Chapter 13

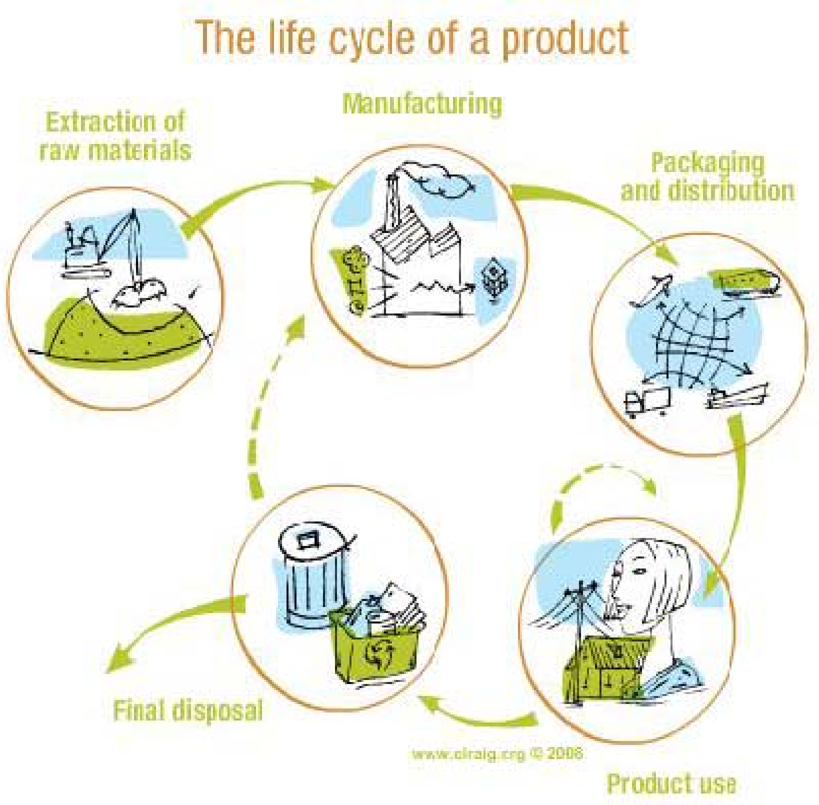
Green Engineering

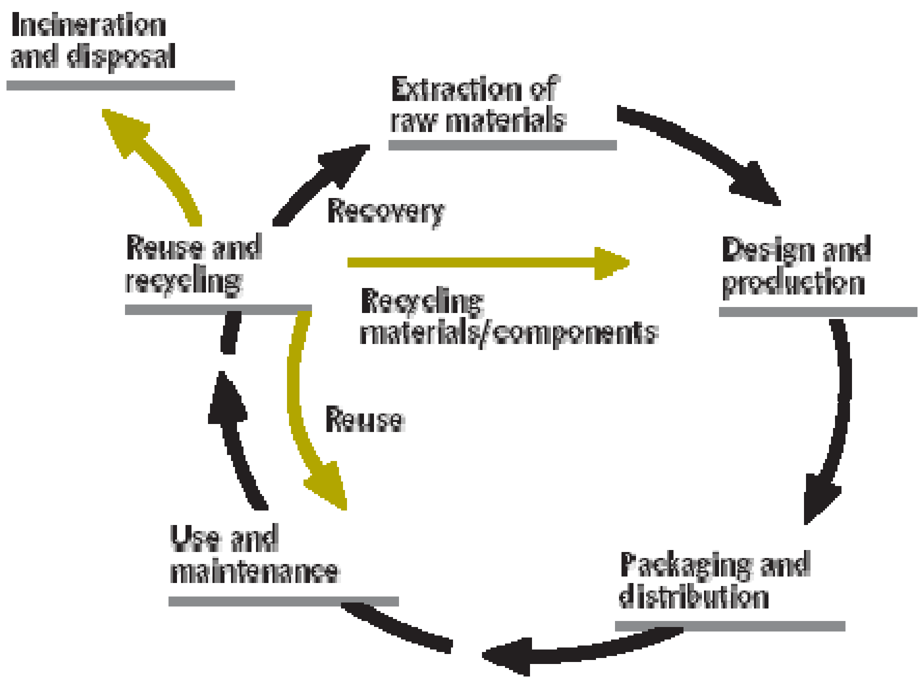
Life-Cycle Concepts, Product Stewardship and Green Engineering

13.1 Introduction to product life cycle concept

Products, services, and processes all have a life cycle. For products, the life cycle begins when raw materials are extracted or harvested. Raw materials then go through a number of manufacturing steps until the product is delivered to a customer. The product is used, then disposed of or recycled. These product life-cycle stages are illustrated in Figure 13.1-1, along the horizontal axis. As shown in the figure, energy is consumed and wastes and emissions are generated in all of these life-cycle. Processes also have a lifecycle. The life cycle begins with planning, research and development. The products and processes are then designed and constructed. A process will have an active lifetime, then will be decommissioned and, if necessary, remediation and restoration may occur. Figure 13.1-1, along its vertical axis, illustrates the main elements of this process life cycle. Again, energy consumption, wastes and emissions are associated with each step in the life cycle.

13.1 Introduction to product life cycle concept





13.1 Introduction to product life cycle concept

Traditionally, product and process designers have been concerned primarily with product life-cycle stages up to manufacturing. That focus is changing. Increasingly, chemical product designers must consider how their products will be recycled. They must consider how their consumers use their products. Process designers must avoid contamination of the sites at which their processes are located. Simply stated, design engineers must become stewards for their products and processes throughout their life cycles. These increased responsibilities for products and processes throughout their life cycles have been recognized by a number of professional organizations. Table 13.1-1 describes a Code of Product Stewardship developed by the Chemical Manufacturers' Association (now named the American Chemistry Council).

Table 13.1-1 The Chemical Manufacturers' Association (American Chemistry Council) Product Stewardship Code

The purpose of the Product Stewardship Code of Management Practices is to make health, safety and environmental protection an integral part of designing, manufacturing, marketing, distributing, using, recycling and disposing of our products. The Code provides guidance as well as a means to measure continuous improvement in the practice of product stewardship.
The scope of the Code covers all stages of a product's life. Successful implementation is a shared responsibility. Everyone involved with the product has responsibilities to address society's interest in a healthy environment and in products that can be used safely. All employers are responsible for providing a safe workplace, and all who use and handle products must follow safe and environmentally sound practices.

The Code recognizes that each company must exercise independent judgment and discretion to successfully apply the Code to its products, customers and business.

