Reverse Engineering for Green Design of Products

Overview

- Green Design
  - Definition
  - Goals
- Motivation
- Reverse Engineering for Green Product Design
  - Disassembly
  - Life-Cycle Assessment (LCA)
  - Function Relation Analysis
  - Improvement of Product

Green Design

- Definition

Green Design is an approach in which environmental attributes are treated as objectives rather than constraints, with minimum loss to product performance, useful life, and functionality.

- Goals
  - Reducing or eliminating the use of toxic materials
  - Increasing energy efficiency
  - Reducing the amount of material needed to perform the same function
  - Extending the life of a product

Motivation

Motivations for incorporating Green Design considerations into the early stages of product design include the following:

- Market demands
  - (e.g.: Energy Star program)
- Regulatory pressures
  - (e.g.: Government imposed take-back programs in Germany)
- Manufacturing costs
  - (e.g.: It is cheaper to recycle aluminum cans than to produce new ones)

Reverse Engineering

- At various points throughout the design process it is useful to examine the competitor's products and other technologies.
- Examples:
  - understanding design opportunity: What shapes and sizes are on the market? What do the products say? What opportunity do they address?
  - Concept refinement: How do the various competitive products work? What is their overall approach to opportunity solution? What technologies are out there that could benefit us? Is there a design that has features that we want and if so how does it work?
  - Final stage: How did competitors use material? How did they manufacture the product? What is it's quality? How does it feel to use?

Reverse Engineering for Green Product Design (REGPD)

This approach is a new type of reverse engineering. It is a method which combines various techniques already in common use today.

REGPD

- Disassembly
- Life-Cycle Assessment (inventory & impact analysis)
- Function Relation Analysis
- Synthesis (improvement)

Reverse Engineering for Green Product Design (REGPD)

- Disassembly
  - The product to be analyzed is taken apart in preparation for the inventory stage of the Life Cycle Analysis (LCA).
  - Information obtained during the disassembly stage may be useful in the improvement stage. Some issues to be aware of may include
    - Variability of materials
    - Recyclability of materials
    - Reusability of components
    - Ease of disassembly
    - Fastening methods

One-Time-Use Camera
Overall View

The printed cardboard cover has two primary functions.

•Instructional

•Decorative

A possible improvement in the design of the camera would be to eliminate the need for the printed cardboard cover by stamping the instructions directly on the case of the camera.

One-Time-Use Camera
Cardboard Cover Removed

The manufacturer has tried to minimize the variability of materials to increase the recyclability of the camera.

Most of the structural parts in the camera are made of Polystyrene (PS)

Each major part has a standardized code stamped on it indicating the material from which it is manufactured. This helps in the reverse engineering process and when sorting the materials for recycling, especially when this function is performed by third parties.

One-Time-Use Camera
Polycarbonate Cover and Viewfinder

This polycarbonate part has multiple purposes:

•contains the viewfinder

•contains the button for the trigger mechanism

•covers the advance mechanism

•magnifies the number on the remaining-picture-count wheel

The cover and the lens are not reused more than once. The material is ground up and recycled.

One-Time-Use Camera
Polycarbonate Cover Removed

One-Time-Use Camera

Front Cover Removed

The front cover has multiple functions:

•protects the printed circuit board

•holds the lens and the lens carrier in place

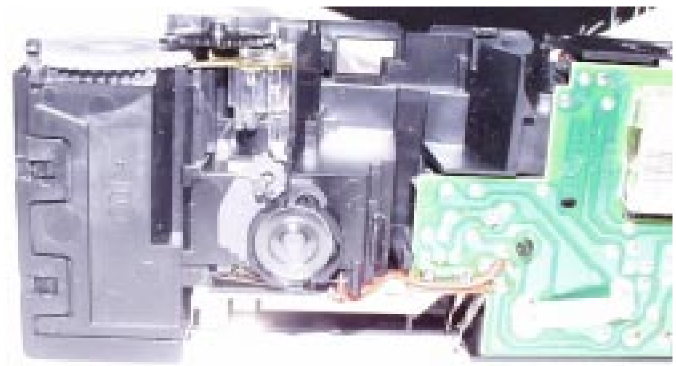
•contains the button to recharge the flash

The front and back covers are ground up and recycled.

The main frame of the camera is reused. The manufacturer keeps track of how many times the frame is used by marking it after each cycle.

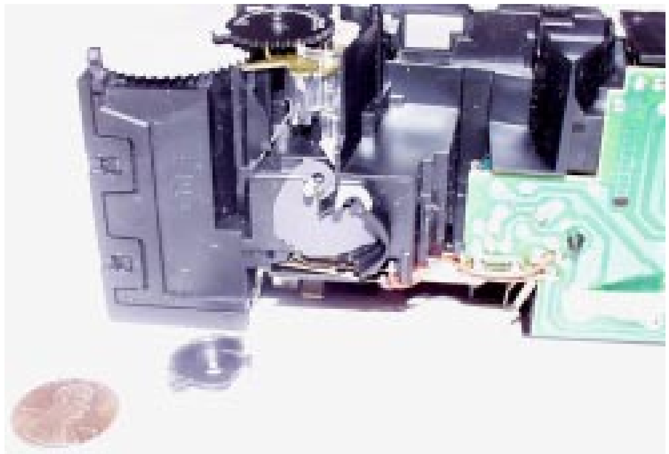
The mainframe is reused up to 10 times before it gets ground up and recycled.

One-Time-Use Camera
Front Cover Removed: Closeup



The viewfinder and the lens do not get reused because according to the manufacturer these are parts that have a direct impact on the product's performance and the customer's perception of product quality.

