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**Steps toward Environmentally Compatible
Product and Process Design:
A Case for Green Engineering**

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13. ABSTRACT (Maximum 200 words) Green Engineering is the study of product and process design for environmental friendliness without compromising product quality and commercial viability. The aim is to identify, develop, and exploit new technologies that can bolster productivity without costing the environment. This is one of the challenges engineers will face in the coming century. Over the past decade, a lot of research and effort has been put into understanding issues such as waste management, materials recovery, and HazMin (Minimization of Hazardous materials and practices) as they relate to products after they enter the waste stream. Attention should also be focussed on the product design itself. The idea is to inject concerns about environmental friendliness into the design process; where, the assessment of environmental friendliness is based on a life-cycle view of the product. This includes the product's manufacturing process, distribution, use, and final disposal.				
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1. Green as in the environment, and Green as in greenbacks

Green Engineering is the study of product and process design for environmental friendliness without compromising product quality and commercial viability. The aim is to identify, develop, and exploit new technologies that can bolster productivity without costing the environment. This is one of the challenges engineers will face in the coming century. Over the past decade, a lot of research and effort has been put into understanding issues such as waste management, materials recovery, and HazMin¹ as they relate to products after they enter the waste stream. Attention should also be focussed on the product design itself. The idea is to inject concerns about environmental friendliness into the design process; where, the assessment of environmental friendliness is based on a life-cycle view of the product. This includes the product's manufacturing process, distribution, use, and final disposal.

Traditionally, products have been designed to satisfy only functional requirements and specifications. Recently, interest has been generated in designing products that not only satisfy functional specification, but are also easy to manufacture, assemble, diagnose, and maintain. This new approach to design is called *concurrent design*. We are interested in extending this idea to include environmental considerations. Some of the questions that arise are: How should a product be designed to reduce hazardous wastes? Can ease of recyclability be engineered into a product's form and materials? What de-commissioning methods should be considered during the design process? How does one evaluate the hazardousness of various products and processes? What are the tradeoffs? These questions point to some important issues that have not traditionally been considered during product design and development, they represent a new area of design that we call Green Engineering. I define Green Engineering as the study of, and an approach to, product/process evaluation and design for environmental compatibility that does not compromise product quality or function. In this framework, a "green" product is both environmentally compatible and commercially profitable.

There are essentially two ways in which green engineering methods can be applied: (a) product selection and (b) product design.

Product Selection. During a procurement process, a buyer might have the option of choosing among a variety of similar products. For example, there may be several competing types of solvents that all satisfy the functional requirements. Actual selection may be based on the criteria such as: price, the supplier's integrity, and product quality. If, however, the life-cycle of the product is taken into account, then the cost analysis can be quite different. A life cycle view of a product includes the cost of transportation, cost of packaging and its disposal, cost of treating any hazardous by-products, cost of using the product, maintenance costs, and the cost of disposal. If the product or its use are environmentally incompatible (e.g. involves the use of hazardous materials), then one has to consider these costs during product selection. We need mathematically sound techniques for evaluating a product based on its physical structure, materials, manufacturing history, reliability, maintenance data, and performance.

Product Design. Environmentability issues can be introduced in a design cycle as three basic steps: (1) designs generated by the engineers are evaluated for environmental compatibility, (2) barriers to hazard minimization, resource recovery (recycling), and energy conservation are identified, (3) these barriers are then translated into recommended design changes and are communicated back to the engineers. For example, a barrier in recycling household appliances is the inseparability of the metal housing from the electrical and electronic modules that often contain hazardous materials and are also potential contaminants in the recovered metal. A proper characterization of this barrier can be translated into specific design

¹Minimization of Hazardous materials and practices.



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changes that either reduce the use of hazardous materials or allow for easy separability of the materials. As will be discussed later, the process of barrier recognition, characterization, and the making of design changes could be an integral part of an existing "design and build" cycle.