Relationship to Guiding Principles

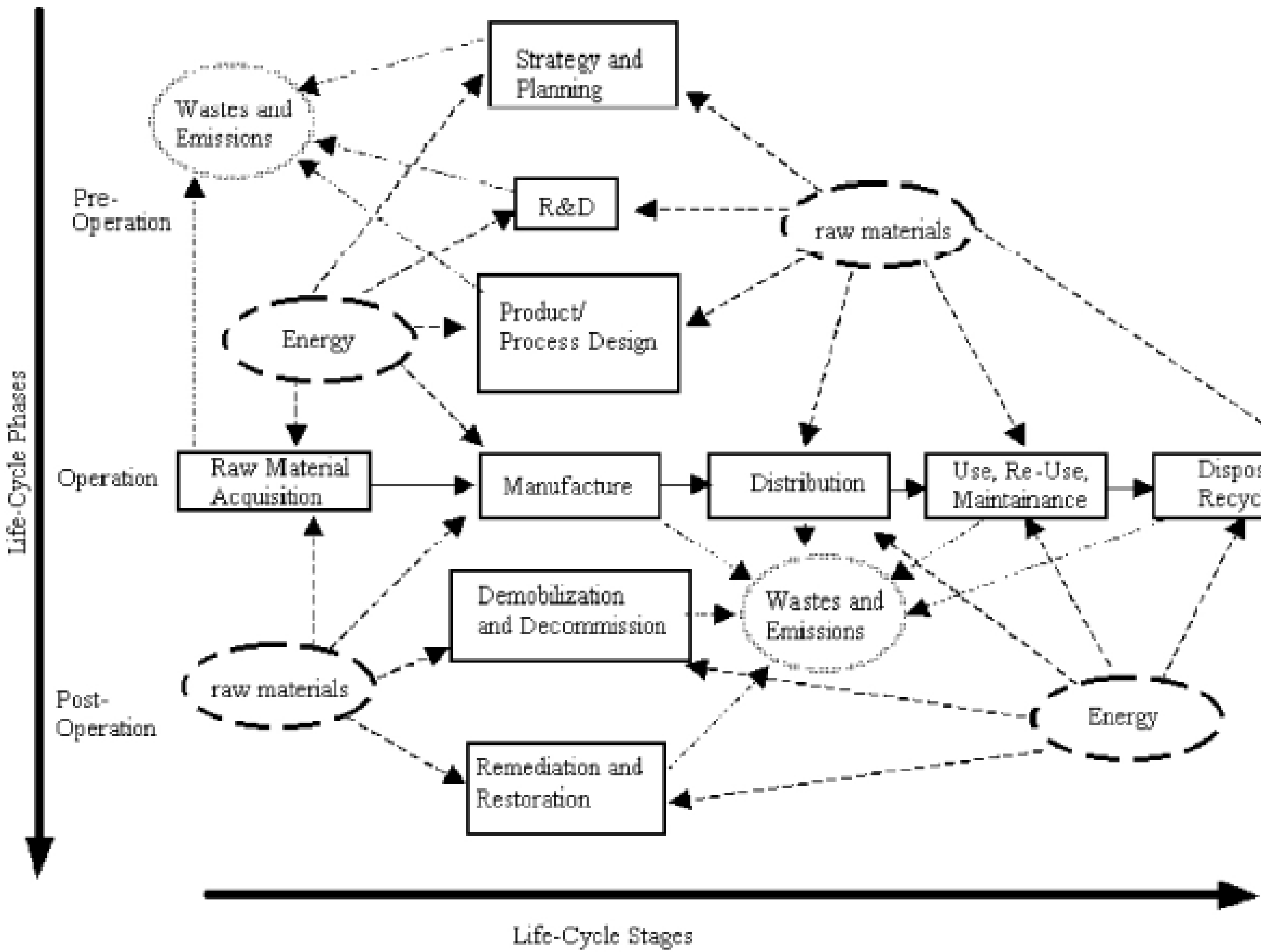
Implementation of the Code promotes achievement of several of the Responsible Care Guiding Principles:

- To make health, safety and environmental considerations a priority in our planning for all existing and new products and processes;
- To develop and produce chemicals that can be manufactured, transported, used and disposed of safely;
- To extend knowledge by conducting or supporting research on the health, safety and environmental effects of our products, processes and waste materials;
- To counsel customers on the safe use, transportation and disposal of chemical products;
- To report promptly to officials, employees, customers and the public, information on chemical related health or environmental hazards and to recommend protective measures;
- To promote the principles and practices of Responsible Care by sharing experiences and offering assistance to others who produce, handle, use, transport or dispose of chemicals.

13.1 Introduction to product life cycle concept

Effective product and process stewardship requires designs that optimize performance throughout the entire life cycle. This chapter provides an introduction to tools available for assessing the environmental performance of products and processes throughout their life cycle. The primary focus is on product life cycles, but similar concepts and tools could be applied to process life cycles.

Sections 13.2 and 13.3 present quantitative tools used in product life cycles assessments (LCAs). Section 13.4 presents more qualitative tools. Section 13.5 describes a number of applications for these tools and Section 13.6 summarizes the main points of the chapter.


Strategy and Planning
Wastes and Emissions
R&D
raw materials
Pre-Operation
Energy
Product/ Process Design
Life-Cycle Phases
Operation
Raw Material Acquisition
Manufacture
Distribution
Use, Re-Use, Maintainance
Disposal, Recycle
Demobilization and Decommission
Wastes and Emissions
raw materials
Post-Operation
Energy
Remediation and Restoration
Life-Cycle Stages

Example 13.3

Selected environmental indices from the Environmental Priority Strategies system.

In the EPS system, environmental indices are multiplied by the appropriate quantity of raw materials used or emissions released to arrive at Environmental Load Units (ELUs), which can then be added together to arrive at an overall ELU for the subject of the life-cycle study. Table 13.8 gives selected environmental weighting factors from the EPS system. Calculate the environmental load units due to air emissions from one kilogram of ethylene production. Emissions are 0.53 kg, 0.006 kg, 0.0009 kg, and 0.009 kg of carbon dioxide, nitrogen oxides, carbon monoxide, and sulfur oxides, respectively (Boustead, 1993).

Solution

Total ELUs due to air emissions are

$0.53 \text{ kg } CO_2 \times 0.09 \text{ ELU/kg } CO_2$

$0.006 \text{ kg } NO_x \times 0.22 \text{ ELU/kg } NO_x$

$0.0009 \text{ kg CO} \times 0.27 \text{ ELU/kg CO}$

$0.009 \text{ kg } SO_x \times 0.10 \text{ ELU/kg } SO_x$

$= 0.05$ ELU.

Note that if quantities of raw materials or water emissions were given, the ELUs for these inputs would be added to the ELUs for the air emissions.

Ecolabels from Around World

Canada
(Environmental Choice)

Nordic Countries
(White Swan)

West Germany
(Blue Angel)

Japan (EcoMark)

United States (Scientific
Certification Systems)*

United States
(Green Seal)

Product Life Cycle Assessment

Motivation

- Integrate and prioritize environmental issues along product lines
- Product stewardship
- Supply chain management
- Environmental labels and other public policy or marketing programs