One-Time-Use Camera
Lens Carrier and Lens Removed



One-Time-Use Camera
Film Cover Removed

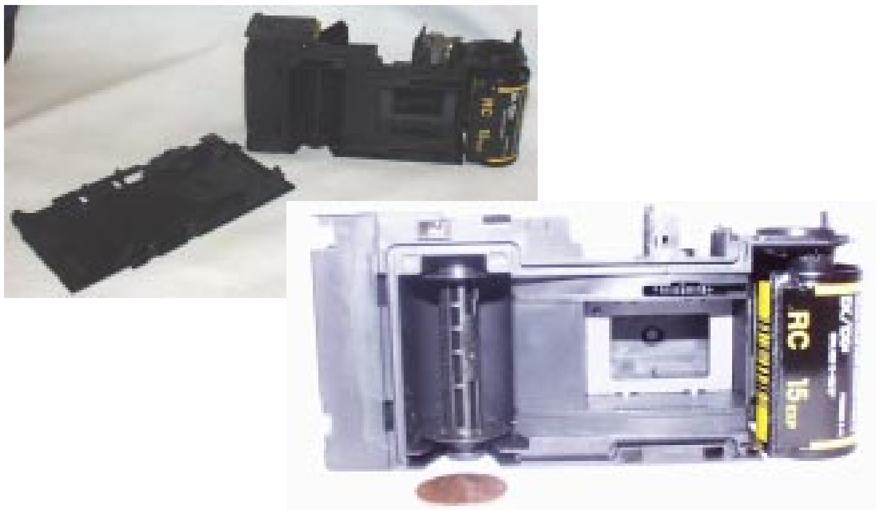
In later models, the film cover has been integrated into the camera’s main frame. This reduces the number of parts which in turn reduces the number of manufacturing, assembly and disassembly steps.

Only snap fasteners (as the ones on the film cover) are used to hold this camera together. The objective is to simplify the assembly process and minimize the number of parts used.

In some cases disassembly of products with snap fasteners is not as simple as the assembly. Parts that are fastened with snap fasteners may be damaged during disassembly if not done carefully. Since the front and back covers are ground up and recycled, it does not matter if they are broken during the disassembly process.

One-Time-Use Camera

Back Cover Removed



One-Time-Use Camera

Film and Reel Removed

After taking pictures, the customer takes the entire camera to the developer. The developer removes the exposed roll and processes the film and sends the rest of the camera back to the manufacturer to begin another cycle.

One-Time-Use Camera

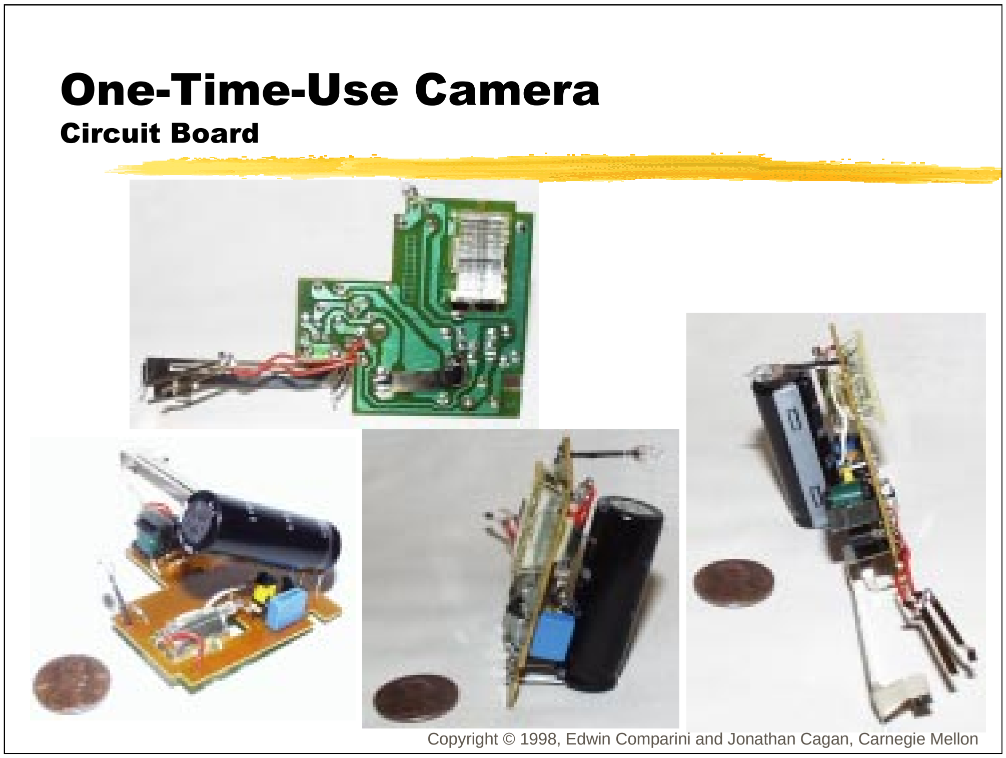
Trigger and Advance Mechanisms Removed

One-Time-Use Camera
Circuit Board Removed

One-Time-Use Camera

Frame Removed

The main frame houses the film, the advance mechanism, the circuit board and the battery. It is reused several times.



The circuit board has several functions:

•charges and triggers flash

•indicates when flash is fully charged

•holds the flash

•holds the battery

The circuit board is reused up to 7 times. It is tested after every cycle.

The circuit board is made out of epoxy resin, glass fibers and copper.

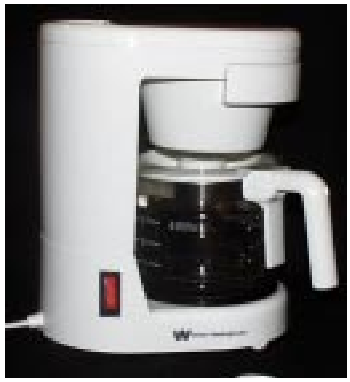
The used batteries are donated to various charities.

