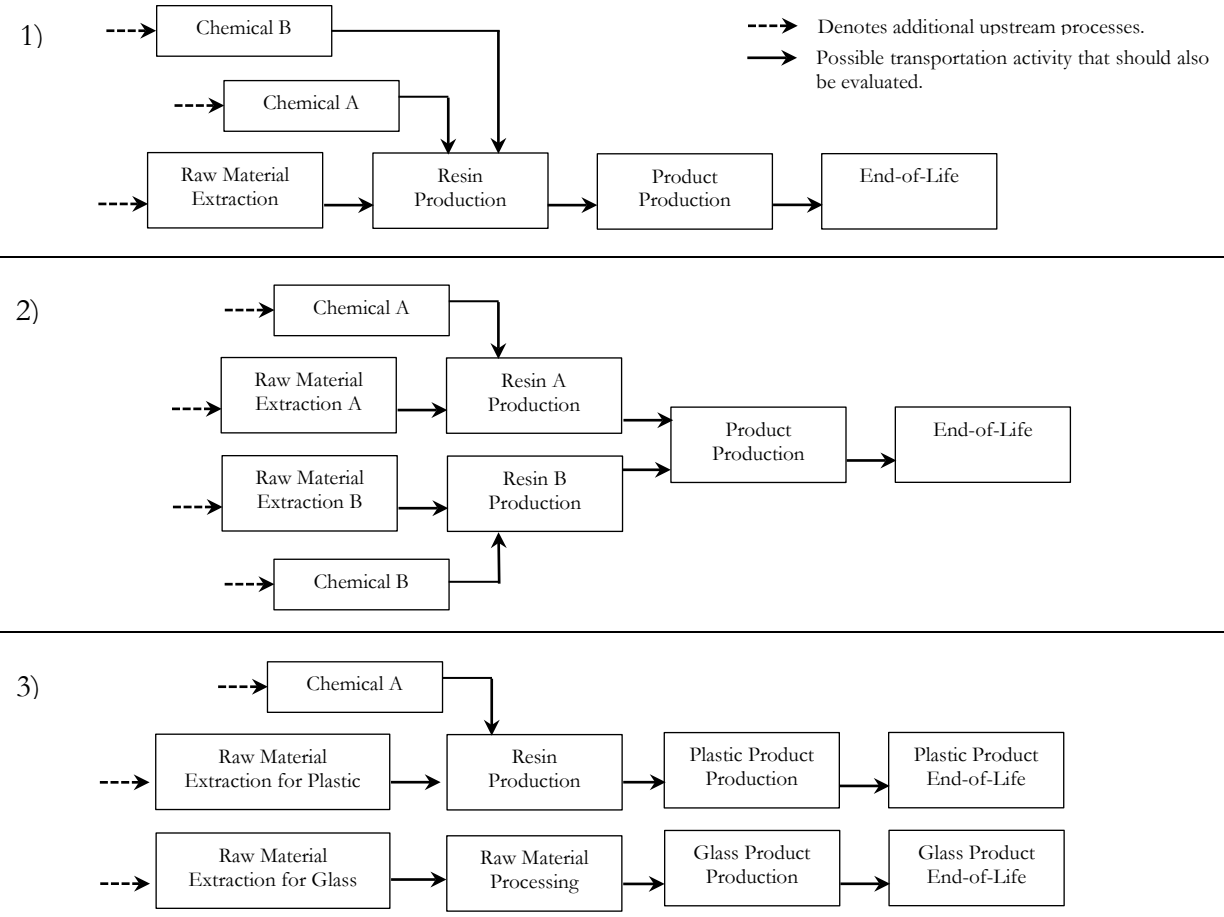
Adapted from the U.S. EPA's report #EPA/600/R-06/060

ISO LCA guidelines include requirements for iterative assessment to refine the system boundary. Having established a system boundary and executed the LCA, the practitioner should evaluate their results to identify that all significant primary and ancillary components have been included.

