Design for product retirement and material life-cycle

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Life-cycle design seeks to maximize the life-cycle value of a product at the early stages of design, while minimizing cost and environmental impact. This paper focuses on product retirement and advanced planning for material recycling. Design for product retirement (DFPR) applies to retirement strategies, i.e. designers' intent for product disassembly and reprocessing of subassemblies and components. The method combines quantitative cost formulae and qualitative guidelines to determine the feasibility and cost benefits of a candidate retirement plan. Material life-cycle analysis (MLCA) addresses essential knowledge used by DFPR, i.e. assessment of residual value of a material when recycled under a certain scenario. For plastic components, we have been developing a standard for evaluating the residual mechanical strength of materials recycled from various product histories and assessing necessary processes to remedy the degradation. This standard, combined with other material compatibility information and disassembly knowledge, makes DFPR a viable tool for life-cycle design. The paper illustrates our prototype computer tool for DFPR using an example from the computer industry.

Keywords: design for product retirement; clumping; material life-cycle analysis

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*). Many prior studies exist in the area of design for assembly (DFA[1]) and design for producibility of components[2]. Design for serviceability (DFS) has attracted significant interest as a method to enhance product ownership quality[3,4].

Recent years have seen a surge of work in environmentally conscious design and manufacturing. Life cycle assessment (LCA) is a broad methodology for identifying environmental burdens that arise from a product or process. The US Environmental Protection Agency[5], the Canadian Standards Association[6] and the Society of Environmental Toxicology and Chemistry[7] are developing documents that address life-cycle concerns from raw material acquisition to final product disposition and include total energy use and pollution impacts. LCA seeks to minimize the environmental impact of the manufacture, use and eventual disposal of products without compromising essential product functions. Allenby's methodology[8] ranks various environmental issues pertaining to each life-cycle stage. Glantschnig[9] focused on waste minimization during manufacturing. So far, most LCA studies have focused on single-material products such as disposable drink containers and children's nappies. For complex products such as cars and appliances, LCA is often too time consuming for designers to implement themselves.

One issue that design engineers have control over is product retirement[10,11]. Does the designer intend to have the product discarded into a landfill, or plan to re-use or recycle part or all the product? By knowing the post-life-cycle intent of the product, the designer can analyse the product from these standpoints and make iterative changes to improve the design. Such practice also leads to the simultaneous design of the product retirement logistics, which will be a required responsibility of any manufacturer, as governments around the world become more conscious of waste management and sustainable development. The key is the 'simultaneous' planning for retirement in the early stages of design, i.e. design for product retirement (DFPR). Engineers could benefit from a structured methodology that analyses product layouts and the advanced product retirement plan during the early stages of development.

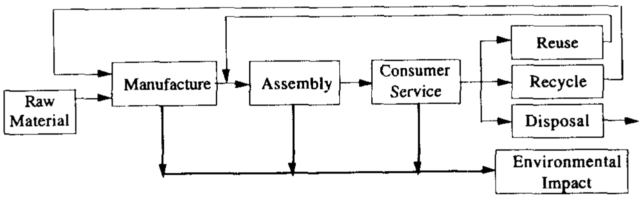

Figure 1 Product life-cycle

One of the most important elements of the product retirement strategy is advanced planning for the disposition of materials recovered from the product. Engineers must extend their views to consider the full utilization of materials and their environmental impact throughout the 'material' life-cycle instead of one 'product life-cycle' (*Figure 2*). For this purpose, designers need the knowledge of the materials' residual value after manufacturing, service, collection and reprocessing. This information is scarce, particularly for plastic materials. Engineers need a model of material degradation[12]

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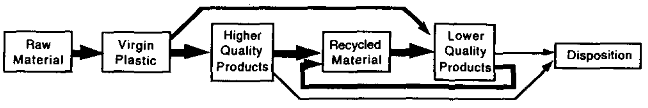


Figure 2 Material life-cycle

so that they can effectively specify the extended use of materials from the initial high-quality products to incrementally decreasing quality ones.

