Proceedings of
The 1996 ASME Design Engineering Technical Conferences and
Computers in Engineering Conference
August 18-22, 1996, Irvine, California

96-DETC/DFM-1270

DESIGNING FOR MATERIAL SEPARATION: LESSONS FROM AUTOMOTIVE RECYCLING

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ABSTRACT

Virtually all of the material in today's automobiles can technically be recycled. The challenge facing engineers is making this recycling process economical, especially for materials in such components as seats and instrument panels. Recycling these components requires the different materials to be separated so that each can be recycled individually. This separation can be accomplished either *manually*, where workers disassembly and sort the vehicle components by hand, or *mechanically*, where the vehicle is shredded and the materials sorted by properties such as conductivity and density. In this paper, the usefulness of including likely separation techniques in DFR guidelines is discussed. Three vehicles were dismantled at the VRDC as part of an effort to establish a baseline of current vehicle recyclability. Concurrently, this allowed examination of the effectiveness of the early design for recycling (DFR) efforts. The applicability of common design guidelines to the two types of separation is discussed, and a simple method for determining the appropriate separation process in the early stages of design is presented.

NOMENCLATURE

ASR	Automotive Shredder Residue
I/P	Instrument Panel
M.R.R.	Material Removal Rate
R.R.	Recyclability Rating
S.R.	Separability Rating

1 INTRODUCTION

Whether motivated by recent legislative efforts or by a moral sense of obligation, automotive manufacturers are attempting to reduce the environmental impacts of the entire life cycle of their vehicles. Specifically, the manufacturers are attempting to improve the recyclability of their vehicles and thereby reduce the percentage of each car which must be disposed of in a landfill. This recyclability improvement has been motivated in large part by proposed European legislation that requires car manufacturers to be responsible for comprehensive recycling and material recovery from their vehicles (see, e.g., (Fiksel, 1996b)). The increased emphasis on recyclability has led to the establishment of the Vehicle Recycling and Development Center (VRDC) in Detroit which serves as the headquarters of the Vehicle Recycling Partnership (VRP), a cooperative effort among Chrysler, Ford, and General Motors as part of the USCAR initiative. Since most of the steel and metals from these vehicles (which constitute about 75% of a vehicles weight) are already recycled (see, e.g., (Klimisch, 1994)), the concentration of recent efforts has been on the vehicle sub-systems which are mostly non-metal - for instance, the polymers in the bumper systems, the instrument panel, the seats, and other interior trim components.

Ideally, recyclability would be as important as other design goals, but realistically, improving the recyclability must be

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addressed within the current constraints of the automotive design process. In the automotive industry, this means that design for recycling (DFR) efforts cannot be allowed to adversely impact more important constraints such as cost, weight, and safety. Perhaps the best example of this is the shift towards a lower metal content in most cars. Over the last 20 years, this percentage has dropped approximately 10% of the weight of the car - from about 85% to about 75%. This has translated to cars which are less recyclable, since the only well developed recycling infrastructure is for steel and other metals. However, the change has resulted in lighter, cheaper, and more (fuel) efficient vehicles. The challenge for recycling efforts is to maintain, or even improve, previous levels of recyclability while allowing the use of materials and designs which better achieve other goals and constraints.

In this paper, the usefulness of including likely separation techniques in DFR guidelines is discussed. This discussion is based on three technology bases: the current separation techniques used by the recycling industry (Section 2.1), the academic and industrial DFR guidelines (Section 2.2), and our disassembly of three vehicles (Section 3). With knowledge of the economically feasible separation techniques, we were able to evaluate the recyclability of these instrument panels. Then, with this knowledge of the economic recyclability of the instrument panels, the DFR guidelines were examined and changes suggested to improve the material separability of designs.

The disassembly of the instrument panels from these three vehicles provides evidence that *a component designed for manual disassembly is not necessarily easy to disassemble mechanically*. As presented in this paper, the likely separation technique to be used, whether manual or mechanical disassembly, affects the specific design guidelines which would be useful to the designer. Examples are also provided to illustrate the difference in design guidelines depending on the separation technique, and a metric for determining the applicability of manual or mechanical separation methods is discussed.

2 BACKGROUND: SEPARATION GUIDELINES AND TECHNIQUES

In this section, the current state of recycling for automobiles is described and expected changes in recycling techniques are discussed. Additionally, current DFR guidelines are discussed. The conclusions drawn about the vehicle disassembly presented in Section 3 are based on the information presented in this section.

2.1 Current Separation Techniques

Recycling efforts in the U.S. exist because a profit can be made; without this incentive vehicles would simply be sent to landfills. Current recycling efforts for a vehicle consists of *manual* and *mechanical* separation.

The advantage of *manual separation* is that the material recovered is more pure than that recovered from mechanical separation, and thus has a higher value. The disadvantage is that the cost is also high due to the worker labor cost. As the mechanical separation techniques are improved, the disadvantages of manual recycling will become overwhelming for materials used in small quantities or with low weight. However, the presence of dirt, oil, and other contaminants which are not completely removed by mechanical separation techniques make manual separation a viable option in certain cases.