As an example, consider a scenario where an LCA practitioner is evaluating a chemical of concern in a plastic item. The practitioner is considering three options for removing the chemical: 1) switching the chemical of concern for another chemical that meets the same functionality, 2) switching the plastic with the chemical of concern for another plastic material that does not have the chemical, and 3) switching the plastic for another material, for example, glass. The three options present unique considerations for the LCA practitioner in system boundary selection. For 1), the practitioner would first consider how the chemical switch affects the performance of the item. If it does not, then the practitioner may only need to consider the difference in chemical production and upstream processes (e.g., raw chemical material extraction and transport) effects. The system boundary would evaluate raw chemical material extraction through chemical manufacturing and the effects in plastic resin or product production. If the function of the item changes (e.g., the item degrades faster so more plastic is needed, or the recyclability properties change) then the practitioner would need to include manufacturing changes and possibly even recyclability in the system boundary for both the status quo plastic and the plastic with the new chemical.

To assess different plastics in 2), the practitioner would need to evaluate a system boundary that includes raw material extraction through plastic resin production and product production, and ultimately end-of-life processes (e.g., recycling, waste management). By comparing two different plastics the practitioner must consider a system boundary that captures the differences in materials before, during, and after the item is used. The practitioner must consider how resin production processes would be different, if the two different types of plastic exhibit different usability characteristics, and how recycling and waste management process may differ. There are likely processes that do not change in the system boundary between two different types of plastics (e.g., blow molding may be the same if the plastics are similar) and it may be possible to treat these processes as equivalent when performing the LCA. Switching from plastic to glass in 3) to eliminate the chemical of concern would require the practitioner to consider the most extensive system boundary to perform the LCA. Unlike 1) and 2), switching from one material to a completely different one creates an assessment that considers two separate production, use, and end-of-life systems with possibly no interrelated processes. The three outlined options for eliminating a chemical of concern in a plastic product highlight the dynamic nature of system boundary selection in LCA. The practitioner should be flexible in their consideration of a system boundary when evaluating multiple options for eliminating impacts. Table 6 shows these system boundaries with simplified major processes for each of the three options.

Table 6 – System Boundary examples for Alternatives for a Plastic Product



This discussion is based on the manuscript by Suh et. al 2004 *System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches* in Environmental Science and Technology (http://dx.doi.org/10.1021/es0263745), Raynolds et. al 2000 *The Relative Mass-Energy-Economic (RMEE) Method for System Boundary Selection* in the International Journal of Life Cycle Assessment (http://dx.doi.org/10.1007/BF02978559), and the U.S. EPA's 2006 report (#EPA/600/R-60/060) *Life Cycle Assessment: Principles and Practice.*

5.2 Case Study for Functional Unit Selection

Establishing the functional unit is one of the critical first steps in LCA. A functional unit is a reference unit for quantifying the performance or functionality of a product or service's life cycle environmental effects. Intermediate and final results are evaluated on a functional unit basis, which allows the practitioner to consider relevant attributes and make comparisons consistently. It is not always easy to establish a functional unit.

Products and services may have several functional units, even in the same application. For example, a chemical may have many functional units, depending on what it is used for. A plastic grocery bag is used to carry groceries, but can then have a second use as a trash bag. When multiple functional units are present, allocation of environmental effects per functional unit may be necessary.

Consider the system boundary example of removing a chemical of concern from a product of interest (a plastic item) and how the functional unit may be affected. The practitioner, faced with three options for avoiding the chemical's impact is deciding between 1) switching out the chemical for another chemical, 2) switching the item's status quo plastic for another plastic that does not contain the chemical, and 3) switching out plastic all-together for glass. The ultimate goal of an LCA is to inform decision-making such that a choice can be made about altering a process within the life cycle of a product to improve environmental performance by producing products differently. The product provides something that the functional unit should capture. Hence, the functional unit should typically relate to what the product provides and not simply be a physical unit of the product.

Consider the example of a light bulb. When choosing between two types of light bulbs, the practitioner could establish the functional unit as *per bulb*. The user would perform an LCA evaluating indicators from raw material extraction through product disposal, normalizing the effects at each stage in the life cycle *per bulb*. This result is valid and useful for looking at improvements to the specific bulb type, but not so useful for comparative purposes. The goal of using lightbulbs is to provide lighting, and a functional unit that is based on a particular quality and quantity of light is needed. For example, a user's goal may be to light a large room and is ultimately interested in comparing between two lighting options that provide equivalent light. One option may use 3,000 lumen bulbs with a 10,000 hour life and the other option 4,500 lumen bulbs with a 5,000 hour life. If the user needs 90,000 lumens for the room then the LCA could have a functional unit of *90,000 lumens per year* as a more effective comparison across lighting options. With functional unit equivalence, the LCA practitioner can compare options based on the goal of providing lighting and has accounted for the different lumens and temporal aspect of bulb lifetimes. The practitioner would now evaluate the life cycle by first establishing the number of bulbs needed in each setup that translate to the *90,000 lumens per year* needed for each bulb type.