2. An approach to Green Engineering

Our approach to Green Engineering has two parts. The first is a set of analysis methods that can be used to measure the environmental compatibility of a given product. The second task is to identify relationships between the results of analysis and features of the design, thus leading up the design changes that can improve a product's environmental compatibility.

Here are some specific aspects of our approach.

- **Disassembly assessment.** To facilitate recycling and hazard isolation, it is important that the different materials in a product be separable. The question is, what design changes should we consider to allow easy disassembly before disposal? Unlike disassembly for maintenance, disassembly for recycling or recovery may be destructive because re-assembly is not of concern.
- **Material evaluation and substitution for recycling.** How can one ensure high quality materials in scrap? What are the economics of recycling plastics, ferrous scrap, and other metals.
- **Material evaluation and substitution to reduce hazardous wastes.** What hazardous materials are being used in the auto and appliance industries today? What design changes can be made to contain or separate out these materials before/after these products enter the waste stream?
- **Degradability evaluation.** Products and packaging that are disposed off in landfills can be designed to degrade faster; in order to provide longer dump life.

To illustrate the approach we will now consider two examples, the first is about analysis the second is about design.

2.1. Life Cycle Analysis and Green Indicators

The notion of life-cycle analysis is based on activity models. The various stages that a product goes through from cradle to grave involves activities. Each activity can be viewed as a black-box that takes certain inputs and produces outputs. As energy and materials are conserved in each blackbox, the outputs of an activity includes products and waste (Figure 2-1). The *decision* input is used for activities that can be done in different ways. For example, if the activity is washing re-usable diapers, the decision input could be used to indicate the type of wash cycle used, in which case, the decision determines the amount of waste water and heat.

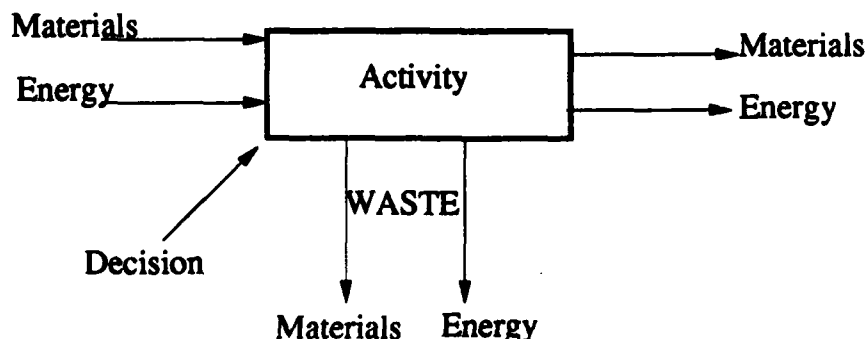
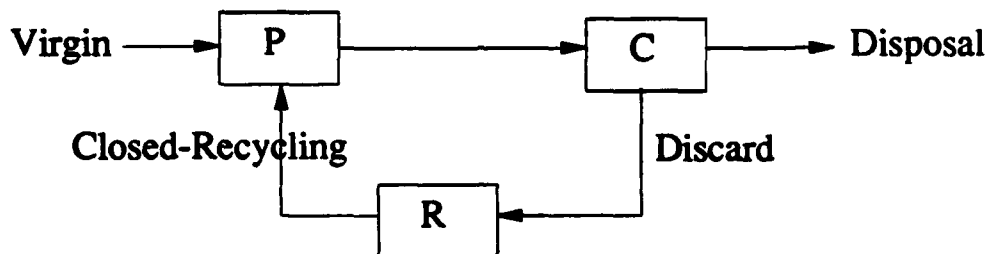


Figure 2-1: An Activity Model

The activity is a basic building block of life-cycle analysis. Consider the life cycle of a material (e.g. glass) that goes from Production (P) to the Consumer (C). After consumption some percentage is discarded and the rest is recycled (R). The three activities are shown in Figure 2-2. The notion of activity can be used to calculate various measures of environmentability. I call these measures *Green Indicators*. One of the *Green Indicators* we can calculate is Total Useful Time. This is the time a material is used by the consumer. If a material is never recycled, then its useful life is the total time it is used by the consumer to perform some function. Hence, the useful life of a styrofoam cup may be five minutes. If, on the other hand, the material was completely recycled and if no raw materials were used in production, then the useful life is infinite. In reality, many materials and products fall somewhere in between the two extremes.