Stewardship: 책무

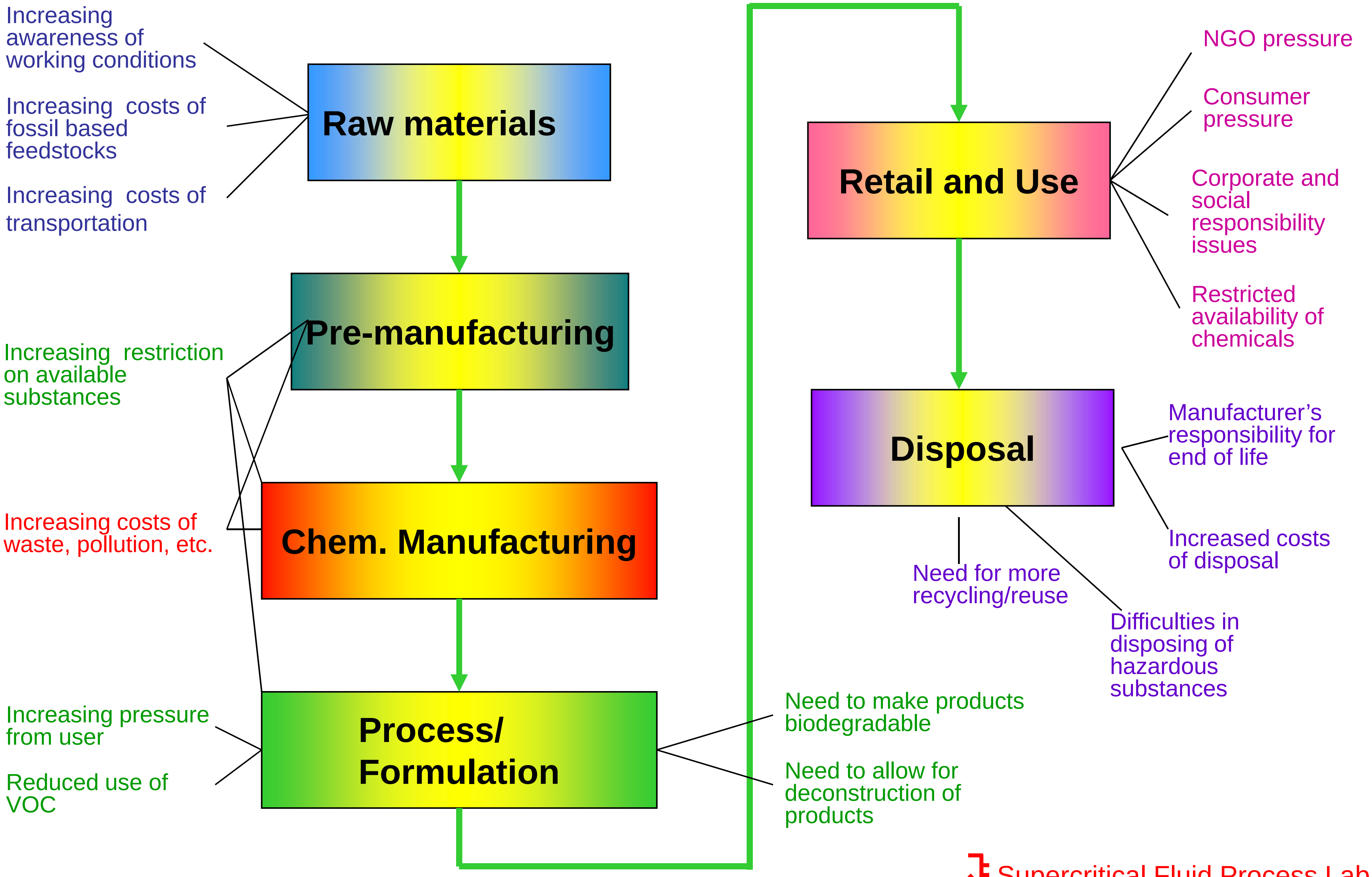
Product Life Cycle Assessment

Products, services, and processes all have a life cycle.

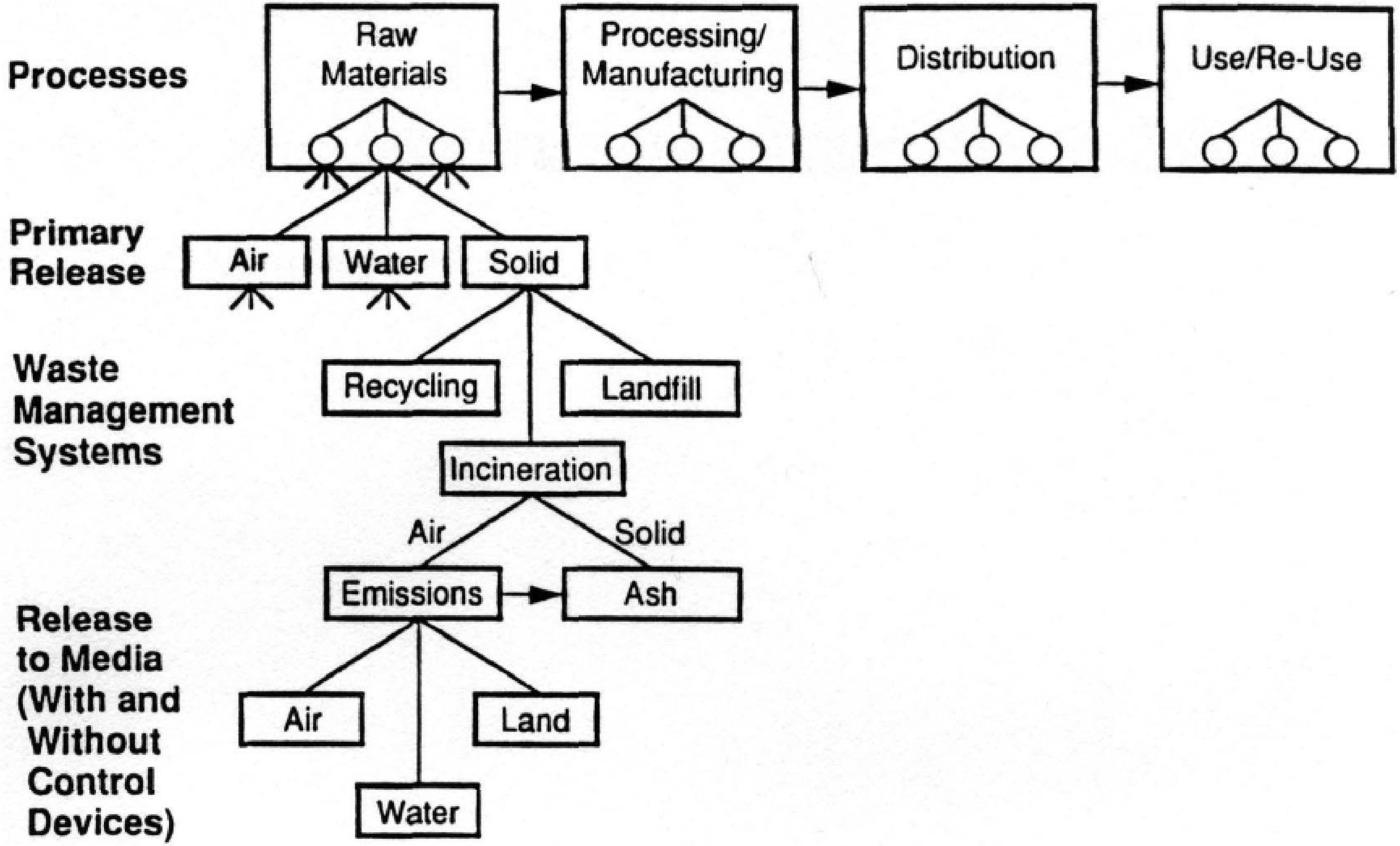
For products, the life cycle begins when raw materials are extracted or harvested. Raw materials then go through a number of manufacturing steps until the product is delivered to a customer. The product is used, then disposed of or recycle.

Processes also have a life cycle. The life cycle begins with planning, research and development. The products and processes are then designed and constructed . A process will have an active lifetime, then will be decommissioned and if necessary, remediation and restoration may occur. Again, energy consumption, wastes, and emissions are associated with each step in the life cycle.

