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Disassembly modeling and analysis.

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Disassembly Modeling and Analysis

by

Andrew Spicer

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through the Department of Industrial and Manufacturing Systems Engineering in
Partial Fulfillment of the Requirements for
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Abstract

The analysis of the disassembly of products for recycling and reuse is important because of the increasing demands for environmentally conscious design and manufacturing that are coming from consumers and governments. An economic analysis is essential since economics is the driving factor that causes this disassembly in many situations. Economic analysis of disassembly is also important due to the costs of potential legislation to regulate recycling.

This research proposes a method for the modeling and analysis of disassembly for reuse and recycling. This methodology is economically based and can be used to generate the profit-optimizing disassembly plan to predict the circumstances of disassembly in a free market and to determine which parts or components of a product are economically feasible to recover. The methodology is the first of its kind to be able to consider products of the greatest degree of complexity.

An application of the methodology to study the recycling of automobiles is presented. This case study considers not only specific vehicles, but also the potential for changes in the economic market or in the design of vehicles.

Dedication

To my parents

Acknowledgments

I was fortunate during the time that I have been involved with this project to get support from many helpful people. First and foremost I have to place Maricon and my parents.

I began my work at the University of Windsor, and this was always home-base. In the past couple of years I required a lot of assistance from people who did more than just their job to help me. Jacquie Mummery, and particularly Tom Williams were instrumental in facilitating this work. I also owe thanks to Rob Mavrinac, Dan Corrin, Steve Karamatos, and my excellent committee members.

The Vehicle Recycling Partnership did me a great favour when they allowed me to come to their facility and I have benefited a lot from the experience. During the course of the project many people contributed their efforts. I learned a lot from Michelle, Ken, Gerry, Anthony, Claudia, Crissy, Tony, Terry and Dave, not to mention all the other students.

There are many others, too numerous to list, who have helped, but three people, whom I am happy to all consider my friends, stand out in particular.

Dr. Wang, for three years, has been my professional mentor. From him I have learned so much about what interests me and also so much about how the business works.

Larry was the one who made this all possible. First, by showing the interest in my work and how the VRP could use it. Second by having faith in our project from day one. And third by always having enormous amounts of time and effort for us "students".

Pavel is the single most impressive person I have met, and perhaps the most rewarding part of this project was becoming his friend. More than anything he inspired me and this work simply by showing how much it was possible for one person to do.

Disclaimer

The conclusions and opinions contained in this thesis are those of the author and do not necessarily reflect those of the United States Council for Automotive Research (USCAR), the Vehicle Recycling Partnership (VRP), or any of their member companies.

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Chapter 1

Introduction

Environmentally Conscious Design and Manufacturing (ECDM) is an area of research of growing importance. As environmental threats become more significant, political and economic forces are pushing manufacturers and designers to produce products which are more "environmentally friendly". In other words, products being designed must have less impact on the environment than their predecessors. The emphasis in ECDM is on *preventing* environmental problems, as opposed to the traditional method of cleaning up after the damage has been done (end-of-pipe treatment).

A number of ECDM techniques have been developed to address a variety of environmental problems. Green Manufacturing is concerned with manufacturing processes which are efficient and avoid the use of toxic chemicals during production, as well as being energy efficient. A great deal of work has also been invested in making products ranging from washing machines to automobiles more energy efficient during their use. Some toxic or hazardous substances are being phased out of the market and replaced by newly developed "clean" replacements. As well, companies are attempting to design their products to be more recyclable.

In order to undertake design for the environment (DfE) efficiently, there must be a methodology for assessing a product in terms of its "enviro-friendliness". The emerging area of Life Cycle Analysis (LCA) studies how to do this. In a life cycle analysis, a product is evaluated on the environmental effects of all the stages of the product's life cycle beginning with the material extraction and ending with the retirement stage. While LCA has its shortcomings -- it is time consuming and expensive, for example -- the life cycle philosophy is a strong one for considering the tradeoffs in design decisions.

The life cycle stage which is relevant to the research described here is the retirement stage. This stage begins when the customer no longer has use for the product.

During retirement (or end-of-life), products may be disposed, incinerated, remanufactured, recycled, or disassembled. If disassembly occurs, the components recovered may be disposed, incinerated, reused, remanufactured, or recycled. An interesting fact about the retirement stage is that it is the only stage which is usually completely out of the control of the designers and manufacturers. Save for some legislation in Europe, the end-of-life of products is entirely driven by economics. That being the case, it is necessary that analyses regarding the retirement stage are based in this economic context.

Disassembly of complex products is a difficult activity to understand. This research, therefore, concentrates on analysis of disassembly on two levels. First, a methodology is presented for the analysis of individual products to determine the profit-optimizing disassembly plan using a software tool specifically developed for this problem. Second, a modeling system for understanding the interactions of the segments of the disassembly and recycling industry for a particular product is presented specifically for the automotive industry in North America. Together, these tools form the basis of a method for an in-depth study into the retirement stage of a product's life cycle.

1.1 Relevance of this Research

Since this work attempts to study the disassembly analysis problem thoroughly, it would likely be of interest to all concerned parties. Specifically, dismantlers, remanufacturers, recyclers, and shredders, manufacturers and designers, and government bodies will be interested for the following reasons:

(1) Dismantlers, Remanufacturers, Recyclers, and Shredders. Dismantlers are in the business of breaking apart complex products, such as automobiles, for the purpose of reselling some components, and recycling others. Remanufacturers take used components, clean and repair them, and then sell them to be used again. Recyclers are those companies which reprocess materials so that they can be incorporated into new products. Shredders process products which are mainly metal, such as automobiles and appliances, by shredding them into small pieces and then separating the materials for recycling or disposal. Together, these companies comprise a large portion of the industries that manage the retirement of products, and may be interested in this research. On the micro level, the dismantlers may benefit from being able to optimize their disassembly processes and improving their profitability. On the macro level, all these industry players may benefit from understanding how changes in the products themselves will affect their industry so that they can restructure themselves accordingly.

(2) Manufacturers and Designers. Manufacturers and designers are being pushed from a variety of directions to make their products more environmentally friendly. In the automotive industry, automakers are being asked to make their vehicles more recyclable, at the same time that they are being asked to increase their fuel economy. As well, the growing competitiveness of the global market requires that the companies get more for their research and development dollars, while avoiding potential penalties for failing to comply with environmental legislation. The manufacturers, therefore, need efficient methods for analyzing the benefits that they may gain from the design changes and from the policies they implement to increase recyclability. This may help them focus their efforts into the most beneficial areas. As well, it is important for them to be able to determine how much potential legislation may cost them.

(3) Governmental Bodies. Governments in most countries take an active role in the protection of the environment through legislation which requires companies to perform -- or not perform -- various activities. As well, they intervene in the market by introducing taxes and subsidies to encourage the desired behaviour. It would be important for governments to have methods for analyzing the financial costs involved in their decisions, as well as to be able to predict what effect their legislation will have in a market economy.

1.2 Research Objectives

The research objectives of this thesis are as follows:

(1) To develop a comprehensive representation method capable of structuring all information relevant to the disassembly of a single product for a computer program, i.e., a modeling language. This includes both physical and economic information.

(2) To develop a software tool capable of interpreting the disassembly modeling language and analyzing it. This involves some simple analysis of the structure of the product, as well as the generation of the profit-optimizing disassembly plan. The software must be capable of optimizing the disassembly for products as complex as an automobile.

(3) To apply the language and the analyzer to actual products -- namely automobiles, including sensitivity analysis. This work can generate a number of benefits. First, there will be some learning regarding the simple analysis of one car in terms of the economics of its recovery. Second, sensitivity analysis will enhance the learning to show which factors have the most influence on these economics. Third, the analysis of multiple automobiles will provide the opportunity to compare them in terms of their design.

(4) To help create a system dynamics model which will be used by the automakers to simulate the entire automobile recycling industry so that they may see the effects of various decisions that they may make.

1.3 Problem Overview

The objectives listed above can be broken into three main categories: (1) disassembly modeling and optimization, (2) application of disassembly modeling and optimization to the automotive industry, and (3) modeling of the automotive recycling industry. This section presents the general problems associated with these categories.

1.3.1 Disassembly Modeling and Optimization

Disassembly modeling is desirable because it is a method required to answer a variety of questions that may come up when designers are considering the disassemblability of their product. These questions may range from "what components must be removed before it is possible to remove this component?", to "what portion of our product is recyclable?", or "how much of the product is economically profitable to recycle?".

It is necessary, therefore, to have a method to strictly specify all the information required to correctly answer these questions. This information can be broken into two broad categories. First, there is the physical information. This includes bits of information with obvious importance such as the material makeup and mass of components, as well as the times to remove these components from the assembly. It also includes *precedence constraints* which restrict the order in which parts may be removed. As well, it is necessary to define which components comprise which other components. It is not correct to assume that a product is made up of a collection of indivisible components. In reality, a product is made up of a collection of some indivisible components and some assemblies, each of which may also be made of assemblies and indivisible components.

The second category of necessary information involves the economic data. This category includes factors such as the cost of labour, the recycling values of various materials, the resale prices for the parts, and the cost of landfilling, or other forms of disposal without recovery.

Once this information has been defined, it is possible to generate and analyze alternate disassembly plans. A disassembly plan is a list of disassembly and product retirement actions to be done. The plan is feasible if no precedence constraints are violated. In most disassembly plans some components remain part of the product. For those components which are removed there are a variety of options for their retirement. These options are known as *Material Recovery Options* (MROs) and include reuse, remanufacturing, recycling, and disposal. For a given disassembly plan for a given product it is possible to determine the dismantler's profit based on the costs associated with the disassembly activities, and the costs and revenues associated with the chosen MROs for the components which have been removed. Conceivably it is feasible to optimize the disassembly plan to find a maximum profit for the dismantler by choosing the right disassembly actions and the best MROs.

Optimization of disassembly plans can be a complex problem. For example, a product with five hundred parts would have 2^{500} different possible solutions, although not all would be feasible. Optimization methods that search through all the solutions, therefore, are not suitable for large problems. This research presents an optimization method which uses heuristics combined with a genetic algorithm for solving large disassembly optimization problems.

1.3.2 Application of Disassembly Modeling and Optimization to the Automotive Industry

The process of applying the disassembly modeling methods to a real-life example are considerably difficult. This section presents an overview of the problems that a disassembly modeler may face. More detailed explanations follow in the appropriate sections.

The disassembly modeling process begins by performing a time study to determine the physical information for the product. At this stage, times and masses are recorded, as well as the precedence constraints and component structures. Then, it is necessary to identify materials which are not marked. This may involve some special equipment.

The second stage involves determining the economic information. Here, research must be done to find out how much the various parts and materials are worth. As well, the cost of labour and landfilling must be identified. This information is generally hard to discover, and likely requires the coöperation of industry players.

1.3.3 Modeling of the Automotive Recycling Industry

Modeling of any industry is a complicated procedure. This form of systems analysis is made difficult by the nature of the interactions between the entities that comprise the system. Each segment of the industry makes decisions and performs actions based on their own set of operating procedures. These segments are connected by information flows and physical flows which are perceived with time delays. Modeling and simulating a system such as this on a computer presents problems which are well handled by System Dynamics, a method developed at MIT for the rigorous study of systems and their behavior based on feedback, dynamics and simulation.

The automotive recycling industry in North America dates back to times long before recycling and environmental consciousness were in vogue. Today, the industry is processing cars at a rate of ten to twelve million per year. The remainder of this section describes some of the segments of the industry as they may appear to an external observer.

When a vehicle has reached an age when no one wishes to keep it, or when it has been involved in a very serious accident, it is often sold into the network of automotive dismantlers in North America. These dismantlers bid for vehicles at auctions or simply buy them directly from the owners. There are a variety of types of dismantlers with their own practices that define what types of vehicles they buy and in what condition, what they do to the vehicles, and who their customers are.

The range of dismantlers is quite broad in terms of what they do with the cars. At one extreme are those dismantlers that specialize in newer cars ("late model") that have been retired for one reason or another. These dismantlers buy these vehicles at a high price and low volume. They remove many components of the vehicle for resale or remanufacturing. At the other extreme are those dismantlers that take as many cars as they can get, as cheaply as possible. They are not concerned with reselling parts. Rather they remove a few components that are of high intrinsic value (e.g., aluminum radiators which can be melted down and sold as ingots), and remove the parts which are required to be removed before they can send the vehicle to the shredder. Dismantlers can be found at any point in this range distributed across North America.

When the dismantlers have finished with the vehicle, their next step is usually to send it to the shredders, for which they are paid by the ton. Shredders also receive many vehicles directly from their final owners. There are about two hundred shredders in North America and they are said to process about 94% of vehicles that become unwanted. They process not only unwanted vehicles, but also appliances, and any other sources of scrap metal. Vehicles are processed by feeding them into a large shredder which rips them into fist-sized pieces. The ferrous pieces are removed with magnetic separation and sold to the steel mills. The non-ferrous pieces are isolated with technology such as eddy-current separators and reprocessed. The remainder is comprised of plastics, elastomers, glass, and other non-metals. This mixture is known as "Automotive Shredder Residue" or auto fluff. Most of the fluff is sent to landfills.

1.4 Application of the Analysis

The United States Council for Automotive Research (USCAR), administrator for the consortia of General Motors, Ford, and Chrysler governs the Vehicle Recycling Partnership (VRP) which was established in November 1991. They were joined by collaborators such as the Automotive Recyclers' Association (ARA), the American Plastics Council, the Institute of Scrap Recycling Industries, and others. According to a USCAR Media Information document, the VRP was founded to identify and pursue opportunities for joint research and development efforts pertaining to recycling, re-use and disposal of motor vehicles and vehicle components, and to promote the increased use of recyclable and recycled materials in motor vehicle design. The goals of the VRP are to (1) reduce the total environmental impact of vehicle disposal, (2) increase the efficiency of the disassembly of components and materials to enhance vehicle recyclability, (3) develop material selection and design guidelines, and (4) promote socially responsible and economically achievable solutions to vehicle disposal.

The VRP opened a facility in Highland Park, Michigan on the Chrysler Center site and named it the Vehicle Recycling Development Center (VRDC). This centre is a meeting place for people to discuss vehicle recycling issues. It is also an active research centre where timestudies are conducted, and recorded, and materials are identified and sorted for recycling. For the research of this thesis, four vehicles were dismantled at the VRDC using a specially designed timestudy. Out of respect for the competitive concerns of the partners, the makes and models of the vehicles which have been dismantled will not be identified.

Information for the disassembly modeling was gathered from the timestudies that were conducted, as well as other research at the VRDC. VRP employees were very helpful as were some students on internships from schools such as The University of Detroit - Mercy, Purdue, The University of Michigan and Georgia Tech. A partner in this work was Pável Zamudio-Ramirez from the Leaders for Manufacturing program at the Massachusetts Institute of Technology. Mr. Zamudio-Ramirez contributed to the development of the disassembly modeling methods, collaborated in application of the methods to automotive examples, and was primarily responsible for the development of the system dynamics model of the automotive recycling industry. Essentially the author and Mr. Zamudio-Ramirez merged their research work into one project.

This thesis proposal is divided into four additional chapters: (1) the literature review, (2) the proposed methodology, (3) the application of the methodology, and (4) conclusions and future work.

Chapter 2

Literature Review

2.1 Environmentally Conscious Design and Manufacturing

Environmentally Conscious Design and Manufacturing (ECDM) is the response to the growing environmental problems being faced today. This approach is proactive rather than reactive, and attempts to prevent environmental problems from occurring, rather than cleaning up after the fact.

Watkins and Granoff (1992) define Environmentally Conscious Manufacturing (ECM) as "those processes that reduce the harmful environmental impact of manufacturing; this includes minimization of hazardous waste, reduction of energy consumption, improvement of material utilization efficiency, and improvement of operational safety." They consider ECM to be "environmental quality control."

Companies today are making a greater and greater commitment to ECDM, as evidenced by Toyota Motor Corporation's basic philosophy: "We supply clean, safe products and dedicate ourselves to making our planet more comfortable to live on and making our society more affluent than ever." [Iwai, 1995].

2.2 Life Cycle Analysis

Life cycle analysis is the tool most often mentioned in conjunction with ECDM. It is a method for guiding action that is informed by the growing social importance of environmental objectives [Field, et al., 1993]. It is a methodology that strives to holistically identify and quantify all environmental impacts involved in the life of a product or process [Curran, 1993].

In the life cycle philosophy, the environmental effects of a product are considered from the beginning of the material acquisition until the product is retired or recovered.

The product that causes the least environmental damage over the entire life cycle is to be preferred.

2.3 The Retirement of Products

The final stage of the life cycle is the retirement. This is the life cycle stage of particular importance to this research. The retirement stage has often been ignored by designers and engineers since it has little or no financial impact on the manufacturer. Consumer demand is altering this attitude, however, as is some governmental pressure.

During a product's retirement stage, there are a variety of things that could happen. There are multiple disposal options, but there are also options that do not include disposal. Reuse, remanufacturing and recycling are known as the Material Recovery Opportunities (MRO) [Johnson and Wang, 1995]. A study of the environmental impact of a product in the retirement stage would consider how much of what kinds of material is dealt with in the various disposal and material recovery options. The material recovery opportunity definitions follow and are from the United States's Environmental Protection Agency (EPA), 1993.

> **Recycling** *is the reformation or reprocessing of a recovered material. Recycling may be defined as "the series of activities, including collection, separation, and processing, by which products or other materials are recovered from or otherwise diverted from the solid waste stream for use in the form of raw materials other than fuel."*
>
> **Remanufacturing** *is an industrial process that restores worn products to like-new condition. In a factory, a retired product is completely disassembled. Its reusable parts are then cleaned, refurbished, and put into inventory. Finally a new product is reassembled from both old and new parts, creating a unit equal in performance and expected life to the original or a currently available alternative. In contrast, a repaired or a rebuilt product usually retains its identity, and only those parts that have failed or are badly worn are replaced.*

> **Reuse** *is the additional use of an item after it is retired from a clearly defined duty. Reformulation is not reuse. However, repair, cleaning, or refurbishing to maintain integrity may be done in transition from one use to the next. When applied to products, reuse is purely a comparative term. Products with no single-use analogs are considered to be in service until discarded.*

Currently, in North America, remanufacturing, reuse, and recycling takes place when and where it is economical to do so. A subject of concern for this research revolves around determining in what cases is one of these material recovery opportunities economically feasible for durables. The question is, for which complex products is recycling, reuse, or remanufacturing worthwhile from a financial standpoint?

Recycling is more than just an environmental tool, and can be economical. It can influence and be influenced by a large number of aspects of a company [Andersen and Kuuva, 1994]. There is a need for models and further research to get a better understanding of recycling

2.4 Disassembly

It is not necessary to deal with a product at the end of its useful life as one homogeneous piece. It is frequently preferable to disassemble the product into separate pieces and to deal with each piece individually.

An analysis of the disassemblability of a product can answer all of the following questions: (1) How may the recovery process itself generate the highest possible return of investment? (2) Is there a particular disassembly sequence which will maximize the return? (3) Is it better to recover only specific components rather than all components? (4) What design characteristics facilitate ease of disassembly and how are they to be employed? [Johnson and Wang, 1995].