One-Time-Use Camera
Polystyrene (PS) Parts

One-Time-Use Camera

Mechanical, Optical and Electrical Parts

Coffee-Maker (White Westinghouse)
Overall View



In the U.S. when a coffee-maker reaches the end of its useful life it does not get recycled; typically it is sent to a landfill.

Polypropylene (PP) is the largest material by volume used in coffee-makers.

Coffee-Maker (White Westinghouse)

Top Cover Removed

This brand of coffee-maker is held together by snap fasteners and common screws and nuts. The only tools needed to disassemble this product is a screw driver and a pair of pliers.

Coffee-Maker (White Westinghouse)
Top Cover Removed

The top cover is easily pried off without any tools.

Coffee Making Process:

•The user pours a measured amount of water into the tank shown.

•The water drains through a hole at the bottom of the tank.

•The water passes through metal tubes where it is heated.

•The vapor pressure that results pushes the water up the vertical tube shown in the picture above. (A check valve prevents the water from returning to the tank.)

•The hot water drains into the filter carrier where it mixes with the ground coffee.

•The hot coffee drips into the glass pot below the filter.

•The glass pot rests on a metal plate that is heated by the same heater element that heats the water in the metal tubes.

The filter carrier slides out for easy cleaning and placement of new coffee and filter.

Coffee-Maker (White Westinghouse)
Bottom View

The galvanized steel plate is fastened to the rest of the coffee maker by four screws and one nut

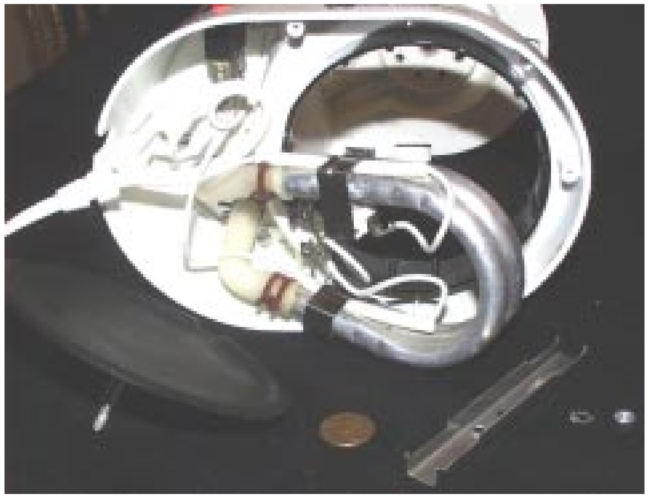
Coffee-Maker (White Westinghouse)
Bottom Cover Removed

Removing the bottom cover exposes the water transport and heating tubes.

A simple switch allows electricity to flow through the heating element shown.

The heating element has two fuses for overload protection.

Coffee-Maker (White Westinghouse)
Hot Plate Removed



Removing one more nut allows the steel hot plate and the heating tubes to come apart.

The steel and plate and the aluminum tubes are separated by a special paste that allows heat transfer between the two metals, but prevents them from corroding each other through galvanic effect.

Coffee-Maker (White Westinghouse)

Tubing and Heating Element Removed

Spring steel fasteners hold the water transport tubes in place. These fasteners are easily removed with a pair of pliers.

The heating element and wires are held in place with metal clips.

Coffee-Maker (White Westinghouse)
Insulator Ring Removed

A phenolic insulator ring prevents the hot plate from coming in direct contact with the rest of the coffee maker structure.

The ring is easily removed with no tools.

Coffee-Maker (White Westinghouse)
Bottom View

Three more fasteners hold the bottom and top structures together.

Coffee-Maker (White Westinghouse)
Top Structure Removed

Coffee-Maker (White Westinghouse)
Rubber Hose Removed: Top View

The rubber tubing is easily removed with no tools.

Coffee-Maker (White Westinghouse)

Disassembled Glass Pot

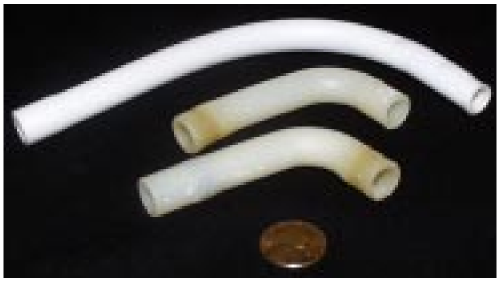
The glass pot handle is fastened to the pot by a single handle.

Coffee-Maker (White Westinghouse)
Polypropylene (PP) Parts

Compare the volume of material used in this coffee maker with the volume used in the Black & Decker model.

Coffee-Maker (White Westinghouse)

Rubber Tubing and Fasteners



The picture on the top right shows the check valve that prevents hot water from backing up into the tank.

Coffee-Maker (Black & Decker)

Overall View

The appearance and function of this coffee maker is very similar to the White Westinghouse model.

As in the previous example, the largest material by volume in this model is polypropylene (PP).

Coffee-Maker (Black & Decker)
Top View

The filter carrier slides out for easy cleaning and replacement of filter and coffee.

Coffee-Maker (Black & Decker)
Bottom View

The galvanized steel plate in this model was held in place by three regular screws and a tamper proof screw at the center of the plate.

The manufacturer’s objective was to prevent the user from attempting to service the unit. Disassembly is made considerably more difficult by this measure. A special tool is required to remove the tamper proof fastener.

Notice the larger area of galvanized steel in this model as compared to the previous example.

Coffee-Maker (Black & Decker)
Bottom Cover Removed

The internal structure in both models is very similar.

A significant difference between the heating components of the two models is that in the Black & Decker model the hot plate is made out of aluminum instead of steel. This eliminates the potential corrosion problem created by having two dissimilar materials in contact with each other, but it increases cost.

Coffee-Maker (Black & Decker)
Hot Plate, Insulator Ring and Switch Removed

Insulator ring comes out easily with no tools.