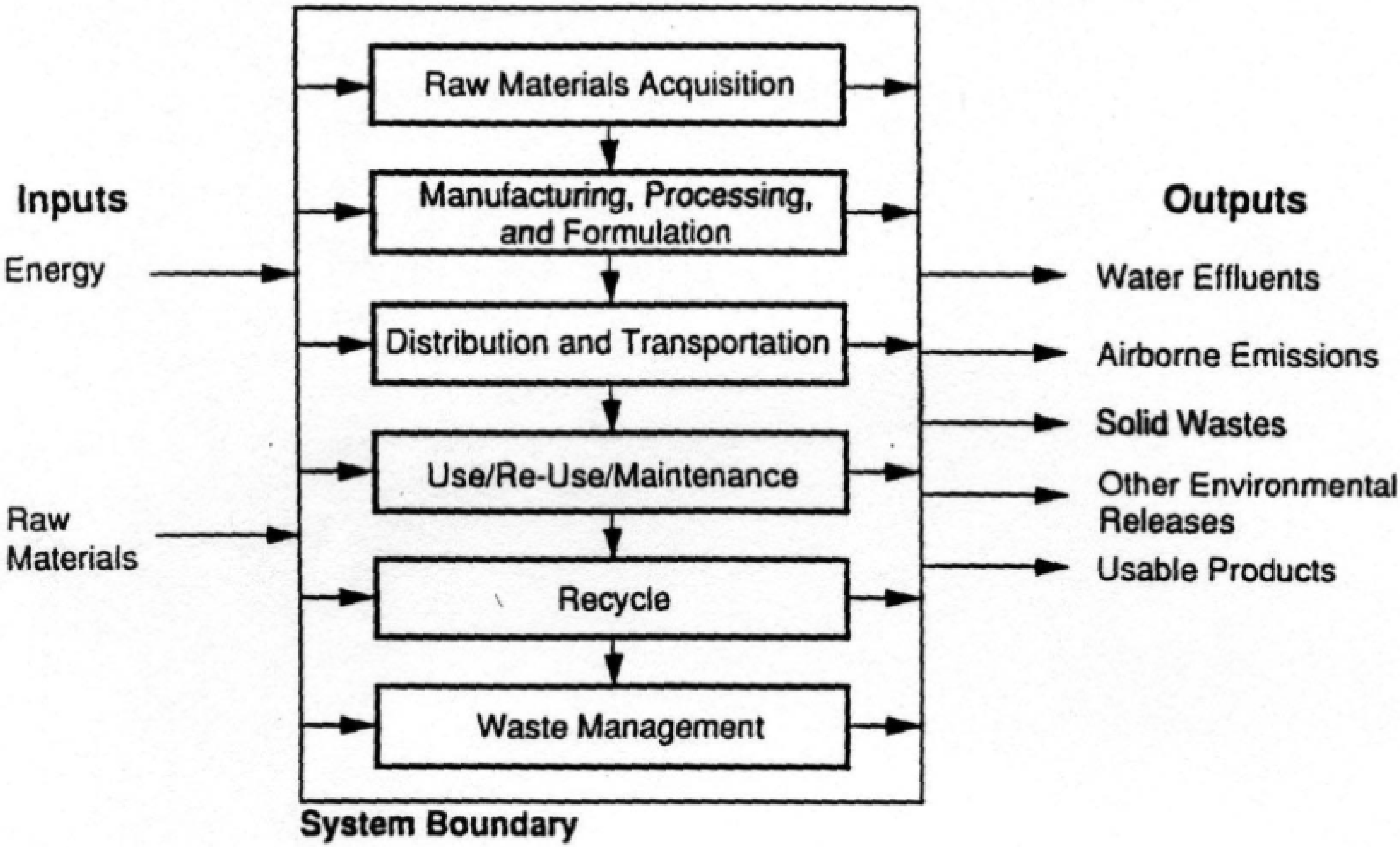
Supply chain pressures



Generic Pathways of Environmental Releases



Life-Cycle Inventory



Product Life-Cycle Assessment

A process

To evaluate the environmental burdens associated with a product, package, process, or activity by identifying and quantifying energy and material usage and environmental releases throughout the life cycle.

To assess the impact of those energy and materials and releases on the environment, and

To evaluate and implement opportunities to affect environmental improvements

13.2.1 Definitions and Methodology

There is some variability in life cycle assessment terminology, but the most widely accepted terminology has been codified by international groups convened by the Society for Environmental Toxicology and Chemistry (SETAC) (see, for example, Consoli, et al., 1993). Familiarity with the terminology of life-cycle assessment makes communication of results easier and will aid in understanding the concepts presented later in this chapter. To begin, a **life-cycle assessment (LCA)** is the most complete and detailed form of a life-cycle study. A life-cycle assessment consists of four major steps.

Four major steps of Life-Cycle Assessment

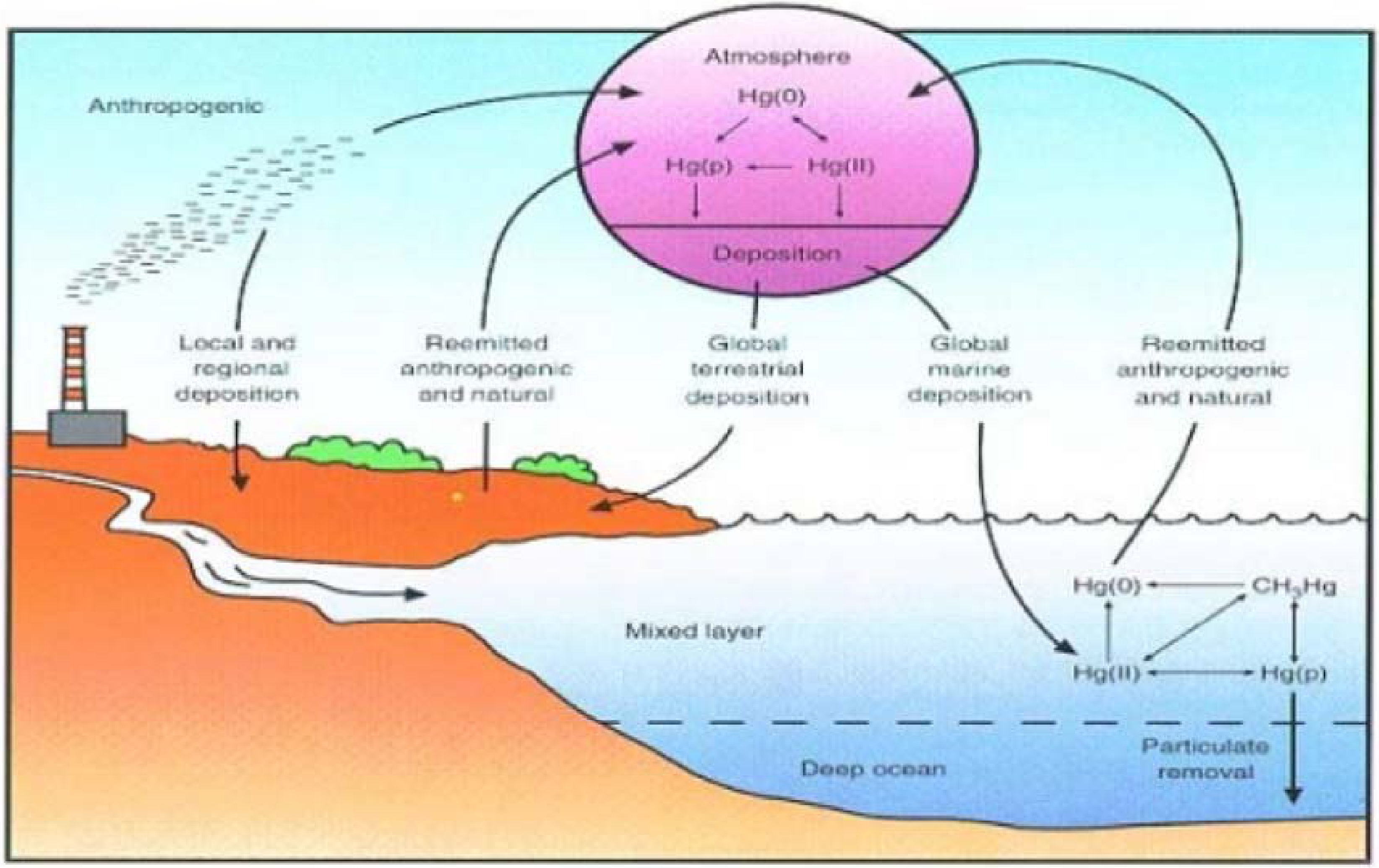
Step 1: The first step in an LCA is to determine the scope and boundaries of the assessment.

Step 2: The second step in a life-cycle assessment is to inventory the outputs that occur, such as products, byproducts, wastes and emissions, and the inputs, such as raw materials and energy, that are used during the life-cycle.