Again, the key is to provide the design engineers with information necessary for specifying in advance the retirement strategy. Naturally, accurate cost data for various retirement and material life-cycle strategies may not be available at the design stage of a product. Major uncertainties include the market demand for re-used components and recycled materials and availability of economical separation and reprocessing technologies. The challenge is to combine qualitative and available quantitative information to allow designers to compare different retirement strategies.

This paper focuses on (1) a methodology for analysing a proposed design and its retirement strategy and (2) the compatibility knowledge, particularly the material degradation model. The next section elaborates on the DFPR methodology. The third section describes the evaluation of a product retirement strategy and the fourth section outlines our efforts to develop the material life-cycle model. The fifth section deals with the implementation of the methodology into a computer tool. The final section closes the paper with conclusions and future work. A coffee maker serves as our illustrative example in this paper.

Design for product retirement

Approach

Our method of design for product retirement (DFPR) is based on a concept called 'clumping'. A 'clump' is a collection of components and/or subassemblies that share a common characteristic based upon the designer's intent. Recycling requires materials and fastening methods in the clump to be compatible with existing reprocessing technologies[11]. Re-use requires easy removal of the clump from the system and high resale value to offset the recovery cost. *Figure 3* shows 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 re-use clump as shown. One would recover the plastic from the housing and the aluminium from the bottom cover and hot plate assembly. Since the carafe is an easily broken item, it can serve as a service replacement. These clumps will not require further end-of-life disassembly. A key consideration is whether or not the clumps can be economically separated, reprocessed and sold.

Our approach performs the retirement analysis based on user input. We require the user to define the retirement strategy by specifying which components are to be clumped and the user's end-of-life intent for each of the clumps. This differs from the approach taken by Navin-Chandra[13] in the ReStar program. His approach uses a component graph to perform an automated search and analysis for optimal retirement plans based on level of disassembly and component material compatibility. The algorithm generates a disassembly sequence, constantly tracking costs and possible revenues gained by further disassembly. In our view, the major drawback of the optimization approach is its relatively high computational intensity and complexity. Our goal is to provide a quick analysis and what-if capability based on system structure and retirement strategy. Thus, we have concentrated on making it easy to change and adjust the structure and strategy representations, and performing the analysis based on total product disassembly and reprocessing in accordance with the user's specifications.

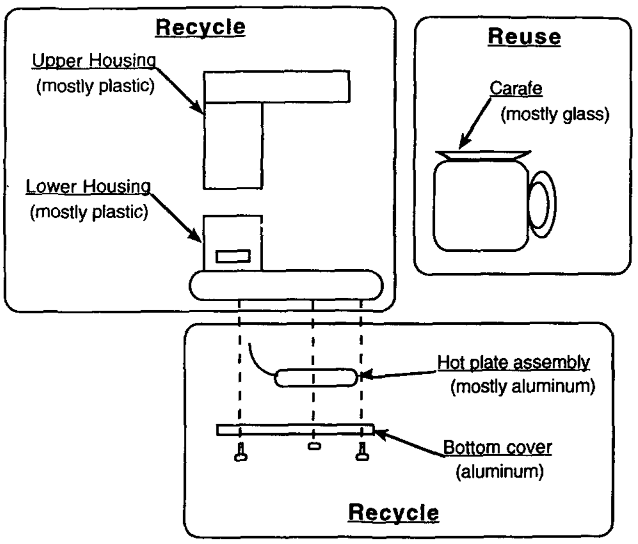


Figure 3 A possible retirement strategy for a coffee maker

Disassembly and reprocessing costs determine the system recycling cost (*Figure 4*). 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 large number of simple, homogeneous clumps may require

