Product Design for Recyclability: A Cost Benefit Analysis Model and its Application

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Abstract --- Increasingly stringent regulations and widely expressed public concern for the environment highlight the importance of disposing solid waste generated from industrial and consumer products. Rather than focusing only on an "end-of-pipeline" treatment for product disposal and solid waste management, emphasis is now being put on designing products for ease of recycling and disposal. This paper addresses engineering design issues from an environmental and economic perspective. A cost benefit analysis model is presented as a tool for assessing the economics of designing for recyclability. Several design for recycling rules, which can reduce the cost of recycling, are presented and integrated with the cost benefit analysis model. The synthesis is implemented with an example.

1. INTRODUCTION

In the United States, every day, thousands of durable goods come to the end of their lives and enter the solid waste stream. More than 10 million vehicles reach the end of their useful lives every year [25], thirty-two million used appliances were discarded by 1990, and an estimated 150 million discarded personal computers will have been landfilled by the year 2005 [14].

How can we deal with this situation? Currently, several methods are used to handle these discarded products: 1) Removal of reusable parts and sale as used parts, 2) Rebuilding used parts to give products a second life, 3) Shredding the remaining hulk and separating steel and other high value materials for recycling, and finally, 4) Discarding the residue, called "fluff", to the waste stream and ultimately to an incinerator or landfill. These steps comprise the entire process called product recycling. It is the process by which unusable materials, parts, and products are given new value. Fig.1 shows the general stages and associated activities in product recycling.

The notion of designing products that facilitate product recycling is interesting and captivating. However, many have not recognized the need to take a balanced economic view of recyclability. Some industrial attempts to achieve 100% recyclability have served as interesting curiosities. However, the long-term and widespread acceptance of recyclability is going to be driven mainly by economics and by legislation. In the context of Green Engineering [20, 10], i.e. designing products simultaneously for environmental compatibility and commercial viability, we have developed a cost benefit model that can be used to assess design for recyclability issues. While recognizing other life-cycle costs such as packaging, manufacturing, re-tooling for design changes, and field service, our model looks primarily at the balance between the cost of recycling processes (e.g. disassembly, shredding etc.) and the benefits (e.g. revenues from recycling). While the model only serves as an analysis tool, we argue that it can be used to evaluate design options.

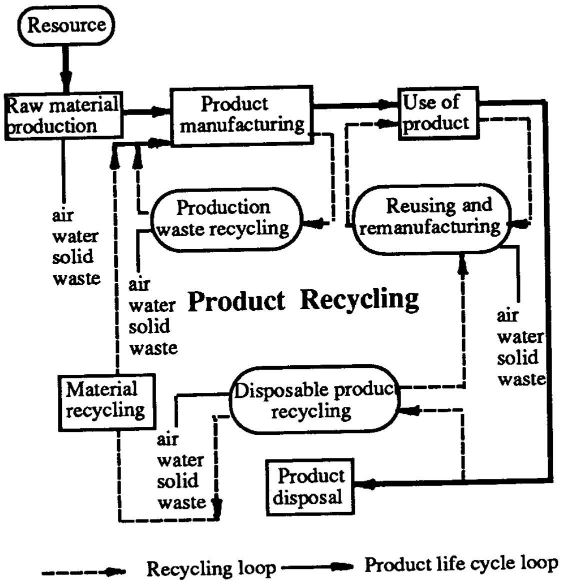

Fig. 1. Product life cycle Recycling Stages and activities

The potential recyclability of a product is determined at the design stage, and thus can be improved by changes in materials, structural layout and inter-part connections. Product and process decisions will now be based, not only on the economics of production, but also on the economics of recycling (Fig. 2). The left half of the figure depicts some of the current costing and revenue sources, while the right half shows the new factors that are entering the design equation.

We envision a design for recycling analysis methodology that integrates design changes and cost benefit analysis as shown in Fig. 3. In this flow chart, design options are proposed based on engineering requirements and are evaluated with a cost model. Several feed-back loops are

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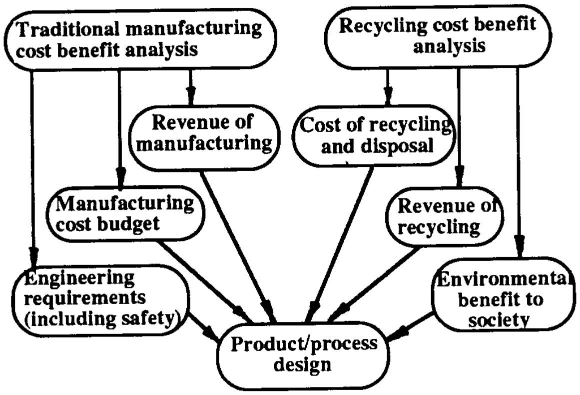


Fig. 2 New Design Analysis Model

suggested as means of allowing for design changes and refinements that move towards improved recyclability.

