Compatibility Analysis of Product Design for Recyclability and Reuse

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Submitted to 1994 ASME Computers In Engineering Conference
February, 1994

ABSTRACT

This paper describes a method for evaluating the compatibility of a product design with respect to end-of-life product retirement issues, particularly recyclability. Designers can affect the ease of recycling in two major areas: 1) ease of disassembly, and 2) material selection for compatibility with recycling methods. The proposed method, called "clumping," involves specification of the level of disassembly and the compatibility analysis of each remaining clump with the design's post-life intent; i.e., reuse, remanufacturing, recycling, or disposal. The method uses qualitative knowledge to assign a normalized measure of compatibility to each clump. An empirical cost function maps the measure to an estimated cost to reprocess the product. The method is an integral part of our life-cycle design computer tool that effectively guides engineers to an environmentally responsible product design. A refrigerator in-door ice dispenser serves as an illustrative example.

1. INTRODUCTION

Life-cycle design is the process of incorporating various values of a product in the early stages of design. These values include manufacturability, serviceability, recyclability, etc. (Figure 1). A great deal of work has been done in the area of design for assembly (DFA; Boothroyd and Dewhurst, 1983) and design for producibility of components (Priest, 1988). More recently, attention has focused on design for serviceability (DFS) as a major product ownership value (Makino, et al., 1989; Gershenson and Ishii, 1991). With the growing concern for the environment, design for recyclability (DFR) has become the newest area of specialization in the DF“X” realm. Although design for recyclability does not address all of the areas of a product’s life-cycle, DFR is a method by which a designer can make immediate and effective decisions about a product's design. These decisions directly influence product disposition at the end of its useful life.

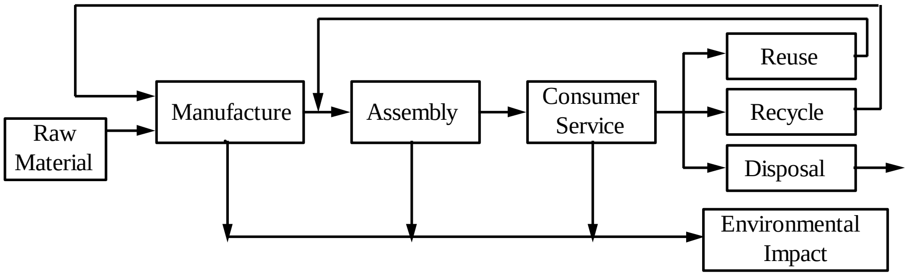


Figure 1: Product life-cycle

Our study seeks to bring together different areas of the product life-cycle to evaluate designs from various standpoints. Two areas of the life-cycle we are currently addressing are product ownership and product retirement. The product ownership phase is composed primarily of serviceability and reliability. A product that is reliable and easily serviceable leads to maximum availability and minimum life-cycle service cost, both of which contribute to maximum customer satisfaction. Our initial work focused on automotive hardware (Gershenson and Ishii, 1991; Bryan, et al., 1992), while recent projects address systems such as home appliances. The methodology revolves around Service Mode Analysis (SMA), which focuses on service phenomena in estimating life-cycle service costs. Service modes are the malfunctions of a system as seen through the customer's eyes, extending the concept of Failure Mode Analysis (Dhillon, 1988) to a wider class of service phenomena.

Our recent thrust is on the advanced planning for product retirement. Does the designer intend to have the product discarded into a landfill, or have considerations been made to re-use or recycle part or all the product? By knowing the post-life-cycle intent of the product, the designer can analyze the product from these standpoints and make iterative changes to improve the design. Hence, designers could benefit from a computer tool that analyzes product layouts and the advanced product retirement plan during the early stages of development.

This paper focuses on 1) a methodology of grouping components that we call “clumping," 2) compatibility analysis of clumps with their post-life intent, and 3) a resulting computer tool for DFR. Section 2 elaborates on DFR issues such as disassembly and material compatibility. Section 3 describes our methodology for the evaluation of a candidate product retirement plan. Section 4 deals with the implementation of the methodology into a computer tool, i.e., clumping strategy. The comparison of two GE ice dispensers and section 5 closes the paper with conclusions and future work.

2. BACKGROUND

For a product to be cost effective at the end of its useful life, a designer needs to analyze retirement costs of the candidate design. The most significant of these costs are collection and transportation, disassembly, and reprocessing. Although collection and transportation costs are beyond the control of the designer, they will contribute to the retirement cost in the form of buy backs from consumers and transportation to a disposition center. Disassembly is the macroscopic separation of subassemblies and/or components, either by hand or machine, and adds labor cost. The more complex the product assembly is, the longer the disassembly time and the higher the disassembly cost. Reprocessing involves shredding the system, separating the regrind, and chemically and/or thermally breaking down and transforming the material into a new material for recycling purposes (Marks, 1993a). Reuse has reprocessing costs associated with the cleaning and inspection of the retired component before it is returned to service. Re-manufacturing a product introduces reprocessing costs for servicing (i.e., disassembly, inspection, cleaning, part replacement and reassembly) the product to return it to a "like-new" state. Disposal of a product by either landfill or incineration incurs handling charges.