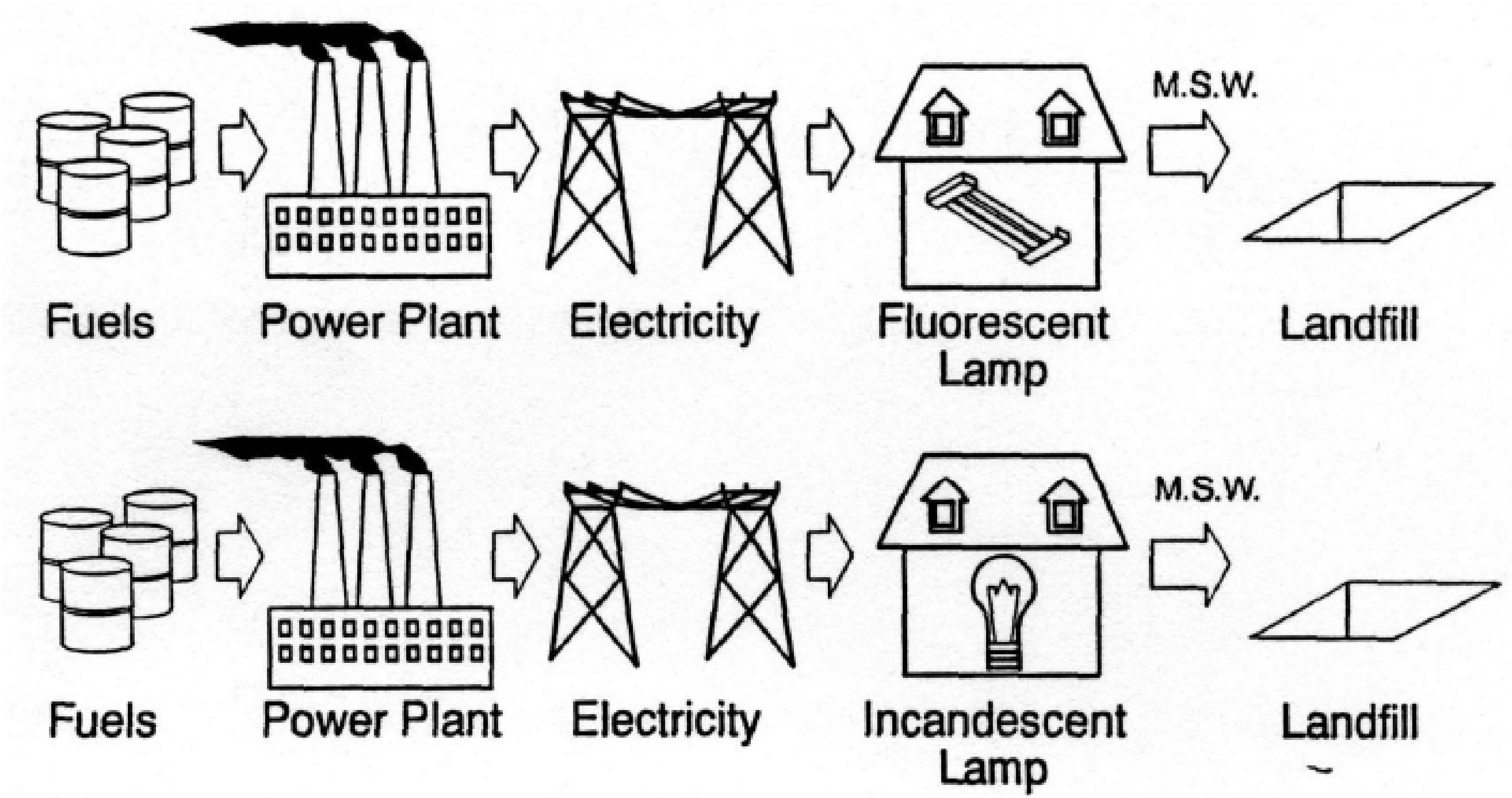
Step 3: The output from a life cycle inventory is an extensive compilation of specific materials used and emitted. Converting these inventory elements into an assessment of environmental performance requires that the emissions and material use be transformed into estimates of environmental impacts.

Step 4: The fourth step in a life cycle assessment is to interpret the results of the impact assessment, suggesting improvements whenever possible (*life-cycle impact assessment*).