2. COST BENEFIT ANALYSIS MODEL OF RECYCLING

The current recycling process involves several activities, each with its associated costs and benefits. Traditionally manufacturers have not been concerned with disassembly, material recovery and disposal costs. These costs have been external to the scope of doing business, but with the advent of green engineering, we are seeing a redefinition of this scope. The economics of recycling and disposal have become main-stream business issues in the face of environmental regulations and product take-back programs. While many of the core environmental issues such as ozone depletion and species diversity will remain externalities in the short term, we are experiencing a growth in the number and variety of environmental concerns that product designers have to deal with.

Fig. 4 summarizes the steps of the recycling process and related costs and benefits as well as some of the environmental factors that we have considered in the development of our model.

According to the recycling process, the cost function of recycling is defined as:

$$Co = Cd + Cs + Cr + Dc$$

$$Cd = Cdh \left(\sum_{j=1}^{n} \sum_{i=1}^{m-g} Tij \right)$$

$$Cs = Csh\,(St)\,(Ws)$$

$$Cr = \sum_{i=1}^{k} (Rci)\,(Wri)$$

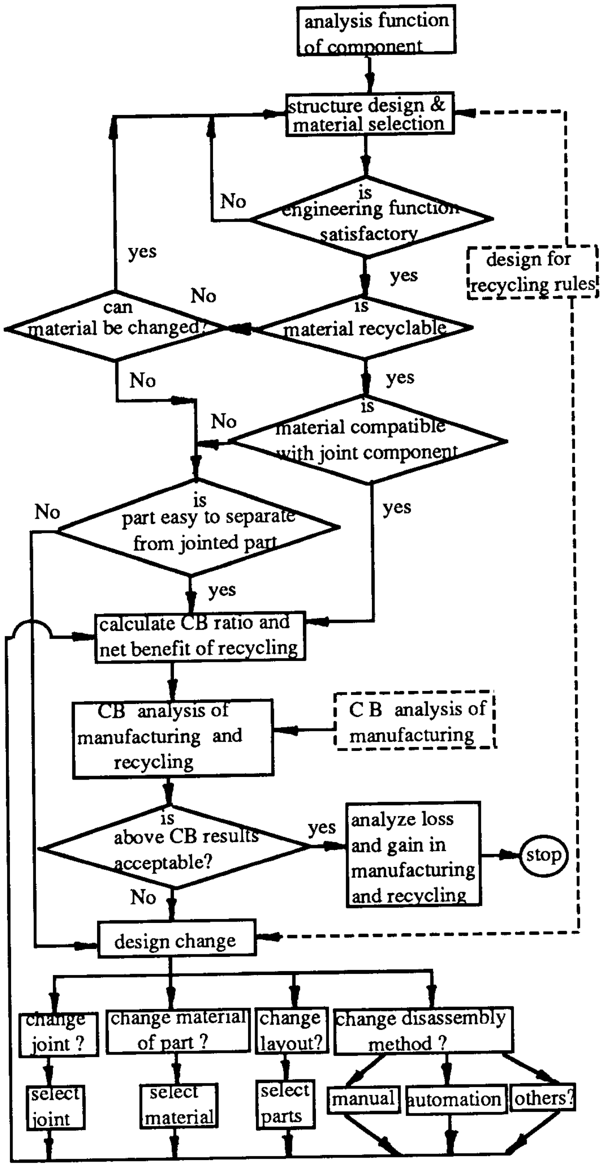


Fig. 3 Design for Recycling Analysis Flow Chart

$$Dc = dc\,(Wd)$$

where:
Co = cost of recycling
Cd = cost of disassembly
Cs = cost of shredding
Cr = cost of material recovery
Dc = cost of dumping.
Cdh = hourly cost of disassembly