Mechanical separation has a relatively lower cost than manual separation. For mechanical separation to be *economically* feasible, however, significant differences in easily measurable properties of the materials are required. Essentially, the distinction between materials must be achievable extremely quickly and accurately. For instance, ferrous metals are very easy to separate from other materials with a simple magnet. Non-ferrous metals can be separated with an eddy current separator with somewhat less accuracy. The only quick measurement that can be done for polymer separation, however, is a density measurement. Specifically, a fluid can be used to separate two polymers; a lighter polymer with a density lighter that the fluid will float whereas a polymer with greater density will sink. If two polymers have approximately the same density, separation is not currently possible. Current state-of-the-art technology requires a difference of at least 0.03 between the specific gravities of the polymers for reliable separation. It must be noted that this technology is not yet economically feasible.

In practice, most current vehicles are dismantled as shown in Figure 1. Reusable/remanufacturable components are manually removed from the car by dismantlers. These components are resold in a market limited to other vehicles of the same model, and often limited to the same year of manufacture. The vast majority of reusable/remanufactured items are powertrain components. When all these components are removed, materials with high value are removed by the dismantlers. For the most part, this consists of aluminum, magnesium, and other large pieces of pure metal. These materials are removed by hand because separate piles of aluminum and steel are worth significantly more than a commingled pile of the two metals.

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Following this, the vehicle is sent to a shredder, shredded, and the pieces mechanically separated based on their material properties. The only requirements for shredding are that the tires and gas tank (and preferably other fluids like oil as well) are removed; the rest of the car (or whatever portions have not been removed by a dismantler) will be sent into a hammer mill or similar piece of equipment which reduces the vehicle to fist-sized pieces. The ferrous metals are magnetically separated into one pile, and the non-ferrous metals are generally separated using an eddy-current machine into another pile. The ferrous metals are then sold to a smelter. The non-ferrous metals, which are worth significantly more, are then separated into specific types of metal, either by the shredder or another company. The remainder of the car, about 25% by weight currently, is called Automotive Shredder Residue (ASR). This ASR, which consists of plastics, rubber, glass, dirt, fluids, and other materials, is currently sent to a landfill.

Since the parts of the car which eventually become ASR form the main portion of material that is currently not recycled, these materials are the focus of recycling efforts, both by automotive designers and by the vehicle recycling community. As noted, the majority of ASR consists of plastics, rubber, and glass. There are markets for many of the individual polymers, but the difficulty in separation, the amount of contamination, and lack of an established recycling infrastructure render the ASR unprofitable to recycle. However, there are several likely changes occurring in the vehicle industry that will most likely increase the profitability of recycling. These include:

- Increased price of virgin materials as raw materials become scarce
- Improved separation and cleaning techniques
- Better design of vehicles for recycling
- Increased use of recycled materials, increasing the market for recyclate

As these changes occur, the value of the plastic, glass, and rubber as recyclate will increase and the costs of recovering the material will decrease. The recycling of materials that are currently designated as ASR (indicated in the shaded area in Figure 1) will become economically possible. Some (if not all) of the above changes will probably occur in the next ten years. This is important because many durable goods currently being designed will not be recycled until that time.

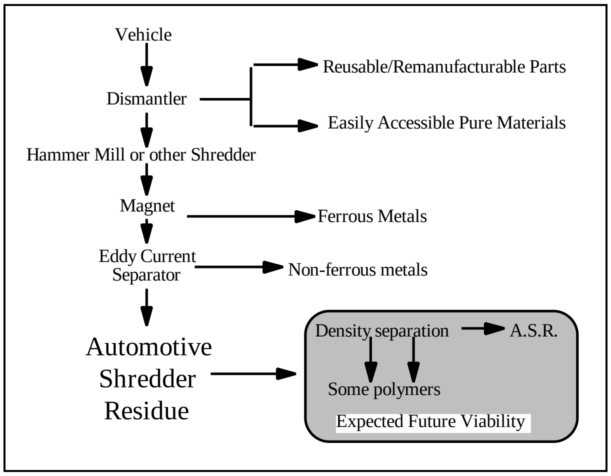

Figure 1 – Current Vehicle Dismantling and Material Separation Process

2.2 Recycling and Disassembly Guidelines

Due to the increased emphasis on product take-back and recycling, a wide variety of guidelines and methods for designing for recycling have been proposed in recent years. It would go beyond of the scope of this paper to provide a comprehensive list, but the German national standard VDI 2243 represents a good example of the state of the art (Beitz, 1993; VDI, 1993) . Admittedly, the standard is still evolving and not completely applicable to US situations. According to VDI 2243, the major problem area in the disassembly of all products lies in the separation of joints. This has provided the impetus for Beitz and coworkers to focus on knowledge-based system to support fastener selection (Beitz, 1993) .

Navin-Chandra (1993) has developed a prototypical software system, ReStar, for disassembly sequence optimization and environmental recovery analysis. The disadvantage of ReStar is that one needs a detailed product model and cost information for a proper analysis and optimization, rendering such an approach inappropriate for the early stages of design.