When considering the tradeoffs of covering a wall in paint or wallpaper, meaningful comparisons cannot be drawn by comparing the materials with the units in which they would be purchased: a volume of paint to a roll of wallpaper. Instead, by establishing the desired function of architectural covering for the wall, a comparable functional unit can be determined. The practitioner in this example is interested in covering the wall of a determinable area for a period of time. Setting the functional unit to wall area for so many years allows for a comparison that captures the similar functionality of both materials, maintenance needed over the period, and the underlying obsolescence in both materials are expected to maintain that functionality for a certain lifetime (i.e., paint and wallpaper will eventually fade and peel at different times).

How can an LCA practitioner decide what is the best functional unit when trying to evaluate the tradeoffs of removing a chemical of concern from a product? The practitioner should start by considering the function of the product and not the product itself. In the case of a plastic item manufacturer, there may be additional functionality characteristics that are required or desirable. For example, if the item has a long useful life, retaining color (or lack of discoloration) may be important. Similarly, other durability-related criteria may be important. For example, when evaluating discoloration or photodegradation, the practitioner may want to include minimum criteria

in the functional unit that captures these effects. The practitioner could set the functional unit to include not photodegrading or discoloring past a minimum level in a set time period. Properties identified in the functional unit have some bearing on the system boundary analyzed. Consider an LCA that evaluates the replacement of a 0.5 liter non-reusable beverage bottle with a 0.4 liter recyclable bottle. Based on the previous examples, it is recommended that the practitioner choose a functional unit that captures the goal of the bottle, to transport beverage, and not the bottle volume or material type itself. For this case, a *per liter* functional unit can be used, which avoids the potential pitfall of evaluating based on the bottles themselves which have different sizes. However, the *per liter* functional unit introduces a new dimension that should be considered in the LCA. It turns out that people may drink less when bottle volumes decrease. If 4 million liters were transported in larger bottles, only 3.6 million liters may be consumed when the smaller bottles were introduced. This means that the system boundary must be expanded to evaluate not only bottle production but also the change in production of the beverage and its upstream components. By using a *per bottle* functional unit, this market dynamic would not have been considered.

The light bulb and bottle functional unit discussions are based on the Danish Environmental Protection Agency's 2004 Environmental News (No. 70) document *The Product, Functional Unit and Reference Flows in LCA* by Bo Weidema, Henrik Wenzel, Claus Petersen, and Klaus Hansen. As of December 2010 it was available online at http://www2.mst.dk/Udgiv/publications/2004/87-7614-233-7/pdf/87-7614-234-5.pdf.

5.3 Case Study for Life Cycle Inventorying

LCI is the quantification of indicators for a system or system-tradeoff, and is performed after the study's goal, scope, and functional unit have been established. The inventorying phase quantifies input and output flows to life cycle components based on the study's goal. While LCA is often thought of for energy and emissions assessment, its framework is generally applicable to any quantifiable flow through a system, such as materials, waste, labor, water, and monetary costs, among others. Producing the LCI requires that the practitioner identify all direct, ancillary (indirect), and upstream life cycle processes that occur from making the product. A properly selected system boundary provides for inclusion of processes that are expected to be the most significant in the LCI.

It is recommended that a broad set of indicators are inventoried to comprehensively evaluate impacts. For example, an LCI of aluminum cans would use a system boundary that includes the production of primary aluminum (which includes secondary aluminum feedstock as well), production of cans from aluminum, filling, distribution, use, and waste management. Used aluminum cans can be recycled into new cans avoiding the use of virgin aluminum and these recycling processes are also included in the system boundary. For each of these life cycle components, a broad set of indicators are evaluated as either process inputs or outputs. This includes energy, resources, non-elementary flows, emissions to air, emissions to water, waste, and co-products. The evaluation of a broad set of indicators may reveal that one component may be responsible for the majority of indicator A while another component may be responsible for the majority of indicator B.