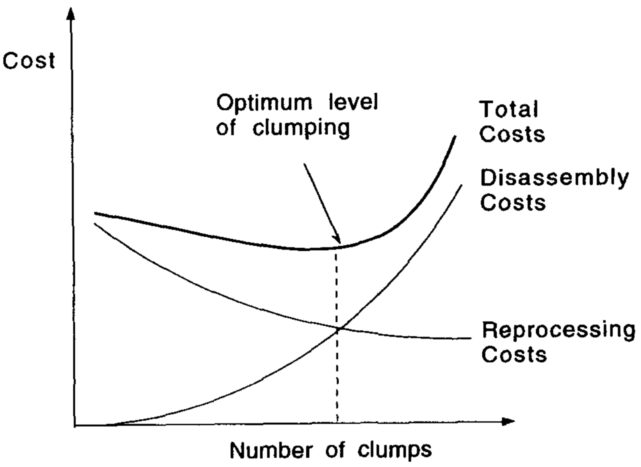


Figure 4 Simplified recycling cost model

more time to disassemble but are simpler to reprocess. Some clumps inevitably lead to disposal due to their complexity and low residual value. Even in such cases, one must ensure that hazardous material can easily be treated or removed from the clump. We calculate the total product retirement cost as:

$$\begin{aligned}\text{Total retirement cost} &= \\ &\text{collection and transportation cost} \\ &+ \text{disassembly cost} \\ &+ \sum_{i=1}^{n} (\text{clump reprocessing cost})_i\end{aligned} \tag{1}$$

where n = total number of clumps.

This paper concentrates on advancd planning for product retirement, and addresses the level at which the product is disassembled, the reprocessing of the resulting clumps and 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 can influence ease of disassembly and ease of clump reprocessing. This paper specifically addresses the methodology that evaluates a clump according to its compatibility with the designer's intent. We also discuss the concept of material life-cycle analysis (MLCA) which forms the most challenging aspect of clump compatibility analysis.

Design representation

Analysis for product retirement requires a systematic method of representing the pertinent attributes of the candidate design. Our product representation scheme, called the LINKER,[4] models the structure of the mechanical system 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[4]. The nature of the search will depend on whether or not the disassembly process requires 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-re-usable fasteners. *Figure 5* shows the LINKER[4] design representation screen for the coffee maker example.

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:

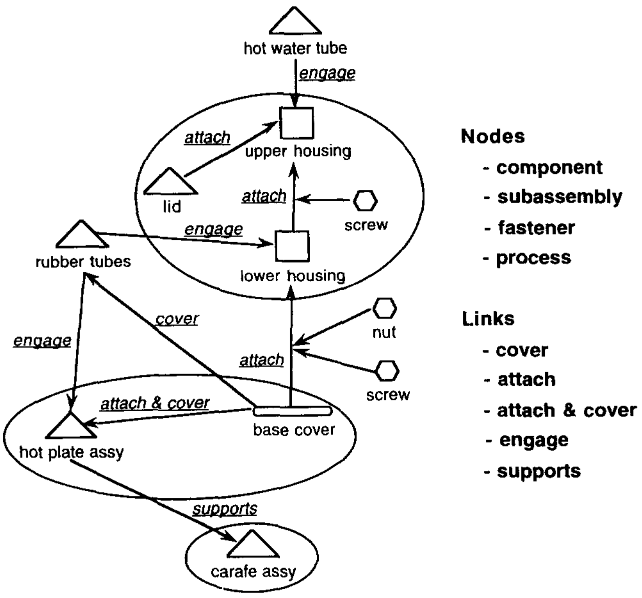


Figure 5 LINKER representation of the drip coffee maker

$$D_s = \sum_{i=1}^{l} C_i + \sum_{j=0}^{m} (f_n \times F)_i + \sum_{k=0}^{n} (p_n \times P)_k \tag{2}$$

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 fasteners 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 cost savings. If the intention of the designer is to dispose of the entire system, he or she could represent the entire system as a single clump. Obviously, this scenario leads to a trivial solution because it requires no disassembly calculation.

The measure of end-of-life product disassembly is a major research topic itself. So far, our methodology has adopted disassembly cost data available for service and repair[3,4]. However, the method of end-of-life disassembly is quite different. The appropriate disassembly method of each clump depends heavily on the retirement intention. If a clump is to be re-used, one must separate the clump non-destructively. If a clump is to be ground into pellets and reprocessed, one can destructively disassemble the clump. Obviously, the development of an advanced measure is an ongoing research topic. This paper adopts the disassembly measures used for product service and repair, on the assumption that it will give a good indication, probably on the conservative side, of the retirement cost.