$$\text{Useful Life (UL)} = \text{Consumer-Time} \left(\frac{\text{Tonnage Closed-Recycling}}{\text{Tonnage Virgin}} + 1 \right)$$

Figure 2-2: Life-Cycle Modeling

For example, let us consider soft drink glass bottles. Of the total annual consumption level, let's assume 30% is recycled and 70% is virgin glass. If the bottle is "used" by the consumer for a one day, what then, is the useful life of the glass? This value is given by equation above. In our example it would be 1.43 days. Note, that as the amount of virgin glass in the bottle reduces, the useful life of the glass increases.

This form of life-cycle modeling can be extended to include secondary markets for recycled products, energy costs, disposal costs etc. It provides us with an integrated picture of a product's life.

2.2. Design for Separability

It is often possible to re-design a product in order to improve recyclability while reducing manufacturing costs. For example, some packages use composite materials (e.g. paper and plastic), as opposed to single-material packaging (e.g. polystyrene). The composite packaging is harder to manufacture and harder to recycle.

Let's reconsider the soft drink bottle example. There are two types of bottle designs that I have come across. The first design, shown on the left of Figure 2-3, allows for the easy separation of the cap, ring and the glass bottle. The plastic ring is designed to deform and easily slip out of the bottle's neck. A second design (right side of the figure), uses a metallic cap and ring. The ring is not separable from the bottle by hand. As many recycling operations require that clear glass be free of metal, the second design poses a barrier to recycling. As shown in the figure, it has two levels of separation. The first is manual, but the second requires some kind of tool to cut out the ring.

A simple geometric Separability analysis, as shown in the figure, can help in assessing design

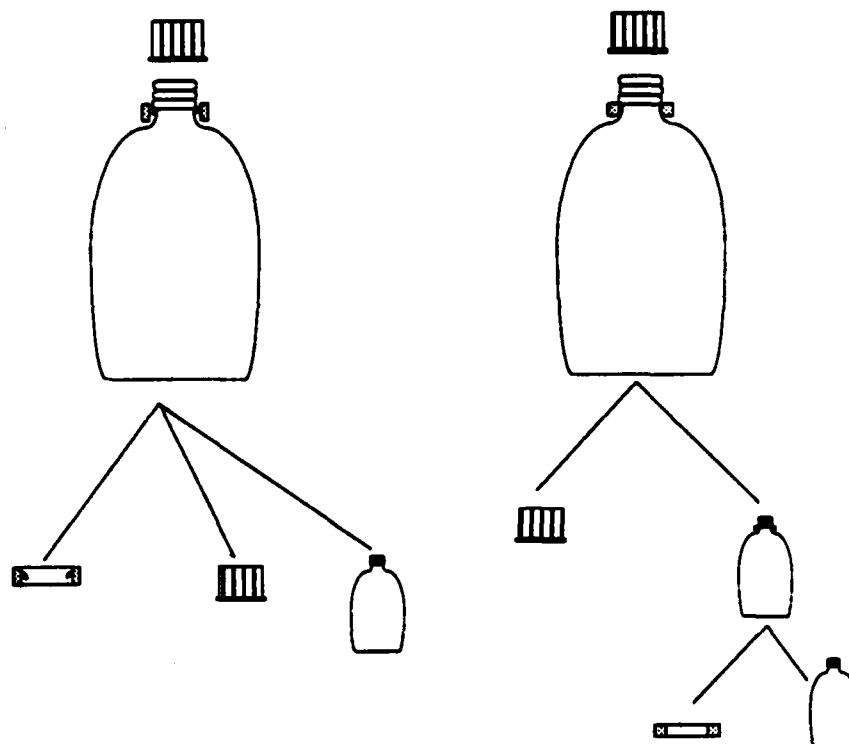


Figure 2-3: Separability

alternatives.