2.1 Approach

Our method is based on a concept called "clumping." A "clump" is a collection of components and/or subassemblies that share a physical relationship, and some common characteristic based upon the designer's intent. Recycling requires materials and fastening methods in the clump to be compatible with existing reprocessing technologies (Marks, et al, 1993b). Figure 2 shows a sketch of the major components making up a household drip coffee maker. One possible clumping strategy would be to group the product into two recycling clumps and one reuse clump as shown. One would recover the plastic from the housing and the aluminum from the bottom cover and hot plate assembly. Since the carafe is an easily breakable item, it can serve as a service replacement. These clumps will not require further end-of-life disassembly. The question is if these clumps can be economically separated, reprocessed, and sold.

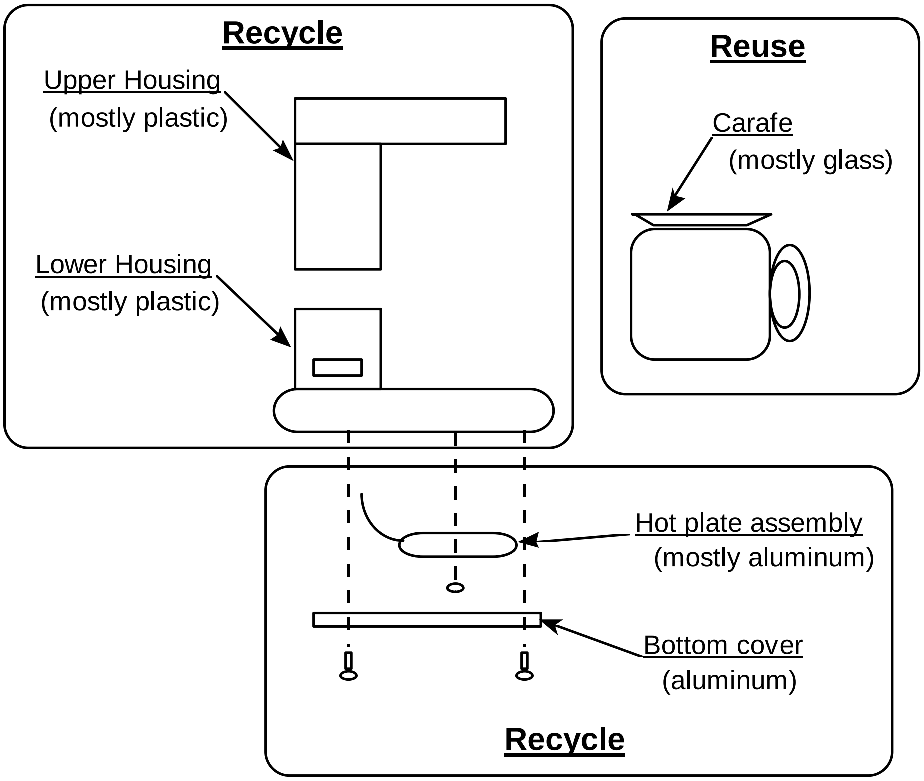


Figure 2: Coffee Maker Showing Possible Retirement Strategy

Disassembly and reprocessing costs determine the system recycling cost (Figure 3). For a given system, as the number of individual clumps increases, the disassembly costs rise, and the reprocessing costs fall. Large, complex clumps, while easily removed from the system, require more complex reprocessing techniques. A larger number of simple, homogeneous clumps may require more time to disassemble, but are simpler to reprocess.

Components can also be grouped for disposal. It is difficult to completely recycle a complex system such as an automobile or refrigerator. If the re-use or recycle value of a portion of the product, one might clump it for disposal and eliminate the disassembly cost. Of course, if the disposal clump contains a hazardous or toxic material, one must disassemble further to isolate and process the offending material. Hence, the general retirement cost equation takes the form:

$$\text{Total Retirement Cost} = \text{Disassembly Cost} + \sum_{i=1}^{n} (\text{Clump Reprocessing Cost})_i \quad (2.1)$$

where: n = total number of clumps

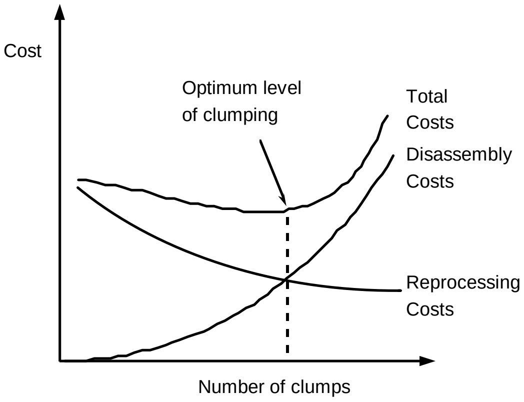


Figure 3: Simplified recycling cost model

This paper concentrates on advanced planning for Design for Product Retirement (DFPR), and addresses to what level to disassemble the product, how to reprocess the resulting clumps, and what are the post-life intents of the clumps. Our method does not include collection and transportation costs, because designers usually do not have control over these issues. However, designers usually do have control over issues such as ease of disassembly and ease of reprocessing the clumps. This paper specifically addresses the methodology that evaluates a clump from its compatibility with the designer's intent.