Compatibility analysis methodology

Design compatibility analysis (DCA) provides the framework for the knowledge-based evaluations of the clumps[14]. 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 moulding, process selection[15], design for contact stress[16] and design for serviceability[4].

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 involves 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.

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.

1. *Re-use* means that the clump will be used 'as is' in another application. Examples include compressors, motors, wire, etc.
2. *Remanufacture* means that the clump will be re-used in the same or different application after minor repairs or overhauls are made. Repairs may include replacing gaskets, seals, bearings, etc.
3. *Primary recycling* refers to reprocessing material back into a form that can be used in another 'high'-value product.
4. *Secondary recycling* refers to reprocessing material into a 'low'-value product, such as fence posts, toys, concrete filler, etc.
5. *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 such as petrol, heating oil and asphalt.
6. *Quaternary recycling* refers to the incineration of materials for the production of heat and/or electricity.
7. *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 re-used, 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 6* illustrates the schematic of a methodology for evaluating a product design and its retirement specifications.

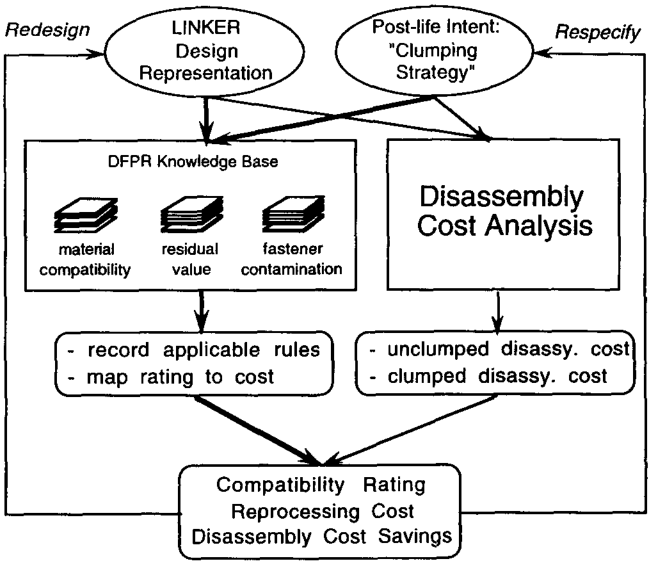


Figure 6 Diagram of system structure

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 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 cannot be economically handled (separated, cleaned and reprocessed) the recycled material may have little or no residual value[17]. 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[11].

The material vendor's information leads to a compatibility chart of materials that can be clumped together depending on the level of recycling desired. A standard IF-THEN format accommodates a database of this material compatibility. 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 an immiscible material with poor tensile properties and impact strength. The information in the current material compatibility database is mostly empirical. As with any knowledge-based system, the user must maintain and update the database 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. Contaminants contained in the clump result from the fastening method and the disassembly method.
2. *Compatibility data for re-use*: If the designer specifies re-use 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 re-use 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 (apart 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. In summary, the pertinent factors in clump compatibility are as follows:

- Post-life intent of the clump
- Materials used in the clump
- Level of contamination from fasteners, etc.
- Availability of economical reprocessing technology for the clump
- Residual market value of materials or components recovered from the clump

The expansion of the clump compatibility data is the most important aspect of our current research activities. Manufacturers can augment this information by producing their own compatibility rules depending on 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.

Design compatibility of a clump retirement strategy

After calculating the disassembly costs of the clumped and unclumped system, one must evaluate the clumps for retirement compatibility using design compatibility analysis (DCA[14]). For each clump, DCA checks the knowledge base for any compatibility information dealing specifically with a component's material and post-life intent for the clump. Each rule contains a compatibility adjective which maps to a [0,1] rating, as shown in *Table 1*.