Coffee-Maker (Black & Decker)
Inner Tank Removed

The polypropylene parts are very hard to disassemble in this model. The entire structure is held together by snap fasteners. This is done to prevent the user from attempting to service the unit.

Notice the amount of material used. Compare to previous model.

Disassembly for servicing, reusing, or recycling is clearly not an objective in this design.

The manufacturer of this model stated that they do not foresee designing for disassembly unless regulatory pressures come into effect. The manufacturer contends that the logistics of a take-back program would be too costly.

Coffee-Maker (Black & Decker)
Top Cover Removed

Coffee-Maker (Black & Decker)

Polypropylene (PP) Parts

Compare the volume of material used in this model to the volume used in the previous model.

Life-Cycle Analysis (LCA)

- LCA is an evaluation of the environmental effect of raw materials taken from the environment (inputs) and the waste released back into the environment (outputs) by an industrial system.

We will use a simplified version of LCA. Boundaries are selected around the specific product.

Life-Cycle Analysis (LCA)

- There are four stages in the traditional LCA approach
  - **Scoping:** definition of purpose
  - **Inventory:** quantification of inputs and outputs to the environment
  - **Impact Assessment:** assessment of the effect of the environmental loads
  - **Improvement Assessment:** assessment of opportunities for improvement

The REGPD approach relies primarily on the inventory and impact assessment stages of the LCA to identify what the greatest loads on the environment are.

Scoping: definition of the purpose of the LCA. What is the LCA going to be used for? Comparing two similar products? Determining the effect of a new product on the environment? Is the desired information for internal or external use?

Inventory: quantification of inputs (energy, raw material) and outputs (environmental releases) throughout the life of the product or activity. How much energy is required to produce, distribute, use and dispose the product? What materials are consumed during all the life-cycle stages of a product? What wastes and pollutants are generated?

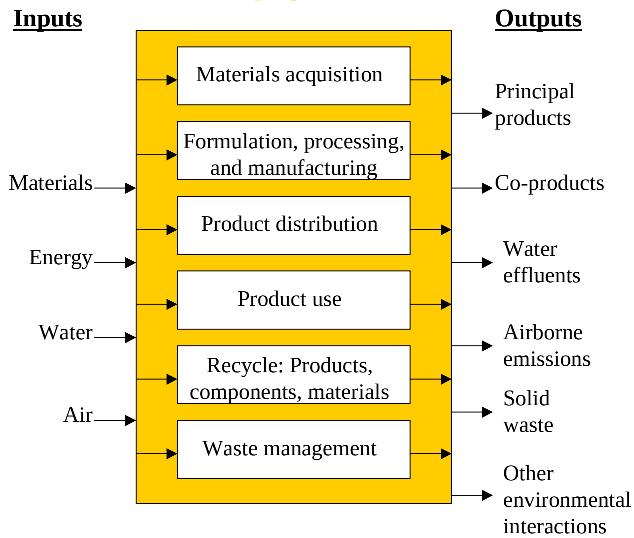
Impact Assessment: quantitative and/or qualitative assessment of the effect of the environmental loads identified in the inventory component. What are the environmental effects of producing the product? How much landfill space will be required for disposal? How do the pollutants affect the environment: Acid rain, ozone depletion?

Improvement Assessment: assessment of opportunities for improvement of economic impact. Can the amounts of pollutants be reduced? Can the product be reused, recycled, refurbished? Can energy be recuperated from the product by incineration?

(Graedel, Allenby, 1995)

Life-Cycle Analysis

Elements of life-cycle inventory (Graedel & Allenby, 1995)



Generic example of life-cycle inventory

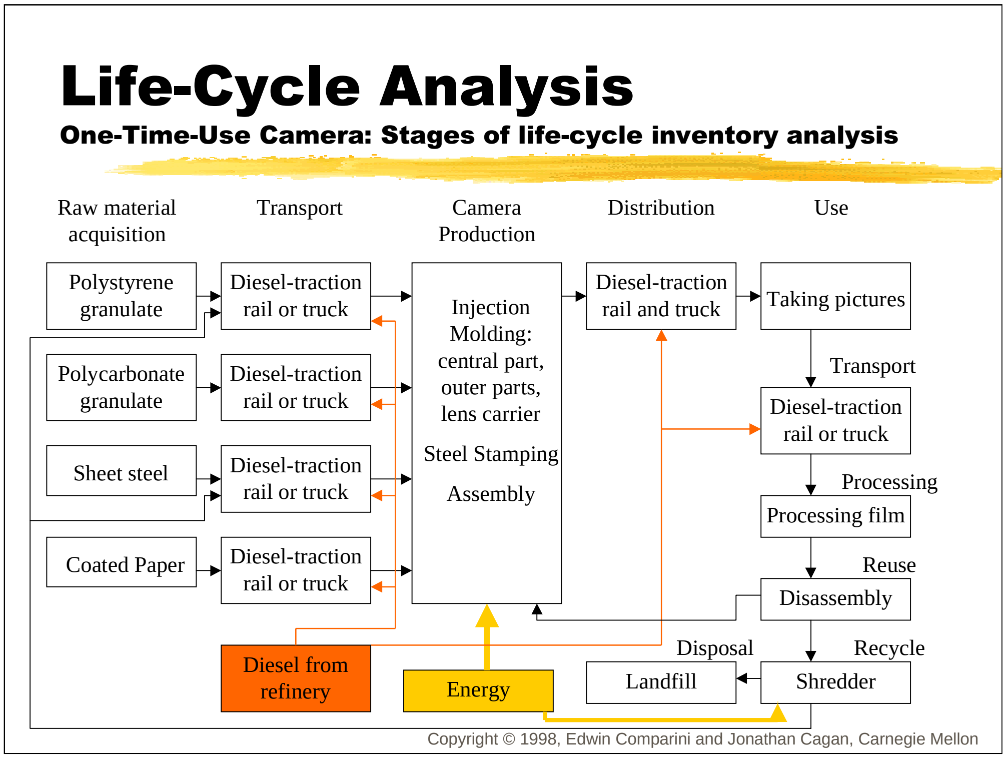
Life-Cycle Analysis

Materials Inventory: One-Time-Use Camera

Material	Weight (+/- 1g)	Material	Weight (+/- 1g)
polystyrene	55g	circuit board (resin, fibers, copper)	23g
cardboard	10g	battery	23g
polycarbonate	8g	roll (polypropylene, polyacetate)	17g
steel	3g		

The material inventory together with the information from the extraction, processing, transportation, use and waste management stages are necessary to obtain an inventory of all the environmental inputs and outputs.