The economics of disassembly and recovery are particularly important since they are the driving force behind recycling of durables in North America. In fact, determining the most profitable retirement method is the best way of predicting the likely end of life for a product [Spicer and Wang, 1995]. Since designers and manufacturers typically expect to have no direct influence on the retirement of their products, predictions based on economics are essential when assessing the retirement stage effects for a life cycle analysis.

GE Plastics (1992) claims that the most significant cost involved in disassembly is that of labour. The other costs of the material recovery process include sorting, cleaning, transportation, and reprocessing [Johnson and Wang, 1995]. These costs can be weighed against potential benefits to determine the retirement plan which maximizes profit.

Navin-Chandra and Bansal, 1994, define the recovery problem as follows. "For a given design (or product) find a recovery plan that balances the amount of effort (e.g. energy) that is put into recovery and the amount of effort that is saved by reusing parts and materials. In this way, recovery is a leveraged process (e.g. you save more emissions than the new ones you create). A recovery process that is not leveraged is not worth pursuing." They are speaking here of optimizing recovery against various objective functions. One potential objective function is the profit to be realized.

It is clear that disassembly need only be a partially completed activity. That is, during the course of disassembly for a particular product, a point may be reached where any further disassembly does not increase the bottom line [Simon, 1991]. As a result, optimal disassembly of a product may include leaving some portion of it untouched, and perhaps unrecyclable.

When optimizing disassembly for recovery, there are at least two potential levels of complexity. At one level, there is the concept of generating an optimal disassembly plan which lists the disassembly operations to be performed. The second level is the optimal disassembly sequence which lists the specific order in which a set of disassembly operations are to be performed.

Two disassembly sequences that remove and separate the same parts -- only in a different order -- may have different profits for a number of reasons. First, setup times and tool changes can affect the overall time to perform the disassembly work and these times can be minimized by ordering the tasks in the right way. Second, disassembly can be modeled so that different orders can affect the ease of access for removal of some parts, thus affecting the total time.

Johnson and Wang (1995) and Girard and Boothroyd (1995) have presented graphical representations of disassembly to illustrate the importance of the disassembly sequence on the overall profit. Johnson and Wang's graph is similar to that in figure 2.1.

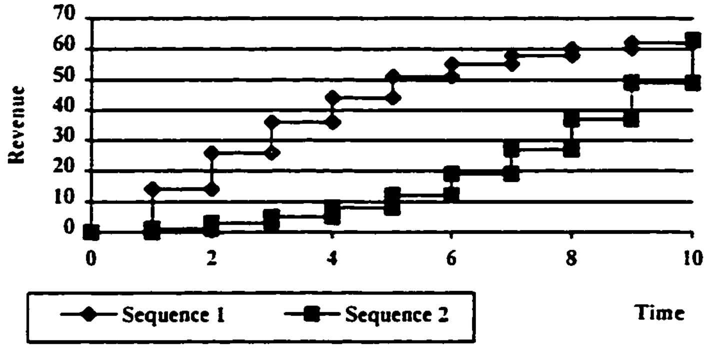

Figure 2.1 Disassembly revenue versus time for two sequences.

The figure depicts two alternate disassembly sequences and shows how revenues change over time. In this case, each disassembly action takes one unit of time, but returns different revenues. If a linear cost function is assumed, it is possible to determine the function of profit versus time for both sequences, and choose the stopping point -- the point of maximum profit -- for either. Since the profit is larger for sequence one, a plan that chooses high revenue parts first, it is argued that sequence is important. However, any plan that chooses parts (in any order) with revenues greater than costs will result in the same profit. This figure actually demonstrates the principle that incomplete disassembly can be more profitable than complete disassembly.

The optimization of disassembly sequences can be simplified to the optimization of disassembly plans if the following two assumptions are made: (1) differences in disassembly costs associated with different amounts of setup are negligible, and (2) the effect of removing some parts to improve access to others can be incorporated into the concept of precedence constraints that simply state that a particular part cannot be removed until some other specific part has already been removed. If these simplifications are permitted, disassembly can be optimized by selecting a list of components to separate or by selecting a list of disassembly actions to perform without regard to order. Otherwise, order is important and the problem is much more difficult to optimize.

Navin-Chandra (1995) has developed a software tool called *ReStar* that solves the more difficult problem of generating optimal disassembly sequences. *ReStar* automatically generates up to tens of thousands of disassembly pathways based on geometric constraints. It is able to optimize the disassembly sequence for products of moderate complexity. *ReStar* can also perform sensitivity analysis.

Johnson and Wang (1995) have developed a method for the optimization of disassembly sequences using a two-commodity network formulation. This method can only be used for problems of moderate size.

Spicer and Wang (1995) developed a method for generating optimal disassembly plans using genetic algorithms. The method can handle large problems, but has been based on a simplification of the problem. Each part was considered to be a single entity. There was no concept of parts coming together to form subassemblies. In other words, the product was modeled as if it was a collection of *n* parts, each indivisible.

Girard and Boothroyd (1995) developed a method for analysis of the economics of disassembly. In their method, a "financial line" that describes the cost implications at each step in the disassembly process is presented. They systematically rearrange the disassembly plan to produce the best financial line. The optimization methods maximizes rate of return, rather than profit.

None of the previously described disassembly planning methods are capable of optimizing the disassembly of complex products such as an automobile.

2.5 End of Life Vehicles

In a report prepared for the Automotive Industry Board of Governors at the World Economic Forum in Davos, Switzerland, in February 1994, Field et al. make a series of comments on the recycling of vehicles over the last few decades.

As little as twenty five years ago, there was an automotive recycling problem caused by the decline of open hearth steelmaking and rising labour costs which prohibited the manual disassembly necessary for producing high quality steel scrap from automobiles. These problems were alleviated by the rise of electric arc steelmaking and the development of large scale shredding machines with magnetic separation facilities [pages A-1, A-2]. Today, no other product with such a large number of materials is as highly recycled. Roughly 75% of the car by weight is recovered and economically reused today [page 4].

The recyclability of the automobile depends on the number and type of materials composing the vehicle and the ease with which they can be identified and isolated [page 6]. The Corporate Average Fuel Economy (CAFE) standards encourage the use of lighter weight materials in automobiles [Arthur D. Little Inc., 1992]. The result is an increase in the difficulty of isolating desired materials, and a potential decrease in the recyclability of vehicles.

There are about 200 shredders in North America that process automobiles. Cars are ripped into fist-sized pieces and then the material is separated using magnets and other technologies. The remaining waste is known as automotive shredder residue (ASR) or "fluff". Arthur D. Little, (1992) makes the projections illustrated in table 2.1 regarding the fluff composition in the year 2000.

Table 2.1 Average fluff composition in pounds

Fluff composition	Junked in 1990	Junked in 2000
Plastics and Composites	184	224.5
Fluids and Lubricants	91	90
Rubber	68	67.5
Glass	87	85
Other Material	117	104.5
Total Fluff	547	571.5
Percent Fluff in Hulk	17%	19%
Percent Plastic in Fluff	34%	39%

The increasing amounts of fluff as a result of changes in the design of vehicles has caused a number of new concerns about automotive recycling. As a result, much work is being done to see how the situation can be improved.

Plastics Engineering (1995) reports that the American Plastics Council is sponsoring projects to promote the development of new dismantling technology and rapid material identification. Other work involves sorting materials with techniques such as infrared spectroscopy. *Automotive Engineering* (1995) describes a tool produced by Bruker Instruments that uses a laser to identify at least 23 different types of plastic for recycling purposes. *Machine Design* (1995) describes a process for recycling automotive seats that involves foam removal at the dismantler.

The automotive companies have also been working at improving automotive recycling. Toyota has set a goal of having the vehicles 85% recycled by 1996 [Iwai, 1995]. The American automotive companies have formed the Vehicle Recycling Partnership. The European companies have dismantling facilities operating on a trial basis.

Perhaps recycling of automobiles should not be such a great issue, however. Curlee et al. (1994) have presented a study which illustrates that while the energy savings of recycling are being reduced by the new material choices, the energy consumption reductions during use of the vehicle are much greater. In other words, sacrificing recyclability for better fuel economy may be worthwhile from a life cycle perspective.

Chapter 3

Proposed Methodology

3.1 Disassembly Modeling

3.1.1 Purpose of Disassembly Modeling

A great portion of the environmental problems being faced today are caused directly or indirectly by the manufacture of products [US Congress, 1982]. Recycling and reuse are important from an environmental standpoint, therefore, because they represent a conservation of industrially added value, of energy, and of material. In other words, recycling and reuse can help relieve the burden placed on the environment by energy production, material processing and manufacturing through the diversion of products with value from waste streams to production streams. This saves the effort that went into their production from being repeated unnecessarily. An economic benefit may also result, since a reduction in waste often corresponds to a financial savings. An additional reason to reuse and recycle is that it reduces the demand for resources which are in limited supply, thus prolonging their availability. Less waste also implies that less space has to be reserved for landfill sites.

As the public awareness about environmental problems increases, governments and corporations are more interested in being perceived as "green". The governmental commitment to environmental health varies from country to country, but in general, governments in North America, Europe, and other regions are responding to the public's concern about these issues. An example of their response is the legislation proposed in Germany which forces some manufacturers to make a full life-cycle commitment to stewardship of their product. Many of the governmental measures are aimed at increasing reuse and recycling. An added benefit of this policy is the reduction of waste disposal facilities costs for the government.

Corporations have been seeing this growing interest in environmental affairs. While it is not clear if many of them are willing to decrease their environmental burden out of altruism, there are a number of other reasons that are driving some improvement. These reasons include: (1) the desire to avoid costs of current or pending environmental legislation, (2) the desire to coöperate with the government's environmental goals to discourage future legislation, and (3) public relations and customer demands. Recycling has been an environmental issue of great importance to the public. In fact, a large portion of the environmental campaign made to the public has revolved around recycling, and therefore, it is one of the activities immediately associated with environmental consciousness in the minds of the consumers. As a result, companies have found it necessary to promote the recycled content and recyclability of their products.

Companies, however, often have no control over the recycling of their own products. Once their products are sold, they belong to the consumers who will make their own decisions about what to do with them at the end of their useful life. Essentially, reuse and recycling of products will be determined by the market economy, unless the company accepts the responsibility to collect and reprocess the products at their own expense. While this may be the direction of some legislation in Europe, corporations generally would prefer to allow the market to deal with the retirement of their products on its own. Therefore, they have an interest in studying how economic factors affect the process of recycling their goods.

In order to understand the recovery process for complex products, it is necessary to have a complete understanding of disassembly. When a complex product has reached the end of its useful life, it is often because the cost of repairing it is large compared to its replacement value. This implies that while the product as a whole is not useful, some of its components may still have value. The only way to realize this value is to disassemble the product and recover the components. This is one justification for disassembly; the other justification is that while the product as a whole may not be fit for recycling due to the mixture of incompatible materials, disassembly may segregate it into separate materials fit for recycling. Disassembly, of course, has costs to weigh against these benefits. The principal one, according to GE Plastics (1992), is the cost of labour.

Those who may be interested in analyzing disassembly include the product designers and the dismantlers themselves. The designers have a variety of questions that they would like to have answered about the disassemblability of their product. These questions include:

(1) How long would it take to fully or partially disassemble the product for recycling? How much would it cost?

(2) Which components or materials can be economically removed and recycled (or reused or remanufactured)?

(3) What disassembly plan would optimize the profit of the dismantler?

(4) How can we predict what disassembly actions might take place at the end of the product's useful life?

The answers to these questions require a thorough understanding of the disassembly problem. The remainder of this chapter considers the information requirements for disassembly modeling and introduces a method for modeling that will form the foundation for tools used to answer disassembly questions.

3.1.2 The Relevant Information

When considering the disassembly of a complex product, the information necessary to answer the relevant questions can be divided into two main classes. The first class is the set of physical information that defines the product. The second class is the set of economic information that defines the market environment in which the disassembly for recovery is being contemplated.

3.1.2.1 The Physical Information

A product is typically made up of an assembly of components. Each of these components may also be made of other components, or may simply be a single indivisible piece of one material. The relationships regarding which components are comprised of which others are collectively known as the *component structure information*. This information is crucial if any understanding about the disassembly of the product is desired.

With enough disassembly, any component can be separated into indivisible pieces. For each of these pieces it is important to know what material it is, its mass, and its condition (whether it is contaminated, etc.). It is also desirable to know if the parts are marked to identify the materials, since materials which are not marked will take longer to sort, may require special equipment for identification, and create the risk of improper sorting.

There is a set of information related to the disassembly processes required to break the product apart. For each disassembly action -- i.e., for each removal of one component from the product or from another component -- there is a time to perform it. These times can be measured and recorded in a timestudy. As well, there are a set of *precedence constraints* which are restrictions defining which disassembly actions are prerequisites for each of the other disassembly actions.

3.1.2.2 The Economic Information

Economic information is of concern because, as stated before, economics is the driving force behind disassembly for product and material recovery in North America. Furthermore, even in jurisdictions that have enforced product recovery legislation, the business costs and benefits are of great interest to the companies involved. To answer questions regarding the economics of disassembly it is necessary to gather economic information for the disassembly model.

3.1.2.2.1 Benefits

The first category of economic information to be gathered about the product undergoing disassembly analysis has to do with the value that exists within it. The first type within this category to be discussed is the resale value of parts. Any component which has a value must be recorded. Within a product there are parts which can be sold for reuse or remanufacturing. For each of these parts the value they hold for the dismantler needs to be included in the model. For example, if a dismantler removes a seat from an automobile which can be sold for fifty dollars, this must be noted. If the seat first requires ten dollars worth of cleaning and repairs, then only a value of forty dollars should be included in the model. Essentially, what should be recorded here is the economic benefit that the dismantler would gain by removing the component and reselling it.

The next information type within this category concerns the benefits from the recycling of materials. In essence, some materials, when removed from the product can be sold to recyclers who will reprocess the material and sell it again for new uses. For example, it may be possible to sell a particular material for one dollar per kilogram. This is the number, therefore, which should be used in the model for the recycling value of this material.

The final information type in the economic benefits of disassembly category involves the benefit to the dismantlers of shredding assemblies. Shredding is always an option when dismantlers have completed removing those components that they wish to remove. They may choose to take the remainder of the product and any components they wish, and shred them. There are more than one type of shredder, but in general, they rip the products fed to them into small pieces. Shredders which are designed for large metallic products come equipped with magnets and other devices for separating as much of the material as possible so that they may be recycled.

Regardless of the type of shredder, when one is conducting a disassembly analysis of a product, it is necessary to know what the "hulk" -- the remains of the product after the chosen set of components has been removed -- is worth if it is to be shredded. For example, if an automobile dismantler owned their own automobile shredder, the value of the hulk would be determined by its material contents. Consider the following example. Imagine that a hulk comprised of eight hundred kilograms of steel and two hundred kilograms of plastic is to be shredded. Imagine further that steel, after being shredded, can be recycled for five cents per kilogram, but the plastic cannot be recycled and must be landfilled at a cost of three cents per kilogram. Assume a cost of two cents per kilogram to operate the shredder. The value to shred this hulk is fourteen dollars, calculated as follows:

shredding value of the steel = (0.05-0.02) * 800 = 24

shredding value of the plastic = (-0.03-0.02) * 200 = -10

total shredding value = 24 -10 = 14

The information necessary to make this sort of calculation would be required for the model.

3.1.2.2.2 Costs

The other category of information that is necessary for the economic modeling of disassembly has to do with the costs involved. One type of costs are those associated with the landfilling of unwanted materials. Landfills typically charge by a particular price per volume. As well, some substances are considered to be toxic or hazardous, and therefore a different rate is charged.

The other cost which needs to be included is the cost of the labour required for the disassembly. Since times are already included in the model for disassembly activities, it is only necessary to add a cost of labour per unit time. However, different disassembly activities may require labour of different skill levels, and so these activities should receive a different cost per unit time.

3.1.2.3 Final Notes on the Information Required for Disassembly Modeling

The physical and economic information which has been described above is what will be used for the models developed in this research. For a disassembly analysis with more depth, more information would be required. The following paragraphs describe what deeper disassembly analysis may achieve, and what additional information would be required.

While the modeling proposed in this research recognizes that the order of disassembly is important by including the concept of precedence constraints, it does not allow for the effect of changing the sequence of actions in otherwise identical disassembly plans. That is to say, two plans which separate the same components but do so in different orders are equivalent in terms of this study. In reality, there is a potential effect on the overall time by changing the order of operations in a disassembly plan There are two causes of this effect. First, the fact that some actions require the same tools and some require different tools creates the possibility of time savings by arranging activities to minimize tool changes. The model would require tooling times to incorporate this effect. Second, the time it takes to remove a component may vary depending on which other parts have been removed and how much access to it is provided. To incorporate this effect the model would need a method of determining the time to remove a part given any condition of the product. Modeling this information would be complex, and gathering it experimentally would require many timestudies.

The disassembly analysis in this research does not fully consider the possibility of destructive disassembly either. In other words, when evaluating a product for disassembly, it may be possible to remove particular parts or materials faster if the prospect of damaging some components is not a concern. If destructively ripping some parts out of the product would be allowed, the modeling problem has been modified and requires additional thought. Times for destructive disassembly actions, and information on how these actions would affect the precedence constraints would be required. Due to the complexity of this information, it might be best to implement this type of system using a CAD tool.

As well, if destructive disassembly were to be modeled, there would be additional economic information required. It would be necessary to have a method to calculate what damaged components would be worth. Furthermore, it would be necessary to consider how destructive disassembly would affect the costs of performing the disassembly.

Incorporating strict sequencing and accounting for destructive disassembly would increase the complexity of the model by orders of magnitude. The model would benefit from increased precision, but this precision would come at a heavy cost. The increased difficulty of modeling the disassembly of a product and the greatly increased number of possible disassembly plans would make the generation of economically optimized disassembly many times more complicated. When disassembly is modeled to this level of detail, optimization for large and complex products becomes nearly impossible. There is no method known to the author for generating optimal disassembly plans using strict sequencing for products with more than fifty parts. There is currently no method known to the author for generating optimal disassembly plans when considering destructive disassembly for products of any size.

The information which will be included in the models presented in this thesis will allow for in-depth analysis of the disassembly of products. Assuming that the only important aspect of the sequencing issue is the precedence constraints is equivalent to assuming that each component has a set time and cost for removal and that this removal can occur only if the component's precedence constraints have been satisfied. This simplification will have a relatively minor effect on the computation of disassembly costs, but will make the optimization procedure possible for much larger products. The inaccuracy produced by the simplification is quite small and is likely smaller than the inaccuracy caused by the difficulties in determining accurate prices for components and materials. In any event, sensitivity analysis on the figures used will render these imprecisions irrelevant.

3.1.3 The Disassembly Modeling Language

A format for explicitly recording the disassembly modeling information is desirable. This is so that: (1) disassembly modeling information can be accounted for without ambiguity, and (2) so that the information can be presented in a machine-readable way. The following paragraphs describe a language which was developed for this purpose.

It is necessary that such a language be capable of unequivocally representing all the information required for the model. This information has been listed in the previous section. The language should also be easy to write in a concise manner. It is also desirable that it be structured to allow for the development of software which will read and interpret it.

The *Disassembly Modeling Language (DML)* has been developed with these goals in mind. It is a language for encoding disassembly modeling information so that it can be read by a computer program which will interpret and analyze it. Each line of a file written in DML conveys one piece of information in a notation known as object-attribute-variable notation (OAV). Each line of DML has three words. The first word usually represents a part, or sometimes a material. The second word represents one of the part's (or material's) attributes. The final word is a value for that attribute.