Consider the example of removing a chemical of concern from a plastic item. As previously described, the LCA practitioner is considering three options: 1) replacing the chemical of concern with a functionally equivalent other chemical that is thought to have fewer impacts, 2) replacing the plastic material with a different plastic that does not contain the chemical of concern, and 3)

replacing the plastic material with a completely different material, in this case glass. As described in the system boundary example, each subsequent option creates a need for an expanded system boundary that may capture different processes or different configuration of processes, ultimately governing the LCI. To evaluate the LCI inputs and outputs, the three options described in Table 6 would be evaluated by considering each process box and each solid black transport arrow. If the practitioner is interested in evaluating water inputs and carcinogenic air emissions, they would evaluate these indicators at each box and connecting transport arrow. In practice, this generalized representation would be extended to all inputs and outputs of interest when performing the LCI. The practitioner may seek to understand the energy, material, and water inputs of each system, as well as the air emissions, solid waste, and wastewater outputs. These inputs and outputs would ultimately be connected to their effects in LCIA. For each component in the system, the inputs and outputs should be based on the functional unit so they can be summed (to evaluate total system performance) and compared.

LCI typically considers a cradle-to-grave system that surrounds the use of a direct process or product of interest. Consider the example of a computer. The direct life cycle component is the use of the computer which consumes electricity, and emissions are generated at a power plant. Following a cradle-to-grave system boundary would require the LCA practitioner to assess everything from the extraction of raw materials in the computer parts to the disposal of the machine. Between these beginning and end-of-life stages are processing of raw materials into finished products, assembly, transportation, and others, and the processes associated with these components may be different for the computer casing, microchips, and chemicals used in electronics, to name a few. An energy assessment for a computer determined that in the life cycle a total of 7,900 MJ were required with only 1,500 MJ resulting from electricity in computer use. The study structured its assessment on the key materials in the computer: semiconductors, printed circuit boards, bulk materials, silicon wafers. It evaluated the extraction and processing of these raw materials into finished materials, and ultimately their assembly, estimating energy requirements of 3,100 MJ from these components. Also, additives (cleaning chemicals, semiconductor manufacturing equipment, and passive components), disk drives and other parts, transportation, packaging, documentation, and other processes were determined to contribute 3,300 MJ to the LCI. The LCI shows that production of the computer accounts for 81% of its life cycle energy requirements (or 4 times more energy is consumed in production than in use). End-of-life disposal processes are not considered, so this assessment represents a cradle-to-use system boundary. In this example, gross energy consumption would be disaggregated by fossil, non-fossil, renewable, and non-renewable when connecting the LCI to an impact assessment.

This discussion is based on two publications: (1) *Energy Intensity of Computer Manufacturing: Hybrid Assessment Combining Process and Economic Input-Output Methods* by Eric Williams that appeared in Environmental Science and Technology, 2004, 28, 6166-6174 [available online at http://dx.doi.org/10.1021/es035152j] and (2) *Life Cycle Assessment of Packaging Systems for Beer and Soft Drinks: Aluminum Cans* by Anna Ryberg, Tomas Ekvall, Lisa Person, and Bo Weidema that appeared in the Danish Environmental Protection Agency's newsletter No. 402 [available online at http://www2.mst.dk/Udgiv/Publications/1998/87-7909-023-0/pdf/87-7909-023-0.PDF].

5.4 Case Study for Life Cycle Impact Assessment

LCIA establishes connections between environmental indicators (such as emissions) quantified in the LCI and the damages they cause to human health (morbidity and mortality), environmental quality, crop loss, the built environment, and other categories. LCIA requires that the LCI has been completed with appropriate system boundary selection to capture the components that cause the greatest impacts. The connections between environmental indicators and their impacts in LCIA is typically based on information from a diverse set of disciplines that can include public health, healthcare, environmental engineering, economics, and many others.

The relationship between environmental indicators and their impacts is often described through the use of midpoint and endpoint damage categories. Midpoint categories are common mechanisms that contribute to the same impact. For example, respiratory effects and human toxicity are midpoint damages that both produce human health impacts. Similarly, aquatic ecotoxicity, aquatic eutrophication, and terrestrial acidification are midpoint damages that each produce ecosystem damages. In these examples, human health impacts and ecosystem damages are considered endpoint damages and the various midpoint damages that contribute to them can be equivalently quantitatively expressed with a single metric (e.g., human health impacts can be quantified using Disability Adjusted Life Years). Once the LCI has been established, midpoint damages can be determined with the assistance of LCIA databases that derive midpoint effects in terms of a reference substance. Table 7 shows potential human health, ecosystem quality, climate change, and resource depletion midpoint categories, midpoint reference substances, and ultimately a common damage unit.