Inventory information can be obtained from publicly available databases and industry surveys or from commercial software.

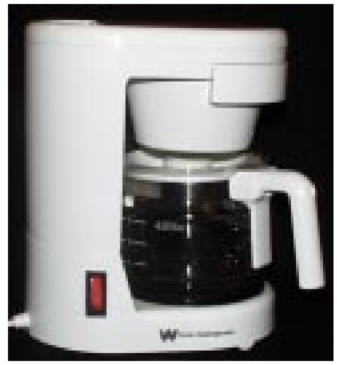


Energy consumption during manufacturing is much higher than during product use.

Life-Cycle Analysis

Materials Inventory: Coffee Maker (White Westinghouse)

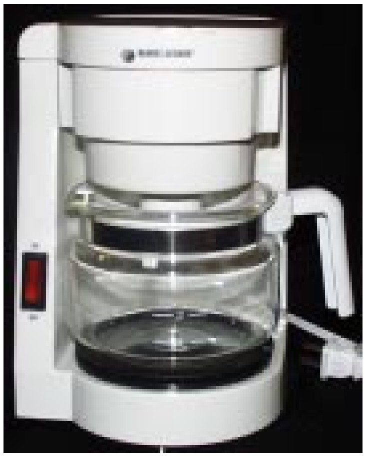
Material	Weight (+/- 1g)
polypropylene	372g
steel	212g
glass	180g
aluminum	91g
rubber	27g
other materials	111g

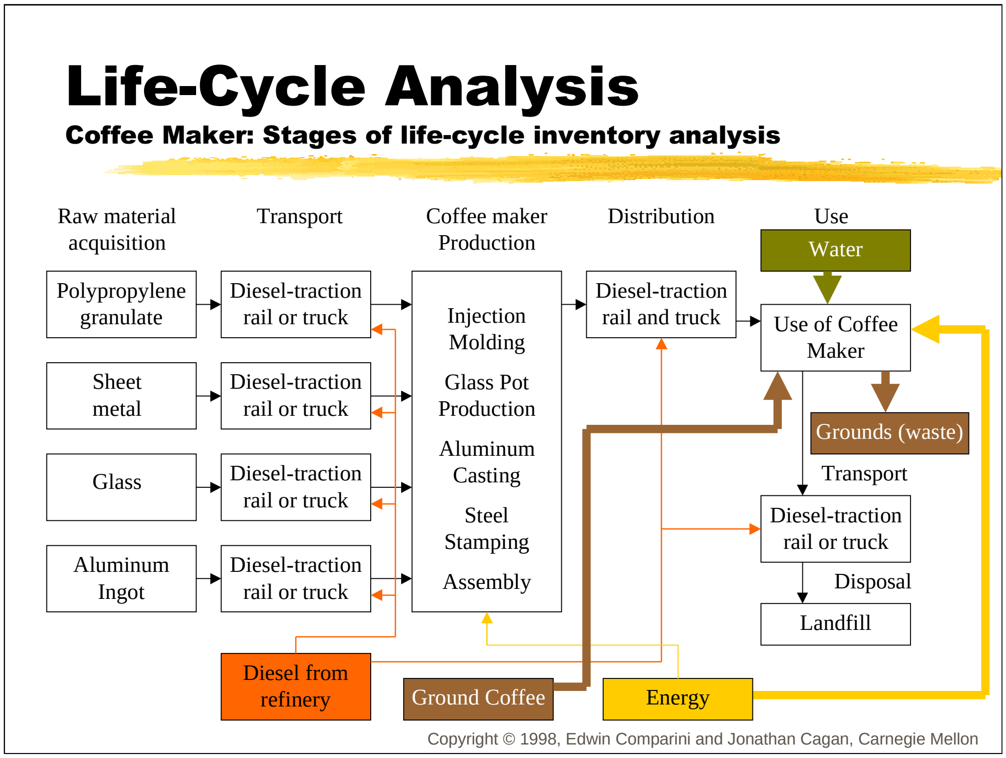


Life-Cycle Analysis

Materials Inventory: Coffee Maker (Black & Decker)

Material	Weight (+/- 1g)
polypropylene	560g
steel	260g
glass	180g
aluminum	80g
rubber	23g
other materials	80g





Energy during use stage is much more than during manufacturing stage.

Life-Cycle Analysis

Impact Assessment

Based on the inventory of inputs and outputs, an assessment of the environmental impact of a product can be made through the use of publicly available data bases or commercial software.

Results from this LCA stage may include the following:

- Acidification Potential
- Global Warming Potential
- Ozone Layer Depletion Potential

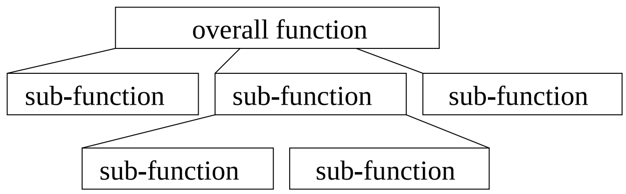
Function Relation Analysis

The objective of this approach is to allow the designer to think of a product in terms of the function it has to perform.