Before demonstrating the DML style with an example, it is important to explain the nomenclature for the parts. The component structure information is the only information which is not explicitly stated in a DML file. Instead, it is implied by the names given to parts. These names are written in an object-oriented style inspired by the way objects are named in the programming language Tcl/Tk. The name given to the product as a whole is simply a dot: "`.`". Each part which is a component of the product is given a name beginning with a dot. For example, "`.widget`", "`.gizmo`", and

"`.foobar`" are three first-level components of the product. Components of components have their name appended to that of the larger assembly. If a widget is made of a "doo" and a "dad", then their names would be "`.widget.doo`" and "`.widget.dad`".

It is important to note that any reference to a part such as ".assembly.component" infers the existence of the part ".assembly" even if there is no DML code which refers directly to that part. As well, please note that ".assembly" is sometimes referred to as the *parent* of ".assembly.component" in this document, while ".assembly.component" is sometimes called the child.

The following is a short example demonstrating some of the style elements of the Disassembly Modeling Language:

```
.SeatFrontRight TIME 300
.SeatFrontRight MASS 25
.SeatFrontRight.Fabric TIME 60
.SeatFrontRight.Fabric MASS 1.5
.SeatFrontRight.Fabric MATERIAL Polyester
.SeatFrontRight.Foam TIME 15
.SeatFrontRight.Foam MASS 4.0
.SeatFrontRight.Foam MATERIAL PUR
.SeatFrontRight.Foam AFTER .SeatFrontRight.Fabric
```

The example above is based on the front passenger seat of a car. The numbers were invented, but the example does demonstrate the DML's OAV format, and the nomenclature of the parts. As well, some of the part's attributes have been introduced for the first time. Basically, the DML code shown above describes the times to remove a seat and separate its fabric and foam. The masses for each part are given, although the mass for the seat should equal the sum of its components. Materials are given for those parts which are not mixed. Since no material is listed for the "`.SeatFrontRight`" it can correctly be assumed that it is mixed. The attribute "`AFTER`" is used to define a precedence constraint -- in this case, that the foam cannot be removed until after the fabric has been removed.

When defining precedence constraints, it is not necessary to list them all. Only the minimum amount of information to infer all the constraints is required. For example, in the following DML code, more than the required amount of information is given:

```
.A BEFORE .B
.B BEFORE .C
.A BEFORE .C
```

The third constraint is redundant since the combination of the first two make it impossible to remove "`.C`" without first removing "`.A`". Only the parts which must *directly* precede the part in question need be listed. The other precedence constraints can be inferred.

The following table lists the attributes for parts and gives a brief explanation.

Table 3.1 Disassembly Modeling Language part attributes.

`TIME`	• The TIME attribute is used to indicate the time to remove the part in question from its parent.
`MASS`	• The MASS attribute is used to indicate the mass of a part.
`MATERIAL`	• The MATERIAL attribute is used to indicate from what material the part is made. The material "Mixed" is used as a special keyword and is the default material.
`MARKED`	• The MARKED attribute is used to indicate whether a part is marked for materials. "Y" means that yes, the part is marked, "N" means that no, the part is not marked, and "NR" means that marking is not required for the part. Examples of parts which can receive an "NR" are those that are made of steel since any dismantler can quickly determine this.
`BEFORE`	• Used for precedence constraints. The BEFORE attribute is used to indicate that the object part must be removed before it is possible to the variable part.
`AFTER`	• Used for precedence constraints. The AFTER

	attribute can also be used to indicate the same information as the BEFORE attribute. Only one or the other is necessary. There is no need to state that ".a" is before ".b" and that ".b" is after ".a".
`RESALE_VALUE`	• The RESALE_VALUE attribute is used to specify the value that a dismantler can realize by removing a part for resale.
`LABOUR_COST_PER_TIME`	• The LABOUR_COST_PER_TIME attribute is used to identify a labour cost for the time invested in removing a particular part. (Spellings with or without a "u" in labour are acceptable.)
`RECYCLE_VALUE`	• Normally, the value from recycling of a product is determined based on information regarding the materials that comprise it. Alternately, the RECYCLE_VALUE attribute can be used to directly specify the value that can be realized by recycling a part.
`LANDFILL_COST`	• Normally, the cost to landfill a product is determined from its mass and from information regarding the materials that comprise it. It is however, possible to use the LANDFILL_COST attribute to directly specify the total cost of landfilling a part.

Most lines in a DML file are OAV triplets conveying information about parts. There is other information which is necessary, however. Information about materials is also required. In order to differentiate between parts and materials in the file, material names are prepended with "`*.Material.`" when they are objects. For example:

```
.SeatFrontRight.Foam MATERIAL PUR
*.Material.PUR RECYCLE_VALUE_PER_MASS 0.50
```

implies that the seat foam is made from PUR which is worth $0.50 per kg.

The following table lists the attributes for materials and offers a brief explanation.

Table 3.2 Disassembly Modeling Language material attributes.

`RECYCLE_VALUE_PER_MASS`	• The RECYCLE_VALUE_PER_MASS attribute is used to indicate how much a material is worth in the hands of a dismantler if they plan on recycling it.
`LANDFILL_COST_PER_MASS`	• The LANDFILL_COST_PER_MASS attribute is used to indicate the cost of disposing of a material.
`SHREDDED_RECYCLE_VALUE_PER_MASS`	• This attribute is used to indicate how much a material is worth in the hands of a dismantler if it is to be shredded and recycled.
`SHREDDED_LANDFILL_COST_PER_MASS`	• This attribute deals with the net cost to the dismantler for material which is sent through a shredder but is then disposed.
`SHREDDER_EFFICIENCY`	• This attribute defines what fraction of a shredder-recyclable material can be recovered.

Although it is known that landfills charge based on volume, it was decided that it was more appropriate to approximate this in the modeling language by including a landfill cost per unit mass. Otherwise, the difficulties encountered in the various densities of materials combined with the various densities of products caused by waste of space would result in a less accurate value and a more troubling modeling experience.

In order to save repeating many similar DML expressions, it is possible to set defaults for any of the attributes for parts or materials. This is done by using the

"`*.Default`" object, followed by any attribute and the value which should be used as its new default. For example:

```
*.Default LABOUR_COST_PER_TIME 0.0055556
*.Default MARKED N
*.Default SHREDDED_LANDFILL_COST_PER_MASS 0.04
*.Default LANDFILL_COST_PER_MASS 0.03
*.Default MATERIAL Steel
*.Default TIME_FACTOR 1.0
```

The final default listed above involves the "`TIME_FACTOR`" attribute, which is actually a special parameter used to modify the times for the disassembly actions. This factor is used to adjust for time allowances given to the dismantlers and is multiplied by their recorded times.

Any lines in DML files which begin with the "#" character should be interpreted as comments.

The Disassembly Modeling Language is capable of completely describing all the relevant information for modeling the disassembly of a complex product. This will be demonstrated in a later chapter of this thesis. The DML is written in a standardized format which makes it possible for software to read, interpret and analyze it.

The DML modeling of some parts involved some tricks, however. These tricks are methods which should be used for the modeling of difficult situations in DML. There is nothing wrong with these methods, but they may not come to mind immediately for the novice modeler.

If a material is contaminated it should not be recorded in the DML as being, say, "ABS". In order to have the software treat the material properly, it-should be identified essentially as a different material. Contaminated ABS could be recorded as "`ABS_Contaminated`". This material could then have its own set of economic costs and benefits.

Consider a part which is comprised of only two components. Lets assume the part is named "`.a`" and the two components are "`.a.b`" and "`.a.c`". The modeling of this situation may seem simple, but when some thought is given to it, it is not so simple. The removal of one component actually frees the other. The best way to model this is to assign all the time to one of the components (say, `.a.b`), and assign a time of zero to the second component (`.a.c`). A precedence constraint is required of the form "`.a.b BEFORE .a.c`" so that `.a.c` cannot be removed without the appropriate time investment.

Consider also parts that are comprised of multiple materials which can be identified. If the part cannot be dismantled -- or the modeler does not wish to dismantle it -- it is still necessary to model the part to identify the materials in sufficient detail for the shredder analysis to work. For example, if a part ("`.part`") cannot be disassembled, but it is known that it is half steel and half ABS, this can be modeled using the DML as follows. Create the parts "`.part.steel`" and "`.part.ABS`". These parts are pure material and can be identified. They, however, cannot be removed and so a time of M (a very large number) should be used. As a result, the material composition of the part will be clear, but it will not be possible to disassemble it.

Sometimes it may not be possible to identify a material, or the effort involved might not be worthwhile (for, say, a very small piece of plastic). For non-metal pieces which are not identified, the material "SKOP" should be used, which is an acronym for "some kind of plastic" or SKOR for "some kind of rubber". For metal pieces which are not identified, "SKOM" should be used, which is an acronym for "some kind of metal". Finally, for pieces of mixed materials that are not to be identified, "SKOS" should be used, which is an acronym for "some kind of stuff". Parts should only be recorded as being comprised of SKOS if the metal content is small enough to be irrelevant in the shredding process.

3.2 The Disassembly Model Analyzer

3.2.1 The Concept of the Disassembly Model Analyzer

Analysis of disassembly models is a complex task, and attempting to do it on paper, or even on a spreadsheet, would be impossible for models of significant size. Software is therefore a necessary tool for this job. This chapter describes a program called *The Disassembly Model Analyzer (DMA)* which was written for this purpose by the author using the C programming language.

Essentially, the DMA is capable of reading and interpreting a Disassembly Modeling Language (DML) file and performing various analyses of it. These analyses range from basic analyses of the structure of the product to optimization of the disassembly plan. The DMA can be used to completely study the economics of disassembly for a given product. Sensitivity analysis can be performed by editing the DML files and running the DMA multiple times.

The DMA has been programmed in C specifically for machines running operating systems of the UNIX family.

3.2.2 The DML Interpreter

When giving the command to start the DMA, the name of the DML file to be analyzed should be given as the only command line argument. This instructs the DMA to begin reading the DML file and interpreting it line by line.

Before the Disassembly Model Analyzer begins reading the file, it internally creates three data structures. The first one holds the default values for the attributes that have been built in. The second and third structures are prepared to hold information about parts and materials. These structures are initially empty. The analyzer then begins to read the DML file.

Whenever the name of a part or material is encountered for the first time anywhere in a DML file, it causes the DMA to add it to the appropriate data structure and initialize it with the current set of default values. This also occurs for parts whose existence is implied by the mention of their children. Part and material names which first appear as the value for a part's attribute are not excluded from this procedure, which allows the construction of DML files without much concern for the order of the statements. The only case in which order is important involves the default value settings. Default value changes affect the set of defaults registered in the DMA's memory. As a result, only those parts or materials which are initialized after a default value has been changed will include the change.

As the DMA proceeds through the file, each line is checked to see if it is a comment or an OAV triplet. If it is not a triplet, it is ignored. Otherwise, the analyzer then determines if the line regards a part, a material, or a default value setting. The DMA will initialize any parts or materials that require it, then set the appropriate attributes to the listed values as defined in the current line.

When the file is complete, the DMA should have an internal representation of all the information necessary for disassembly modeling. In order to help avoid coding errors, the DMA can analyze the model to check for potential errors caused by misspellings or omitted data. These errors include parts without mass, parts whose masses do not equal the sum of the masses of their components, and parts which can be removed with zero time.

3.2.3 The Basic Structure Analysis

The first uses of the DMA to be discussed are the basic structure analyses. These analyses are relatively simple but can be revealing. The basic analysis includes model reports, path and cumulative time reports, material breakdown reports, and precedence constraint reports.

All the basic structure analyses can be selected from the main DMA menu. Whatever report the user desires, they will have the opportunity of viewing it on the screen or saving it to a file. The following paragraphs describe what each of the basic analyses are, and how they are performed.

A model report is a summary of all the information included in the model. This report simply lists all the parts and for each it says what the mass, material, time to remove and marking status are. It also shows the parents and children of each part, as well as all the parts that must precede it directly or be directly preceded by it according to the constraints. It includes the economic information -- such as resale value -- for each part. Following the parts, the report lists all the materials in the model and their economic information. If there are any apparent errors in the model, warnings will be included in the report.

A path to a part shows all the other parts which must be removed in order to get to the one in question. This includes all the direct precedence constraints, as well as those which are implied. A DMA user can select a report which lists the paths for each of the parts in the product, as well as the cumulative times for each path. The cumulative time for a part is simply the sum of the times for all parts in the path, and it represents the total time necessary to remove the desired part from the beginning of the disassembly of the product, assuming no prior disassembly.

The material breakdown analysis provides a variety of information about the material make-up of the product. In begins by listing all the materials in the product, and how much of each there is. It then repeats this analysis for the total of the parts which are resellable. Next, it classifies the materials as to whether they are recyclable by the shredder or not. Shredder recyclability is determined by the values which are given for the material's SHREDDED_RECYCLE_VALUE_PER_MASS. If this value is considerably below zero, it is assumed that the material is not economically recyclable after it has been shredded. The material breakdown analysis also lists all the materials that are in parts which are marked for material identification, not marked, or not required to be marked.

The precedence constraints analysis generates a distribution of the number of precedence constraints (both direct and implicit) for the parts. For example, it might reveal that there are twenty parts with no other parts in their path, ten with one part in their path, three with two parts in their path, etc. This analysis is also repeated specifically for parts with resale values.

These basic structure analyses are not very complicated, but they are useful in two ways. First, they allow the software to help to answer simple questions that might be asked about the product. Although the questions are simple, it is useful to have a method for quickly and automatically getting the answers. Also, the basic structure analyses are good tools for general comparisons of two similar products. For example, by performing the basic structure analysis on two automobiles the effect of design differences may become evident.

3.2.4 The Disassembly Plan Analysis

The Disassembly Model Analyzer allows the user to perform a disassembly plan analysis. The user may define a disassembly plan by choosing which parts to remove and the DMA will make the plan feasible by ensuring that no precedence constraints are violated. The Analyzer will then compute what the costs, benefits, and profit for the plan would be.

As a stand-alone tool, the DMA's disassembly plan analysis is not very useful. It is a fundamental part of the DMA's optimizer, however, since its profit calculation represents the function to be optimized. Furthermore, the analysis of a single plan is not as simple as it may appear. The following paragraphs explain the procedure used to determine the profit for a disassembly plan.

A disassembly plan is a list of the parts which will be removed from the product or from other parts. Prior to the disassembly plan analysis, the plan must be checked to ensure that it is feasible and no precedence constraints are violated. Once this is done it is possible to begin determining the profit for the plan by calculating the costs and benefits of each disassembly action.

The labour costs are relatively easy to determine. Each part that has been removed has a known time for removal and a labour cost per unit time. Multiplying these gives a cost for each part, and summing over all parts gives the total.

From the DMA's viewpoint, the disassembled product is a set of *n* pieces which have been separated, including what remains of the product. Some of these pieces may be complete parts. Some could be parts which have been partially disassembled. Others may be indivisible pieces of a single material. For each of these there may be many choices -- resale, recycling, shredding, or landfilling. The DMA chooses the best of these options for each piece. The best option is defined as the one with the greatest benefit.

First, each part which has been separated to see if it is complete. If it is and it has a resale value, then resale is a possibility. Otherwise this option does not exist. Second, each piece -- whether complete or not -- may be recycled. If the part has a RECYCLE_VALUE or if the piece is comprised of a single material, then it can be recycled. The recycling value for this part is calculated by the DMA. Third, any piece can be shredded. Based on the materials which remain in the piece, it is relatively easy to calculate the value to shred the part as the example in Chapter 3 shows. Finally, any part can be landfilled. Again, the DMA can calculate the value to do this.

For each piece that has been separated, these values are calculated. Those which do not apply -- such as resale values for parts which are not complete -- are ignored. Of those that remain, the highest value is chosen as the option for that part. This routine is completed for each piece which has been separated, and when the values are added together and the labour cost is subtracted then the profit is known.

3.2.5 The Disassembly Plan Optimizer

The disassembly plan profit-optimizer is the most significant part of The Disassembly Model Analyzer. The task it performs is quite difficult, but most useful. In general it attempts to find the disassembly plan for the modeled product which results in the greatest profit to the dismantler. It does this by using some heuristics to simplify the problem, and then by using genetic algorithms to optimize the remaining portions. The following sections explain, in detail, each of the steps of the optimization procedure that the DMA uses.

3.2.5.1 Identification of the Parts to be Resold

Because some parts have a resale value much greater than the costs of disassembly, the problem can be simplified by identifying those parts and removing them from consideration. Keep in mind that this does not refer to all parts with some resale value, but only for those where the value is large enough so that the decision to remove them is obvious.

If it is desired to remove a part for resale, it is necessary that the precedence constraints for that part be met and that the components that comprise the part be left intact. These conditions imply some costs.

The first set of costs involve the labour necessary to remove the part in question and to satisfy the precedence constraints. Let the sum of these costs be C_1.

The second set of costs involves the cost of the lost opportunity experienced because it is not possible to remove any of the part's components. Let the upper bound of the sum of these costs be C_2. C_2 can be calculated using a recursive function which works its way down through the component structure of the part in question and ultimately determines an upper bound on the potential value of the parts comprising it.

The third cost is the lost opportunity of not being able to sell any other parts of which the part in question may be a component. This cost is simply the maximum resale value of any part which includes the one being analyzed. Let this cost be C_3.

If R is the resale value of the part in question and S is the value of the part if it is shredded, then:

$$R - S - C_1 > \max (C_2, C_3, 0)$$

is a sufficient but not necessary condition that the optimal plan includes selection of this part for resale. The condition is sufficient because if we decline to remove the part, no other set of benefits can compensate for passing up the net gain of reselling this part. The condition is not necessary, however, because the calculations of the lost opportunities C_2 and C_3 does not count the full set of costs that those opportunities would incur. Furthermore, the condition is not necessary because the calculation does not include the other potential benefits from removing the precedence constraint parts. Since the condition is not necessary, it is possible that a part which does not meet this criteria may still be chosen for removal and resale at a later stage in the optimization.

The DMA takes advantage of this condition by identifying all parts which meet it and marking them for removal. The parts are kept intact by noting that their components must not be removed from them. The Analyzer also makes sure to mark the precedence constraint parts for removal. If there are many parts which meet this criteria, it can result in many parts being solved and removed from future stages of the optimization.

3.2.5.2 Parts Which Are Trivially Undesirable

In contrast to those parts which are so valuable that it is easy to see that they should be removed, there are some which are quite worthless and should obviously never be removed. These parts are trivially undesirable, and the second step that is followed by the DMA's optimization is to identify them.

There are two benefits to removing a part. First, the part itself may have some value. Second, the part may be part of a precedence constraint for another part that has value. When this second possibility may be ruled out, it is easy to judge a part simply on its own merits.

Let us first consider parts that are not involved in the condition of any precedence constraints. For simplicity these parts will be referred to as having no "afters". If one of these parts has a value when removed -- from resale or recycling -- less than the sum of the cost to remove it plus its own shredder value, then it is clear that there is no reason to remove it. The part is trivially undesirable. It is possible to make this analysis for any part in the product that has no "afters".