Table 7 – Midpoint and Endpoint Damage Categories with Impact Metrics

Midpoint Category	Midpoint Reference Substance	Damage Category	Damage Unit
Human Toxicity (Carcinogens and Non-Carcinogens)	kg_{eq} cloroethylene into Air	Human Health	DALY
Respiratory (Inorganics)	kg_{eq} $PM_{2.5}$ into Air	Human Health	
Ionizing Radiation	Bq_{eq} carbon-14 into Air	Human Health	
Ozone Layer Depletion	kg_{eq} CFC-11 into Air	Human Health	
Potochemical Oxidation [Respiratory (Organics) for human health]	kg_{eq} ethylene into Air	Human Health and Ecosystem Quality	DALY for Human Health and PDF × m^2 × yr for Ecosystem Quality
Aquatic Ecotoxicity	kg_{eq} triethylene glycol into Water	Ecosystem Quality	PDF×m^2×yr
Terrestrial Ecotoxicity	kg_{eq} triethylene glycol into Water	Ecosystem Quality	
Terrestrial Acidification or Nutrification	kg_{eq} SO_2 into Air	Ecosystem Quality	
Aquatic Acidification	kg_{eq} SO_2 into Air	Ecosystem Quality	
Aquatic Eutrophication	kg_{eq} PO_4^{3-} into Water	Ecosystem Quality	
Land Occupation	m^2_{eq} organic arable land-year	Ecosystem Quality	
Global Warming	kg_{eq} CO_2 into Air	Climate Change	kg_{eq} CO_2 into Air
Non-Renewable Energy	MJ total primary non-renewable	Resources	MJ
Mineral Extraction	MJ additional energy	Resources	

(Adapted from Jolliet et al. 2003, International Journal of Life Cycle Assessment)

Wernet, et. al, 2011 evaluate the life cycle impacts of energy use in chemical production for 99 substances. The authors define the system boundary as cradle-to-production and use existing databases for life cycle processes to determine the energy consumption and emissions in the LCI.

Using this inventory, the study evaluates four impacts: 1) Cumulative Energy Demand (CED) which captures the amount of primary energy demand needed (MJ/kg) to produce the chemical; 2) Global Warming Potential (GWP, in kg CO_2eq/kg) to evaluate the potential of greenhouse gases to have warming effects on the planet; 3) Ecoindicator 99 which evaluates emissions impacts to human health, ecosystem quality, and resources, and using a weighting scheme that combines the final damages into a single score; 4) Ecological Scarcity, another single impact score weighting scheme based on actual pollutant and resource flows compared to a maximum allowable; and 5) the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) which evaluates midpoint damages. The study uses several impact assessment approaches to evaluate a suite of impacts and viewpoints that may be of interest to diverse decision-makers associated with the system. Having established endpoint damage units for chemical production, the study is able to assess impacts instead of quantities of emissions developed in the LCI. While LCIs may show that emissions are equivalent for life cycle processes across certain chemical components, the impacts may differ due to temporal, geographical, and ultimately population and environmental exposure effects.

There are many impacts that the practitioner can include and selecting what should be included can be challenging. To start, the practitioner should identify the areas of protection that may be of interest. Areas of protection are human health, natural environment quality (i.e., impact to ecosystems that support life on earth), natural resources (i.e., extraction and harvesting of materials for use by humans), and man-made environment (i.e., the synthesized or built environment including buildings and food crops). If the practitioner has evidence to support that any of these areas of protection can be excluded from the LCIA then this filter can be used to focus on other impacts. The practitioner should be cautious in excluding impacts (the purpose of LCA is to identify comprehensive impacts that may not have been realized with other approaches) but if previous analyses or LCAs have been performed and have shown, for example, that natural resource use or impacts to the buildings are negligible then these areas of concern can be excluded and the others focused on. Without any information suggesting that an impact can be excluded from the LCIA, the practitioner should assume that a comprehensive set should be evaluated and use an iterative approach to refine and improve the LCIA. For a product LCA example, in the first iteration, the practitioner may determine that the use of a chemical leads to negligible eutrophication impacts but human carcinogenic effects are potentially significant. In subsequent iterations, the practitioner should then focus their efforts on improving the understanding of human carcinogenic impacts determined to better understand how reductions to these impacts are best implemented.