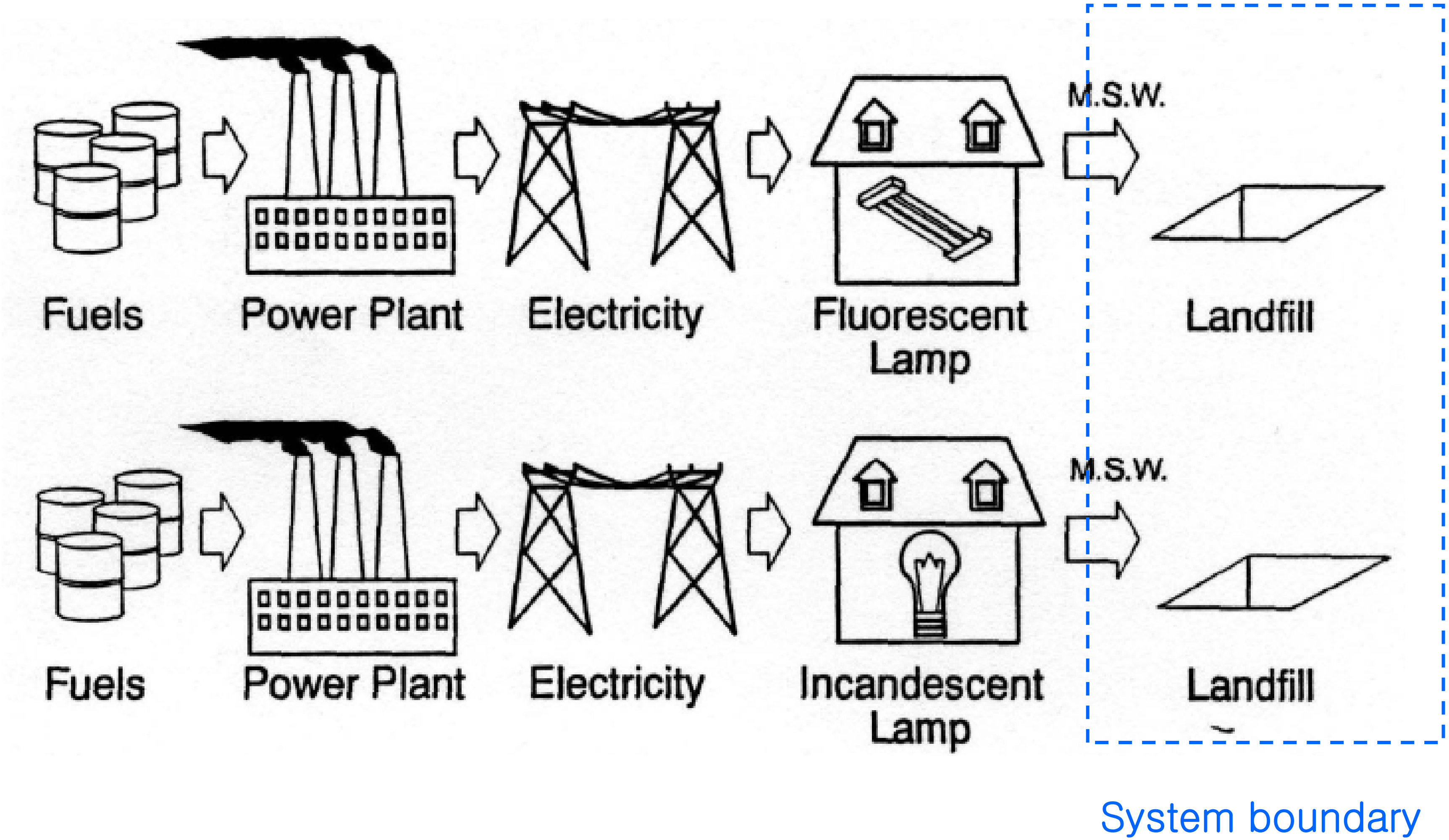
Mercury Cycling in the Environment



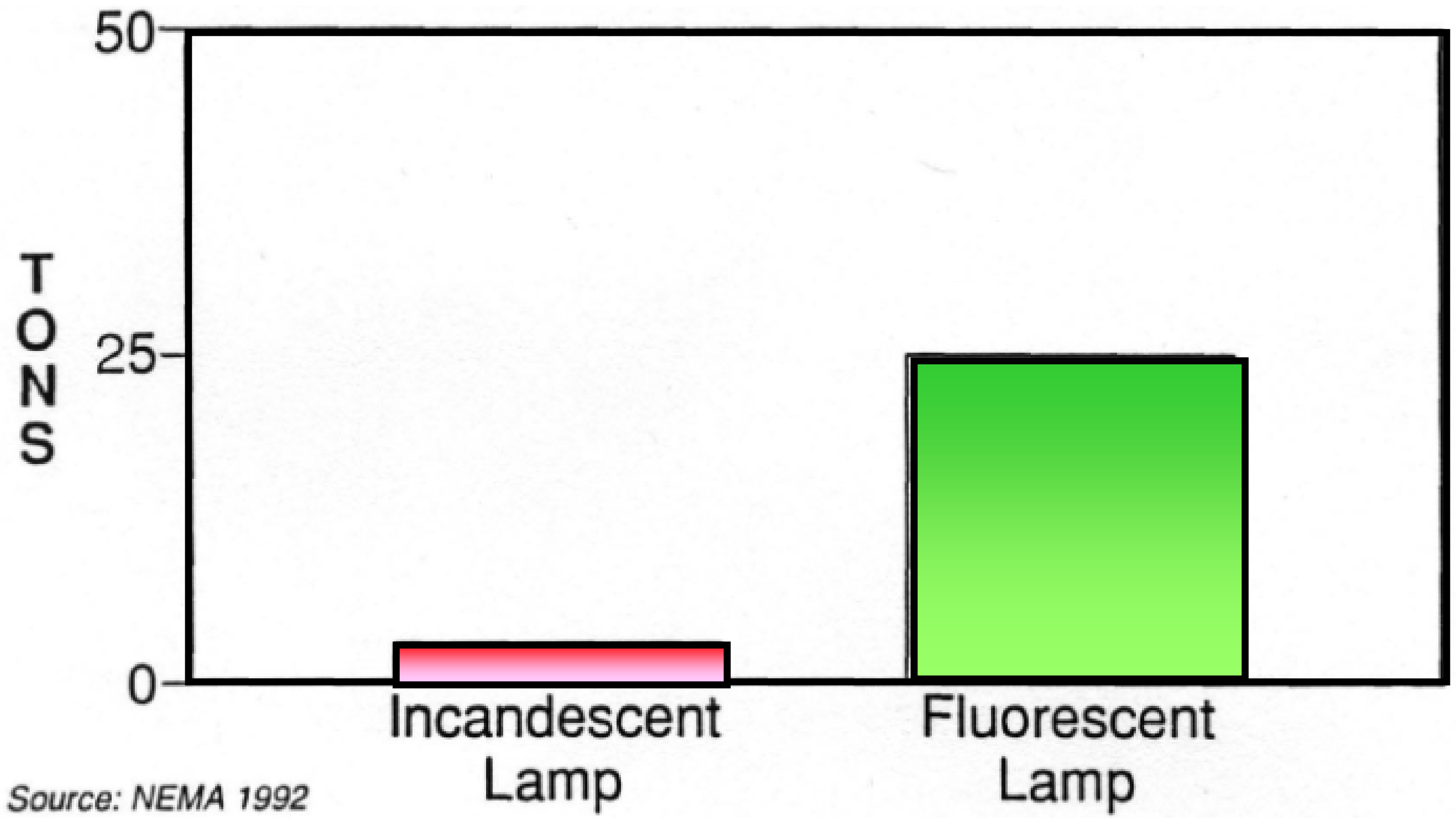
Lightening Life-Cycle Assessment



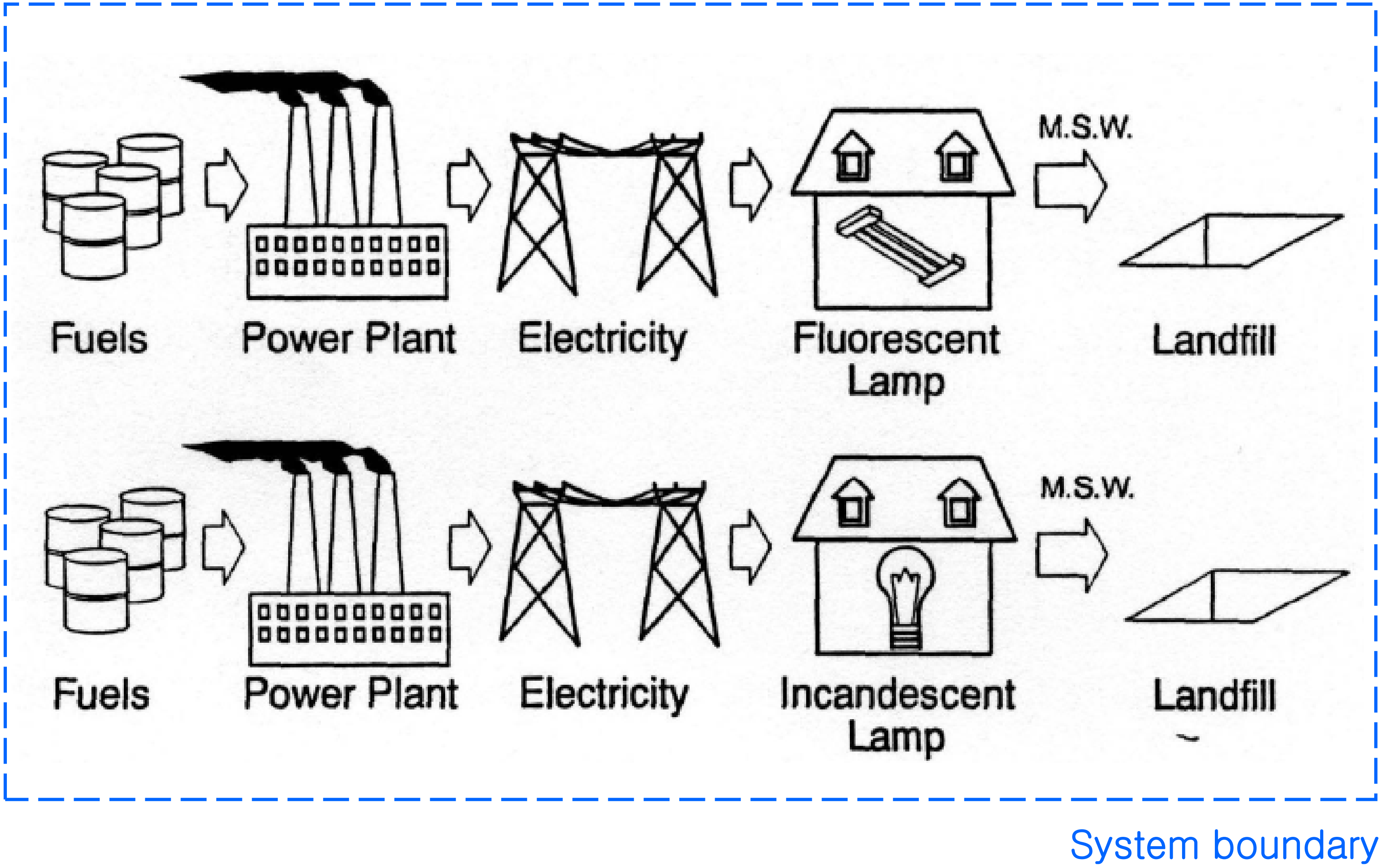
Lightening Life-Cycle Assessment



Mercury entering MSW in the U.S. from lamp annually



Lightening Life-Cycle Assessment



Mercury released into environment from use and disposal lamps

- Use and disposal of incandescent lights release, on average, 4 to 10 times the amount of mercury into the environment than use and disposal of fluorescent lights

- EPA estimates aggregated national electricity demand could be reduced by 50% ; Annual CO_2 emissions by 232 million tons; SO_2 emissions by 1.7 million tons, and NO_2-emissions by 0.9 million tons

Problem and Possible Actions

Problem

Reduce mercury levels associated with lighting systems in order to reduce overall release of mercury into environment

Possible Actions

1. Ban fluorescent lamps from MSW
2. Encourage more use of fluorescent lamps

Functional unit

Another critical part of defining the scope of a life cycle assessment is to specify the **functional unit.** The choice of functional unit is especially important when life-cycle assessments are conducted to compare products. This is because functional units are necessary for determining equivalence between the choices.