Once the main function has been identified and the corresponding sub-functions sufficiently refined, the designer may select from various catalogs specific components that satisfy the sub-functions.

Function Relation Analysis

•Design method in which the designer focuses on the function and sub-functions that the product or system has to perform and not on a particular solution.
•The designer works from function to form
•Function structure - hierarchical breakdown of function components.



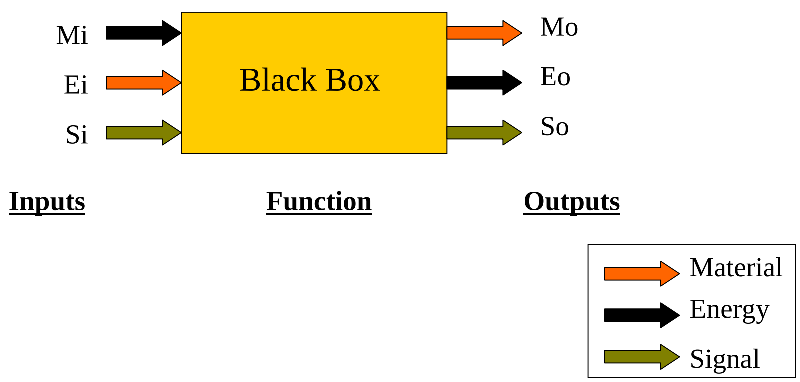
- Functions of subsystems together accomplish some desired task
- Breakdown helps organize and make design achievable

Function Relation Analysis

- Procedure
  - Express overall function for the design in terms of conversion of inputs and outputs.
  - Break down overall function into a set of essential sub-functions.
  - Draw a block diagram showing the interactions between sub-functions.
  - Draw the system boundary.
  - Search for appropriate components for performing the sub-functions and their interactions.

Function Relation Analysis

Step 1 Overall function: conversion of inputs and outputs

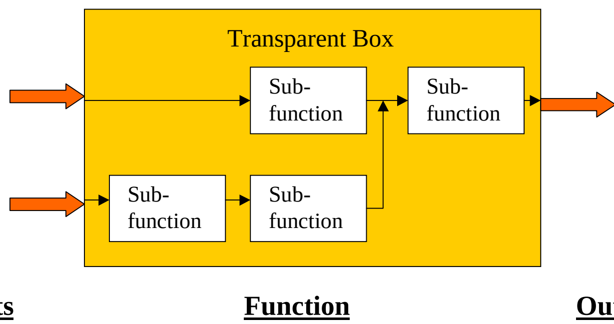


Step 1 of generic example of function relation analysis

Important: Signal transformation is taken into account in function relation analysis, but not in traditional LCA

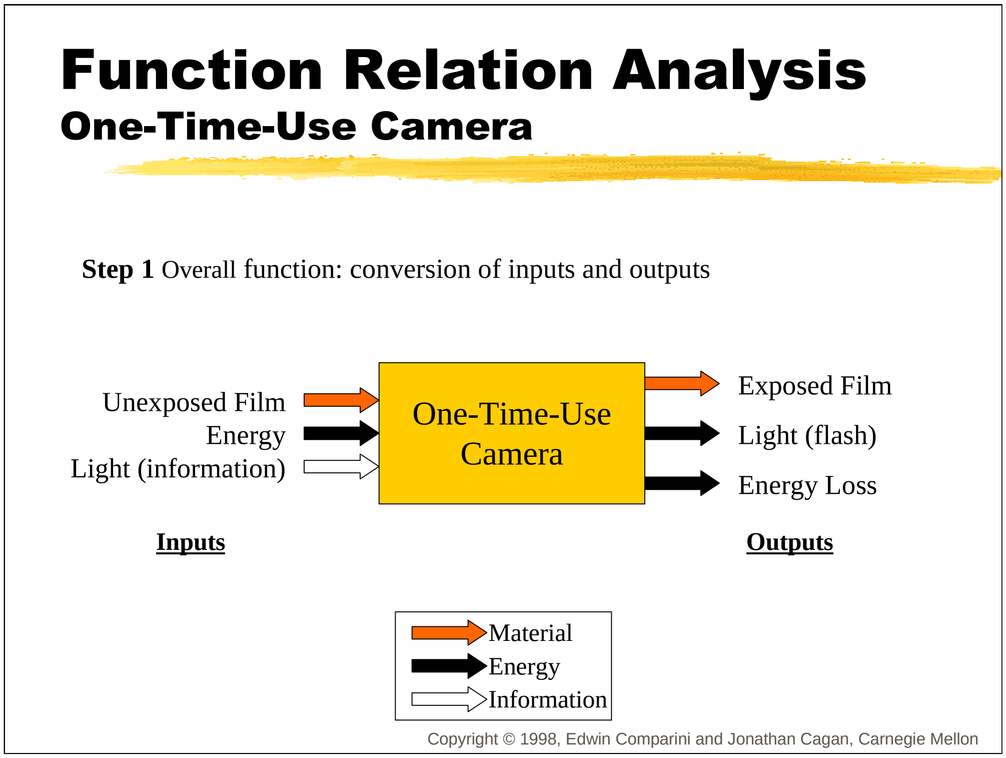
Function Relation Analysis

- **Step 2:** Breakdown of overall function into a set of essential sub-functions
- **Step 3:** Draw block diagram
- **Step 4:** Draw system boundary