Now consider a part which had only one after. Imagine that that one after was a part which was later discovered to be trivially undesirable. Since the part which can only come after this one is worthless, the after is irrelevant. The part can be analyzed as above, with regard only for its own value.

Based on these facts, the DMA begins searching for trivially undesirable parts among those that have no afters. If, through the discovery of trivial parts, some other parts are found to have afters which are irrelevant, they too will be analyzed in this manner. Depending on the specifics of the disassembly model in question, many parts may be eliminated from consideration in this manner.

Parts which do not have a time associated with them are assumed to be inseparable, and so they are also included with the trivially undesirable parts and removed from consideration.

3.2.5.3 Grouping of the Remaining Parts

Once as many parts as possible have been removed from consideration because they have very high resale prices; or must precede a part with a very high resale price; are a component of a part with a very high resale price; or because they are trivially undesirable, the next step for the DMA is to separate the remaining parts into independent groups.

Parts belong in the same group if they may influence each other's potential value if removed. Any parts which are involved in a precedence constraint with each other belong in the same group. As well, all the components of a part with a resale value belong in the same group. These are the only conditions which govern the creation of groups, other than the fact that if A belongs in the same group as B, and B belongs in the same group as C then all three must go into a group together.

Using these simple rules, the DMA assigns parts to groups, hopefully creating as many small groups as possible. Each group is independent and can be optimized separately, so the creation of groups essentially breaks the problem into a number of smaller problems.

3.2.5.4 Optimization by Enumeration

Some groups are small enough to optimize simply by trying every possible combination of removing or not removing the individual parts. The user is asked by the DMA about the maximum size of a group that they wish to optimize using enumeration.

All groups smaller than or equal to the specified size begin optimization by enumeration. A solution for a group is simply represented by a series of ones and zeros corresponding to the parts in the group. A zero means that for this solution, the corresponding part will not be removed. A one means that it will be. Once all the possible combinations of ones and zeros have been evaluated for the current group, the combination with the highest profit can be chosen as the solution for this group. Unfortunately, some groups are too large to solve using this method, and so another method should be used. The next section deals with this alternate method.

3.2.5.5 Optimization by Genetic Algorithms

Groups that are too large for enumeration range in size from the teens to hundreds of parts. The larger the group gets, the more difficult it is to solve. Considering the number of possible solutions, methods which try to evaluate them all are not practical. It may be possible to solve the problem analytically, but the combination of the precedence constraints and the subassembly structures increases the complexity a great deal. It was decided, therefore, to apply genetic algorithms to the problem.

3.2.5.5.1 Introduction to Genetic Algorithms

Genetic algorithms (GA) are a class of search mechanisms based on the principle of survival of the fittest. Essentially it simulates an environment in which solutions to the problem being solved are represented by "individuals". These individuals reproduce at rates based on their "fitness", which is actually a value associated with the objective function being optimized. The populations of these individuals are therefore able to evolve over time, producing better and better individuals. Ultimately, the answer to the problem is the solution represented by the individual with the best fitness ever witnessed over time.

More specifically, the genetic algorithm begins by creating a population of random individuals for the first generation. These individuals reproduce to create the next generation. There are various methods of reproduction which will be explained below. The parents for the next generation's children are selected randomly with probabilities proportional to their fitness. So, if an individual in the current generation represents a solution which is two times better than another individual then it has an expected number of offspring which is double that of the other. There is not necessarily a limit to the number of children that an individual may parent. The population size from generation to generation is typically constant, however. Once the new generation has been populated with children, it supplants the old generation and the process begins again. This is repeated for a number of generations which is specified by the user.

The individuals in genetic algorithms are frequently, but not necessarily, represented as a bit string -- that is, a string of ones and zeros. The most common methods of reproduction are crossover, mutation, and replication. Currently, the genetic algorithm used within the Disassembly Model Analyzer does use a bit string representation. It also uses mutation and replication as two of its reproduction operators. It does not use crossover, rather it has a customized form of mutation called resale mutation. The specifics of the GA used in the DMA will be discussed later. The following paragraphs explain replication, mutation, and crossover in general.

Replication is the simplest of the reproduction operators. During replication, a child is simply made as a genetically identical copy of the parent.

Mutation is similar to replication, except that some minor, random change is introduced into the child. In other words, a copy of the parent's genetic information is made, and then the possibility of changing each bit is considered with a small probability. For example, let us say that a parent has been selected which is represented by the bit string "`0101101001`". The child will be a copy of this, except that for each bit there is a probability p for which the parent's bit will be changed to the opposite value. If p in this case was equal to 0.1, then the expected number of mutations in the above example would be 1.

Crossover can be used to produce two children from two parents. Essentially, a crossover point is randomly selected, and both parents are divided there. The beginning part of one parent is combined with the end of the other parent to produce one child. The other child is produced from combining the other halves of the parents. For example, if the following two chromosomes are the parents and the crossover point is indicated by the asterisk, the children are shown below in the second pair of chromosomes:

Parent 1: `1001011010101*10010101`
Parent 2: `1101101001001*01010101`

Child 1: `1001011010101 01010101`
Child 2: `1101101001001 10010101`

Crossover with multiple crossover points is also possible.

The general goal of all these operators is to pass on the genetic information of the parents to the children in a way which might result in an improvement of their performance. This is the basic idea of evolution. Parents pass their traits to their children, although there is chance involved in the process. The children may be different because of mutations or due to the combination of traits from both parents. As a result, the child may be more or less fit than the parents. In nature, survival of the fittest ensures that on average those children who are more fit will produce more children, and thus their successful genes will be passed on. In genetic algorithms this is promoted by the selection mechanism that causes individuals with better objective function evaluations to be more likely to be parents.

The reproduction operators described above are the standard operators used for the simplest applications of genetic algorithms and are mentioned at the beginning of any book on the subject. It is not necessary, however, that an application of genetic algorithms use only these operators, or even use them at all. In fact, it is quite appropriate to develop custom operators specifically for the problem in question. The only requirements of these operators is that they can produce children from parents while preserving some of their traits and possibly creating new and superior individuals.

3.2.5.5.2 Genetic Algorithms Applied to Disassembly Optimization

The genetic algorithm applied to the disassembly optimization problem in the Disassembly Model Analyzer is slightly different from the basic genetic algorithm described above. Crossover was not used and an additional operator was created.

The Disassembly Model Analyzer begins optimizing the disassembly plan for the group in question by asking the user for various parameters. These parameters are (1) the number of generations for which to run the algorithm, (2) the number of individuals per generation, (3) the fraction of children which will be produced by mutation, (4) the fraction of children to be produced by resale mutation, (5) the probability of a mutation occurring for any given bit within a child being produced by mutation, and (6) the probability of a resale mutation occurring for any given bit within a child being produced by resale mutation.

Once the user has entered these variables, the DMA proceeds to randomly generate the initial population of the appropriate size. These individuals should then be evaluated based on the disassembly plan analysis described in section 3.2.4. It is possible, however, that these individuals may refer to solutions which are infeasible. The DMA, therefore, adjusts these solutions to nearby feasible solutions prior to evaluation. In fact, the DMA has two distinct methods for correcting the solutions and it evaluates both corrected solutions which correspond to the current individual and rewards the individual with the higher fitness.

The first way in which infeasible solutions are corrected deals with de-selecting parts which were selected in violation of a precedence constraint. In other words, when the DMA is correcting a solution in this manner, it scans the solution for parts which have been removed in violation of an unsatisfied precedence constraint. It fixes these problems by changing the solutions so that these parts are no longer selected. This does not cause new violations by definition because, there can be no parts for which all the precedence constraints were satisfied that rely on a part removed in violation of a precedence constraint.

The second way in which infeasible individuals are corrected deals with satisfying the condition segment of precedence constraints which have been violated. In other words, the DMA scans the solution for parts which have been removed in violation of precedence constraints, and then fixes these problems by removing those parts which will satisfy the constraints. This does not cause new violations because once all the precedence constraints for the part are satisfied, then any precedence constraints for the parts removed to correct the problem will also be satisfied, by definition.

The DMA temporarily makes both types of these corrections to any solution for evaluation purposes. In other words, any individual is mapped by the DMA to two feasible solutions, and then the maximum profit of these solutions is recorded as the fitness of the individual. Individuals that directly represent feasible solutions are mapped to the two identical solutions which would result if the corrective measures were applied to them.

The individuals' genetic information is not permanently changed during the correction and evaluation procedure. If an individual represents an infeasible solution, it is left this way. It is possible at any time to determine the solutions to which the individual is mapped by the DMA, and therefore to see what solution produced the fitness assigned to the individual. There are two related reasons that the individual's genetic information is not changed. First, making the change would likely decrease the diversity of the population and eliminate some potentially valuable genetic data, thus making it potentially more difficult to reach some preferable solutions. Second, the two mechanisms used to map the individuals to feasible solutions are not the only possible mechanisms to do so. For each of *n* precedence constraints which has been violated either of the two methods may be applied, and so there are 2^n combinations of the potential correction mechanisms and 2^n possible mappings. Some of these mappings may be better than both of those which are evaluated by the DMA. The best possible mapping may be closer to the lesser of the two evaluated mappings, and so permanently changing the individual's genetic information to that of the greater of the two evaluated mappings would take the individual further away from the better answer.

Once the individuals of the initial solution have been evaluated, the individual with the highest fitness is evaluated to see if it is superior to the current best "answer". If it is, the answer is then updated. The process of creating the new generation then begins and it is the same throughout all generations and will be repeated as many times as specified by the user.

The new generation is created one child at a time. For each child, the method of reproduction is first selected randomly based on the numbers entered by the user. A parent is then randomly selected with each individual from the old generation having a probability proportional to the difference between its fitness and the lowest fitness of any in the population.

If the selected reproduction method is replication, the child just becomes an exact copy of its parent.

If the selected reproduction method is mutation, then the child is produced from the parent as explained above. The child is made as a copy of the parent, and then bit by bit, there is a probability of a mutation which has been supplied by the user. If, based on that probability, the bit in question is selected to mutate, then a one will be changed to a zero, or a zero will be changed to a one.

The third possible reproduction method is resale mutation. This genetic operator was specifically developed for the disassembly plan profit optimization problem. It is based on the regular mutation, but is specifically aimed at changing individuals to reflect the possibility of resale. The necessity for this operator is caused by the fact that mutation by itself would be unlikely to make all the changes to an individual that would be necessary to make a part complete and eligible for resale. In other words, it is necessary that all the components of a part be intact for resale, and mutation would be unlikely to randomly cause this to happen, partially because there is no benefit for individuals who have a resale part nearly complete over individuals who have an incomplete resale part. The resale mutation operator was developed to counter this lack of inclination to complete and resell parts as individuals change from generation to generation.

Resale mutation begins as regular mutation does by making a copy of the parent. Next, each of the parts which may be resold is analyzed one at a time. Each of these parts is evaluated against the probability defined by the user regarding the rate of parts being chosen for resale mutation. If a part is selected for a resale mutation, the DMA makes changes to the individual to remove the part in a complete fashion. These changes involve (1) removing the part, (2) ensuring that the components of the part are all intact, and (3) satisfying the precedence constraints for the part.

Once all the children have been produced by one of these reproduction methods, they are all evaluated for fitness using the same procedures as the initial population. The group is then searched to see if a new "champion", better than any other previously living individual exists. If it does, it becomes the new answer. Proceeding, the "new generation" becomes the "old generation" to represent the passage of time, and the process begins anew.

When the number of generations specified by the user have been completed, the process is done. The champion at that point represents the analyzer's closest guess at the optimal solution for the current group. It may or may not be optimal, but if the analyzer was given enough time, it should be near optimal. The analyzer then repeats the entire process for any other groups requiring optimization by genetic algorithms. Upon completion of optimization of all the groups, a report summarizing the optimization is then printed or sent to the output file.

3.2.5.6 Output of the DMA's Optimizer

The output file produced by the DMA during the steps in profit optimization of disassembly plans contains a lot of information. First, the file lists those parts which have been initially selected for resale. It then lists all the groups created and their members. The trivially undesirable parts are not listed, but they are any parts that do not belong to the groups or the resale list.

The next information to be found in the file is a summary of the optimization parameters that the user specified. The file then proceeds to list the profit value of the best answer found after each group which was optimized by enumeration. Once the optimization by genetic algorithms begins, there is data for each generation of each group. At each of these points, the average fitness of the generation and the best answer to date is listed. These numbers can be used to make a graph to show the progress over time of the analyzer in its optimization.

Once the optimization efforts are complete, the best answer is printed to the output file. The decision for each part in the model is listed in the file. In other words, for each part it is identified whether it is to be removed or not, and whether it is complete, partially disassembled or fully disassembled in this solution. The values for the options considered by the disassembly plan analyzer (e.g., resale, recycling, etc.) are also listed, along with the corresponding values. This information fully specifies the meaning of the solution.

The final information sent to the output is a statistical analysis of the solution. The amounts of each type of material resold as parts, recycled by the dismantler, landfilled by the dismantler, recycled by the shredder and landfilled by the shredder are listed. (The determination of whether material shredded will be recycled or landfilled is based on price.) As well, the number of parts and the revenue received for them is given, along with the revenue received by the dismantler for the recycling of materials and the sale of the hulk to the shredder. Landfill costs and dismantling times and costs are also included. All these figures provide a quite useful analysis of the optimal disassembly plan for the product. As such they are essentially for any consideration of the economic feasibility of the reuse and recycling of the components of the product. They also serve as a predictor of the likely retirement of the item in a free market economy without regulation of the dismantling and recycling industries.

Chapter 4

Application of Disassembly Modeling and Analysis

4.1 The Vehicle Recycling Development Center Project

4.1.1 Purpose

The Vehicle Recycling Development Center (VRDC) is a research centre belonging to The Vehicle Recycling Partnership, which is a consortium of General Motors, Ford, and Chrysler under the umbrella of USCAR, the United States Council for Automotive Research. The VRDC is located in Highland Park, Michigan in building 144 of the Chrysler Center complex.

The purpose of the VRDC is to conduct research aimed at increasing the knowledge level for automotive recycling techniques. A major focus of the centre is the dismantling of vehicles for the recovery of parts and materials. With this in mind, the author of this thesis, working with a student from MIT, Pável Zamudio-Ramirez, began a project to study the economics of the automotive recycling industry on both a micro and a macro level.

The micro level analysis is concerned with the disassembly modeling of individual automobiles. The goals of this research include determining the economic feasibility of the reuse and recycling of various components and materials in the vehicles. This economic feasibility can be judged by the profit-optimizing disassembly plan and the sensitivity analysis. Modification of the model can result in learning about the effect of changes in the design of the vehicles.

The macro level analysis involves the modeling of the interactions between the segments of the entire industry. This computer based model will allow the automakers to use it as a "management flight simulator" to see how the variables they have control over can affect the system. As well, events -- such as an energy crisis, for example -- can be simulated to see their effect and to help discover the best reaction to them.

The two levels are interconnected in an important way. The sensitivity analysis of the disassembly model in the micro level analysis can lead to knowledge about how changes in the design and economic environments can affect the overall behaviour of the automotive recycling industry. This knowledge is an essential segment of the industry model.

The following sections describe the main steps in gathering of data and information for the VRDC project. These activities were carried out jointly by the author and Mr. Zamudio-Ramirez.

4.1.2 Dismantling

A total of four cars were fully dismantled for this project during the summer of 1995. Two family-sized sedans -- manufactured by two different companies -- were selected, and two of each were disassembled. From each pair, one car was carefully studied in an in-depth timestudy. The second car from the pair was used as a control experiment, which is discussed later in this chapter. Out of consideration for the wishes of the sponsors, the makes and models of the cars will not be identified. The following segments provide more details on the work involved.

4.1.2.1 Timestudies and Time Factor Analysis

The timestudies were performed by experienced dismantlers employed by the VRDC. In the case of each car involved in this study, the dismantlers had recently worked on other cars of the same type. The dismantlers followed procedures which were similar to, but not identical to the typical routine at the VRDC. The dismantling was also more in-depth than the typical VRDC timestudy and involved the removal and break-down of more components.

For each of two cars -- one from each of the models being analyzed -- the parts were removed from the car one by one in the main dismantling area. Each part was recorded in a spreadsheet, along with its weight, its material (if applicable), the time to remove it, its markings (if applicable), and its fasteners. As well, the component structure information and precedence constraints were recorded in the spreadsheet after discussions with the dismantlers. The cars were disassembled until only the body-in-white remained, except for the rear windows which the dismantlers were not able to remove from either vehicle. The front clip (front end) was then cut from the car.

By the time the timestudies had begun for the cars, the gas tanks and fluids had already been removed. These steps were excluded from modeling. The processes take about twenty five minutes and are required of any car before being sent to the shredder.

During these operations there were a variety of very small parts which were not included. Essentially these parts included bolts and screws and other fasteners. Another problem which was encountered despite efforts made to prevent it was that the dismantlers were more familiar with the make of one vehicle than the other. The best attempts were made to minimize the effect of this.

Once these parts had been removed from the car, they were sent to the secondary dismantling area where they were broken down to a greater degree. Parts were disassembled as much as possible, or as much as seemed reasonable. All the disassembly activities were recorded similarly to the main dismantling. Materials which were not marked or easily identified were put aside for identification by machine or by experts.

During the time of the project, the VRDC was in possession of a Bruker P/ID 28 machine which was used to identify the materials. A user would take a plastic sample and hold it in front of laser beam for four seconds, at which point the machine would indicate the suspected material's name, as well as a "hit quality" which implied the degree of certainty. The laser beam caused the plastic to reflect an infrared light back to the instrument which was interpreted to indicate the most likely material.

During all stages of the time study, times were recorded (with a digital stopwatch) beginning when the dismantler was ready to start, and ending when the operation had been completed. These times did not record, therefore, actions such as acquiring tools, or moving to the appropriate position. As a result, simply summing the disassembly times for a series of actions would not result in an accurate estimate of the time required to do the job. It was necessary to perform further analysis to account for this effect.

It was decided to estimate the relationship between the sum of the individual times for disassembly actions and the actual time required for all the actions in a linear fashion. In other words, it was felt that a decent approximation could be made by multiplying the sum of the individual times by a factor to determine the total real time required. To estimate this factor, further disassemblies were conducted.

Two cars, one of each model, was disassembled to the same extent as the dismantling performed in the main dismantling area for the first pair of cars. In this case no interruptions were made, and the dismantlers were asked to work as they would in a typical environment in the automotive dismantling industry. They were timed from start to finish for each of the cars.

The times gathered from the second trials were compared to the sums of the times from the first trials for the parts which were removed. A time factor -- the ratio of the two numbers -- was calculated at about 4. This implied that the time required to perform a set of disassembly actions was actually four times greater than the sum of the individual times for the actions. After consideration, this number was rejected because the dismantlers had worked at a lower intensity than could be expected in a typical environment. Based on estimates from discussions, as well as visits to dismantlers, a time factor of two was estimated and used for the project.

4.1.2.2 The Economic Information

Many of the automotive dismantlers in North America are connected through an on-line database known as the Hollander system. This system allows dismantlers to check prices for parts available for resale at other dismantlers. When interested in a particular part, the system will perform a search beginning in the local area and expanding until a good sample of parts at various dismantlers has been investigated.

Using the Hollander system, the resale prices for the parts which could be resold from vehicles of the same model, year, and make were researched within the region. For each part for each vehicle a sample of values was recorded from actual dismantlers in the area. These prices were placed in a spreadsheet and the median value was determined and used in the models.