For example, if paper and plastic grocery sacks are to be compared in an LCA, it would not be appropriate to compare one paper sack to one plastic sack. *Instead the products should be compared based on the volume of groceries they can carry.* Because fewer groceries are generally placed in plastic sacks than in paper sacks, some LCAs have assumed a functional equivalence of two plastic grocery sacks to one paper sack.

Differing product lifetimes must also be evaluated carefully when using life-cycle studies to compare products. For example, a cloth grocery sack may be able to hold only as many groceries as a plastic sack, but will have a much longer use lifetime that must be accounted for in performing the LCA. As shown in the problems at the end of this chapter, the choice of functional unit is not always straightforward and can have a profound impact on the results of a study.

Four major steps of Life-Cycle Assessment

Step 1: The first step in an LCA is to determine the scope and boundaries of the assessment.

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Life-Cycle Inventory

A life-cycle inventory is a set of data and material and energy flow calculations that quantifies the inputs and outputs of a product life-cycle. Some of the values that are sought during the inventory process are objective quantities derived using tools such as material and energy balances. As is shown later in this section, other values are more subjective and depend on choices and assumptions made during the assessment.

Life-Cycle Inventory

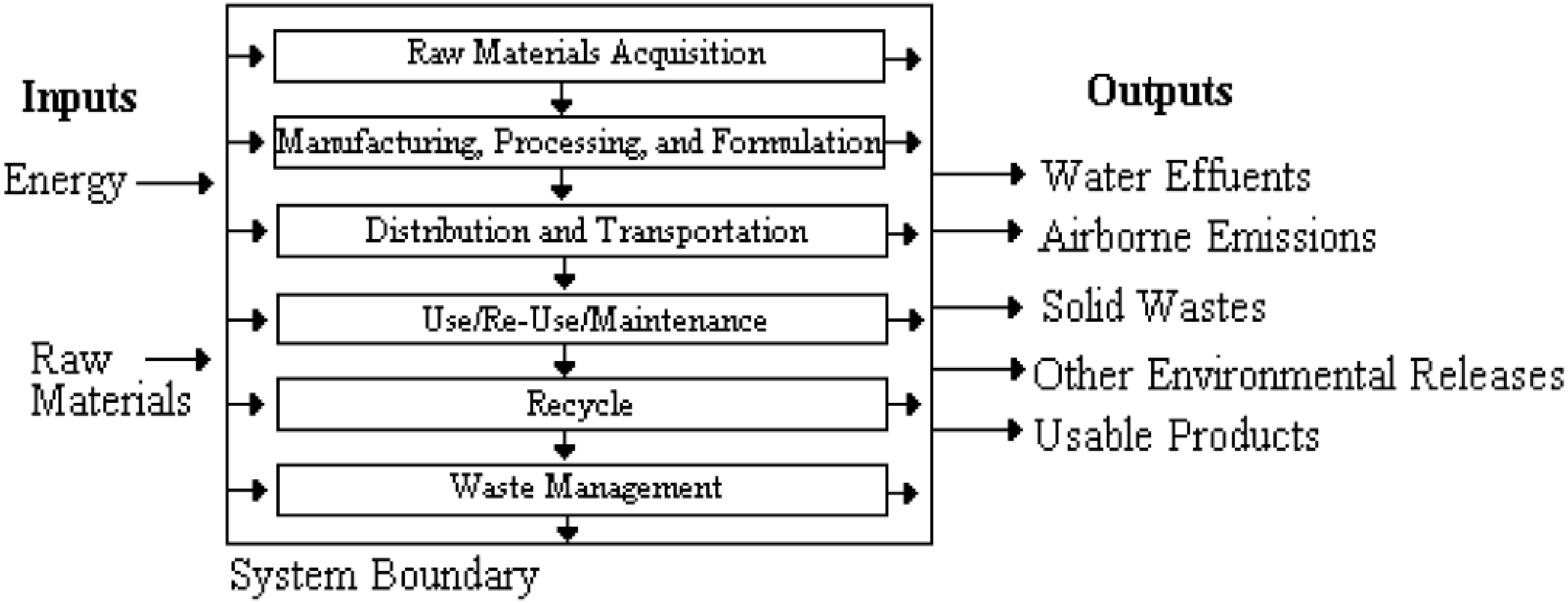


Figure 13.3 Life cycle inventories account for material use, energy use, wastes, emissions and co-products over all of the stages of a product's life cycle.

Inventory=목록을 만들다

Life-Cycle Assessment

Life-cycle inventories do not by themselves characterize the environmental performance of a product, process, or service. This is because overall quantities of wastes and emissions, and raw material and energy requirements must be considered in conjunction with their potency of effect on the environment. Simply stated, a pound of lead emitted to the atmosphere has a different environmental impact than a pound of iron emitted to surface waters. To develop an overall characterization of the environmental performance of a product or process, throughout its life cycle, requires that life cycle inventory data be converted into estimates of environmental impact.

Product Life-Cycle Assessment

The process of producing life-cycle impact assessments is generally divided into three major steps (Fava, et al., 1992). They are:

★ **classification, where inputs and outputs determined during the inventory process are** classified into environmental impact categories; for example, methane, carbon dioxide and CFCs would be classified as global warming gases.

★ **characterization, where the potency of effect of the inputs and outputs on their** environmental impact categories is determined; for example, the relative greenhouse warming potentials (see Chapter 11) of methane, carbon dioxide and CFCs would be identified in this step.

★ **valuation, where the relative importance of each environmental impact category is assessed,** so that a single index indicating environmental performance can be calculated.

Potential Applications

- Applications internal to a company or companies
- Applications external that seek to influence or support public policy or environmental claims

Sample Case Study

Purpose

Evaluate Strategies for Environmental Improvement

Product

Liquid Fabric Conditioner Product Packaging

Baseline Condition for Comparison

Non-Recycled, 64 oz. (1.89 **L**) Virgin HDPE Bottle

Summary of Life-Cycle Analysis

Strategies for Packaging Improvement	% Decrease in Energy Needs			% Decrease in Emissions		
	Process	Transport	Feedstock	Solid	Aqueous	Airborne
1. Incorporate 25% Recycled Plastic	3	0	9	9	(+4)	4
2. Encourage 25% Consumer Recycling	3	2	11	11	(+4)	5
3. Triple-Concentrate (3X) Product	55	53	56	55	54	55
4. Market Product Soft Pouch	3	18	67	85	(+12)	24
5. Market 3X Product in Soft Pouch	68	73	89	95	63	75
6. Market 3X Product in Paper Carton	53	58	94	91	40	62
7. Encourage 25% Composting for 6	53	58	94	92	40	62

Source: Procter & Gamble

Lightening System

Programs are being established to encourage more use of energy efficient lighting systems which generally use mercury bearing light sources; for example;

- EPA's Green Lights Program established in 1991 aimed at persuading companies to upgrade their lighting system to more efficient sources

- Utilities are sponsoring demand side management (DSM) programs to reduce the demand for electricity

Life-Cycle Impact Assessment

A systematic, quantitative or qualitative process for identifying, characterizing and valuing potential impacts to human health, ecosystems and natural resources associated with a product or process life cycle

- could be quantitative or qualitative
- three steps: identification, characterization and valuation
- endpoints of concern include human health, ecosystem health and resource stocks