The work in Design for Disassembly is growing, but less extensive than efforts in Design for Assembly. In general, design for disassembly efforts are intended to reduce the time and effort required to remove components or materials from a product. Boothroyd and Alting (1992) provide a good overview, as does Fiksel (1996) . Extensive overviews are given in (Scheuring, 1994; Scheuring, et al., 1994) . Noller (1992) states some of the differences between design for disassembly and DFA. For example, complete nesting can slow disassembly by not providing a location for the disassembler to reach, grasp, or otherwise handle. Other sources for academic design guidelines and efforts facilitating recycling are, e.g., (Babyak, 1991; Berko-Boateng, et al., 1993; Burke, et al., 1992; Kuuva and Airila, 1993; Matysiak, 1993; Seegers, 1993; Spath, et al., 1995).

Automobile manufacturers have also established vehicle recycling guidelines. Chrysler, Ford and General Motors each have their own recycling guidelines. Although slightly different in detail, they are very similar and all focus on the following issues:

- material selection, e.g., reduce overall material diversity, avoid the use of laminates or make them out of compatible materials which can be recycled as a mixture,
- fastener selection, e.g., reduce fastener count and diversity, avoid incompatible adhesives which degrade

recyclability of materials, use snap fits where appropriate, and

- component design issues, e.g., avoid paints and laminates, build in planes for easy separation and access.

GM also includes packaging issues in their GM-520M recycling standard. It should be noted that all auto-makers are emphasizing the link between use of regulated substances and recycling and refer from their recycling guidelines to appropriate regulated substance elimination guidelines (e.g., Chrysler's CS9003 and GM's 1000M standards) because many components with regulated substances will have to be recycled, whether it is profitable or not. For example, chromium plated plastics may not be landfilled in Europe. Although many suppliers have been exposed to the various recycling standards, these recycling guidelines are not (yet) disseminated on a large scale by the automakers. Weber (1991) provides a good overview on the efforts of the German auto-industry with respect to plastic recycling.

Although many design for recycling guidelines have been established, it is our observation that most (if not all) current guidelines concentrate on manual disassembly of products. Many fail to note that there is a much larger variety of recycling and separation which needs to be considered. For example, in the case of recovering products for material recycling, the following three stages are typically considered (VDI, 1993) ; 1) material separation, 2) sorting, 3) processing. Furthermore, the apparent lack of profitability in plastic recycling is causing industries to consider and integrate other options, like shredding, pyrolysis, incineration, into their product design efforts (APC, 1994; Leaversuch, 1994; Wood, 1991) . We believe that the choice of separation process has significant technical and economical ramifications and the formal inclusion of its selection in the design process is imperative. In the following section, we will discuss the findings obtained at the VRDC through the disassembly of three vehicles, and their instrument panels in particular, which emphasize the lack of consideration of alternative separation techniques.

3 VEHICLE INSTRUMENT PANEL DISASSEMBLY CASE STUDY

In this section, the disassembly of the instrument panels from three late-model sedans is discussed. The method of disassembly is indicated along with the metrics used to rate the recyclability, where this recyclability evaluation is based on the separation techniques presented in Section 2. The results of the process are presented and the effects of the design for recycling efforts are discussed.

3.1 Process of Disassembly

Three vehicles, part of detail dismantling projects at the Vehicle Recycling Development Center (VRDC), were chosen to provide an indication of the recyclability of current vehicles. Specifically, the instrument panel on each vehicle was removed from the car and disassembled as far as possible by hand, with times and weights recorded for each disassembly. The cars chosen included a foreign luxury sedan, a foreign sports sedan, and a domestic midsize sedan. While the expected purchasers of these vehicles differ considerably, each vehicle offers an interesting view on recyclability of current vehicles.

The actual disassembly process was performed by two experienced auto mechanics at the VRDC Highland Park facility. The vehicle was broken down into major components (e.g., doors, seats, instrument panel). This process was videotaped and the times for removal of the component from the vehicle were recorded along with the fastening method. These individual components were then disassembled by a third mechanic.

While all components of the vehicle were disassembled, in this work the concentration was on the instrument panel (I/P), where the I/P is taken to consist of essentially everything between the driver and the firewall except the heating/air conditioning (HEVAC) unit and the steering column. Hence, the I/P includes the passenger air bag (if applicable); the wiring, instrument cluster, controls, and the radio; the duct system; and the top skin and supporting structure. Once removed from the vehicle, the I/P was separated by hand into individual components, the time for this process recorded, and the components weighed. Final items such as the radio, HEVAC control cluster, and instrument cluster were not broken down to pure materials; it was assumed that the small material quantities would make manual disassembly of these components impractical. Additionally, the air bag unit, when included, was not disassembled for safety reasons. Estimates as to the quantity of various materials within the air bag unit were based on previously fired modules available at the VRDC.

3.2 Recyclability assessment

As stated, the three vehicles were disassembled to determine their recyclability and the factors which influenced this recyclability. Towards this end, there are a number of different calculations that are used at the VRDC to evaluate vehicle recyclability. These calculations are based on two ratings for each component: a *recyclability rating* and a *material separation rating*. Tables 1 and 2 provide definitions for each rating, as well as examples of automotive components which fit in each category. For this work, the chance of an item (e.g. a starter which is both remanufacturable and recyclable as a material) being classified as both rating 1 and rating 2 does not matter, since the only concern was material recycling.