To determine the recycling value of plastic and other non-metal materials, research was done into publications such as *The Plastics News* which lists prices for recycled materials. The value required for the model, however, is essentially the scrap price. Based on discussions with various parties at the VRDC it was determined that a rough but fair method of estimating the scrap price would be to take twenty percent of the prices for the recycled materials. Since all attempts to get real prices that recyclers were willing to pay failed, this estimate was used.

To determine the recycling value of the metals, publications such as *American Metal Market* and interviews with various parties were considered. The recycling value for metals paid to the dismantler was estimated at 55.3% of the quoted scrap price. This discount rate was determined by comparing the known scrap price of ferrous metals to the price that dismantlers were being paid and then further subtracting estimates of handling and inventory costs. The assumption was then made that this rate could be used as a decent estimate of the difference between the quoted scrap price of various metals and the recycling value that the dismantler could actually realize.

The value to the dismantler of metals which would be shredded was slightly more complicated. For any of the metals, the dismantler recycling value described in the previous paragraph was first multiplied by an efficiency of 95% to represent the possible degrading of the metal in the shredding process and the recovery costs. A one cent per pound shredding cost was then subtracted from the resulting value. This calculation was used to determine the recycling value of metals to be shredded.

There were two landfill costs to be estimated. First, the cost for the dismantler to landfill material is required. Second, the cost to the dismantler for material sent to the shredder which ultimately ends up in the landfill is required. The second cost can be estimated based on interviews with shredders who have said they pay about US $12.50 per cubic yard of Automotive Shredder Residue (ASR) to be landfilled. This price includes transportation. Using a density of 1250 pounds per cubic yard for ASR results in a cost of one cent per pound. The cost of the shredding should also be added, resulting in a total of US $0.02 per pound.

For direct landfilling from dismantlers, there is no cost of shredding, of course, but it is assumed that the density of material to be landfilled by the dismantlers is half that of the ASR. So, the price paid to the landfill including transportation comes to US $0.02 per pound. A 10% handling cost for the dismantler is added resulting in US $0.022 per pound.

Including benefits, some dismantlers may earn up to twenty US dollars an hour. This value was used as the cost of labour for the models. It may be more appropriate to use the marginal cost of labour, but this number is difficult to estimate because of complications in the allocation of costs such as inventory, handling, and sales force expenses. Personal communications with Ken Schram of Schram Auto Parts indicated that the industry average of the total costs involved in operating a dismantler amount to about fifty US dollars per hour per dismantler.

4.1.2.3 Single Car Analysis

An important part of the VRDC project is the modeling of both cars in the Disassembly Modeling Language, and the analysis of these models with the Disassembly Model Analyzer. The disassembly modeling process can provide a variety of information of interest for the project. This section discusses these analyses.

The economically optimal disassembly plan is a crucial element in the study of these vehicles. The plan basically shows, under the current conditions, which parts make economical sense to reuse or recycle. The plan can also be used as a best guess of the likely behaviour of the dismantling industry when dealing with the vehicles in question.

Sensitivity analysis of the economically optimal disassembly plan is even more useful. It can be used to determine the effect of changes in the variables on the economic feasibility of reuse and recycling for various parts. This type of analysis can give insight into the true potential for improvement, as well as into which areas can provide the greatest improvement compared to the amount of effort required.

4.1.2.4 Design Comparisons

A further piece of insight available from the disassembly modeling of the vehicles comes from the comparison of the two models and their profit optimizing disassembly plans. Conceivably, the optimal plans and the corresponding sensitivity analyses can be compared for the two vehicles in an attempt to indicate the differences between them which have significant results in the economics of recovery. With the significant differences identified, the designs resulting in these differences can be considered in detail with the aim of discovering design guidelines that can make a difference.

Another way to investigate the effect of design changes is to create a "virtual" redesign of a current model and perform an analysis of this new, imaginary model. In this way, the methodology is capable of exploring the possible effects of different design options.

4.1.3 Industry Interviews

There are many industrial players of significance to the automotive recycling industry. They have information which is crucial to an understanding of the function of the industry. It is appropriate, therefore, to conduct many interviews with these players.

Many sources were consulted to determine prices to be used for the analysis, or to help understand how the industry works. Some of these sources are cited in this work. Others required confidentiality.

4.1.4 The System Dynamics Model

An aspect of the VRDC project of significance is the system dynamics model of the industry. This model incorporates valuable information from every stage in the investigation to create a simulator of the entire industry. The model can be used to learn about the effect design decisions by the automakers may have on the recycling of vehicles, or to learn about the effect of events beyond the automakers' control. Since the System Dynamics Model is not the main focus of this thesis, *Disassembly Modeling and Analysis*, and since it was primarily the work of Mr. Zamudio-Ramirez, discussion of it has been centralized in Appendix F.

4.2 Analysis of "Car A"

4.2.1 Introduction

Car A is a mid-sized family car. Both specimens of car A which were dismantled were manufactured in 1993. The previous section, "The Vehicle Recycling Development Center Project", describes what was done to these vehicles in detail. This chapter describes and interprets the results of analyses of the model.

4.2.2 The Economic Information

The methods used to calculate the economic information have been described in the previous chapter. The resale value of parts, the recycling values of the materials, the landfill costs of the materials, and the labour costs were calculated for car A.

The resale value of parts was determined using the Hollander system on August 10, 1995 to research the regional market for the parts which were removed from car A. The following table summarizes the results.

Table 4.1 Part Resale Values.

Part – DML Name	Resale value (US$)
.DoorFrontRight	525.0
.DoorFrontLeft	430.0
.DoorRearRight	425.0
.DoorRearLeft	425.0
.SeatRearBottom	25.0
.SeatRearBack	25.0
.SeatbeltFrontRight	40.0
.SeatbeltFrontLeft	40.0
.SeatbeltRearRight	40.0
.SeatbeltRearLeft	40.0
.SteeringColumnAssembly	200.0
.SteeringColumnAssembly.Base	50.0
.TailLightCoverRight	65.0
.TailLightCoverLeft	65.0
.TailLightCoverCenter	50.0
.FasciaRearLower	200.0
.EnergyAbsorberRearLeft	40.0
.EnergyAbsorberRearRight	40.0
.DeckLid	163.0
.Battery	20.0
.AirCleanerAssembly	113.0
.HeatBoxAssembly	20.0
.HeatBoxAssembly.Motor	28.0
.BrakeBooster	45.0
.CoolingFanShroudAssembly	70.0
.CruiseServo	48.0
.WheelRearRight.Cover	33.0
.WheelRearRight.Rim	85.0
.WheelRearLeft.Cover	33.0
.WheelRearLeft.Rim	85.0
.WindshieldWiperMotor	40.0
.WindShieldFront	50.0
.FrontClip	2115.0
.FrontClip.RadiatorHeatExchanger	85.0
.FrontClip.ACCondensor	135.0
.FrontClip.MarkerLightFrontLeft	17.0
.FrontClip.MarkerLightFrontRight	17.0
.FrontClip.LightFrontAssembly.HeadLightLeft	60.0
.FrontClip.LightFrontAssembly.HeadLightRight	60.0

The non-metals have no shredder recycling value. In other words, they receive the value "-M".

For metals recycling values are required for dismantler recycling and for recycling via the shredder. The dismantler recycling values were discounted from the quoted scrap prices as explained in the previous chapter. The shredder recycling values were discounted further to account for the extra costs involved with shredding and the losses therein.

Table 4.3 Non-ferrous metal recycle values.

Material	Recycle value per mass (US$/kg)	Shredded recycle value per mass (US$/kg)
Aluminum	0.6513	0.5968
Copper	1.2600	1.1750
Ferrous	0.0600	0.0900
Lead	0.1339	0.1052
Magnesium	1.2174	1.1346

The values related to the shredder, however, are not the values which were ultimately used in the modeling. The do not reflect the reality of the relationship between shredders and dismantlers, and so they were replaced.

In the North American automotive recycling industry, shredders pay dismantlers a flat rate per unit mass. The shredder recycling and landfill values described above are based on the idea of a shredder which is owned by the dismantler or a shredder that pays the dismantler a fair price based on knowledge of the material content of what is sold. It is possible to model the realistic shredder using the DML in a way which will still allow the analyzer to determine which shredded materials will be recycled and which will be landfilled.

Consider, as an example, that shredders pay dismantlers six cents per kilogram. One criteria of the modeling, therefore, is that any material sent to the shredder results in a reward of six cents. On the other hand it is necessary to be able for the analyzer to

The total mass of car A as modeled was about 1345 kilograms. 19.7% of the vehicle was non-metals, and 9.3% of the vehicle was non-ferrous metal. The remainder was steel or iron.

There was a total of 430 precedence constraints in the model. Of the 551 parts, only 133 had no constraints, and 68 had one constraint. One part had as many as 25 constraints.

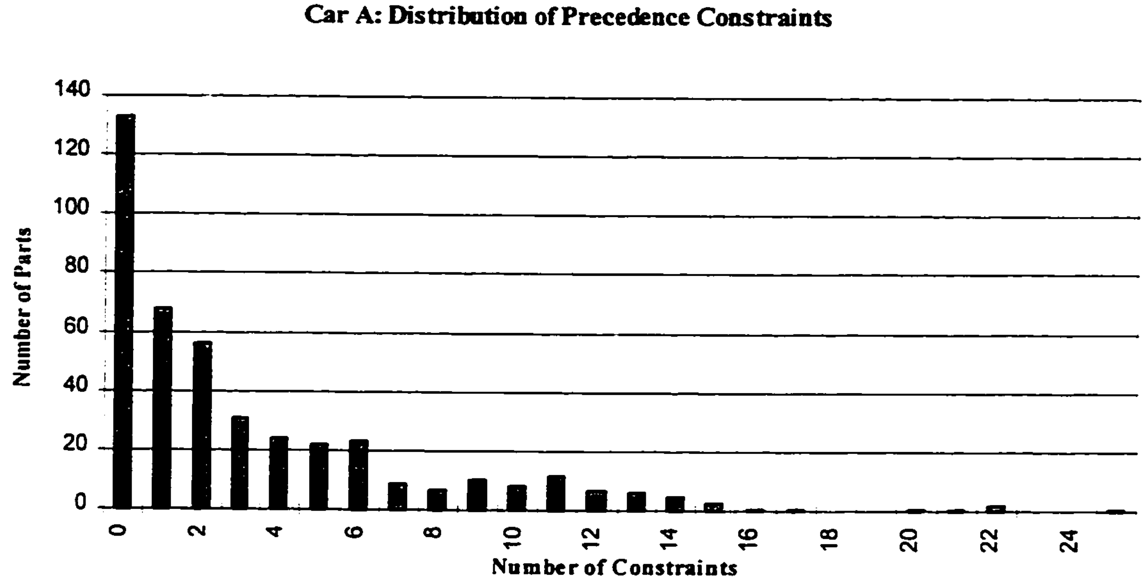

Figure 4.1 Histogram of Precedence Constraints for Car A.

4.2.5 Optimization of the Disassembly Plan

The next step in the analysis of the disassembly model for car A was to generate the profit optimizing disassembly plan. This simply involved using the Disassembly Model Analyzer's optimization function.

When the DML file was interpreted by the analyzer and the optimizer was started, a large number of parts were immediately identified for resale. A further amount of parts were removed from consideration as trivially undesirable. At this point the optimizer divided the remaining parts into as many independent groups as possible.

Based on experience during the development process of the DMA, it was known that attempting to solve groups smaller than fifteen parts by enumeration was practical. When the optimizer was done creating the groups for the car A analysis, there was only one group larger than fifteen parts. Group two had twenty one parts which included portions of the front seats, the A and C pillar trim panels, the kick panels, the carpet, and a handful of others. For this group the genetic algorithm was used.

The parameter settings which were used for optimization of group two were as follows. The generation size was 150 individuals and there were a total of 500 generations. All the children were produced by regular mutation, and none by resale mutation since none of the parts in this group had any resale value. The probability of a mutation for children being produced by regular mutation was one per ten parts.

The entire optimization process -- including the identification of resale parts, and trivially undesirable parts, as well as the division and optimization of the groups -- took one and a half hours on an SGI Indy with a 133 MHz R4600 RISC processor and 64 MB of RAM.

The following output is the analysis of the profit-optimizing disassembly plan generated by the analyzer. All masses are in kilograms. The time is in seconds.

```
************************************************
Resale:
43 parts were reused, with a total mass of 844.833862.
These parts were resold for $8206.000000.
Breakdown by mass of materials in resold parts.
SKOP: 13.632002
Textile_contaminated: 2.180000
Textile: 0.230000
ABS_contaminated: 1.020000
ABS: 6.240000
Shoddy: 0.240000
Ferrous: 598.411987
SKOS: 39.573002
Glass: 20.042000
Aluminum: 114.673996
PUR: 5.000000
```

```
Polyester: 0.600000
PP: 5.020000
TPO: 0.280000
Lead: 0.080000
Elastomer: 0.092000
Xenoy: 18.240002
SKOR: 0.520000
SKOM: 0.060000
PET: 2.450000
Copper: 4.732000
PC: 0.380000
Magnesium: 1.723000
PUR_contaminated: 1.200000
Zinc: 5.554000
PC-ABS: 0.400000

Dismantler Recycling:
The dismantler recycled material with a mass of
3.780000.
These materials were sold for $0.736564.
Breakdown by mass of materials in dismantler recycled
parts.
ABS: 0.540000
Ferrous: 1.620000
PP: 0.200000
TPO: 1.420000

Shredding:
The dismantler sent a mass of 498.553009 to the
shredder.
The shredder paid the dismantler $29.911381 for this.
Breakdown by mass of materials in shredded parts.
SKOP: 16.896000 (landfilled)
Textile_contaminated: 3.190000 (landfilled)
Textile: 0.190000 (landfilled)
ABS: 0.600000 (landfilled)
Shoddy: 10.947001 (landfilled)
Ferrous: 354.391968 (90.0% recycled) (10.0% landfilled)
SKOS: 30.701994 (landfilled)
Aluminum: 2.016000 (90.0% recycled) (10.0% landfilled)
PUR: 6.420000 (landfilled)
Polyester: 0.240000 (landfilled)
PP: 3.500000 (landfilled)
PC_contaminated: 0.040000 (landfilled)
Rubber: 4.727000 (landfilled)
```

According to this plan, it is economical for the dismantler to resell forty-three parts. On closer analysis, it can be shown that no resellable parts are left on the vehicle. Any resellable parts which have not be resold are actually components of larger parts which have been resold. Determining which parts ought to be resold is not as easy as it seems. It is not correct to simply sell "all the parts" because there is actually more than one meaning to this. Complete selling of the parts can be done in multiple ways due to the fact that some resellable parts are components of larger resellable parts. In reality, the optimizer has made the best selection of the possible combination

Another evident fact is that there is very little material recycling by the dismantler. In fact, the material recycling by the dismantler is only worth seventy four cents! This number is very small and some comments need to be made about it. First, while recycling these materials may have an incremental profit, to do so requires an initial investment for the infrastructure costs which could never be recovered at the rate of 74 cents per car. Furthermore, this 74 cents revenue has to be compared to the six cents per kilogram that could have been received if the material was sent to the shredder. It is likely that these components which have been recycled were only removed to satisfy some precedence constraints in order to get resellable parts. In a real situation, a dismantler likely would not find the 74 cents worthwhile and would throw those parts back into the car to be shredded.

Note that the dismantler sent absolutely nothing to the landfill. This is as a result of the fact that the shredder is willing to pay six cents per kilogram for any material from the vehicle. There is a strong incentive for the dismantler to shred material rather than landfilling it himself. This payment, however, also eliminates the financial disincentive of not recycling for the dismantler and allows him to save landfill costs.

The results obtained from this first optimization are interesting, but not very realistic. That is because it is virtually unheard of for a two year old car in perfect running condition to find its way into a dismantler's hands -- unless that dismantler is part of a car theft organization. A second optimization was made where the car was assumed to be much older and the resale value of all the parts was set to zero.

After the removal of the trivially undesirable parts, the groups were formed for this new DML file. The four groups which were larger than fifteen parts had 16, 16, 40, and 45 parts, respectively. The members of these groups are listed below.

```
Problem groups
*******************
Group 1
16 members:
0: Part #1: .DoorFrontRight
1: Part #2: .DoorFrontRight.Panel
2: Part #3: .DoorFrontRight.MirrorPanel
3: Part #4: .DoorFrontRight.Panel.Handle
4: Part #5: .DoorFrontRight.Panel.Light
5: Part #6: .DoorFrontRight.Panel.SpeakerCover
6: Part #8: .DoorFrontRight.Panel.TopCover
7: Part #13: .DoorFrontRight.Panel.Base
8: Part #14: .DoorFrontRight.Shoddy
9: Part #15: .DoorFrontRight.Structure
10: Part #17: .DoorFrontRight.Structure.Mirror
11: Part #21: .DoorFrontRight.Structure.Mirror.House
12: Part #22: .DoorFrontRight.Structure.Mirror.Lens
13: Part #23: .DoorFrontRight.Structure.Mirror.Electrical
14: Part #24: .DoorFrontRight.Structure.Mirror.House.Plastic1
15: Part #27: .DoorFrontRight.Structure.Mirror.House.Aluminum
*******************
Group 2
16 members:
0: Part #28: .DoorFrontLeft
1: Part #29: .DoorFrontLeft.Panel
2: Part #30: .DoorFrontLeft.MirrorPanel
3: Part #31: .DoorFrontLeft.Panel.Handle
4: Part #33: .DoorFrontLeft.Panel.Light
5: Part #34: .DoorFrontLeft.Panel.SpeakerCover
6: Part #36: .DoorFrontLeft.Panel.TopCover
7: Part #41: .DoorFrontLeft.Panel.Base
8: Part #42: .DoorFrontLeft.Shoddy
9: Part #43: .DoorFrontLeft.Structure
10: Part #44: .DoorFrontLeft.Structure.Mirror
11: Part #45: .DoorFrontLeft.Structure.Mirror.House
12: Part #46: .DoorFrontLeft.Structure.Mirror.Lens
```

```
13: Part #47: .DoorFrontLeft.Structure.Mirror.Electrical
14: Part #48: .DoorFrontLeft.Structure.Mirror.House.Plastic1
15: Part #51: .DoorFrontLeft.Structure.Mirror.House.Aluminum
********************
Group 7
40 members:
0: Part #92: .SeatFrontRight
1: Part #109: .SeatFrontRight.BottomFoam
2: Part #117: .SeatFrontLeft
3: Part #128: .SeatFrontLeft.LateralCover
4: Part #137: .SeatFrontLeft.BottomCover
5: Part #138: .SeatFrontLeft.BottomFoam
6: Part #143: .SeatRearBottom
7: Part #144: .SeatRearBottom.Cover
8: Part #145: .SeatRearBottom.Base
9: Part #146: .SeatRearBottom.Base.Foam
10: Part #150: .SeatRearBack
11: Part #151: .SeatRearBack.Base
12: Part #152: .SeatRearBack.Cover
13: Part #159: .APillarTrimLeft
14: Part #160: .APillarTrimLeft.Clips
15: Part #161: .APillarTrimLeft.ABS
16: Part #162: .APillarTrimRight
17: Part #163: .APillarTrimRight.Clips
18: Part #164: .APillarTrimRight.ABS
19: Part #174: .CPillarRight
20: Part #175: .CPillarLeft
21: Part #176: .SeatbeltFrontRightCover
22: Part #177: .BPillarUpperRight
23: Part #178: .SeatbeltFrontLeftCover
24: Part #179: .BPillarUpperLeft
25: Part #181: .BPillarLowerRight
26: Part #182: .BPillarLowerLeft
27: Part #207: .QuartertrimRight
28: Part #208: .QuartertrimRight.Shoddy
29: Part #209: .QuartertrimRight.PP
30: Part #210: .QuartertrimLeft
31: Part #211: .QuartertrimLeft.Shoddy
32: Part #212: .QuartertrimLeft.PP
33: Part #213: .KickPanelRight
34: Part #214: .KickPanelLeft
35: Part #370: .Carpet
36: Part #371: .Carpet.Shoddy
37: Part #372: .Carpet.Carpet
38: Part #373: .RearHeaterDuct
```

```
41: Part #529: .InstrumentPanel.Radio
42: Part #532: .InstrumentPanel.TrayAssembly
43: Part #541: .InstrumentPanel.Ashtray
44: Part #544: .InstrumentPanel.CenterBezel
*******************
```

The following table shows the parameters which were used for the genetic algorithm optimization of each of these groups. Resale mutation was not used because no parts had resale values.