This discussion is based on studies by Olivier Jolliet and colleagues titled *IMPACT 2002+: A new life cycle impact assessment methodology* in the International Journal of Life Cycle Assessment (available online at http://dx.doi.org/10.1007/BF02978505) and Gregor Wernet and colleagues titled *The Environmental Importance of Energy Use in Chemical Production* in the Journal of Industrial Ecology (available online at http://dx.doi.org/10.1111/j.1530-9290.2010.00294.x). Additional discussion is available in the article *Critical Analysis of the Mathematical Relationships and Comprehensiveness of Life Cycle Impact Assessment Approaches* in the journal Environmental Science and Technology (http://dx.doi.org/10.1021/es051639b).

5.5 Case Study for Data Quality, Uncertainty, and Sensitivity Assessment

Data collection in LCA should be designed to reduce the uncertainty in final results so that recommendations within known uncertainty bounds can be established, while at the same time performing the analysis without extensive and unnecessary effort. Priority should be given to reducing the largest uncertainties first, those that have the potential of shifting results to outcomes that produce different decisions. Variation in parameters is the result of technological, geographical and temporal aspects. Technological aspects describe the representativeness of model data used to evaluate particular life cycle processes. Geographical aspects consider how well data represents the region under consideration. Lastly, temporal aspects describe how well model data represent a process that may be older or younger than the information being used. For example, evaluating production processes today with data from a manufacturing facility that is several decades old may introduce considerable uncertainty. Uncertainty is not relegated to parameters only but can also appear because of scenario selection and the underlying mathematical models.

Data Quality Assessment (DQA) can be used as a first step in identifying where parameter uncertainty may exist in a LCA. DQA uses a pedigree matrix that ranks life cycle components or their underlying parameters. The pedigree matrix is constructed by identifying the factors that are most likely to affect the uncertainty of the parameters and a scoring rubric for the factors. For example, factors may include acquisition method, independence of data supplier, representativeness, temporal, geographic, and technological. For each, a rubric (possibly on a scale of 1 to 5 where 1 is best) would be developed defining how the life cycle components or parameters should be scored. For example, for temporal correlation, the rubric could show 1) less than three years of difference to year of study, 2) less than five years of difference, 3) less than 10 years of difference, 4) less than 20 years of difference, and 5) age unknown or more than 20 years of difference. When evaluating the life cycle component or parameter, a score would be assigned to the temporal correlation factor, and a similar rubric and score would be developed for the other factors. With the pedigree matrix constructed and scoring completed, the parameter uncertainty analysis would compare total or average scores across all factors for the life cycle components or parameters being evaluated. The higher the score (assuming the pedigree matrix has been constructed with high scores for unrepresentative data) the higher the uncertainty is for the components or parameters and the practitioner should focus on these in follow up assessment or sensitivity analysis.

Table 8 shows a sample pedigree matrix. The practitioner should evaluate the critical parameter within this matrix by filling in the matrix, scoring the parameter based on the pedigree criteria identified.

Table 8 – Sample Pedigree Matrix

Criteria	Indicator Score				
	1	2	3	4	5
Impact on Final Result	Parameter is the top contributor to final result	Parameter is within the top 5 contributors to final result	Parameter is within the top 10 contributors to final result	Parameter is not likely to affect final results significantly	Parameter contribution is unknown
Acquisition Method	Measured data	Calculated data based on measurements	Calculated data partly based on assumptions	Qualified estimate (by industrial expert)	Nonqualified estimate
Independence of Data Supplier	Verified data, information from public or other independent source	Verified information from enterprise with interest in the study	Independent source, but based on nonverified information from industry	Nonverified information from industry	Nonverified information from the enterprise interested in the study
Representation	Representative data from sufficient sample of sites over and adequate period to even out normal fluctuations	Representative data from smaller number of sites but for adequate periods	Representative data from adequate number of sites, but from shorter periods	Data from adequate number of sites, but shorter periods	Representativeness unknown or incomplete data from smaller number of sites and/or from shorter periods
Temporal Correlation	Less than three years of difference to year of study	Less than five years of difference	Less than 10 years of difference	Less than 20 years of difference	Age unknown or more than 20 years of difference
Geographical Correlation	Data from area under study	Average data from larger area in which the area of study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with very different production conditions
Technological Correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study, but from different enterprises	Data from processes and materials under study, but from different technology	Data on related processes or materials, but same technology	Data on related processes or materials, but different technology
Range of Variation	Estimate is a fixed and deterministic number	Estimate is likely to vary within a 5% range	Estimate is likely to vary within a 10% range	Estimate is likely to vary more than 10%	Estimate is likely to vary under unknown ranges

With high-uncertainty parameters identified, techniques such as Monte Carlo simulation can be used to identify the sensitivity of results. Huijbregts et. al, 2003 use Monte Carlo simulation to evaluate the parameter uncertainty effects for insulation options used in Dutch housing. The authors consider any parameter contributing more than 1% to the total output uncertainty. For process flows, environmental interventions, and impact factors, a log-normal distribution was assigned to each parameter to evaluate uncertainty in overall results.