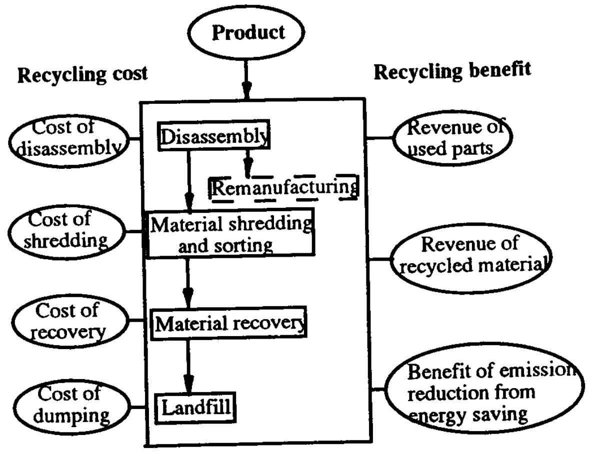


Fig. 4 Recycling Process and Associated Costs and Benefit

T_{ij} = time for disassembling ith of j type joint
m = number of same type of joints in the product
n = number of different type of joint such as screw, etc.
g = number of joints on which the connecting parts and joint are made of the same or compatible materials
Csh = hourly cost of shredding
St = time to shredding one ton of material
Ws = weight (ton) of material to be shredded
Rc_i = material recovery cost of one ton of type i material (i may be steel, plastics, etc.)
Wri = weight of type i material to be recovered in a product
k = number of different type of materials in the product
dc = cost of dumping one ton of solid waste
Wd = weight (ton) of dumped waste

The benefit of recycling is defined as:

$$Re = Rp + Rm + Er$$

$$Rp = \sum_{i=1}^{n} Pu_i$$

$$Rm = \sum_{i=1}^{m} Pm_i$$

$$Er = \sum_{i=1}^{m} Es_i \sum_{j=1}^{h} Em_j (Ec_j)$$

where:
Re = total benefit from recycling
Rp = revenue from used parts
Rm = revenue from recovered materials
Er = benefit of emission reduction from energy saving
Pu_i = revenue of a reusable parts
n = number of reusable parts disassembled in a product
Pm_i = revenue of type i recycled material
m = number of types of recycled material in a product.
Es_i = energy saving of recycling type i material
Em_j = type j emission reduction
Ec_j= externality cost of type j emission
h = number of types of emissions such as So2,particulates etc.

Based on the above analysis, the cost benefit analysis model of recycling is defined as follows.

$$R_{b/c} = \frac{Rp+Rm+Er}{Cd+Cs+Cr+Dc}$$

$$R_{b-c} = (Rp + Rm + Er) - (Cd + Cs + Cr + Dc)$$

where:
Rb/c is a cost benefit ratio of recycling and R_{b-c} is the net benefit of the recycling.

The above formulas are modeled in DEMOS, a decision modeling software system that was developed by Max Henrion and Granger Morgan in the Department of Engineering and Public Policy, Carnegie Mellon University [19]. Fig. 5 represents relationships among the major variables in the model. For a particular organization or product, the actual factors that are internal and external to the decision making process are going to be different. The cost benefit model we present is representative of the way in which this methodology can be applied to the assessment of product recycling processes.

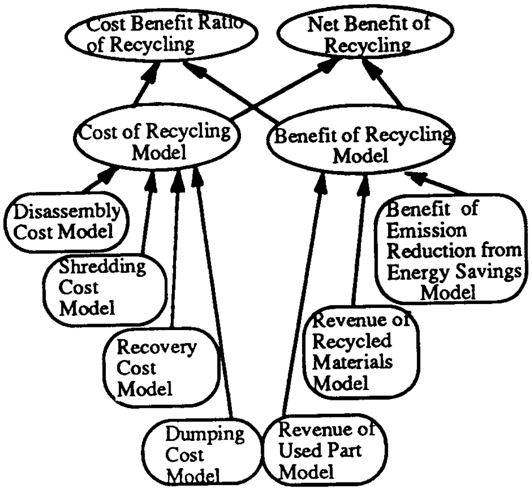


Fig. 5 Diagram of Cost Benefit Analysis Model of Recycling

3. SUGGESTED RULES TO INCREASE COST BENEFIT ANALYSIS RESULTS

3.1 Select Suitable Material for Ease of Recycling

One of the important changes that can be made to a design is material substitution. The cost of product recycling is affected by the materials used in the product. The mix of materials, the toxicity of materials, the compatibility of materials, and the recyclability of the materials determine the cost and economic viability of recycling.

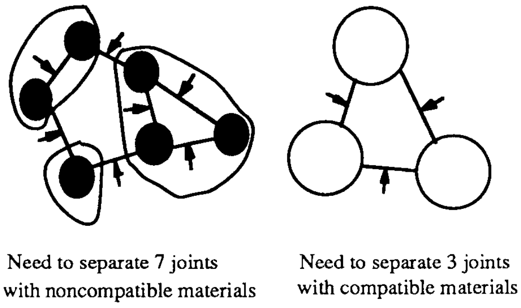
1. **Materials Mix:** The larger the variety of materials used, the harder the separation task will be. Having a large variety of materials in a product can complicate and increase the costs of separation, sorting and handling.