Table 4.5 Optimization parameters for optimization without resale.

Group	Size	Number of Generations	Generation Size	Percent children by mutation	Mutation rate per part
1	16	175	150	100%	1/10
2	16	175	150	100%	1/10
7	40	350	400	100%	1/30
15	45	350	440	100%	1/30

The computation time for this model was about eight hours on the same SGI Indy.

The following output is the analysis of the profit-optimizing disassembly plan generated by the analyzer.

```
**********************************************

Resale:
No parts were resold.

Dismantler Recycling:
The dismantler recycled material with a mass of
47.740005.
These materials were sold for $27.032295.
Breakdown by mass of materials in dismantler recycled
parts.
Aluminum: 28.719999
Xenoy: 18.240002
PC: 0.380000
PC-ABS: 0.400000

Shredding:
```

* *

The following pie chart illustrates the relative magnitudes of the material flows resulting from this disassembly plan.

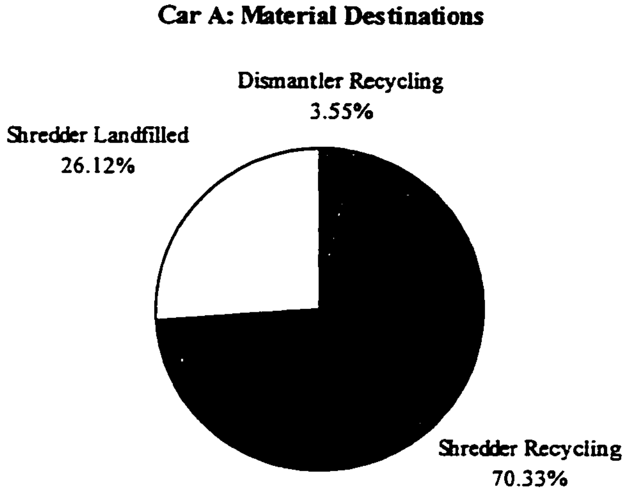

Figure 4.3 Material Destinations for Optimal Plan for Car A (without resale).

The profit in this scenario is, of course, much less than the scenario that included resale. The dismantler of this type is oriented around recycling, but the main recycling revenue is from the scrap metal recycled via the shredder. The dismantler has recovered nearly fifty kilograms of material from disassembly for recycling. Greater than half of this recycling is aluminum. Of the 260 kilograms of non-metals in the vehicle, only about seven percent was recycled. The following figure illustrates the composition of the automotive shredder residue projected by this disassembly plan.

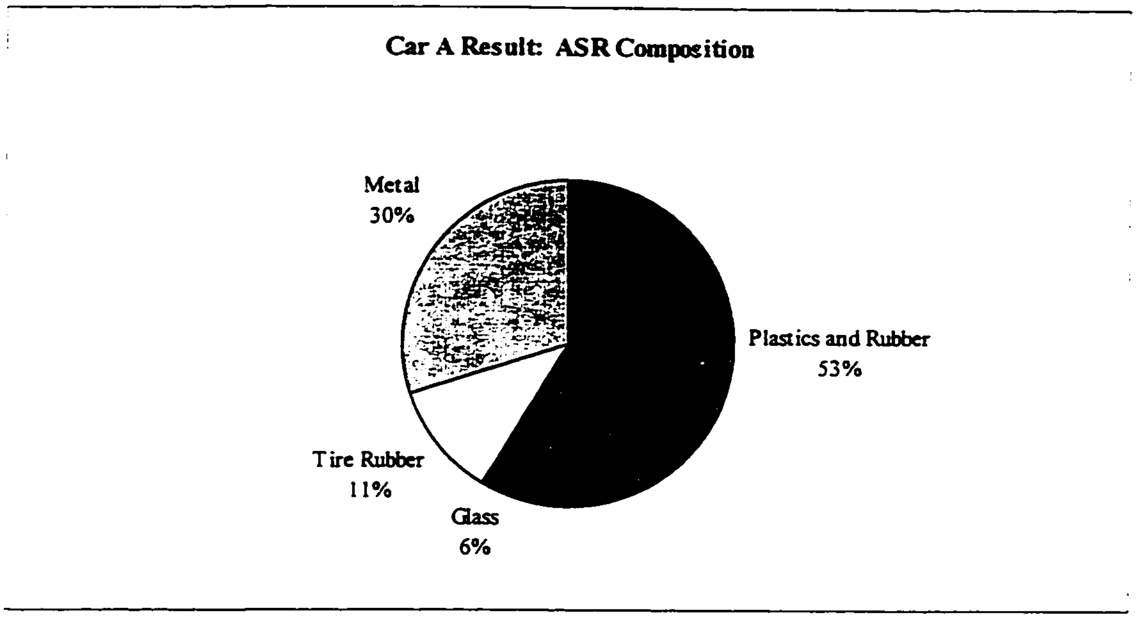

Figure 4.4 Shredder Residue Composition in Car A's Profit-Maximizing Disassembly Plan

The total weight of the vehicle as modeled is 1345 kilograms. In the optimization with no resale 74% of the vehicle was recycled. This is close to the figure (75%) often mentioned as the current industry-wide recycling rate.

The main inference which can be drawn from the optimal disassembly plans of car A is that, for this vehicle, recycling of non-metals is not currently economically feasible in today's market. This is confirmed by the fact that very little non-metals recycling is currently going on in the industry. In *Disposal Practices for Post-use Automotive Plastics* [American Plastics Council, 1994], it is estimated that less than five percent of plastic automotive parts disposed in 1992 were recycled. It is not clear from the two optimizations performed here how far this recycling is from being economically feasible. The following two sections research this question in greater detail.

4.2.6 Sensitivity Analysis

The purpose of a sensitivity analysis is to investigate how changes in a variable affect the final result. In this case, sensitivity analyses were performed on the recycling values of materials, the shredder's scrap price, resale prices and on the cost or time of disassembly. The sensitivity analyses (other than those regarding resale prices) were only performed for the case where Car A had no resellable parts, since this scenario represents the majority of cars which are retired at an older stage. These studies were done by modifying the DML files by changing the appropriate variables and then running the profit optimizer to generate the disassembly plan. Graphs were then made to visualize the influence of these factors on various measures of the plan.

Sensitivity analysis was carried out on the values for non-metal recycling. The effects were investigated between changes in the recycling value from -50% to +800%. Materials that are currently not recyclable remained that way throughout the analysis. The following chart illustrates the results. As can be seen from the graph, there is not much change in the percentage of the vehicle being landfilled. Metal, tire rubber, and glass comprise from 40% to 50% of what is disposed. The remainder is plastics and rubbers which were not economical to remove for recycling. By the time recycling values reach 800% more than the current value they are probably beyond the virgin prices for the same material, which is unrealistic. Nevertheless, the results at 800% have changed very little from the base case. The disassembly plan for Car A does not seem to be sensitive to the recycling prices for non-metals. (See Appendix A for the numbers used to create this graph.)

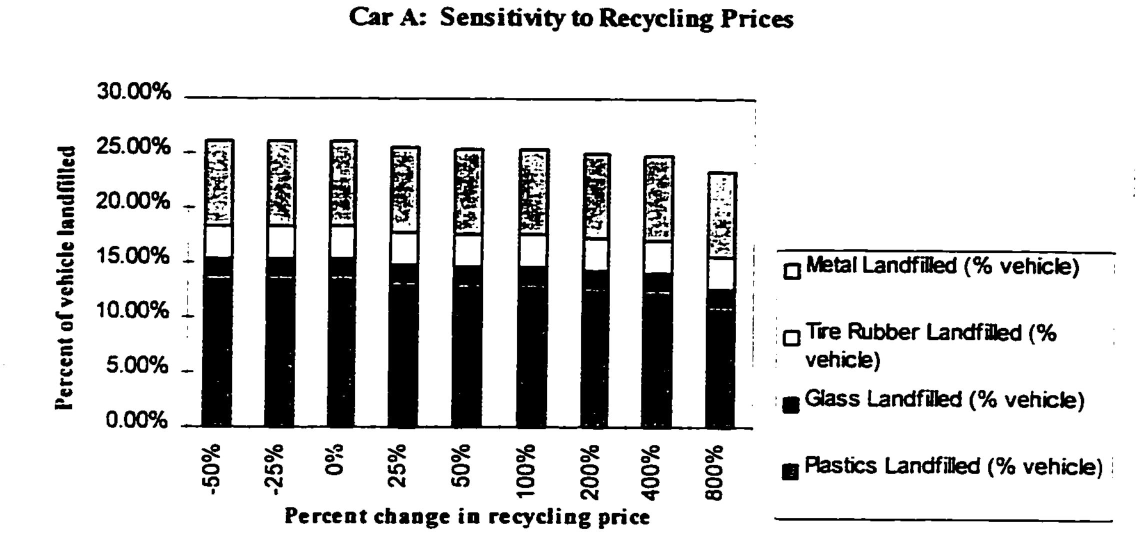

Figure 4.5 Sensitivity of Non-Metals Recycling Prices for Car A

Sensitivity analysis of the scrap price that shredders are willing to pay revealed that this variable is not very significant to the dismantlers when they are deciding how to dismantle a vehicle. There was essentially no change in the percent of the vehicle landfilled as the scrap price was changed from 25% of the current value to 200% of the current value. That is not to say that the scrap price is not important, however. The decline of scrap price could endanger the viability of the shredders or some dismantlers, or may lower the price for old cars until many owners simply abandon them rather than sell them.

The optimal disassembly plans were not sensitive to resale prices, either. Varying the resale price between 1% and 100% of the current prices for Car A's parts resulted in no significant change in the material flows resulting from the disassembly plan.

As modeled, the cost of disassembly is simply the product of the labour rate and the amount of time. Therefore, the sensitivity analysis of these two variables can be combined into one analysis of the cost of disassembly. The disassembly costs were varied from 50% more than the present to 100% less. Figure 4.6 illustrates the resulting flows of material to the landfill. It can be seen that the impact of reducing the dismantling costs by as much as 75% is negligible. Dismantling costs reduced by 100% still result in more than 20% of the vehicle ending up in the landfill. The main reason for this disappointing outcome is that there is a great deal of material in the vehicle that cannot be recycled or cannot be separated. (See Appendix A for the numbers used to create this graph.)

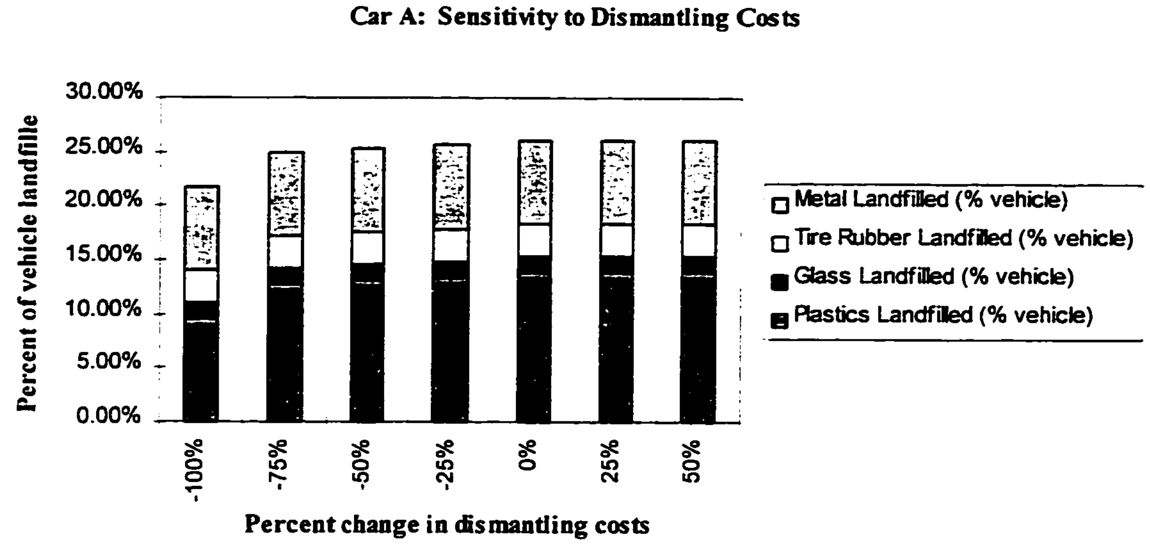

Figure 4.6 Sensitivity of Disassembly Cost for Car A

No sensitivity analysis was performed for landfill costs. That is because landfill costs have no direct effect on the dismantling plan in these runs as the entire amount of landfilling is done by the shredder, and the shredder simply pays a flat rate per unit of mass for all scrap. It is true that landfill costs would affect the shredder's bottom line, and thus the rate paid for scrap, but this would be similar to the sensitivity analysis which was performed on scrap price where no sensitivity was seen.

From studying the sensitivity analyses, it seems that simple changes in recycling value or disassembly costs will not have a significant effect on the economic recyclability of this vehicle. In other words, for cars similar to this one, the dismantling practices on a car-by-car basis in industry would likely continue as they are now, without regard to changes in the variables discussed. (This does not consider the possibility of an industry-wide collapse, however.)

4.3 Analysis of "Car B"

4.3.1 Introduction

Car B, like Car A is a mid-sized family car. Both specimens of Car B which were dismantled were manufactured in 1992. The procedures used for Car B were similar to those for Car A as described in sections 4.1 and 4.2. This chapter describes and interprets the results of analyses of the model.

4.3.2 The Economic Information

For the most part, the economic information required for Car B had already been gathered for Car A. The material prices, the labour costs, and the landfill costs were all the same for both cars. The part resale values were different, however, and are listed in the following table.

Table 4.6 Car B Part Resale Values

Part -- DML Name	Resale value (US$)
.SeatFrontRight	250.00
.SeatFrontLeft	250.00
.SeatRearBottom	100.00
.SeatRearBack	100.00
.SeatbeltRearRight	55.00
.SeatbeltFrontRight	55.00
.SeatbeltRearLeft	55.00
.SeatbeltFrontLeft	55.00
.Console1	25.00
.Console2	25.00
.SteeringColumn	162.50
.DoorFrontLeft	850.00
.DoorFrontRight	725.00
.DoorRearLeft	500.00
.DoorRearRight	500.00
.SpareTire	60.00
.TailLightLeft	45.00
.TailLightRight	45.00
.FasciaRear	300.00

.AirCleaner	100.00
.Radio	112.50
.Cluster	115.00
.HVAC	65.00
.HVAC.HeaterCore	45.00
.HVAC.ACCore	75.00
.Windshield	125.00
.WindshieldWiperMotor	45.00
.DeckLid	300.00
.WheelRearRight.Rim	34.98
.HubCapRearRight	15.00
.WheelRearLeft.Rim	34.98
.HubCapRearLeft	15.00
.FrontClip	3150.00
.FrontClip.Hood	174.50
.FrontClip.FasciaFront	83.33
.FrontClip.ParkingLightRight	25.00
.FrontClip.ParkingLightLeft	25.00
.FrontClip.HeadLightRight	99.98
.FrontClip.HeadLightLeft	99.98
.FrontClip.RadiatorFanAssembly	210.00
.FrontClip.Condenser	151.33
.WiperTransmission	45.00
.DriveTrain	2834.91
.DriveTrain.Alternator	70.00
.DriveTrain.ACCompressor	162.50
.DriveTrain.Starter	75.00
.DriveTrain.SteeringPump	82.50
.DriveTrain.Engine	900.00
.DriveTrain.Transmission	850.00
.DriveTrain.Cradle	70.00
.DriveTrain.WheelLeft.Rim	34.98
.DriveTrain.HubCapLeft	15.00
.DriveTrain.WheelLeft.Rim	34.98
.DriveTrain.HubCapLeft	15.00

4.3.3 The DML File

The DML file for Car B was created using a process similar to that for Car A. The file was 2485 lines long and was 98 kilobytes. 591 parts were represented..

4.3.4 The Basic Structure Analysis of Car B

As modeled, the mass of Car B was about 1266 kg. 18.1% of the car was non-metals, and 7.7% was non-ferrous metal. Compared to Car A, Car B had a greater proportion of ferrous metal, 74.2% as compared to 71.0%.

The following figure illustrates the distribution of precedence constraints for Car B. There were totally 500 precedence constraints. Ninety-three parts could be removed without any constraints. Fifty-nine parts had only one constraint. At the other end of the spectrum, there was one part with twenty constraints, and four parts with nineteen constraints.

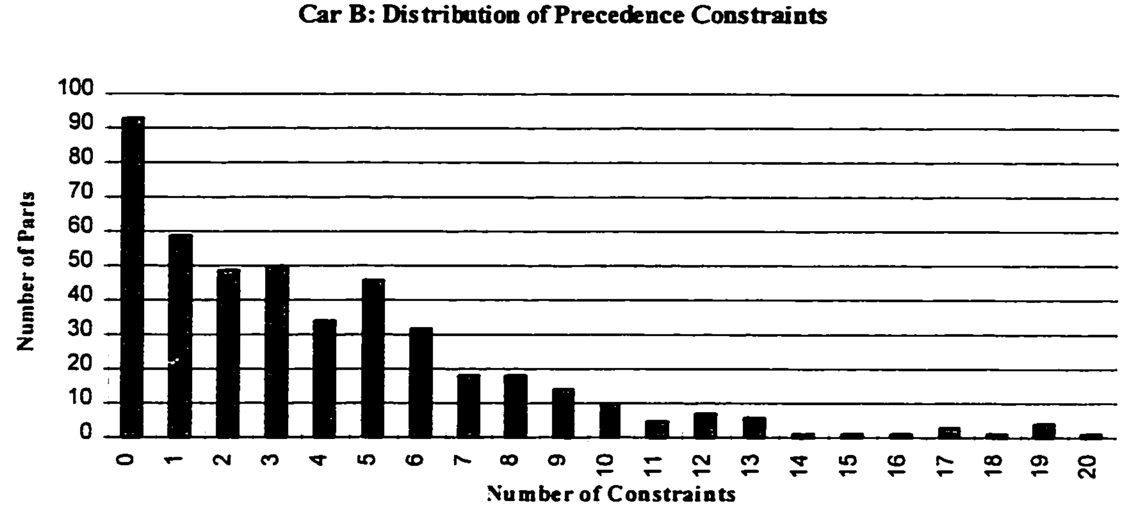

Figure 4.7 Histogram of Precedence Constraints for Car B.