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Table 1 – Recyclability Ratings[1]

Rating	Description	Examples
1	Part is remanufacturable.	starters, alternators
2	Material in part is recyclable - with a **clearly defined** technology and infrastructure.	most metals, catalytic converters
3	Material is technically feasible to recycle - infrastructure to support recycling is not available.	most thermoplastics, glass, seat foam
4	Material is technically feasible to recycle with further process or material development required.	armrests steering wheels, airbag modules
5	Material is organic - can be used for energy recovery but cannot be recycled.	headliners wood products
6	Material is inorganic with no **known** technology for recycling.	heated glass, fiberglass headliners

Table 2 – Material Separability Ratings[2]

Rating	Description	Examples
1	May be disassembled easily manually. Approximate disassembly time is less than one minute.	lower steering column cover
2	May be disassembled with effort manually. Approximate disassembly time one to three minutes.	instrument cluster, radio
3	May be disassembled with effort requiring some mechanical means or shredding to separate component materials. The process has been *fully proven*.	engines, sheet metal
4	May be disassembled with effort requiring some mechanical separation or shredding to separate component materials. The process is currently *under development*.	instrument panels
5	Cannot be disassembled. There is no known process for separation.	heated backlights

The definitions in Table 1 and 2 are increasingly being used by the Big Three as well as their suppliers, and may become standards for the North-American automobile industry. It should be noted that the definitions in Tables 1 and 2 assume that the assembly or part has already been removed from the vehicle. That is, the disassembly time of the I/P from the vehicle is not included in the separation ratings of the components of the I/P.

Once the instrument panels had been separated to pure materials where possible, the individual components were given a recyclability rating and a material separability rating. For example, the top skin, which forms the first surface of much of the I/P, was given a recyclability rating (R.R.) of 3, since the materials can technically be recycled, but a material separation rating (S.R.) of 4, since separation of the foam from the substrate and surface material is not reliable. On the other hand, the steel skeleton which supported the I/P for each vehicle was given an R.R. of 2, since steel is currently recycled and an S.R. of 3, since it would take more than three minutes to remove it, but it can be easily separated from a shredded I/P.

With these ratings, the recyclability of the part can be determined. Unfortunately, there are several possible interpretations for “recyclable”, as shown by the differences in Table 3. *Current* recyclability refers to materials that would be recycled in this country if the vehicle were disposed of today, and corresponds closely to the definition of recyclability used in the Federal Trade Commission (FTC) Environmental Marketing Guides. Realistically, this includes the steel and most of the other metals in the vehicle for most vehicles. *Feasible recyclability* also includes material which can be recycled, even if it is not currently economical to do so. This includes many of the polymers used in current vehicles. A third definition of recyclable can be seen in the proposed European legislation, which will allow up to 10% of the vehicle to be burned for energy recovery - and that weight counted as recyclable.

Table 3 – Definitions and Assessments of Recyclability

Definition:	Recyclability Rating Must Be[3]:	Material Separability Rating Must Be:
Current Recyclability	(1),2	1-3
Feasible Recyclability	(1),2,3	1-3
E.U. Recyclability	(1),2,5	1-3

The ratings for each component were combined to provide an indication of the recyclability of the entire I/P. Component weights were summed for each recycling category and for each separation category. A **percent recyclability** (by weight) can then be calculated for the vehicle. For instance, the current recyclability of the instrument panel can be determined by summing the weight of the components with a R.R. of 2 and a S.R. of 1,2, or 3, and then dividing this weight by the total weight of the I/P. In the same way, the future recyclability would sum the weights of components with an R.R. of 2 *or 3* and an S.R. of 1-3 before dividing by the total weight.

This number does not indicate the entire story for a system as complex as a vehicle, since intermediate efforts towards increasing recyclability rarely affect this “score”. For instance, the ISO 1043 (and related SAE J1344) standard material marking of parts does nothing to improve the final percent recyclability for a vehicle, but greatly facilitates material

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[1] The recyclability rating categories were defined by the VRP, and are being promoted as an industry standard.

[2] The material separability ratings were also defined by the VRP.

[3] There is a debate on whether remanufactured parts (category 1) should count as recyclable parts. Current FTC guidelines prohibit this, but recent hearings may change this.

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identification and sorting. Accordingly, the calculations included in this work provide a quantitative value, but the additional discussion of the good and bad points of the various instrument panels is much more informative than this value.

3.3 Results

The results of the 1994 foreign luxury sedan, a 1994 foreign sports sedan, and a 1993 domestic midline sedan instrument panel disassembly were as follows.

1994 Foreign Luxury Sedan

The emphasis on recyclability has affected the (lower volume) luxury market much as it has the higher volume lower-priced markets. While the effects of this effort were somewhat hidden in this vehicle by the concentration on other design goals, there were a number of good points for recyclability in this particular I/P. Chief among these were the part material markings and the ease of manual disassembly for a number of components.