2.2 Design Representation

The underlying product representation, called the LINKER, (Eubanks, et al., 1992) models the structure of the mechanical systems and captures the necessary data for our evaluation. The LINKER is a hierarchical, semantic network comprising components and subassemblies (nodes), and the relationships between the nodes (links). Links can be actual connections between components or other geometrical relationships that generate assembly or disassembly requirements. The inference of disassembly steps becomes a network search that results in a list of links that must be addressed to disassemble a system. The nature of the search will depend on whether the disassembly process involves accessing a certain component for service, or if it involves end of life disassembly. In general, nodes contain data for material type, part or material cost, part weight, the name of the item or process, a user-defined part number or code, and the next higher assembly (if applicable). Links contain data for link type, removal and installation time, and fastener type. Fastener data modifies the link data to include information about tooling requirements, clearance, and the cost of non-reusable fasteners. Figure 4 shows an example of a LINKER design representation screen.

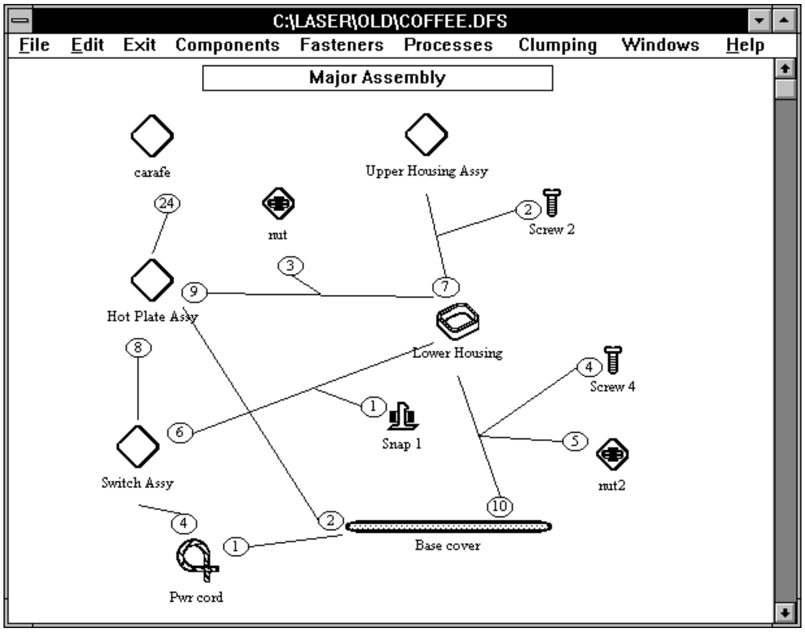


Figure 4: LINKER Representation of Drip Coffee Maker

2.3. Disassembly Cost Analysis

System disassembly cost is a key factor in the analysis for product retirement. The total disassembly time for a system (with no clumps) is calculated by summing the individual disassembly times for each element in the system. (Equation 2.2) (Marks, 1993a).

$$D_s = \sum_{i=1}^{l} C_i + \sum_{j=0}^{m} (f_n \times F)_j + \sum_{k=0}^{n} (p_n \times P)_k \qquad (2.2)$$

where: D_s = system disassembly cost
C_i = time to remove component
F_j = time to remove fastener
P_k = time to remove or undo process
f_{nj} = number of faster associated with one link
p_n = number of process points associated with one link
l = total number of components in system
m = total number of links with fasteners
n = total number of links with fastening processes

For a complex design, the system will contain clumps for re-use, recycling, and disposal. The system disassembly cost becomes the summation of removal times for the clumps and any remaining unclumped components, generally resulting in a cost savings. If the intent of the designer is to dispose of the entire system, he could represent the entire system as a single clump. Obviously this would be a trivial solution because no disassembly calculations would be made.

2.4 Compatibility Analysis Methodology

Design Compatibility Analysis (DCA) provides the framework for the knowledge-based evaluations of the clumps (Ishii, 1992). DCA applies qualitative ratings to expert knowledge to determine a rating for a design. These qualitative ratings (excellent, very good, good, fair, bad, and very bad) are mapped to a [0,1] measure. The intent of DCA is to model a design review in which various "experts" from differing areas rate a design based upon their own specific knowledge. If all experts give the design a rating above 0.5, then they have agreed that the design is acceptable, in which case, we take the highest rating for the design. If there exists at least one rating below 0.5, then that individual has determined that there is a flaw in the design and it is unacceptable, therefore, we take the lowest rating for the design. DCA has proved its worth in many applications including design for injection molding (Ishii, et al., 1989), process selection (Yu, et al., 1993), design for contact stress (Ishii, et al., 1993), and design for serviceability (Eubanks and Ishii, 1993).