4.3.5 Optimization of the Disassembly Plan

Just as the profit-optimizing disassembly plan was generated for Car A with and without resale parts, the same was done for Car B.

For the case with parts for resale, when the *Disassembly Model Analyzer* broke the problem into groups there were no groups with more than 15 members. Therefore, it was possible to generate the optimal solution without using genetic algorithms. The time required for this was about forty minutes, but this time is not comparable with the other times mentioned because this particular optimization was performed using a slower machine, a Sun Sparc 2.

Following is the summary output for the disassembly plan generated.

```
*********************************************
Resale:
35 parts were reused with a total mass of 852.845154.
These parts were resold for $11269.871094.
Breakdown by mass of materials in resold parts.
Textile_contaminated: 2.740000
PUR: 23.538000
Ferrous: 617.030090
SKOP: 7.605999
PVC: 0.400000
PP: 4.501000
SKOS: 51.236992
Leather_contaminated: 0.020000
ABS: 2.163000
Polyester: 0.621000
TPO: 0.237000
Elastomer: 0.110000
PE: 1.200000
PC-ABS: 2.328000
Copper: 5.612999
SKOR: 25.000999
Magnesium: 2.188000
POM: 0.120000
Glass: 17.927000
Carpet: 0.170000
PE_contaminated: 0.473000
Brass: 0.960000
Aluminum: 83.183998
Zinc: 2.704000

Dismantler Recycling:
The dismantler recycled material with a mass of
16.760000.
These materials were sold for $2.108832.
Breakdown by mass of materials in dismantler recycled
parts.
PUR: 2.320000
```

```
Ferrous: 5.280000
PP: 2.400000
Elastomer: 5.900000
PE: 0.860000

Shredding:
The dismantler sent a mass of 396.767944 to the
shredder.
The shredder paid the dismantler $23.803261 for this.
Breakdown by mass of materials in shredded parts.
Ferrous: 316.987061 (90.0% recycled) (10.0% landfilled)
SKOP: 3.911000 (landfilled)
PP: 3.603000 (landfilled)
SKOS: 38.052002 (landfilled)
ABS: 0.035000 (landfilled)
Nylon_contaminated: 0.069000 (landfilled)
Shoddy: 2.080000 (landfilled)
Polyester: 0.145000 (landfilled)
PPO: 0.759000 (landfilled)
TPO: 0.067000 (landfilled)
Elastomer: 0.061000 (landfilled)
PE: 1.468000 (landfilled)
PC-ABS: 0.085000 (landfilled)
Copper: 1.256000 (90.0% recycled) (10.0% landfilled)
SKOR: 16.944000 (landfilled)
Magnesium: 0.815000 (90.0% recycled) (10.0% landfilled)
Cardboard: 2.320000 (landfilled)
Nylon: 0.012000 (landfilled)
HDPE: 0.904000 (landfilled)
ABS_contaminated: 0.480000(landfilled)
Tin: 0.400000 (90.0% recycled) (10.0% landfilled)
PP_contaminated: 2.732000 (landfilled)
PE_contaminated: 0.163000 (landfilled)
Aluminum: 3.292000 (90.0% recycled) (10.0% landfilled)
SKOM: 0.024000 (landfilled)
SKOR_contaminated: 0.057000 (landfilled)

Total shredder recycling: 290.475037
Total shredder landfilling: 106.246033

Dismantler Landfilling:
No material was landfilled by the dismantler.

The total dismantling standard times were 6899.000000.
```

```
The time factor was 2.000000 and the total real time
was 13798.000000.
The total dismantling cost was $76.656151.
**********************************************
```

The following graph illustrates how much of Car B ends up being reused, recycled, and landfilled, based on the profit-maximizing disassembly plan.

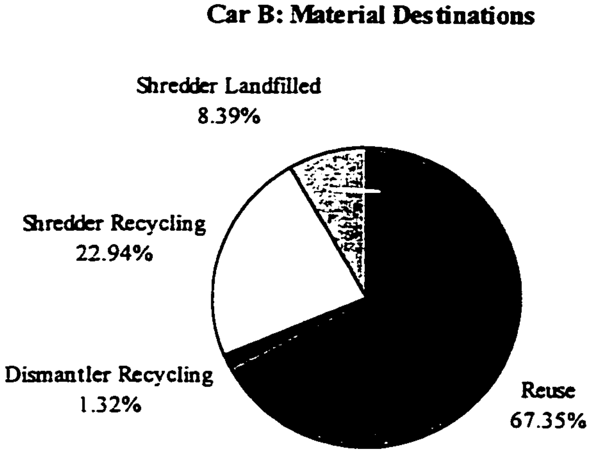

Figure 4.8: Material Destinations for Optimal Plan for Car B.

When comparing the optimal plan for Car B to that of Car A, it is found that they are quite similar in a fundamental way. Both plans call for reuse for any parts that have sufficient value, and for very little recycling on the part of the dismantler. The rate of reuse is higher in the case of Car B, and this results in a lower amount being sent to the landfill. There are two possible explanations for this. One is that since this car weighs less than Car A and has a higher ferrous metal component, perhaps a greater portion of the vehicle's weight is accounted for by parts that are resellable. The second possible explanation is that particular parts were found to have resale values for Car B, but values could not be found for the same parts on Car A. In any case, the important learning for this optimization is that parts were selected for disassembly and resale from Car B such that no resellable parts remained on the car, and that there was very little material recycling by the dismantler.

Since most cars that enter the recycling industry are older and have few to none economically reusable parts, it is more important to consider the profit-maximizing disassembly plan for Car B when all the resale prices have been removed.

When the *Disassembly Model Analyzer* was asked to optimize the disassembly plan for Car B without resale parts, it began by trying to break the problem into independent groups. There was only one group that had more than fifteen parts, but this group had 161 parts. The members of this group are listed below.

```
Problem groups
*******************
Group 1
161 members:
0: Part #1: .SeatFrontRight
1: Part #2: .SeatFrontRight.HeadRest
2: Part #3: .SeatFrontRight.HeadRest.Fabric
3: Part #4: .SeatFrontRight.HeadRest.Foam
4: Part #8: .SeatFrontRight.LeverHandle
5: Part #9: .SeatFrontRight.RightLateralCoverUpper
6: Part #10: .SeatFrontRight.RightLateralCoverLower
7: Part #11: .SeatFrontRight.LeftLateralCover
8: Part #12: .SeatFrontRight.BottomFoam
9: Part #13: .SeatFrontRight.BottomFoam.PUR
10: Part #14: .SeatFrontRight.BottomFoam.Wire
11: Part #15: .SeatFrontRight.BackFabric
12: Part #16: .SeatFrontRight.BottomFabric
13: Part #17: .SeatFrontRight.Frame
14: Part #18: .SeatFrontRight.LateralFoam
15: Part #19: .SeatFrontRight.Frame.BackFoam
16: Part #23: .SeatFrontLeft
17: Part #24: .SeatFrontLeft.HeadRest
18: Part #30: .SeatFrontLeft.LeverHandle
19: Part #31: .SeatFrontLeft.LeftLateralCoverUpper
20: Part #32: .SeatFrontLeft.LeftLateralCoverLower
21: Part #33: .SeatFrontLeft.RightLateralCover
22: Part #34: .SeatFrontLeft.BottomFoam
23: Part #35: .SeatFrontLeft.BottomFoam.PUR
24: Part #36: .SeatFrontLeft.BottomFoam.Wire
25: Part #37: .SeatFrontLeft.BackFabric
26: Part #38: .SeatFrontLeft.BottomFabric
27: Part #39: .SeatFrontLeft.LateralFoam
28: Part #40: .SeatFrontLeft.Frame
```

```
29: Part #41: .SeatFrontLeft.Frame.BackFoam
30: Part #45: .SeatRearBottom
31: Part #46: .SeatRearBottom.Fabric
32: Part #47: .SeatRearBottom.Foam
33: Part #48: .SeatRearBottom.Foam.PUR
34: Part #49: .SeatRearBottom.Foam.Wiring
35: Part #53: .SeatRearBack
36: Part #54: .SeatRearBack.ArmRestLeft
37: Part #55: .SeatRearBack.ArmRestLeft.Fabric
38: Part #56: .SeatRearBack.ArmRestLeft.Foam
39: Part #57: .SeatRearBack.ArmRestLeft.Base
40: Part #58: .SeatRearBack.ArmRestLeft.Base.Plastic
41: Part #59: .SeatRearBack.ArmRestLeft.Base.Foam
42: Part #60: .SeatRearBack.ArmRestRight
43: Part #61: .SeatRearBack.ArmRestRight.Fabric
44: Part #62: .SeatRearBack.ArmRestRight.Foam
45: Part #63: .SeatRearBack.ArmRestRight.Base
46: Part #64: .SeatRearBack.ArmRestRight.Base.Plastic
47: Part #65: .SeatRearBack.ArmRestRight.Base.Foam
48: Part #66: .SeatRearBack.LeftSide
49: Part #67: .SeatRearBack.LeftSide.Backing
50: Part #68: .SeatRearBack.LeftSide.Fabric
51: Part #69: .SeatRearBack.LeftSide.CentralArmRestBraket
52: Part #72: .SeatRearBack.LeftSide.CentralArmRest
53: Part #74: .SeatRearBack.LeftSide.CentralArmRest.Foam
54: Part #75: .SeatRearBack.LeftSide.CentralArmRestFabric
55: Part #76: .SeatRearBack.LeftSide.Foam
56: Part #77: .SeatRearBack.LeftSide.Foam.PUR
57: Part #78: .SeatRearBack.LeftSide.Foam.Wire
58: Part #80: .SeatRearBack.RightSide
59: Part #81: .SeatRearBack.RightSide.PP
60: Part #82: .SeatRearBack.RightSide.ABS
61: Part #83: .SeatRearBack.RightSide.Backing
62: Part #84: .SeatRearBack.RightSide.Fabric
63: Part #85: .SeatRearBack.RightSide.Foam
64: Part #86: .SeatRearBack.RightSide.Foam.PUR
65: Part #87: .SeatRearBack.RightSide.Foam.Ferrous
66: Part #89: .APillarLeft
67: Part #90: .APillarRight
68: Part #93: .KickPanelLeft
69: Part #94: .KickPanelRight
70: Part #95: .ScuffPlateRight
71: Part #96: .ScuffPlateLeft
72: Part #97: .BPillarLowerLeft
73: Part #98: .BPillarLowerRight
```

```
74: Part #99: .CPillarRight
75: Part #100: .CPillarLeft
76: Part #104: .ThirdBrakeHousing
77: Part #105: .ThirdBrakeHousing.Foam
78: Part #106: .ThirdBrakeHousing.PP
79: Part #107: .ThirdBrakeLight
80: Part #108: .ThirdBrakeLight.Rim
81: Part #113: .ParcelTray
82: Part #115: .ParcelTray.SpeakerCovers
83: Part #116: .ParcelTray.SpeakerCovers.Grills
84: Part #117: .ParcelTray.SpeakerCovers.Bases
85: Part #164: .LowerIPLeft
86: Part #165: .LowerIPLeft.Vent
87: Part #168: .Closeout
88: Part #169: .LowerIPRight
89: Part #170: .Console1
90: Part #171: .Console1.Cover
91: Part #172: .Console1.Cover.Lever
92: Part #173: .Console1.Cover.Plastic
93: Part #174: .Console1.Square
94: Part #175: .Console1.AshTray
95: Part #176: .Console1.Elastomer
96: Part #177: .Console1.Box
97: Part #178: .Console1.Ferrous
98: Part #179: .Console1.Base
99: Part #180: .Console2
100: Part #181: .Console2.Cupholder
101: Part #182: .Console2.Cupholder.Base
102: Part #183: .Console2.Cupholder.Case
103: Part #184: .Console2.Cupholder.Tray
104: Part #194: .HeaterDuct
105: Part #195: .HeaterDuct.Foam
106: Part #196: .HeaterDuct.PE
107: Part #197: .SteeringColumn
108: Part #198: .SteeringColumn.AirBag
109: Part #201: .SteeringColumn.Assembly
110: Part #202: .SteeringColumn.Assembly_CoverPanels
111: Part #291: .Carpet
112: Part #331: .ClusterBezel
113: Part #336: .Radio
114: Part #339: .Cluster
115: Part #340: .GloveBoxDoor
116: Part #348: .GloveBoxLiner
117: Part #349: .IPShell
118: Part #350: .IPShell.Duct1
```

```
119: Part #351: .IPShell.Duct2
120: Part #352: .IPShell.Duct3
121: Part #353: .IPShell.Duct4
122: Part #356: .IPShell.Duct5
123: Part #357: .IPShell.Duct5.Face
124: Part #358: .IPShell.Duct5.Body
125: Part #359: .IPShell.Duct5.SKOS
126: Part #360: .IPShell.Duct6
127: Part #361: .IPShell.Duct6.SKOS
128: Part #362: .IPShell.Duct6.Main
129: Part #370: .DashReinforcement
130: Part #371: .HVAC
131: Part #372: .HVAC.Motor
132: Part #376: .HVAC.Panel1
133: Part #377: .HVAC.Panel1.PP
134: Part #378: .HVAC.Panel1.SKOS
135: Part #379: .HVAC.HeaterCore
136: Part #380: .HVAC.MotorCover
137: Part #381: .HVAC.HeaterCore.PipeSupport
138: Part #387: .HVAC.Panel2
139: Part #388: .HVAC.MotorCover.Top
140: Part #391: .HVAC.Panel2.PP
141: Part #392: .HVAC.Panel2.SKOS
142: Part #404: .HeatDucts
143: Part #415: .SteeringColumnKnuckle
144: Part #418: .ECU
145: Part #419: .ECU.Brackets
146: Part #420: .ECU.Panels
147: Part #421: .ECU.Box
148: Part #422: .ECU.Box.Case
149: Part #423: .ECU.Box.PCBs
150: Part #468: .AirBagSensor
151: Part #469: .AirBagSensor.TopCover
152: Part #470: .AirBagSensor.BottomCover
153: Part #471: .AirBagSensor.PCBAssembly
154: Part #472: .AirBagSensor.Case
155: Part #473: .WireHarnessInsulatorRight
156: Part #474: .WireHarnessInsulatorLeft
157: Part #476: .SteeringColumnCowlSeal
158: Part #477: .SteeringColumnCowlSeal.Ferrous
159: Part #478: .SteeringColumnCowlSeal.Inner
160: Part #479: .SteeringColumnCowlSeal.Outer
*******************
```

The group with 161 parts was optimized using genetic algorithms. A generation size of 200 individuals was used for 1600 generations. The standard mutation rate was 1/45. The computation time for this model was about 16 hours, using the SGI Indy that was used for Car A.

Following is the analysis output of the profit-optimizing disassembly plan generated by the analyzer.

```
************************************************
Resale:
No parts were resold.

Dismantler Recycling:
The dismantler recycled material with a mass of
1.840000.
These materials were sold for $1.036288.
Breakdown by mass of materials in dismantler recycled
parts.
PC-ABS: 1.840000

Shredding:
The dismantler sent a mass of 1263.711914 to the
shredder.
The shredder paid the dismantler $75.822708 for this.
Breakdown by mass of materials in shredded parts.
Textile_contaminated: 2.740000 (landfilled)
PUR: 25.858000 (landfilled)
Ferrous: 939.297119 (90.0% recycled) (10.0% landfilled)
SKOP: 11.517000 (landfilled)
PVC: 0.400000 (landfilled)
PP: 10.503999 (landfilled)
SKOS: 89.289009 (landfilled)
Leather_contaminated: 0.020000 (landfilled)
ABS: 2.198000 (landfilled)
Nylon_contaminated: 0.069000 (landfilled)
Shoddy: 2.080000 (landfilled)
Polyester: 0.766000 (landfilled)
PPO: 0.759000 (landfilled)
TPO: 0.304000 (landfilled)
Elastomer: 6.071000 (landfilled)
PE: 3.528000 (landfilled)
PC-ABS: 0.573000 (landfilled)
```

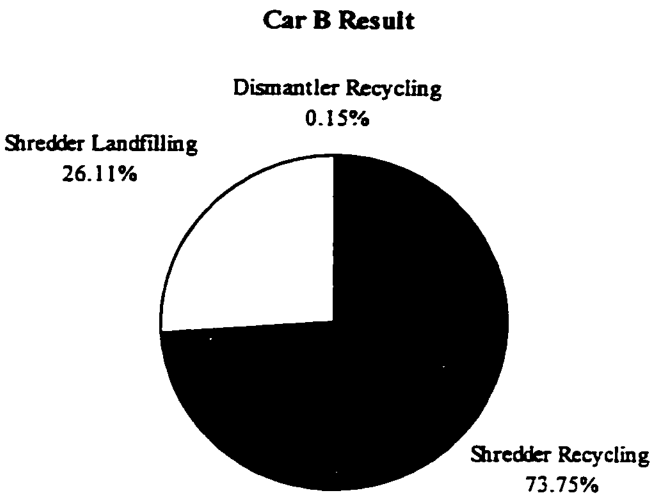

Figure 4.9 Material Destinations for Optimal Plan for Car B (without resale).

The amount of the vehicle which winds up in the landfill is about 26%. The number is very close to that of Car A. The amount of dismantler recycling was considerably lower for Car B, but was offset by a greater amount of shredder recycling. Car B, which weighed about 1266 kilograms as modeled, had a slightly higher proportion of material that was metal. On the other hand, Car A had more material in parts that were economically recyclable.

When the composition of Car B's automotive shredder residue is examined in the next figure, it is found to be very similar to that of Car A. The metal and tire components of the ASR each account for one more percentage point at the expense of the plastics & rubber and glass components.

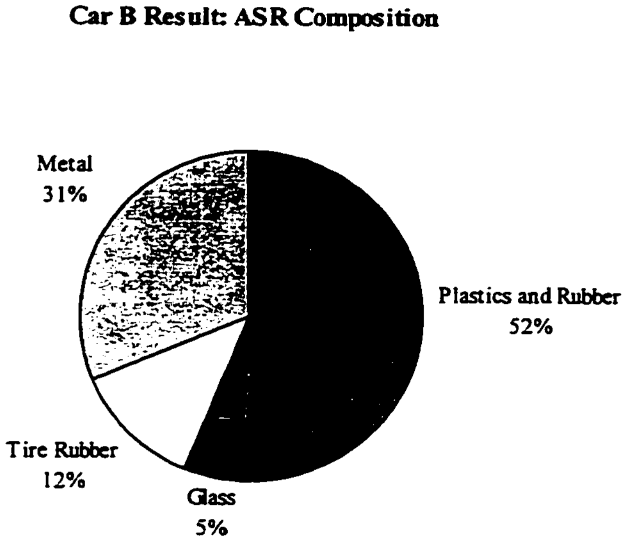

Figure 4.10 Shredder Residue Composition in Car B's Profit-Maximizing Disassembly Plan

Overall, the results for Car B are similar to those for Car A. The amount of the vehicle that is expected to be recycled is about 74%. For this car, recycling of non-metals by the dismantler does not seem to be economical given the economic data that was used to represent today's market. There is the possibility that changes in recycling prices of disassembly costs could make recycling more attractive, and this is investigated in the next section.