In addition to parameter uncertainty, scenario and model uncertainties can exist and should be evaluated for the effects on final results. Scenario uncertainty describes the consideration that the system being evaluated is based on normative behavior but other choices may exist that lead to the system operating differently. For example, a manufacturer may assume in the LCA that waste

products will be recycled. However, when certain conditions arise, it may be the case that these waste products are disposed of in a landfill. Scenario uncertainty can be addressed by considering larger system boundaries and the best and worst case possibilities for critical life cycle processes. Model uncertainty arises from the limitations of assessing large systems with frameworks that do not capture entirely or accurately the true behavior of these systems. Model uncertainties include spatial and temporal characteristics lost by the aggregation of emissions and nonlinearities in economic and ecological processes. Using a similar approach to scenario uncertainty analysis, model uncertainty can be evaluated.

LCA should ultimately be practiced as an iterative process, to reduce the uncertainty in the critical parameter, scenario, or model factors. For example, a practitioner identifies that the manufacturing of a product dominates emissions in the life cycle but is based on a 30-year old data from literature (potentially highly uncertain). The practitioner should then seek out newer data that may be more representative for the manufacturing process they are interested in by contacting manufacturers and industry partners, or identifying newer and more up-to-date literature. This may involve time and other resources (for example, a fee to access a newer dataset or reference material) and the practitioner should budget for this prior to starting the LCA.

This discussion is based on the Danish Environmental Protection Agency's 2003 Environmental Project No. 862 *Reducing the Uncertainty in LCI* by Bo Weidema, Ebbe Holleris Petersen, and Henriette Ølgaard (as of February 2011 it was available online at http://www.lca-center.dk/resources/781.pdf), and the 2003 manuscript by Mark Huijbregts et. al *Evaluating Uncertainty in Environmental Life-Cycle Assessment. A Case Study Comparing Two Insulation Options for a Dutch One-Family Dwelling* in Environmental Science and Technology (available online at http://dx.doi.org/10.1021/es020971+).

6 Recommendations for Future Work

The deliverables presented and discussed in this report were completed during the initial stages of the California Green Chemistry Initiative and future projects can help expand the background information for LCA practitioners and can guide alternatives analysis. The tools, guidelines, and case studies are useful for providing the framework of LCA and the relevant resources available to practitioners, but as the Green Chemistry Initiative moves forward, additional resources will be valuable.

The availability of California product specific LCA data will be needed and the Green Chemistry Initiative should explore the possibility of developing and maintaining a database for practitioners. The data available for processes involved in chemical manufacturing and use are sparse. Literature reviews by UC Berkeley did not produce a rich body of work in these areas, likely due to these processes often being associated with private industry and the proprietary nature of industry data. While some chemical process data exist in commercial datasets, generally only a handful of possible chemicals are included. With such a broad set of chemicals in use, the state should explore the possibility of developing or compiling California-specific data in publicly-available repositories. These repositories may need to be compiled over long time periods as practitioners develop relevant data, and conflicts between proprietary data and public reporting will likely arise.

The development of California-specific life cycle impact characterization factors may be valuable. High-resolution impact factors for a broad suite of impact categories may help develop specific understanding of local effects. LCA practitioners are sometimes faced with the challenge of applying US-based impact factors to local regions within the country.

As future regulations are adopted, additional case studies should be developed to aid practitioners. Currently, regulations and rules for producers and users of chemicals of concern in California are not finalized. Therefore, the case studies presented in this report are general and give practitioners methodological considerations for simplified situations. As regulations and rules are finalized, more specific case studies should be developed that focus on LCA for California and relevant products.

The deliverables in this report are a foundation for future work that will develop specific guidance for LCA practitioners and product designers. The tools, existing guidelines, and case studies provide a methodological base for developing focused information and guidance for alternatives assessment.