3. EVALUATION OF CLUMP RETIREMENT PLAN

This section describes our proposed method for estimating the cost of retiring each clump of components as specified by the designer. The method comprises two steps. 1) Using a knowledge-based technique to qualitatively evaluate the retirement compatibility and assign a rating between zero and one. 2) Using an empirical function to map the [0,1] rating to actual cost.

3.1. Factors Involved in Clump Retirement

The post-life intent is one factor that influences retirement compatibility. This paper adopts seven different types of intent as defined below.

Reuse means the clump will be used "as is" in another application. Examples include: compressors, motors, wire, etc.

Re-manufacture means the clump will be reused in the same or different application after minor repairs or overhauls are made. Repairs may include: replacing gaskets, seals, bearings, etc.

Primary recycling refers to reprocessing material back into a form that can be used in another "high" value product.

Secondary recycling refers to reprocessing material into a "low" value product, such as fence posts, toys, concrete filler, etc.

Tertiary recycling is the chemical decomposition of a polymer down to its basic elements, or monomers. This leads to either new plastics, or other products like gasoline, heating oil, and asphalt.

Quaternary recycling refers to the incineration of materials for the production of heat and/or electricity.

Disposal refers to elimination of the waste product without recovering any intrinsic value, i.e., heat or electricity. This option decreases the disassembly costs in this analysis, but continues to be a bad environmental choice.

If the intent is recycling, the materials in each clump affect the retirement compatibility depending on separation and processing technologies available. An example would be separating plastics and ferrous metals. The metal can be easily separated magnetically after shredding the clump. However, other dissimilar materials such as polyethylene terephthalate (PET) and high density polyethylene (HDPE) are almost impossible to separate and difficult to reprocess for high residual value. The fastening methods between the components in each clump also affect its compatibility. An example is the use of an adhesive to attach two components; the adhesive may contaminate the materials during reprocessing, therefore decreasing the compatibility of the clump.

Another factor influencing retirement cost is the method of disassembly into a planned set of clumps. Disassembly can take two forms, destructive and non-destructive. One must non-destructively separate a clump if it is to be reused, while recycling or disposal may not require the clump to be intact. While the expansion of the disassembly measure is an important part of our work, this paper will not deal with this issue in detail.

Hence, the two major factors over which the designer has control are material compatibility and system disassembly. These two issues must be evaluated with respect to the design structure and the designer's post-life intent for the product. If the results of the analysis fail to meet expectations, the designer can examine two options: 1) redesign the product structure (configuration, materials, etc.), or 2) rethink the retirement strategy. Figure 5 illustrates the schematic of a methodology for evaluating product design and its retirement specifications.

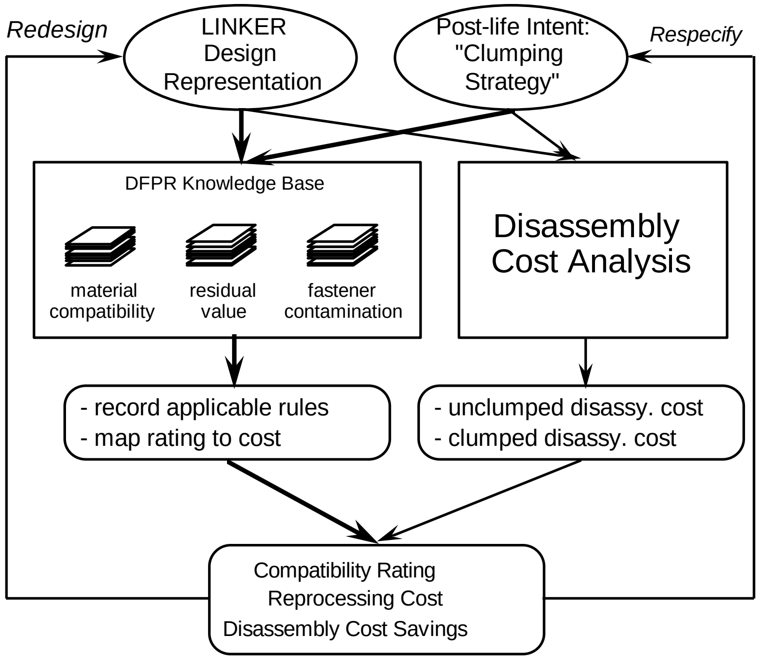


Figure 5: Diagram of System Structure

3.2 Clump Compatibility Knowledge

Advanced planning for retirement, i.e., clumping, requires knowledge of environmentally compatible treatment of the product at the end of its useful life. A designer may designate a clump is for disposal, re-use, or recycling. If a clump is for recycling, the clumped components should be manufactured of materials compatible with currently established reprocessing methods. If the set of materials in a clump can not be economically handled (separated, cleaned, and reprocessed), the recycled material may have little or no residual value (Seegers, 1993). If the average life cycle of a product is more than a few years, it may be difficult to predict government legislation, landfill and raw material availability, and developments in processing technology. Then, the designer needs to base his or her decisions upon current technologies, but should also consider potential developments in technology and trends in society (Marks, et al, 1993b).