Table 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, represent a piece of expert knowledge. A C-data contains an 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. Clause (3) shows an example of knowledge available to our program. Our system has over 80 C-data covering commonly used materials and fasteners:

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)

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:

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

Hence, DCA represents a function which maps LINKER representation data, the retirement strategy and the compatibility knowledge to a rating from zero to one inclusive, as follows:

$$\text{DCA:[LINKER,RetirementStrategy, C - Database]} \rightarrow [0,1] \quad (4)$$

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 7*.

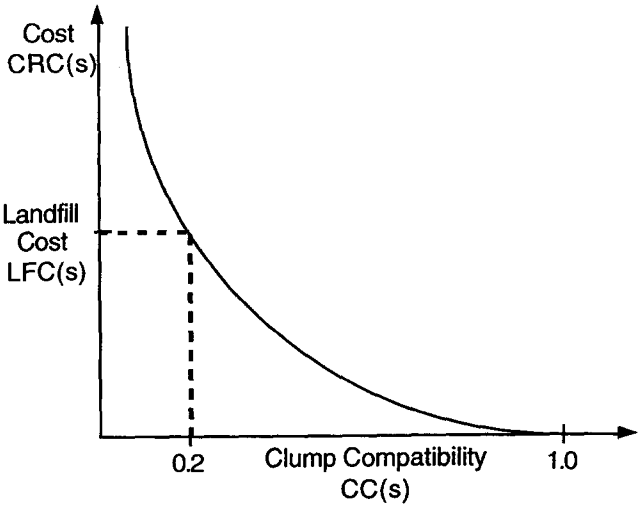


Figure 7 Clump reprocessing cost

In informal discussions several of our industrial collaborators indicated that the cost of reprocessing hazardous materials has increased severalfold in the last few years, and at a much higher rate than landfill costs for inert or environmentally benign materials. Therefore a clump with $CC(s) = 0$ indicates that there is a hazardous or toxic material in the clump and a reprocessing cost of infinity. Our collaborators further stated that clean waste streams of easily reprocessed materials can be sold to third-party recyclers at almost breakeven prices. If clump compatibility $CC(s) = 1.0$, we assume that the cost to reprocess the clump is equal to the market value of the recovered material. To complete the cost model, if the clump has a rating of 'incompatible', i.e. $CC(s) = 0.2$, then we assume that the clump is not worth reprocessing. Designers should specify this clump as a disposal clump. Hence we assign a standard landfill cost for the clump, computed as a function of its weight or volume. The cost decays exponentially as the compatibility increases. Equation (5) shows the resulting cost function:

$$CRC(s) = LFC(s) \times \frac{\ln(CC(s))}{\ln(0.2)} \quad (5)$$

where

CRC(s) = clump retirement cost
LFC(s) = landfill cost
CC(s) = clump compatibility

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

Material life-cycle analysis

Our current retirement compatibility data include a rather qualitative and simplistic knowledge of material compatibility and degradation. For DFPR to be more effective, we need a method of estimating the residual value of the materials recovered from the product, i.e. material life-cycle analysis (MLCA). This type of information is scarce, particularly for plastic materials. Recycled plastics usually possess varying rheological and mechanical properties depending on the history of the materal. The full potential of recycling is limited because it is impossible to generate reliable engineering data for the numerous generations and mixes of recycled plastics. This uncertainty in properties makes it difficult for engineers to design with recycled plastics.

The key technology needed to conduct life-cycle design of recycled plastics is to model the degradation process of plastic material. From the materials perspective, we must (1) investigate what processing and operational factors affect mechanical and rheological properties, (2) develop a good measure of degradation and (3) identify a measurable material property that is a good indicator of degradation. Such a material degradation model will help processors to maintain the processing material to the designer's specification by mixing the recycled plastic with virgin materials or by adding appropriate compatibilizers. Design engineers would

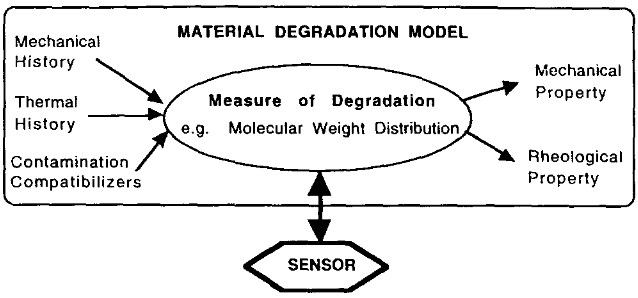


Figure 8 Material degradation model for plastics

also be able to predict the quality of plastic material recovered at the end of a product's life, and specify its next use.