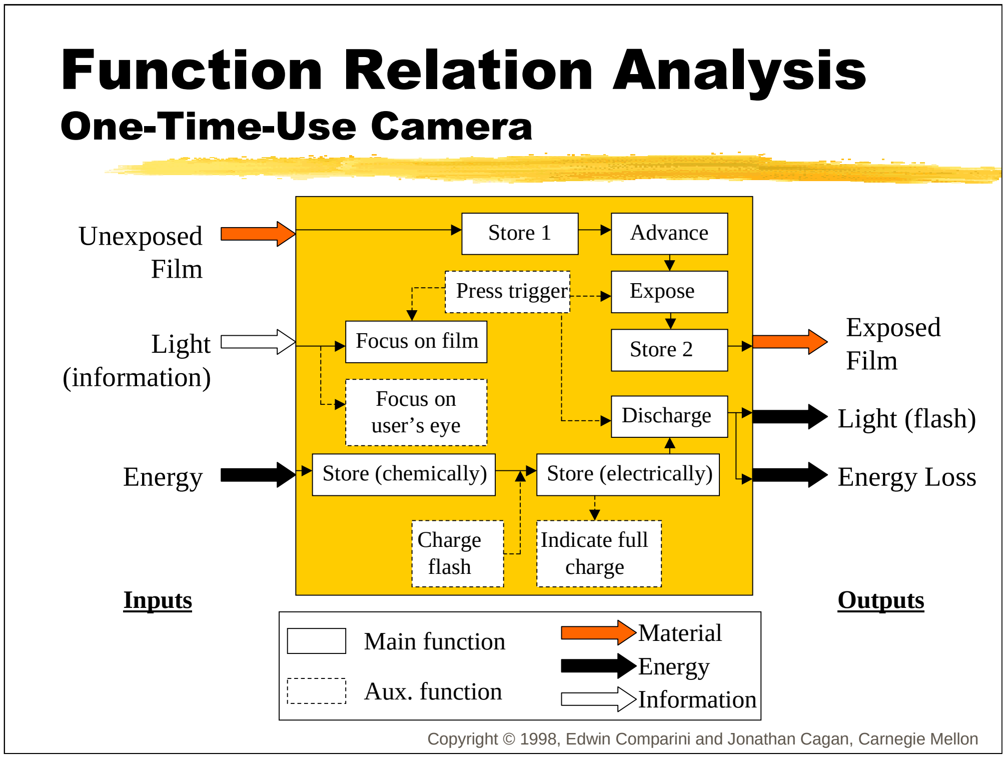


Steps 2, 3 & 4 of generic example

The objective of this approach is to allow the designer to be free to choose the components that satisfy the individual sub-functions. Once a sufficient level of sub-function refinement is reached, the designer can choose components from catalogs.



Step 1: Conversion of inputs and outputs



- **Step 2:** Breakdown of overall function into a set of essential sub-functions
- **Step 3:** Draw block diagram
- **Step 4:** Draw system boundary

Main functions serve the overall function directly.

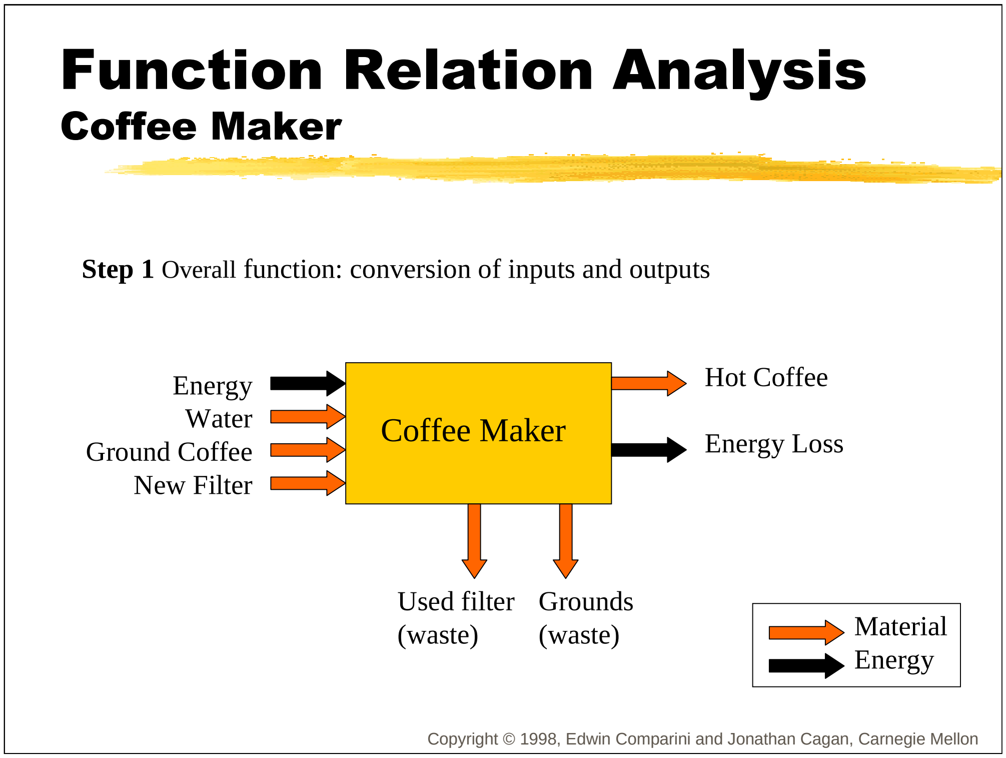
Auxiliary functions contribute to the overall function indirectly. They are supportive or complementary and are often determined by the nature of the solution.

In some cases in may not be possible to make a clear distinction between main and auxiliary functions.