The part material markings were extremely impressive. Although the ISO 1043 standard only states that parts heavier than 100 grams (0.22 lb.) must be marked, parts which were much smaller than this were marked as to material content - even when there was no room for the part number. More importantly, many of the larger (and more economically recyclable) parts were marked with extremely large letters. The ISO 1043 standard, equivalent to SAE J1344, merely states that letters should be at least 3 mm high and larger where possible. The manufacturer did an excellent job of using larger markings when room was available, making the material identification much faster and easier.

Disassembly of certain components was also quite easy - although it seemed that this vehicle was designed more for serviceability than end-of-life disassembly. The use of snap fits and easily accessible fasteners made this I/P fairly easy to disassemble, although lack of familiarity with the design caused the dismantlers at the VRDC difficulty in the disassembly process. However, while these snap fits made access to many parts quite easy, the efforts seems to have stopped at the level needed for serviceability. In many cases the final disassembly to pure materials was difficult or impossible.

Despite the noted good points above, the current recyclability of this instrument panel is 22%, and the technically feasible recyclability is 33%. This vehicle seems to have been designed for complete manual separation, which simply would not be economical. While the marking of the various small parts is impressive, these markings are not useful for recyclability, since the material quantities are too small to justify manual separation on a value removed per time basis. In addition, the use of laminates of incompatible materials and the use of a variety of materials both hamper recycling this I/P. For instance, the center bezel in the I/P consists of plastic, wood, and aluminum bonded together. This bezel would be extremely difficult to recycle. In addition, a total of eleven different plastics were found in the disassembly of this vehicle. This precludes separation of the I/P by mechanical means because significant density differences would not be distinguishable. Given that manual recycling would be economically infeasible, this results in an essentially unrecyclable I/P.

1994 Foreign Sports Sedan

Manufacturers of sports sedans, also motivated by the expected legislation in Germany, have made significant improvements in recyclability. Unfortunately, the particular vehicle examined as part of the documented study does not greatly improve on the recyclability of the luxury sedan, since both current and technically feasible recyclabilities were very similar to the luxury sedan values. The I/P was well marked as to material type, and the lower driver's side I/P cover was even marked on the first surface, allowing a dismantler to identify the material without even removing it from the vehicle. However, some large pieces, such as the driver's side knee blocker, were not marked as to material type. This hinders manual identification of the I/P materials.

The main problems found with this instrument panel were the use of a variety of materials (14 in all) and the use of non-removable (and contaminating) adhesives on these materials. The presence of nylon flocking in the glove box and the use of glue to attach some pads rendered a number of components essentially unrecyclable. In addition, the use of such a large variety of materials resulted in an I/P that could not be mechanically separated, much as the I/P from the luxury sedan. Even the duct system consisted of mixed materials, with polyethylene and polypropylene being used for different sections of the ducting.

1993 Domestic Midline Sedan

A 1993 midline sedan was also disassembled for comparison. This vehicle provided a good baseline, having been produced in essentially the same form for several years prior to 1993, and thus designed even before that - when recyclability was even less of a consideration. While this vehicle scarcely represents the state-of-the-art where design for recycling is concerned, it was the most recyclable of the three instrument panels examined and provided a distinct contrast to the other vehicles. The current recyclability of this I/P is about 35%, and the technically feasible recyclability is around 55% - much higher than the other vehicles examined. This recyclability resulted from a higher metal content and less laminate use, a result of the age of the design and the intended users of the vehicle. While the recyclability of this I/P is high, the achievement of other design goals such as aesthetics and safety is noticeably lower than for either of the other sedans. The challenge for new vehicles is to achieve higher levels of recyclability than even this older vehicle while using materials that allow greater achievement of other design goals.

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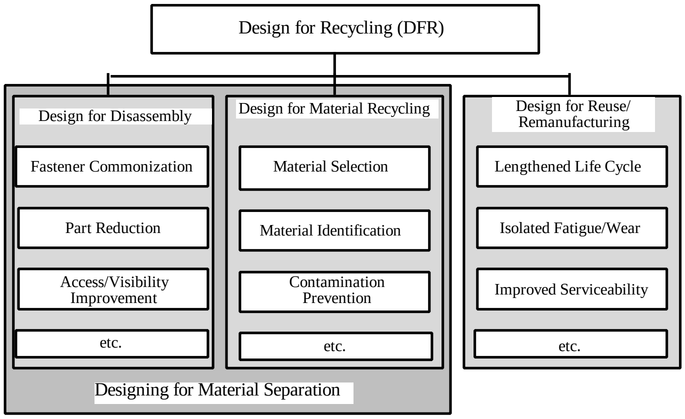

Figure 2 – Relationship of Designing for Material Separation to DFR Efforts

3.4 Lessons Learned

The main lesson learned from these disassemblies is that I/P's currently in production have not been designed for economically feasible recycling. While some efforts towards manual disassembly and material identification have been made, little consideration seems to have been given to mechanical separation of the polymers in these instrument panels. Indications from this work and related work at the VRDC indicates that economical material separation will require some of the disassembly to be accomplished mechanically. In general, the variety of materials, long disassembly times, and use of laminates and adhesives reduced the recyclability of the I/Ps. This recyclability could be increased by considering requirements of the separation techniques to be used. In the next section, the lessons from this disassembly are used to suggest guidelines for considering likely material separation techniques in designing for recycling.