On the basis of material vendor's information, one can create a compatibility chart of materials that can be clumped together depending on the level of recycling desired. A standard IF-THEN format accommodates a data base of these material compatibilities. For example, if the first material is polypropylene (PP), and the second is high density polyethylene (HDPE), and the post-life intent of the clump is recycling, then the two materials are incompatible because the mixing of PP and HDPE results in a immiscible material with poor tensile properties and impact strength. The information in the current material compatibility data base is mostly empirical. As with any knowledge-based system, the user must maintain and update the data base as new technologies develop.

1) Compatibility Data for Recycling: The reprocessing cost for a clump is a function of the material compatibility. Therefore, the designer must avoid incompatible materials in a recycling clump. Degradation of a material’s mechanical properties will affect the compatibility of the clump. The reason for this is that the recovered material may no longer have the functional properties that are needed from it. Contaminates contained in the clump result from the fastening method and the disassembly method.

2) Compatibility Data for Reuse: If the designer specifies reuse as the post-life intent for the clump, the compatibility of the components becomes less important. Net value (resale value-disassembly cost-remanufacturing cost) determines the reuse clump compatibility. Also, the connection of the clump to the rest of the system, must provide for easy non-destructive disassembly.

3) Compatibility Data for Disposal: If disposal is the clump's post-life intent, neither the material nor the fastening method is important (aside from being non-hazardous and non-toxic). The removal of the disposal clump may be destructive.

Whatever the post-life intent, the boundary links need to be broken. A boundary link is any physical link (non-"covers" link) connecting the clump to the rest of the system. The cost routine calculates the disassembly costs by looking at all boundary links and all non-clumped links depending on the nature of the clumps. The cost routine does not evaluate the links within the clump.

As discussed later, expansion of the clump compatibility data is the most important aspect of our current research activities. The manufacturer can augment this information by producing their own compatibility rules dependent upon their needs and knowledge of their products. The current knowledge base contains information about materials and user intent. We are currently implementing an editor for compatibility data into the program that will allow the user to input these rules directly into the program's knowledge base. This will ensure the knowledge base to be up to date as technologies develop, governments pass legislation, and recycling infrastructures evolve.

3.3 Clump Retirement Compatibility

After calculating the disassembly costs of the clumped and unclumped system, one must evaluate the clumps for retirement compatibility using DCA. The analysis routine looks first at the components in the clump. It checks the knowledge base for any rules dealing specifically with components' material and post-life intent for the clump. Each rule is assigned a compatibility adjective which maps to a [0,1] rating, as shown in Table 3.1.

Table 3.1: DCA Rating Assignments for Material Compatibility Chart

Level of Compatibility	DCA Rating
"very_compatible"	1.0
"compatible"	0.8
"some level of compatibility"	0.6
"incompatible	0.2
"hazardous"	0.0
"no_info"	0.5

The compatibility rules, or C-data, are modeled to represent “expert” knowledge. A C-data contains it's ID number, the associated design components/features, a compatibility descriptor such as “very good” or “poor,” reasons and suggestions, and most importantly, the conditions for the data to be true (Ishii, 1992). An example of knowledge available to our program is listed below:

C-data:

ID = dfr016
elements = material_A, material_B, intent
descriptor = incompatible
reason = One ppm of PVC mixed with PET will cause discoloration of the PET.
suggestion = Try substituting polycarbonate for PVC.
conditions = material_A = "pet",
material_B = "pvc",
intent is primary_recycling. (3.1)

The program then individually compares each component with every other component, fastener, and process in the clump, creating the set $[0,1]^n$, where n is the number of matching compatibility data for the clump. We then map $[0,1]^n$ into a single clump compatibility rating $CC(s) \in [0,1]$ for each clump, s, using the following function.

1) the maximum in the set, if it consists only of numbers greater than or equal to 0.5.
2) the minimum in the set, if it contains at least one number less than 0.5.
3) 0.5 if rule set is empty, indicating neutral compatibility.

3.4 Clump Retirement Cost

In our model, retirement compatibility within each clump determines the clump reprocessing cost. We use an empirical function as shown in Figure 6. The cost decays exponentially as the compatibility increases. The cost curve is a result of a series of discussions with industry. If clump compatibility CC(s) = 1.0, we assume the cost to reprocess the clump is equal the market value of the recovered material. A clump with CC(s) = 0 indicates that there is a hazardous or toxic material in the clump and a reprocessing cost of infinity. If the clump has a rating of “incompatible," i.e. CC(s) = 0.2, then we assume that the clump is not worth reprocessing and it must be disposed of. Hence we assign a standard landfill cost for the clump, computed as a function of its weight or volume. The resulting cost mapping is shown in equation 3.2.

$$\mathrm{CRC(s)} = \mathrm{LFC(s)x}\,\frac{\ln(\mathrm{CC(s)})}{\ln(0.2)} \tag{3.2}$$

where:

CRC(s) = Clump Retirement Cost
LFC(s) = Land Fill Cost
CC(s) = Clump Compatibility