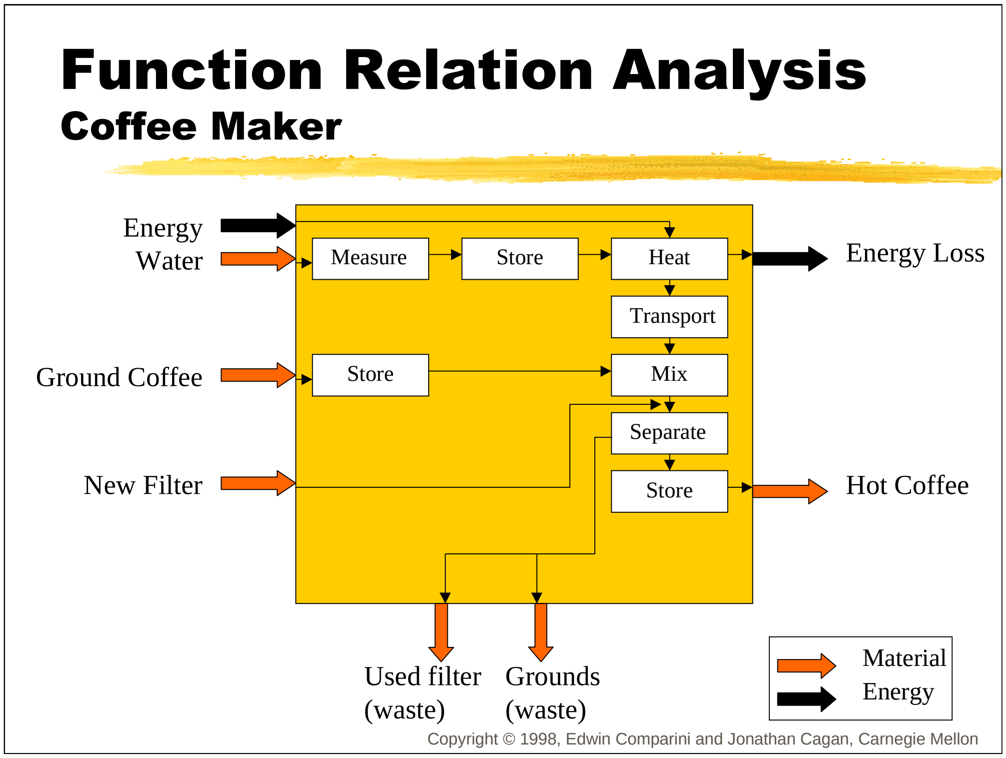
It is important to examine the relationship between the various sub-functions, paying attention to their logical sequence or interconnections.

(Pahl, G. & W. Beitz, 1977)

Function sharing can reduce the number of components, which may directly reduce the environmental impact of the product (e.g.: film cover integrated into main frame of camera; viewfinder, trigger button, and magnifying lens integrated into structural component.)



Step 1: conversion of inputs and outputs



- **Step 2:** Breakdown of overall function into a set of essential sub-functions
- **Step 3:** Draw block diagram
- **Step 4:** Draw system boundary

Improvement

One-Time-Use Camera

- What are the advantages of a one-time-use camera over a conventional camera? Disadvantages?
- Why is minimizing material variability desirable?
- What type of fastening mechanism is used in the camera? Why?
- What has the manufacturer done to reduce the product's impact on the environment? How can the environmental impact of the camera be further reduced? How about eliminating the cardboard cover? What changes would need to take place to eliminate cardboard cover?
- The manufacturer does not reuse the lenses and the battery in other cameras. Why? How would a faulty lens or battery affect consumer perception of the product?
- The manufacturer reuses the printed circuit board (PCB) and the main case. How can the manufacturer ensure the quality of the reused parts? Would it be helpful to know how many times the parts have been used?

•The LCA for the camera reveals that the majority of the energy consumption in the life of the product takes place during the manufacturing stage.
One possible improvement that may reduce the amount of energy consumed may be to reduce the number of parts in the camera by integrating two or more parts into a single part. (e.g.: film cover integrated into the main frame)

Another improvement may be to eliminate the printed paper and stamp the instructions directly on the camera. This would eliminate one type of material and the corresponding processes and wastes (e.g. bleach, ink, printing, cutting, etc.)

Improvement

Coffee Maker

- In qualitative terms, how does the power consumption during the manufacturing stage compare to the power consumption during the use stage? What impact does that have on the product design?
- What can you say about the variability of materials in the coffee maker?
- One coffee maker manufacturer uses a tamper proof fastener to prevent disassembly. Why?
- Has the manufacturer taken any steps to reduce the product’s impact on the environment?
- How can the coffee maker’s impact on the environment be reduced?
- Coffee makers that have reached the end of their useful lives are discarded. What are the difficulties in establishing a take-back program for the used coffee makers?

The use stage of the life of the coffee maker is the one that has by far the largest consumption of energy and waste production. Possible areas of improvement include reduction of energy consumption, reduction of coffee grounds (waste) (e.g. making a coffee maker that maximizes the coffee it can obtain from ground coffee.)

It is evident from comparing the two coffee makers that a solution that uses less material is sometimes possible. In the coffee maker that uses less material (White Westinghouse), the walls of the water tank also have a structural function for the overall product. This is another example of how function sharing can reduce a product’s environmental impact.

Implementing manufacturing-for-disassembly features may be a good way of anticipating possible future regulations that require take back of products.

Reduction of the variability of materials may be another area of improvement in the coffee makers.

Summary

The proposed Reverse Engineering for Green Product Design approach involves the following steps:

- Dissecting the product to generate an inventory of the materials used.
- Performing a Life-Cycle Assessment to determine which life-cycle stage has the largest environmental impact.
- Determining possible improvements for the stage with the largest impact. For example:
  - **Material Extraction Stage:** improving material selection; use of recycled materials; use of non-toxic materials; use of renewable sources.
  - **Manufacturing Stage:** improving manufacturability of product; reducing the number of steps; reducing the number of components used (function sharing).
  - **Distribution Stage:** reducing amount of packaging materials.
  - **Use Stage:** improving efficiency of product.
  - **Waste Management Stage:** improving recyclability of product; use of non-toxic materials.

(continued)

Summary (cont...)

•Performing a Function Relation Analysis to establish the functions and sub-functions that must be performed by the product.
•Determine if function sharing to reduce the number of components needed is feasible.
•Selecting new components or improving the original components in order to improve the "greenness" of the product.