4 DESIGNING FOR MATERIAL SEPARATION

There are four fundamental lessons learned from the disassembly described in Section 3 and the related examination of separability techniques and DFR guidelines in Section 2:

- The limiting factor in economic recycling of complex, integrated assemblies (such as instrument panels) is the separation into pure material streams.
- Both manual and mechanical separation have their advantages and disadvantages.
- Significant value must be retained in a part for manual separation to be economically feasible
- Different design techniques should be employed depending on whether one wants to facilitate manual separation or mechanical separation.

The challenge, then, is to aid separability by providing a *method* for selecting the technically and economically most appropriate separation technique, and *guidelines* for designing for each separation technique. In this section, a metric and method for the selection of manual or mechanical separation techniques is presented, and the difference in the guidelines depending on this selection is examined.

Designing for material separation, as defined here, is limited to material recovery. While some of the manual separation techniques may aid design for reuse/remanufacturing, the emphasis of these guidelines is the separation into pure materials so that these materials can be reprocessed and used to create new components. As such, the guidelines discussed here draw from work on design for disassembly and design for material recycling much more than product reuse/remanufacturing (Figure 2).

In the discussion of design guidelines presented in this section, design for disassembly and design for material recycling guidelines have been evaluated and categorized according to the separation technique for which each guideline is applicable. For instance, the manual separability guidelines listed here incorporate many design for disassembly guidelines, as might be expected. However, some design for material separation guidelines are also beneficial in designing for manual separation and are included as well..

4.1 Distinction between manual and mechanical separation

As was seen in the examination of the different vehicles, it is possible to design for manual separation without facilitating mechanical separation. The best example of the opposite situation, designing for mechanical but not manual separation, is metal recovery for the vehicle as a whole. The steel can easily be separated once the vehicle has been shredded, but accomplishing this by hand would be quite difficult. These distinctions occur because manual and mechanical separation have different requirements:

- *Manual Separation* requires more effort on improving the disassembly and sorting process for the component or assembly, since the primary limiting factor for manual separation is the (labor) time required for this separation. If the materials in the part being considered require significant time to separate and identify, manual separation will not be economically feasible. Guidelines appropriate for manual separation are those that suggest ways to reduce the (manual) disassembly effort and those that make visual material identification easier and quicker.
- *Mechanical separation*, on the other hand, requires more effort in creating an assembly or component which can be separated *quickly and easily* into pure streams of materials based on material properties. If the materials used do not have distinctive properties which can be used for separation, economical recycling will not be possible. Disassembly effort and visual identification are not important for mechanical separation, but material selection is critical to this separation effort.

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Our intent is not to indicate that all DFR guidelines are applicable exclusively to one separation technique or the other. In fact, many design guidelines - such as reduction of the number of materials used, standardization of material types, and the use of recyclable materials - are applicable for either type of separation. There are, however, a significant number of possible design techniques which are only useful for one type of separation. To provide a comparison with the discussion of DFR guidelines presented in Section 2, the distinction in designing for manual or mechanical separation is illustrated with examples of fastener selection, material selection, and component design guidelines.

***Fastener Selection* -** A number of different techniques can be used when designing for manual separation, all intended to reduce the amount of time it takes to dismantle the components. Specifically, these include reducing the number of fasteners, commonizing the fastener types, using snap fits, and avoiding non-removable fasteners. When considering mechanical disassembly, the only concern is the separability of the fastener material from other materials in the component because the fasteners will be shredded with the component. Accordingly, the number and type of fastener used is not important. Instead, integral fasteners and material-compatible fasteners are greatly preferred. If this is not possible, ferrous fasteners are preferred in plastic assemblies because they allow for easy magnetic separation.
Example: A thermoplastic casing designed for manual separation would utilize snap fits or a few common screws. The same case designed for mechanical disassembly could be sonically welded together, since the case will be shredded prior material separation.

***Material Selection* -** Perhaps the most interesting distinction in the material selection guidelines is that between component and assembly. If an assembly which contains two polymers is being considered for manual separation, the designer should attempt to create components made of one material or the other, so that the components do not need to be disassembled as well. However, if the same assembly is being designed for mechanical separation, it does not matter whether the individual components of the assembly are mixed materials or not since the entire assembly will be shredded anyway. For manual separation, large masses of a single material are important. For mechanical separation, reducing the total number of different materials in the assembly is more important. In addition, it is extremely important to note the specific material properties which will be used in the mechanical separation and to make sure there is sufficient distinction to allow easy and accurate separation. A metal plate riveted to a plastic component would be extremely difficult to disassemble manually, yet can easily be separated using mechanical means.
Example: Thermoplastics are generally mechanically separated by density. If an instrument panel is to be disassembled manually, a top skin substrate made of a polycarbonate and ABS blend (specific gravity of approximately 1.1) could be used in conjunction with a module case made of glass-filled polypropylene, which has approximately the same density. If the instrument panel is to be mechanically separated, as suggested above, these materials would not be separated - and the ABS and the polypropylene are not compatible for recycling, rendering both components unrecyclable.