Identification, Characterization and Valuation

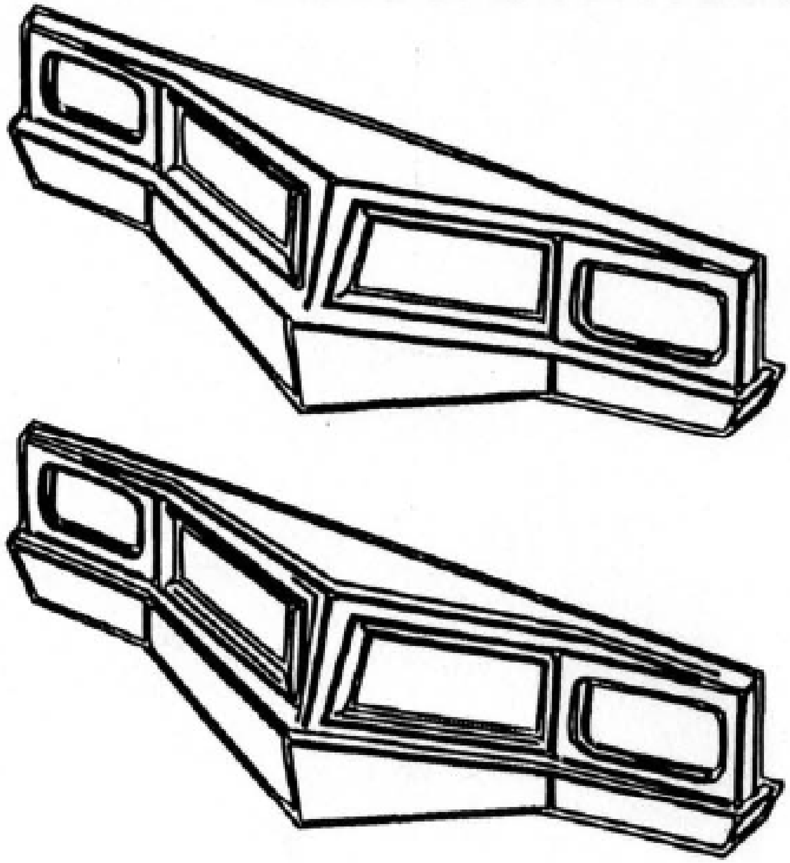
- Identification: identify all inventory elements that contribute to a particular impact (e.g., identify all greenhouse gases)
- Characterization: convert emissions into estimated environmental impacts (e.g., use global warming potentials to convert emissions of many greenhouse gases into carbon dioxide equivalents)
- Valuation: condense multiple impacts into a single environmental metric (e.g., compare global warming to other environmental impacts such as water acidification)

Case Study : Volvo EPS system

- Uses environmental load units (ELU)
- ELUs calculated by multiplying inventory elements by ELU/kg
- Best illustrated with a case study

Case Study : Volvo EPS system

Which Front End Is More Environmentally Sound?



GMT - composite
Material consumption: 4.0 kg
(0.3 kg scrap)
Component weight: 3.7 kg

Galvanized steel
Material consumption: 9.0 kg
(3.0 kg scrap)
Component weight: 6.0 kg
Painted area: 0.6 m^2

Case Study : Volvo EPS system

Calculating ELUs

- Presume steel bumper takes 9.0 kg of iron

  ELU due to iron consumption =

  9.0 kg * 0.38 ELU/kg =

  3.4 ELU

- Sum over all inventory elements

Case Study : Volvo EPS system

ELU/kg for various inventory elements

Raw materials	(ELU/kg)
Co	12300
Cr	22.1
Fe	0.38
Mn	21
Mo	4200
Ni	700
Pb	262
Pt	42000000
Rh	42000000
Sn	4200
V	42
Oil	0.168
Coal	0.1
Land	(ELU/m²)
Areable land	2.93
Forested land	1.05
Residual land	0.98
Energy	(ELU/kg)
Oil	0.33
Coal	0.28
Electricity (MJ)	0.014

Emissions – air	(ELU/kg)
CO_2	0.04
CO	0.04
NO_x	245
N_2O	0.6
SO_x	6.03
CH	10.2
PAC	600
Aldehyde	20
HCl	
F	1E-07
Hg	10
Cd	
Emissions – land	**(ELU/kg)**
As	
Cd	
Cr	
Cu	
Hg	
Ni	
Pb	
Sn	
Tl	

Emissions – water	(ELU/kg)
Suspended matter	1E-07
BOD	0.0001
COD	0.00001
TOC	0.00001
Oil	0.00001
Phenol	1
Phosphorus	2
Nitrogen	10
DDT	10000
PCB	10000
Dioxin	100
Al	1
As	0.01
Cd	10
Cr	0.5
Cu	0.005
Fe	1E-07
Hg	10
Mn	1E-07
Ni	0.001
Pb	0.01
Zn	0.00001

Case Study : Volvo EPS system

Calculation of Environmental Load Values

Materials & Processes	Production (ELU/kg)	Production (kg)	Production (ELU)	Product use (ELU/kg)	Product use (Kg)	Product use (ELU)	Waste – Disposal (ELU/kg)	Waste – Disposal (kg)	Waste – Disposal (ELU)	Waste – Incineration (ELU/kg)	Waste – Incineration (kg)	Waste – Incineration (ELU)	Waste – Reuse (ELU/kg)	Waste – Reuse (kg)	Waste – Reuse (ELU)	(ELU)
GMT-composite																
GMT	1.58	4.0	6.32							−0.081	2.7	−0.22	−1.58	0.3	−0.47	5.63
Petrol				0.64	29.4	18.84										18.84
Compression moulding	0.021	4.0	0.08													0.08
Total sum																24.55
Galvanized steel																
Galvanized steel	1.02	8.0	8.16										−0.82	7.6	−6.26	1.90
Petrol				0.64	48.0	30.72										30.72
Spot welding	0.0028	48	0.13													0.13
Painting (m^2)	0.082	0.6	0.05													0.05
Steel stamping	0.042	8.0	0.34													0.34
Total sum																33.14

Case Study : Volvo EPS system

Which bumper is better?

Controversy of Life-Cycle Impact Assessment

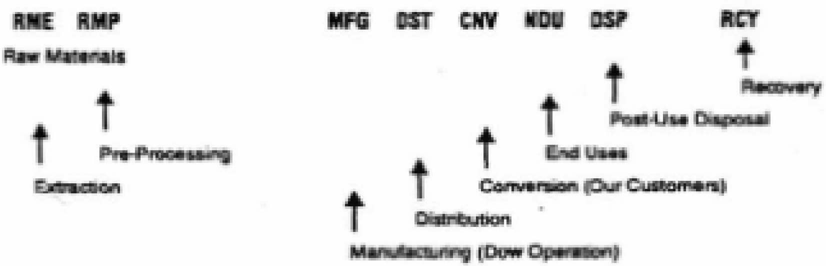
- Inventory elements summed over space and time
- No thresholds
- Valuation step is problematic

So, what do we do?

Qualitative matrix approach

Exhibit 2. Life-Cycle Product Evaluation Framework Used by Dow Chemical Company

Environmental Dimensions	RME	RMP	MFG	DST	CNV	NDU	DSP	RCY
Safety Fire Explosion								
Human Health								
Residual Substances								
Stratospheric Ozone Depletion								
Air Quality								
Climate Change								
Natural Resource Depletion								
Soil Contamination								
Waste Accumulation								
Water Contamination								
Public Perception Gap								
Competition								



RATING SYSTEM

Hazard or Effect	Exposure (Volume, Frequency) HIGH	MEDIUM	LOW
HIGH	-9	-9	-3
MEDIUM	-9	-3	-1
LOW	-3	-1	

Vulnerabilities

9	Proven Implemented Solution
3	Project Initiated Resources Allocated
1	Project Identified

Opportunities

From S. Noesen, Dow Chemical Company (reprinted with permission).

Example : Motorola's Life-Cycle Matrix Table 13.5-2 (pp453)

Summary

Products Life-Cycle Assessment

- A valuable conceptual tool for evaluating and prioritizing environmental impacts along a product chain
- Very difficult to compare products
- Very difficult to perform quantitative impact assessments
- Semi-quantitative methods are emerging

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