Our laboratory is developing a material degradation model that could be incorporated into our DFPR methodology. The initial study[12] established that engineering thermoplastics retain their mechanical properties though many generations of regrind, if the processing and service conditions are not severe and the recycling processes do not introduce significant contaminants. The current research seeks an advanced degradation model that defines a physics-based measure of degradation, predicts the mechanical and producibility properties, and identifies the effect of various factors influencing degradation (*Figure 8*). The project also includes the development of a sensor that can be used in the manufacturing environment. Such a degradation model provides a more quantitative basis for the compatibility analysis of retirement clumps.

Implementation and example

The LINKER allows the user to evaluate a design from various stages of the life-cycle: assembly analysis, labour operation and labour step analysis for service, and product retirement analysis. Many companies require designers to analyse layout designs for manufacturability and serviceability. By integrating DFPR into a tool that uses the same product representation and database, designers can make advanced plans for product retirement and thus consider recyclability in their designs with minimal additional time burden. Our experience with industrial collaborators indicates that this integrated feature is an essential key to promoting DFPR. Our prototype life-cycle design tool runs in a PC-Windows 3.1 environment using the Toolbook software construction kit.

Figure 9 is a screen dump from our life-cycle design tool showing the LINKER representation of the coffee maker described earlier. For a product of this complexity, even a novice user can construct this graph, input the pertinent information, and analyse the life-cycle costs in less than one hour. Each node or link has a data page that the user can access by double clicking on the graphical icon. *Figure 10* shows an example data page that accepts information pertinent to retirement analysis. Other data pages contain information for assembly and service analysis. Thus, LINKER is a graphical front-end to an object-oriented product definition. We believe LINKER can serve as a broader tool for competitive product and process development by providing multi-faceted analyses from a single-product representation. In addition, such a tool could be used to support ISO 9000 activities since it provides a means of documenting device structure, component data and serviceability requirements. It is probably reasonable to assume that product retirement plans will be included in future ISO 9000 specifications.

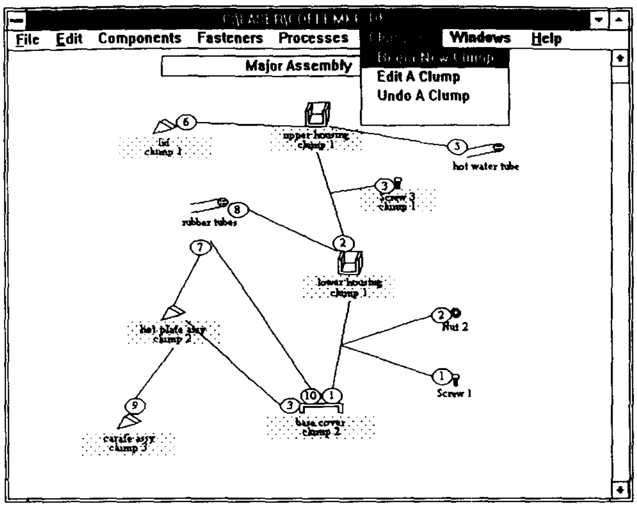
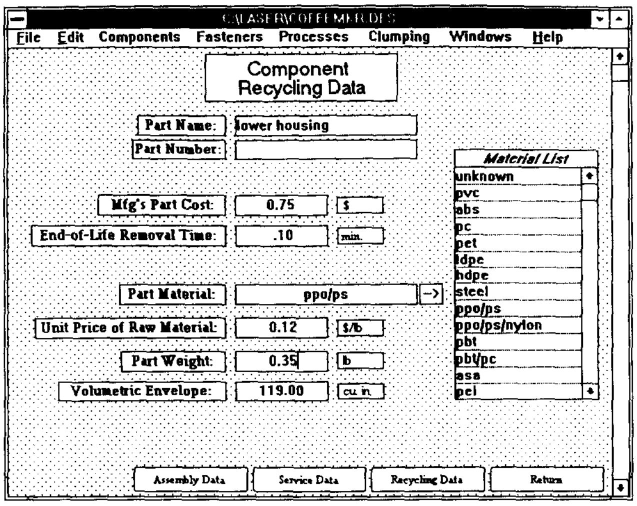