2. **Toxicity of materials:** The use of toxic materials will causes environmental problems during manufacturing, separation, material recovery and disposal. Efforts to solve these environmental problems will add to the cost.

3. **Materials recyclability:** Materials that are hard to recycle are often not recycled because the cost of recycling outweighs the cost of purchasing virgin material. It is hence important to select materials that have some value in the post-consumer recycling market.

4. **Recycled Materials:** To keep the recycling market alive, it behooves a green designer not only to design for recyclability but to also design with recycled material. Many issues of quality, strength, color stability, and uniformity arise in the context of recycled products. These issues are currently outside the scope of our analysis.

5. **Materials Compatibility:** If compatible materials are selected for subassemblies, then one can reduce the cost of disassembly. If we use compatible materials within subassemblies and use easily separable joints between groups, then the time spent on separating parts will be reduced. This means that the type of materials to be separated for recycling are reduced. Fig. 6 shows the relationship of material compatibility and cost of recycling.


Need to separate 7 joints with noncompatible materials

Need to separate 3 joints with compatible materials

Fig. 6 Material Compatibility and Cost of Recycling

3.2 Design for Ease of Disassembly

Another approach for improving product design for recycling is to design it for ease of disassembly. Product recycling costs and benefits are also affected by structural design, joint type, and disassembly methods.

1. **Structural design** determines the layout of the parts and complexity of the product, as well as the paths and difficulty in reaching a particular part or subassembly. These aspects directly affect disassembly time and cost.

2. **Joint types** affect disassembly cost by increasing the time and tools required for disassembly. This indicates that quick fasteners need to be used to reduce disassembly cost [3].

3. **Operating methods** for disassembly can be dictated by the nature of the design. For instance, it is impossible to use power tools if the layout of the parts does not permit power tool insertion.

Based on the above discussion, some material selection and design for disassembly rules are suggested in Table 1 and Table 2. These rules are a compilation of our own experiences, communication with some professionals, and published sources.

Table 1 Suggested Rules for Material Selection

- Use recyclable materials if engineering requirements are satisfied.
- Use compatible materials for adjacent parts and subassemblies.
- Use recycled materials if they meet the engineering requirements.
- Avoid using toxic materials.
- Minimize material variety if possible.
- Avoid secondary finishes such as painting, coating, etc.

Table 2 Suggested Rules for Ease of Disassembly

- Choose joints that are easy to disassemble if the material is not recyclable or compatible.
- Simplify and standardize component fits and interfaces.
- Identify separation points.
- Use water-soluble adhesives where possible.
- Label materials to ease identification and separation.
- Layout plastic parts close to the top level of the disassembly path.
- Design for ease of handling and cleaning of components.
- Choose easy separating joints for parts which have reuse value.
- Provide "easy to see" access for disassembly.
- Use rust proof joints if parts to be exposed to harsh environments.
- Use the same size of joints (same system) for adjacent parts.
- Provide access for hand tool and power tool operation.

4. EXAMPLE OF APPLICATION OF THE MODEL

In this section we examine an example that illustrates the cost benefit analysis method in the context of Green Engineering Design. The example involves the dashboard of a popular compact car. We selected the 1985 model because this model were available in scrap yards. The total weight of the dashboard is about 20 kg. Steel accounts for approximately 43% of the total weight, plastic accounts for 47%. Copper and other materials make up the remaining 10% by weight. Our analysis is centered around two scenarios: (1) The current disassembly method that involves the removal of only one part, the radio. The rest of the dashboard is left in the car for the shredder. (2) In our second scenario we considered many levels of disassembly including complete disassembly (except wires and wire harnessers). The data from these cases are shown in Table 3. The data have been collected from our own disassembly experiments, and time-motion studies carried out in the field. We have also used interviews with disassemblers and a shredder to elicit cost information.

Table 3 Results of Cost Benefit Analysis of A Dashboard

	Scenario one only disassemble reusable parts value (Std.Dev)	**Scenario two disassemble most parts** value(Std.Dev)
parts disassembled	1 (radio)	51
weight after disassembly	19 kg	2.3 kg
time of disassembly	15' (2')	114' (17')
net benefit of recycling	\$35 (\$13)	\$-170 (\$37)

The results show that while current recycling methods yield a profit, complete disassembly can lead to losses (\$-170). After the radio is removed the remaining materials are worth a lot less than the cost of disassembly and separation. To carry this analysis further we considered the affect of design changes that would reduce disassembly time.