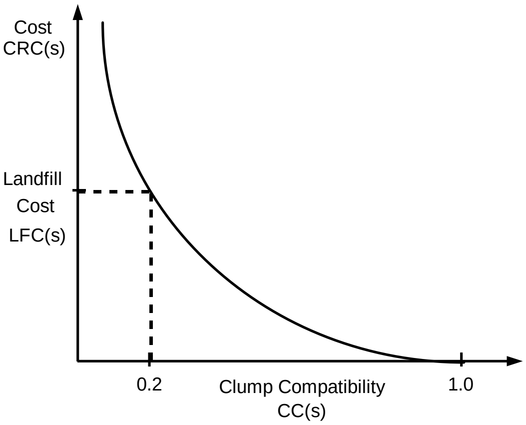


Figure 6: Clump reprocessing cost

If a clump has a high value, CRC(s) < 0 for CC(s) = 1, one may profit from its reuse or recycling. Currently the model does not consider this case; our industrial collaborators indicate that they are quite happy if they can break even.

4. IMPLEMENTATION AND EXAMPLE

Figure 7 represents how, through a common design description, the user can evaluate a design from various stages of the life-cycle. Our computer tool allows for design for assembly evaluation, labor operation and labor step analysis for service, and advanced planning for system recycling.

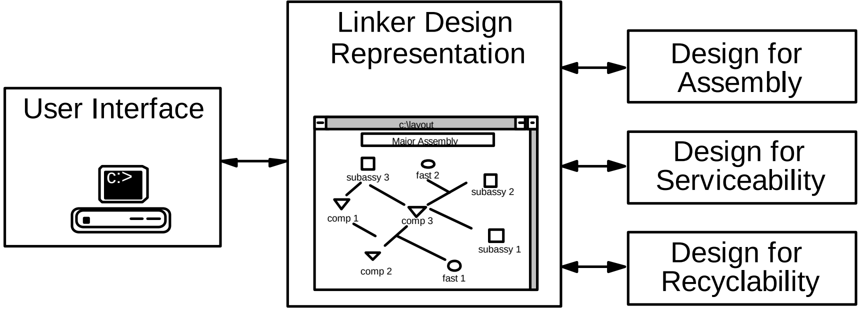


Figure 7: Integrated Life-cycle Design Tool

Figures 8 shows one of two refrigerator in-door ice dispensers we modeled and analyzed using our integrated life-cycle design tool. These subsystems presented a good test case, because they represent a mixture of components and materials. The primary difference between these two designs is that the 1992 model dispenses ice using a primarily mechanical system of springs, wires, and an inertial damper, whereas the 1993 model dispenses ice using an electro-mechanical solenoid assembly. The 1993 model is a simpler design and has fewer moving parts.

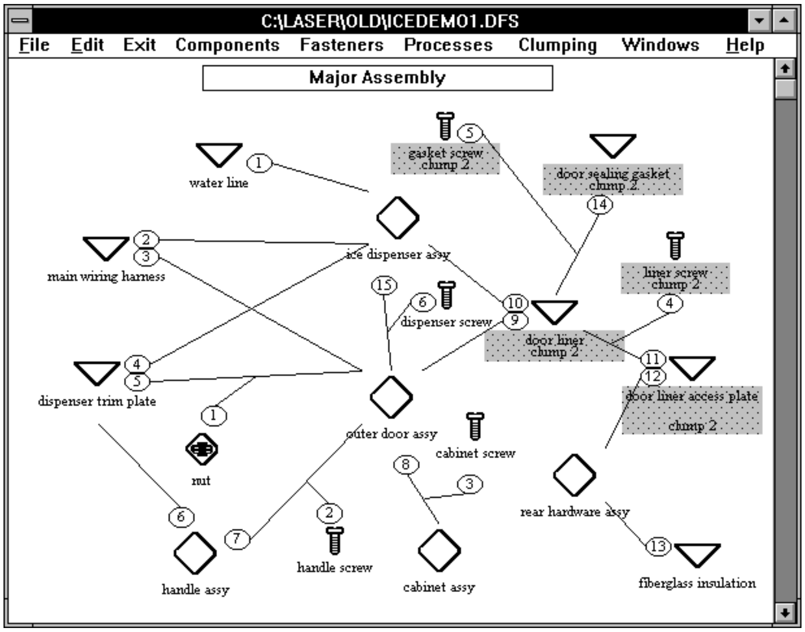
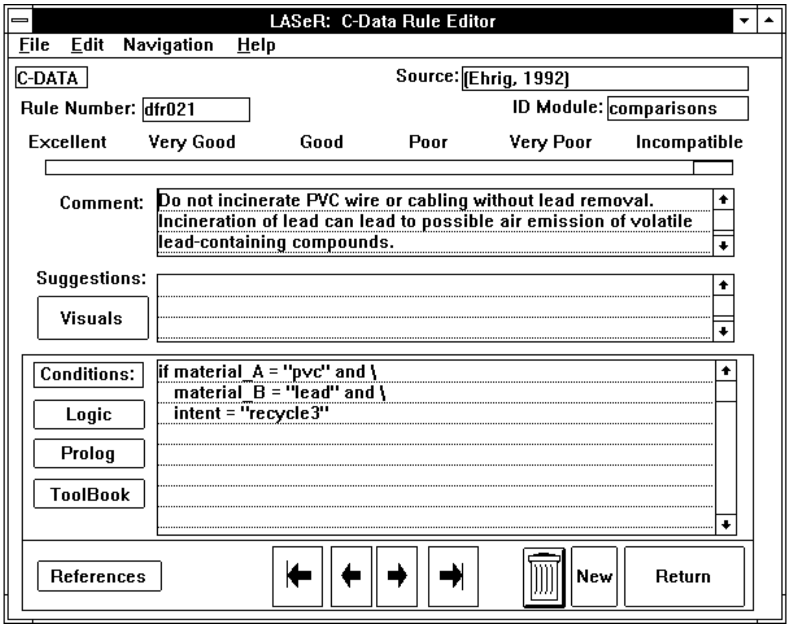