3. Green Engineering in a CAD environment

As environmental analysis is a very knowledge intensive task, automation is a promising mode of transferring the technology into practice. There are essentially two areas in which the proposed technology can be applied: (a) as an evaluation tool to be used by a procurement agency, (b) as an evaluation and design modification tool for the product designers.

Automated Evaluation. To make it possible to automate the evaluation of existing products, we need information about the products in an electronic form. The representation would include the following information: (a) physical structure, (b) bill of materials, (c) components, (d) joints and fixtures. A computer-based representation that captures such information has been developed by the National Institute of Science and Technology (formerly National Bureau of Standards). The representation is called the Product Data Exchange Standard (PDES). PDES is designed to allow organizations to transfer complex product information electronically. It is our aim to be able to use Expert Systems technology to read a PDES datafile and evaluate it for aspects such as separability, recyclability, hazardousness etc.

Automation in Design. Computer based evaluation methods can be used to develop design recommendations that are fed back to the designer. Both these steps (evaluation and recommendation) could be carried out in a computer aided design (CAD) environment. Existing CAD systems for Concurrent Engineering have been configured to support knowledge sources about maintainability, reliability, manufacturability etc. We are currently working on introducing environmentability knowledge into the Design Fusion system developed at CMU.

4. Implications for Engineering Design Education

The basic tenet of Green Engineering is to develop environmentally compatible products without compromising product quality. The goal is to seek out and exploit new technologies and materials that can improve product quality and performance with respect to a variety of aspects, including the environment.

It is important to teach our engineering students the basic principles of Green Engineering. We don't want our engineers making decisions about products without being aware of the long term environmental impacts. For example, a designer who is choosing a material for a plastic bottle to package liquid soap might have a choice between Poly-Vinyl Chloride (PVC) and Polyethylene (HDPE). It turns out that in many U.S. communities HDPE is more readily separated and recycled than PVC. Knowledge of this simple fact can make the packaging recyclable. This may not seem as an important consideration for the engineer, but if one takes a life-cycle view of the product the picture is very different. Many communities are now considering a "pay as you throw" policy for garbage. Consumers who buy non-recyclable products will be penalized with higher garbage pickup charges. Under these conditions, consumers will shy away from products packaged in non-recyclable containers. This has important implications for the product's marketability.

An understanding of the life-cycle of products is an important part of an engineer/designer's job. Students should be taught how to recognize and confront relevant tradeoffs in product design.

5. Implications for Marketing

Is Environmental Friendliness marketable? Is there a premium market? What are the economics of collection, separation and materials recovery? Can this reduce costs over time?

We need research data on the costs of materials recovery and disposal, and the implications for energy management.

6. Conclusion

Almost every human activity drains or damages non-renewable resources of our planet. Since the 1960's many environmental groups have actively campaigned to encourage polluting industries to change their ways. Many industries were quick to respond in situations where environmental violations were apparent. There are, however, several areas in which clear-cut scientific standards are not available. In these situations some environmentalists have resorted to radical means, and industries have shunned environmentalists and have blamed them for being anti-science and anti-progress. This can lead to a never-ending battle. We have to strive towards a **Productive Environmentalism**: the search for technological solutions that bolster progress without destroying the environment. This is our challenge for the coming century.

I believe that engineers and designers can play an important role in solving this problem. We have to teach our engineers/designers how to be environmentally conscious while making design decisions.

Green Engineering encompasses the following ideas:

- Product improvement on all aspects, including the environment.
- Environmentability assessment with the use of Green Indicators that take a life-cycle view of a product.

- Product redesign for environmentability.
- Introduction of environmental consciousness in the traditional engineering curriculum.
- Identification and development of new technologies and materials for economically viable "green" products.
- Market issues relating to the viability of Green Engineering.

This has been a preliminary report of our research in Green Engineering. We are currently working on the development of "Green Indicators", analysis methods that can be used to evaluate designs.