In order to evaluate how a cost benefit analysis result of this model responses design changes, we used some of the "design for recycling" rules and concepts from the design analysis flow chart shown in Figure 3. Three design and operation method changes were considered for the dashboard recycling problem. We base these changes on the assumption that full disassembly is a desirable goal. Let's see how the economics stack up. (Note, these design changes were not actually made. We base our analysis on time-motion data.) Our analysis does not include the costs of re-tooling and procedural changes associated with redesign and product take-back. We assume that design for recyclability changes will be part of the continuous improvement and QFD process in an organization.

(1) Change joint type and material combination

There are about 50 staples in the duct system and each of staple needs more than 40 seconds to be disassembled. These joints could be changed to snap fits to allow for easy disassembly. With this design change option, all staple joints can be eliminated. Most parts in the duct system don't need to be separated because the contaminated steel can be removed while staple joints are eliminated. The reminders are almost the same type of plastics. The disassembly time will be reduced from 1.9 hour to about 1.2 hour.

(2) Change disassembly operation method

The second change is based on the assumption that one can use a power tool for disassembly. Based on our time motion study conducted in the field, we estimated that disassembly time will be reduced from 1.9 hours to 1.3 hours for dashboard disassembly by using power tool.

(3) Combination of Above Two Changes

Combination of change 1 and 2 reduce disassembly time from 1.9 hour to about 0.6 hour.

Table 4 shows that with suitable design and disassembly operation changes, the losses from dashboard recycling will be reduced. For example, the original recycling loss is about \$170 for our second scenario, but with change-3 the loss is only about \$6. Further more, Fig. 7 shows that the probability of under break even point (net benefit of zero) is about 0.6, still leaving 40% of chance to gain from dashboard recycling. These results show that design for recycling is costly, but a suitable design with ease of recycling in mind can improve the economic feasibility of recycling.

Table 4 The Results of Cost Benefit Analysis of Dashboard Recycling after Design and Operation Method Change

Mean value of Net Benefit of Dashboard Recycling after Change Design Design and Operation Method

	disassembly time	**(Std.Dev)**	**net benefit**
Before change	1.9 hour	(17')	\$-170
Change 1	1.2 hour		\$-83
Change 2	1.3 hour		\$-92
Change 3	0.6 hour		\$ -6

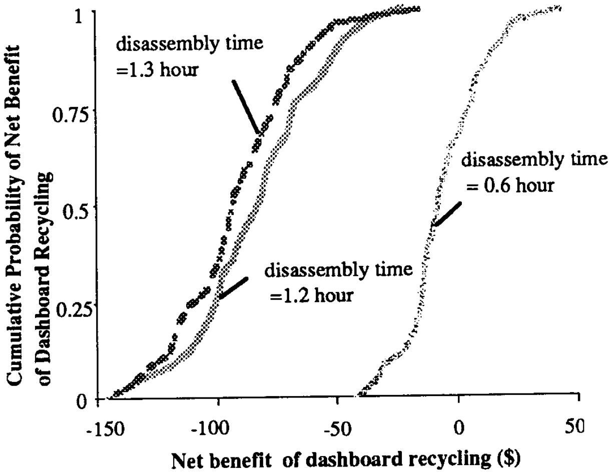


Fig. 7 Cumulative Probability of Net Benefit of Dashboard Recycling after Design Change

CONCLUSION

This paper develops a method and introduces a computer-based analysis tool that may be used to analyze design changes. By taking a cost-benefit approach, we have emphasized the need to consider design for environment in terms of it's economic viability.` To demonstrate the applicability of the model, a simple example based on the the disassembly of an automobile dashboard was presented. The results show that with the current material recycling technology and market prices, complete disassembly is not profitable because the costs far outweigh revenues from the materials and parts that are recovered.

Several "design for recycling" rules are suggested as means of improving the economics of recycling. By adopting easily separable joints, using compatible materials, and by providing easy access for power tools, the net benefit can be much improved. The cost benefit model is presented as a method for evaluating alternative ways of improving recyclability.

Finally, it should be noted that design for recyclability does not imply that a product can be fully recycled while making a profit. A balance has to be struck between the amount of effort that is invested into the disassembly of a product and the revenues that are realized. This balance also depends on what we wish to count as revenues and benefits. In addition to direct monetary benefits of recovery, one might wish to include the value of emission reduction, the benefits of avoiding future environmental liabilities and perhaps the value of environmental quality.

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