***Component Design* -** For manual disassembly, a number of techniques are useful for decreasing disassembly time. One of these is simply application of design for serviceability guidelines, since a component which is easy to disassemble for servicing will usually be easy to disassemble for recycling. While this relationship tends to fall apart for small components with mixed materials (as seen in the disassembly of the luxury sedan), it still provides a benefit to both serviceability and recyclability. For mechanical separation, of course, designing for serviceability does not affect recyclability. In fact, components which must be serviced are strong candidates for manual separation since they must be easily disassemblable.
Example: Radios, climate control units, instrument clusters, and engine control units are components illustrative of the use of electronics in a car. Although much work in both industry and academia is done on the improvement of the disassembly of electronic goods, it is hard to believe that manual disassembly for material recycling of, say, pagers and telephones, as well as disassembly of car radios will ever be profitable. The housings often represents the largest concentrated volume of material to be recycled (see, e.g., (Glantschnig and D'Anjou, 1994)). Given the right material choice, the housing material could easily be separated using mechanical means from the other materials found in electronic assemblies.

4.2 A Metric for Selecting the Most Appropriate Separation Technique

Having divided recycling guidelines into guidelines dealing with manual and material separation, it is necessary to help designers choose the most appropriate separation technique for their design. In this section, suggestions are made for the definition and use of a metric to help a designer determine the most likely method of separation in the early stages of design.

In (VerGow and Bras, 1994), several important characteristics of a metric are presented. In short, these are:

- simple - it should be easy to use;
- easily obtainable - at a reasonable cost;
- precisely definable - it is clear as to how the metric can be evaluated;
- objective - two or more qualified observers should arrive at the same value for the metric
- valid - the metric should measure (correctly) the property it is intended to measure;

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- robust - relatively insensitive to changes in the domain of application;
- enhancement of understanding and prediction - good metrics should facilitate the development of models that will assist us in predicting process and product parameters.

A metric to be used for determination of a separation technique must have these characteristics as much as possible to be useful for designers in practice. Unfortunately, the uncertainty inherent in our economy forces some tradeoffs between various characteristics.

As noted previously, manual separation is preferred for the generally higher value of the resultant material. Manual separation is only economically viable when the dismantler is able to remove a high value component quickly, or when the *value removal rate* is high. The value removal rate can be defined as in Equation 1.

$$\text{Value Removal Rate}\left(\frac{\$}{\text{sec}}\right)=\frac{(\text{Material}(\text{kg}))\left(\text{Value}\left(\frac{\$}{\text{kg}}\right)\right)}{\text{Time(sec)}} \qquad (1)$$

Essentially, the value removal rate must be greater than the cost of the dismantling operation for a profit to be made. A high value removal rate can be accomplished in two ways: by removing materials which have a large value per pound, or by removing a larger mass of a lower value material quickly.

Although the value removal rate could be a metric for use in design, the major disadvantage of this metric is that the assessment of the value removal rate for a candidate design requires the designer to know the value of the material being separated as recyclate, a difficult task even for a component being recycled today. Since, as noted, a metric should be simple and easily obtainable, the *material removal rate (M.R.R.)* was created as a possible metric (Eqn. 2). The underlying assumption in this is that the relationship between plastic prices and dismantling costs will not change significantly - if recyclate prices rise, so will dismantling costs. While this is not completely accurate, it greatly reduces the complexity of calculating the metric value - essentially trading some accuracy for greatly increased simplicity. Rather than requiring information on prevailing dismantler costs, including labor, overhead, etc., and information on material prices, it only requires the designer to provide the approximate weight of the material and the time it would take to remove this material.

$$\text{M.R.R} = \frac{\text{Material(kg)}}{\text{Time(sec)}} \qquad (2)$$

The material removal rate metric also treats all plastics as having the same value. While this is not completely accurate, it should be noted that this metric is intended for the use of designers in the early stages of design. Some high value materials, such as polycarbonate, may be more likely to be recycled manually than indicated by this formula, and some, such as polypropylene, may be less valuable than indicated here. However, for automotive applications, the materials being chosen will not be recycled in any volume from these vehicles for approximately 10-15 years. The inherent uncertainty in future material prices is too great to be confident in the relative values of these materials. On average, a high removal rate provides a good indication of the likelihood of manual separation, especially when one considers that removal of large volumes (whether low or high valued materials) tend to facilitate the establishment of recycling infrastructures and reduce landfill more strongly than small volumes.