Figure 8: Design Representation of 1991 GE Ice Dispenser

Our implementation of a rule in the knowledge base regarding tertiary recycling for a combination of PVC and lead, typical of electrical wire with solder joints, is shown in the compatibility data card (Figure 9).



C-DATA

Source: (Ehrig, 1992)

Rule Number: dfr021

ID Module: comparisons

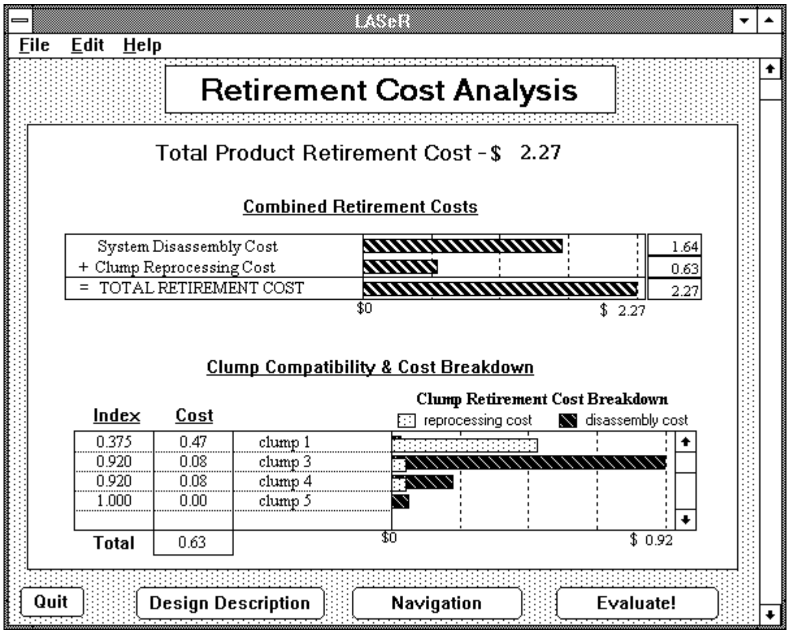
Comment: Do not incinerate PVC wire or cabling without lead removal. Incineration of lead can lead to possible air emission of volatile lead-containing compounds.

```
if material_A = "pvc" and \
   material_B = "lead" and \
   intent = "recycle3"
```

Figure 9: Compatibility Rule Editor

Figure 10 shows the retirement cost summary for the 1991 model ice dispenser. Displayed are the disassembly times for the components and fasteners in the system, the compatibility index for each clump, and the retirement cost breakdown for each clump, including the reprocessing and disassembly costs for each individual clump. A net savings results when the clump disassembly cost is less than the system disassembly cost. This indicates that the clumping strategy is a satisfactory one based on cost. If the clump disassembly cost is greater than the system disassembly cost, a net increase in cost would be the result.

Figure 11 shows the normalized assembly, service, and recycling costs for the two dispensers. The three analyses result in differing scales (i.e., T-downs, cost for a given set of labor operations, and recycling cost). Hence, the values for the 1992 model in Figure 13 are all normalized to 100% and the 1993 values scaled appropriately. For all three areas of the life-cycle analysis, the new (1993) ice dispenser model shows a significant decrease in cost. Assembly costs were reduced by 19%, service by 27%, and recycling costs by 23%. The fewer numbers of components in the new model contributed significantly to these decreased costs. It should be noted that we assumed proportional clumping strategies for both ice dispensers, since we normally compare clumping strategies for a single design to improve its overall recyclability.