Figure 9 Life-cycle design tool showing a clumped coffee maker



Component Recycling Data

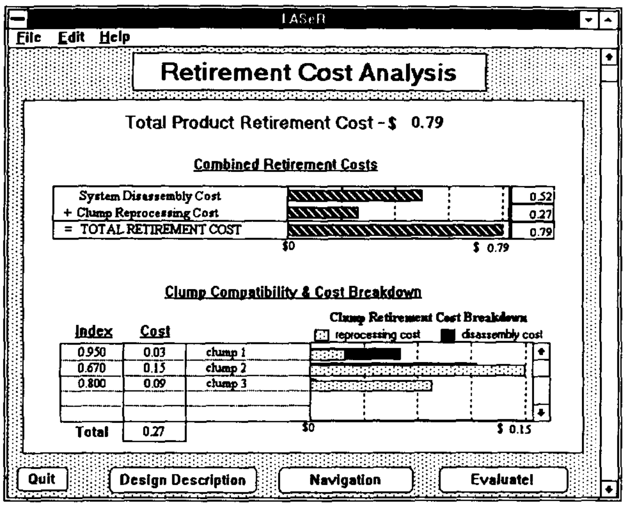
Part Name: lower housing
Part Number:
Mfg's Part Cost: 0.75 $
End-of-Life Removal Time: .10 min.
Part Material: ppo/ps
Unit Price of Raw Material: 0.12 $/lb
Part Weight: 0.35 lb
Volumetric Envelope: 119.00 cu in

Material List
- unknown
- pvc
- abs
- pc
- pet
- ldpe
- hdpe
- steel
- ppo/ps
- ppo/ps/nylon
- pbt
- pbt/pc
- asa
- pei

Figure 10 Data input page for product retirement analysis

Figure 11 shows the retirement cost summary for the coffee maker. 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 clump.

To test the validity of our life-cycle costs, we applied our tool to two models of an indoor ice dispenser from GE refrigerators. 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 electromechanical solenoid assembly.



Retirement Cost Analysis

Total Product Retirement Cost - $ 0.79

Combined Retirement Costs

System Disassembly Cost	0.52
+ Clump Reprocessing Cost	0.27
= TOTAL RETIREMENT COST	0.79

Clump Compatibility & Cost Breakdown

Index	Cost	
0.950	0.03	clump 1
0.670	0.15	clump 2
0.800	0.09	clump 3
Total	0.27	

Figure 11 Retirement cost analysis of a coffee maker

The 1993 model is a simpler design and has fewer moving parts. For all three areas of the life-cycle analysis, the new (1993) ice dispenser model showed a significant decrease in cost. Assembly costs decreased by 19%, servicing by 27% and recycling costs by 23%. The smaller number of components in the new model contributed significantly to these decreased costs. Note 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.

The case study established the high potential of our tool as a life-cycle design aid in the layout stages of product development. The key feature is the consolidated design representation LINKER, which allows rapid evaluation of various life-cycle costs.

Conclusions and future work

This paper has presented a method for evaluating the design of a mechanical system and its end-of-life retirement strategy (design for product retirement, DFPR). 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. The paper has focused on the compatibility evaluation of the re-use, recycling 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. The paper also outlined the development of a material life-cycle analysis (MLCA) method. The central issue in MLCA is to estimate the residual value of a material recovered from a product. For plastic materials, we are developing an advanced material degradation model that allows engineers to provide quantitative compatibility measures for use in DFPR.

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 cars, we may need to wait for ten 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 costs 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 in value through manufacture, use and reprocessing. In particular, we are interested in the effect of contamination in the recycling process. 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 is inadequate. We need a rigorous 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.

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