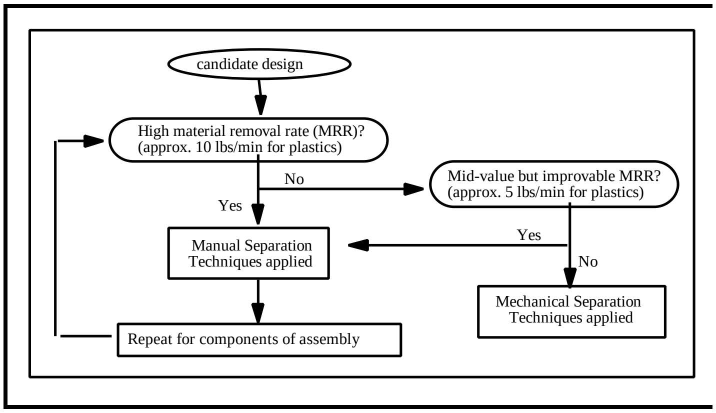

Figure 3 – Separation Technique Choice

The material removal metric can be used by the designer to decide which separation technique is likely to be used, and then to design specifically for this technique (Figure 3). Values for the M.R.R. are approximate at best, and need to be examined further, but preliminary results from entire vehicle disassembly studies indicate any plastic item with a removal rate greater than 10 lb/min is currently likely to be removed manually. In fact, many plastics with an M.R.R. greater than 5 lb/min will probably be economical to manually separate. These figures are based on time studies performed at the VRDC, in which sub-assemblies of several vehicles were disassembled. For instance, the disassembly times for the instrument panels discussed in Section 3 were combined with the value of materials removed from these instrument panels to aid in determining a cut-off value for the M.R.R. Unfortunately, the material removal rate for most of the I/P components was less than one pound per minute - indicating a need for mechanical separation.

In Figure 3, a flowchart of appropriate choices of separation techniques is given based on material removal rates. In this figure, 10 lb/min is taken as a high cutoff value - manual separation is likely, and use of manual separation techniques to further improve the removal time is appropriate. Five pounds per minute can be taken as the medium value M.R.R. - manual separation techniques should be used if there is a likelihood of improving the removal time. If the M.R.R. is lower than this, mechanical separation is likely to be the only economically viable choice. It should be noted that if manual

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separation techniques are recommended, any mixed material components of the original part must also be evaluated. If mechanical separation is appropriate, however, the entire assembly will be shredded, and consideration of component separation is not needed.

A critical issue in using either value removal rate or material removal rate is determining the disassembly time. Although this is still a problem in many cases for engineers unfamiliar with recycling issues, many automotive engineers have become familiar with estimating disassembly times using the ratings described in Table 2 through exposure to various examples of good and bad designs. In addition, rules of thumb such as allowing about 5 seconds to remove a screw (using air tools) facilitate quantification of disassembly times without performing a detailed disassembly exercise (which would be impossible in the early stages of design anyway).

5 CONCLUSIONS AND FUTURE WORK

Many current Design for Recycling efforts seem to focus on manual separation and disassembly. While improvement of manual disassembly is a worthwhile goal, achieving economically viable manual disassembly requires significant value to be retained in the part. Reusable/remanufacturable components arguably retain the highest value, but the increasing rapidity of revisions for a automobile results in parts which can only be used in other vehicles of the same year. This makes reuse/remanufacture a limited proposition at best. Much of the focus must necessarily be on recovering the materials in the vehicle. Recycling the material does not retain the value added to the part in the shaping and machining - and the lower value means that the recycling effort must cost very little to be economical.

A number of lessons have been learned through an examination of current separation techniques and DFR guidelines (see Section 2) and through the disassembly of the three different lines of vehicles (see Section 3), We have shown that mechanical separation of the majority of the materials in the instrument panel is currently not technically feasible, and that manual separation is currently not economically feasible. However, it appears that mechanical separation offers the cost savings needed to *economically recycle* a vehicle. The extensive infrastructure developed to recycle the metals in automobiles serves as an indication of the profitability of this type of material recovery. In this paper, we identified the need for designers to recognize the likely separation technique during design, and noted the differences in design guidelines which are applicable to the two separation techniques. Having recognized the need to chose a separation technique, we identified issues which must be addressed in creation of a metric to aid designers in choosing the likely separation technique. A simple material removal rate metric has been suggested for use in the early stages of design.

It is worth noting that this choice of separation technique must be made even if a recycling level is mandated by regulation. For instance, suppose legislation forces a manufacturer to recover and recycle their product, regardless of the economic aspects of doing so. While this regulated recyclability may result in an economic loss for the company, selecting the most appropriate separation technique will limit these losses, making the recycling process *as economical as possible*.

This paper represents a building block for our continuing work. For the material removal rate metric proposed, or similar metrics, to be useful, the boundary value of the material removal rate (between expected manual and mechanical separation) must be more closely examined, and the accuracy of the assumptions investigated. Additionally, the applicability of this work beyond the automotive realm will be analyzed, since the automotive industry is fairly unique in the life span and complexity of their products. The usefulness of similar separation technique choice metrics for other classes of consumer products (i.e. electronics, appliances) must also be examined.

ACKNOWLEDGMENTS

The authors would like to thank the researchers at the VRDC and other members of the VRP who aided in the vehicle analysis, including Chris Golomb, Andrew Spicer, Pavel Zamudio-Ramirez, Mark Russell, and Wendy Lange. The support of the Chrysler Corporation is gratefully acknowledged as well. Stewart Coulter is currently supported by a Department of Energy Integrated Manufacturing Fellowship. The support of NSF Grant DMI-9410005 and NSF Grant DMI-9414715 is gratefully acknowledged.

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