Total Product Retirement Cost - $ 2.27

Combined Retirement Costs

System Disassembly Cost	1.64
+ Clump Reprocessing Cost	0.63
= TOTAL RETIREMENT COST	2.27

Clump Compatibility & Cost Breakdown

Index	Cost	
0.375	0.47	clump 1
0.920	0.08	clump 3
0.920	0.08	clump 4
1.000	0.00	clump 5
Total	0.63	

Figure 10: Retirement Cost Analysis for 1991 GE Ice Dispenser

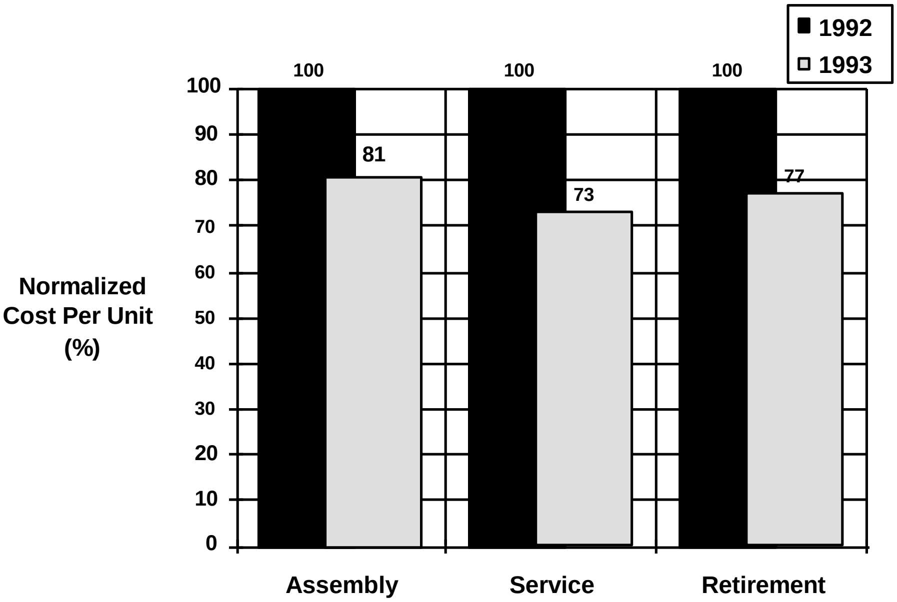


Figure 11: Life-cycle Cost Comparison for 1992 and 1993 GE Ice Dispensers

5. CONCLUSIONS & FUTURE WORK

This paper presented a method for evaluating the design of a mechanical system and its end-of-life retirement strategy. Our method assumes that designers specify in advance the level of disassembly of the product and post-life intent for the remaining clumps of components. This paper focused on the compatibility evaluation of the reuse, recycle, or disposal of the clumps and estimation of the clump retirement cost. We incorporated this method into our existing Life-cycle design tool, which uses a common design description to perform simultaneous analyses of assembly, serviceability, and product retirement issues.

We are not able to claim the validity of our approach with quantitative measures, until a product that used our method in its design is ready for retirement. For appliances and automobiles, we may need to wait for another 10 years before we can claim success. However, our method and the integrated tool have encouraged designers in industry to critically address retirement issues at the early design stages. Many of our industrial collaborators indicate that such awareness alone is extremely valuable. They also indicate that the life-cycle integration of our approach that allows designers to simultaneously evaluate manufacturing, service, and retirement cost attracts actual usage of the tool without an excessive burden on the engineers.

The immediate and urgent challenge for our future work is the expansion of the clump retirement compatibility knowledge. We are focusing on several fronts.

1) **Material compatibility data:** The current program provides material compatibility analysis based solely on a binary comparison. There may be cases where several materials can be recycled together to yield a suitable substance for application to other products. We need to expand our knowledge base and our compatibility analysis methods to handle these cases.

2) **Material degradation model:** We need to develop a model of how materials degrade their value through manufacture, use, and reprocessing. In particular, we are interested in the effect of contamination in the recycling process. Many products, particularly plastic parts, use inserts, glues, and fasteners of a different material, creating the possibility for contamination. The labor cost to remove the contamination can be quite high compared to the value of the recycled material. We need to revise our implementation and update our knowledge base to flag incompatible materials with respect to unacceptable weight or volume ratios.

3) **End-of-Life disassembly measures:** The current method of comparison between destructive and non-destructive disassembly at the end of a products life needs to be expanded. If a clump is destructively removed at the end of its life, contamination between materials becomes an issue due to non-compatible materials left behind during disassembly. We need to include some type of a measure that correlates the method of disassembly with the proposed clump reprocessing cost model.

4) **Inclusion of our environmental impact factors:** Waste management through recycling is only one part of the equation in environmental product design. Manufacturing and assembly processes consume electrical energy and can generate pollution and hazardous waste. Our design compatibility analysis must also include issues such as the cost and impact of total energy consumption, and pollution impacts throughout the product life-cycle.

Close collaboration with industry plays a major role in our continuing work. By soliciting product retirement knowledge and feedback on our methods and tools from industry, we can ensure the practical utility of our research results. Through such efforts, we hope to prove the validity of our work by getting quantitative measurement of design improvement in environmental compatibility.

ACKNOWLEDGMENTS

Sponsors of this research include the National Science Foundation / Division of Design and Manufacturing, NASA Lewis Research Center, and General Electric. The authors would also like to thank our collaborators from Geon Vinyl, Digital Equipment Corporation, Eastman Kodak, Nissan, and Rockwell International. Special thanks go to Matt Marks for his support and encouragement.

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