4.3.6 Sensitivity Analysis

The sensitivity analysis for Car B concentrated on two areas: the recycling values for non-metals, and the disassembly costs. For both cases, a series of DML files was created based on Car B with changes in the appropriate variables. Each DML file was then loaded into the *Disassembly Model Analyzer* and the profit-maximizing disassembly plan was generated. The sensitivity analyses were performed for the no-resale scenario, only.

To examine the sensitivity of the profit-maximizing disassembly plan for Car B with respect to the recycling values of the non-metals, optimizations were performed with the recycling prices varied from 50% less than present to 800% more. The following graph illustrates how much material winds up in the landfill for each of the plans generated, as well as the composition of the automotive shredder residue.

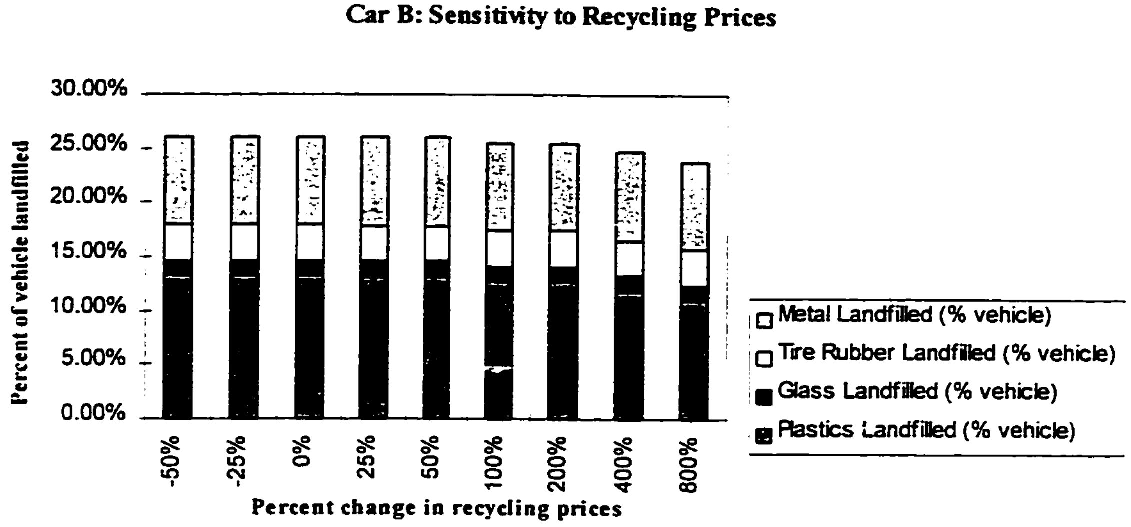

Figure 4.11 Car B: Sensitivity to Changes in Recycling Prices

This first sensitivity analysis continues to illustrate the similarity of the results for Cars A and B. The amount of material to be sent to the landfill from Car B does not seem to be sensitive to changes in recycling prices.

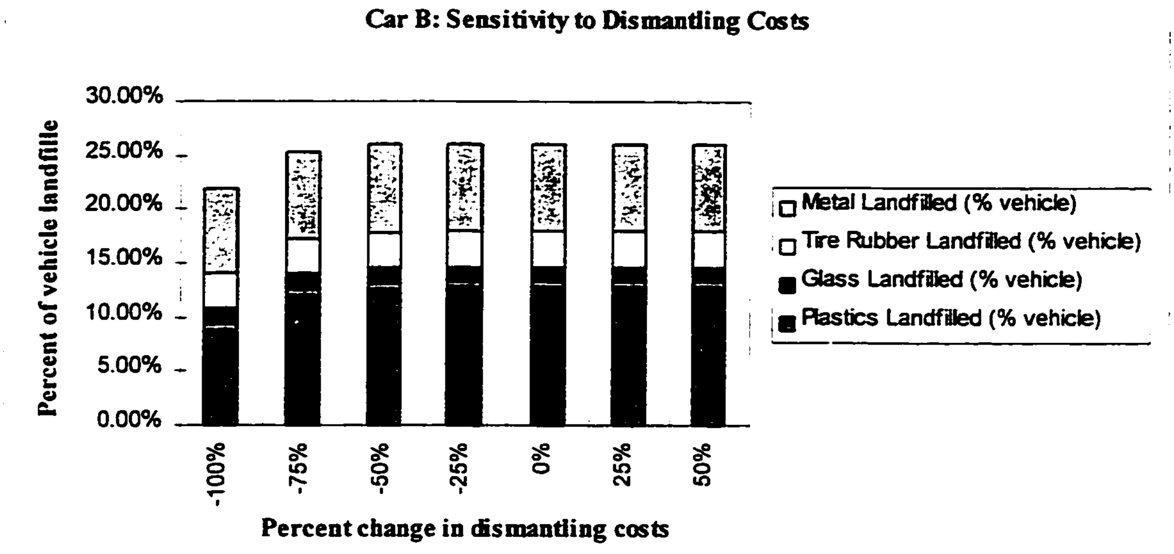

Figure 4.12 Car B: Sensitivity to Changes in Dismantling Costs

Again, Car B does not seem to be sensitive to changes in dismantling costs, either. When dismantling costs are reduced by as much as 75% there was virtually no change in the amount of recycling. Even when the costs were reduced to zero, the recycling rate was still in the range of 75 to 80%.

It would seem to be clear that the disassembly modeling and analysis methods used to study Car B indicate that disassembly and recycling of non-metal materials from this car is not economical. The projected recycling rate for Car B is 74% and a significant change in this value does not seem likely, despite possible changes in non-metal material recycling prices or in disassembly costs.

Based on what has been learned from Car A and Car B so far, it would seem that cars such as these will continue to been dismantled in the same manner as they are now, despite changes in recycling prices or in disassembly costs. In other words, cars designed such as these cannot hope to have improved rates of disassembly for recycling. The question that remains, however, is the ability of design changes to increase the rate of recycling. The following sections of this chapter explain how disassembly modeling and analysis was applied to this question.

4.4 Virtual Design for Recycling Concept Cars

4.4.1 Introduction

The ideal way to study the effect of design on the profit-optimizing disassembly plan, if cost and time were no object, would be to design entire cars and model them using the *Disassembly Modeling Language*. This, however, would be too difficult and time-consuming.

An alternate method was followed for this research. It is possible to begin with a DML model of a product and to then alter it to simulate design changes. In this case, the DML file for Car B was altered twice to create virtual Design for Recycling (DfR) concept cars. A concept car is a model developed to demonstrate a particular technology or theme without regard to overall practicality. These DfR concept cars are referred to as "virtual" because they are not real -- they only exist in the computer where they have been modeled.

To investigate the possible influence of Design for Recycling on the economics of disassembly for recycling, two virtual DfR concept cars were created by modifying Car B's DML file. The files were then analyzed using the *Disassembly Model Analyzer*. The following sections explain how the DML files were altered, and what results were encountered.

4.4.2 The Virtual DfR Concept Cars

Since the purpose of this part of the research was to investigate the potential extent to which Design for Recycling could influence the practices of the dismantlers, the concept cars were created as aggressively as possible. In other words, the design changes that were made were made to be as helpful as possible to potential dismantling recyclers.

Two redesigns were conducted. The first revision began with Car B and consisted of design changes that will be discussed below. This virtual concept car will be referred to as "Car DfR1". The second revision began with Car DfR1 and continued to make more changes. This car, "Car DfR2", therefore, went further towards the Design for Recycling ideal.

The changes that were made will first be summarized, and then they will be listed for both of the cars. Some of the changes involved consolidation of a complex part with multiple materials into a single part of only one material. In other cases, parts were changed to be the same material as other parts in the same assembly. Contaminated materials were made to be uncontaminated. For some parts the times for disassembly were decreased or precedence constraints were relaxed. The following two tables list the design changes that were made for Car DfR1 and Car DfR2.

Door panels changed to (uniform) PP
Carpet, Trunk Carpet, and Floor Mats changed to (uniform) PP
Parcel Tray changed to (uniform) PP
Various IP Ducts changed to (uniform) PP
GloveBoxLiner made (uniform) PC/ABS
Made headliner (uniform) PET. Merged headliner shoddy with headliner and made PET
All contaminated materials were changed to uncontaminated
Changed seat fabrics to PET
Battery Case (Tray) made PP
Front seats changed so that foam is not molded onto wire frames
Rear seats changed so that foam is not molded in -- comes out easy.

Table 4.7 Design Changes Made to Car B to make Car DfR1.

IP Skeleton changed to one material: PUR
Times to remove .IPShell and to disassemble it are reduced
A variety of small pieces are changed from SKOP or SKOS to uni-material plastics.
Front seat fabrics made easier to remove, and some constraints relaxed.
Rear sear bottom fabric made easier to remove
Rear pass-through made TPO
Fascias made easier to remove
Door panels made easier to remove
Radiator End Caps made PP
Radiator made faster to disassemble

Table 4.8 Design Changes Made to Car DfR1 to make Car DfR2.

4.4.3 The Analysis of the Virtual DfR Concept Cars

Both of the virtual concept cars were created by making changes to Car B's Excel spreadsheet, and from there the DML files were generated for use in the analyzer. Following is the summary report generated for the profit-optimizing disassembly plan for Car DfR1.

```
***********************************************
Resale:
No parts were resold.

Dismantler Recycling:
The dismantler recycled material with a mass of
5.540000.
These materials were sold for $1.451428.
Breakdown by mass of materials in dismantler recycled
parts.
PP: 3.700000
PC-ABS: 1.840000

Shredding:
The dismantler sent a mass of 1259.759888 to the
shredder.
The shredder paid the dismantler $75.585594 for this.
Breakdown by mass of materials in shredded parts.
PET: 7.780000 (landfilled)
PUR: 25.858000 (landfilled)
Ferrous: 938.230103 (90.0% recycled) (10.0% landfilled)
SKOP: 10.134001(landfilled)
PVC: 0.080000 (landfilled)
PP: 30.713997 (landfilled)
SKOS: 68.134995 (landfilled)
Leather: 0.020000 (landfilled)
ABS: 2.678000 (landfilled)
Nylon: 0.081000 (landfilled)
Polyester: 0.766000 (landfilled)
PPO: 0.759000 (landfilled)
TPO: 0.237000 (landfilled)
Elastomer 6.071000 (landfilled)
PE: 3.697000 (landfilled)
PC-ABS: 0.988000 (landfilled)
Copper: 6.868999 (90.0% recycled) (10.0% landfilled)
SKOR: 0.745000 (landfilled)
```

```
Magnesium: 3.003000 (90.0% recycled) (10.0% landfilled)
Glass: 17.927000 (landfilled)
Cardboard: 2.320000 (landfilled)
Tire_rubber: 41.199997 (landfilled)
HDPE: 0.904000 (landfilled)
Tin: 0.400000 (90.0% recycled) (10.0% landfilled)
Brass: 0.960000 (90.0% recycled) (10.0% landfilled)
Aluminum: 86.476006 (90.0% recycled) (10.0% landfilled)
SKOM: 0.024000 (landfilled)
Zinc: 2.704000 (landfilled)

Total shredder recycling: 932.344238
Total shredder landfilling: 327.415863

Dismantler Landfilling:
No material was landfilled by the dismantler.

The total dismantling standard times were 12.000000.
The time factor was 2.000000 and the total real time
was 24.000000
The total dismantling cost was $0.133334.
*********************************************
```

Following is the summary report generated for the profit optimizing disassembly plan for Car DfR2.

```
**********************************************
Resale:
No parts were resold.

Dismantler Recycling:
The dismantler recycled material with a mass of
14.036000.
These materials were sold for $4.791608.
Breakdown by mass of materials in dismantler recycled
parts.
PET: 0.900000
PUR: 2.796000
PP: 4.171000
TPO: 0.840000
PC-ABS: 1.840000
Aluminum: 3.489000
```

```
Shredding:
The dismantler sent a mass of 1251.263916 to the
shredder.
The shredder paid the dismantler $75.075829 for this.
Breakdown by mass of materials in shredded parts.
PET: 6.880000 (landfilled)
PUR: 29.295002 (landfilled)
Ferrous: 938.230103 (90.0% recycled)  (10.0%
landfilled)
SKOP: 8.447000 (landfilled)
PVC: 0.080000 (landfilled)
PP: 34.625996 (landfilled)
SKOS: 57.160992 (landfilled)
Leather: 0.020000 (landfilled)
ABS: 3.265000 (landfilled)
TPO: 0.237000 (landfilled)
PA: 0.081000 (landfilled)
Polyester: 0.766000 (landfilled)
PPO: 1.117000 (landfilled)
Elastomer: 6.071000 (landfilled)
PE: 3.697000 (landfilled)
PC-ABS: 0.988000 (landfilled)
Copper: 6.868999 (90.0% recycled) (10.0% landfilled)
SKOR: 0.745000 (landfilled)
Magnesium: 3.003000 (90.0% recycled) (10.0% landfilled)
Glass: 17.927000 (landfilled)
Cardboard: 2.320000 (landfilled)
Tire_rubber: 41.199997 (landfilled)
HDPE: 1.164000 (landfilled)
Tin: 0.400000 (90.0% recycled) (10.0% landfilled)
Brass: 0.960000 (90.0% recycled) (10.0% landfilled)
Aluminum: 82.987007 (90.0% recycled) (10.0% landfilled)
SKOM: 0.024000 (landfilled)
Zinc: 2.704000 (landfilled)

Total shredder recycling: 929.204163
Total shredder landfilling: 322.059998

Dismantler Landfilling:
No material was landfilled by the dismantler.

The total dismantling standard times were 236.000000.
```

```
The time factor was 2.000000 and the total real time
was 472.000000.
The total dismantling cost was $2.622243.
*********************************************
```

Two figures are presented to illustrate how much of the DfR cars gets recycled and how much gets landfilled according to the profit-maximizing plans. The following figure is for Car DfR1.

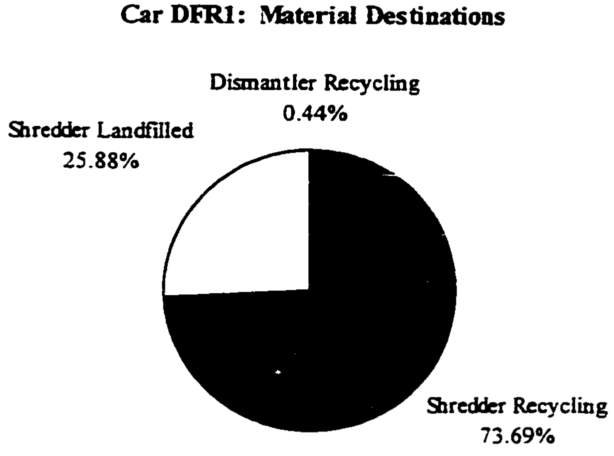

Figure 4.13 Material Destinations for Optimal Plan for Car DfR1.

The figure below illustrates the material destinations for Car DfR2's optimal disassembly plan.

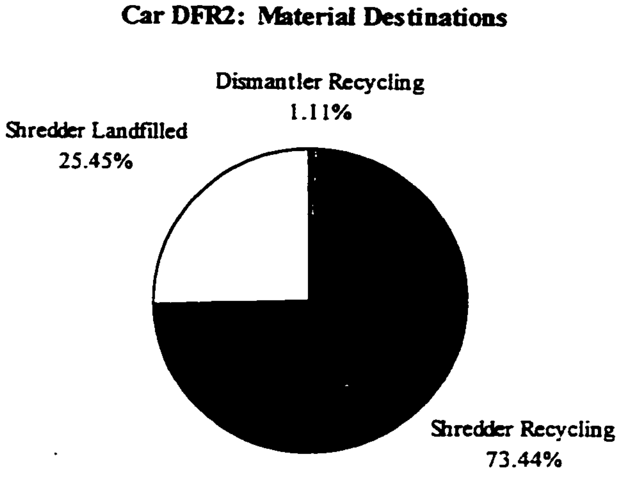

Figure 4.14 Material Destinations for Optimal Plan for Car DfR2.

It can be seen from these graphs that the amount of dismantler recycling under the profit-maximizing disassembly plans for the DfR concept cars is not much better than that for Car B. This would seem to indicate that the Design for Recycling efforts were a failure, since their main purpose was to increase the ability of the dismantlers to recycle materials. It is too early to draw this conclusion, however, for reasons to be discussed at the end of this section.

As another form of comparison between the Virtual DfR Concept Cars and Car B, the following figure compares the amount and composition of the material to be sent to landfill based on the optimal disassembly plans for the three cars.

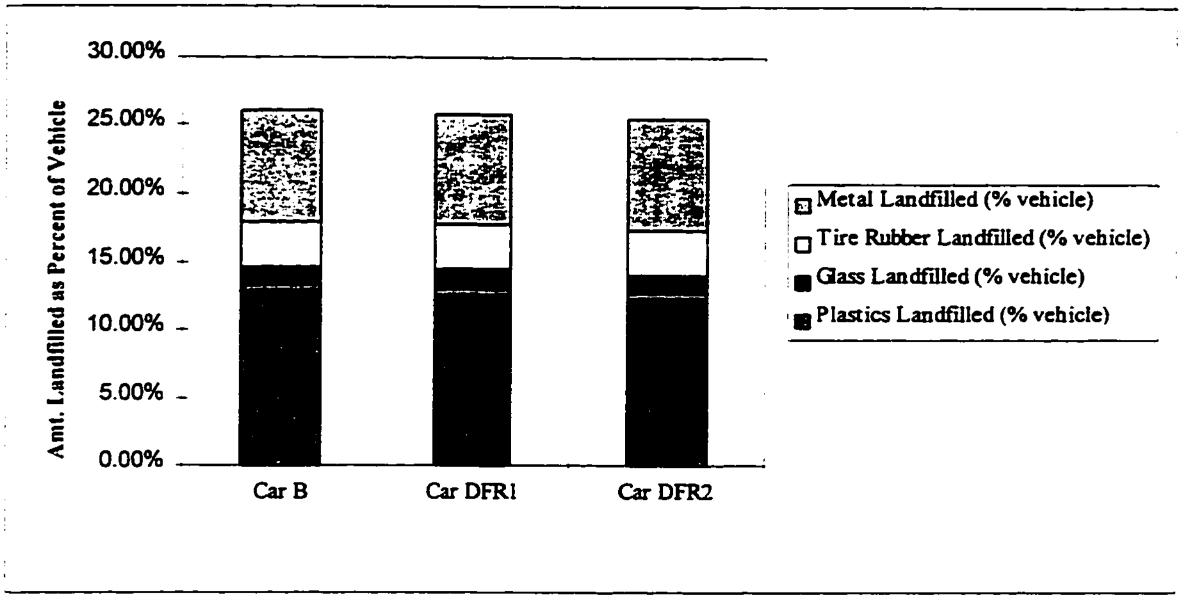

Figure 4.15 Comparison of Car B and the DfR Re-designs.

It is quite evident from this graph that there has been little improvement and little change from Car B to the redesigned DfR cars. This conclusion is dependent on the material values and disassembly costs that were used in these optimizations. The potential benefit of Design for Recycling cannot be ruled out if there is a chance that a future economic environment would encourage dismantlers to take advantage of the DfR changes made for these cars. For this reason a sensitivity analysis was performed.

4.4.4 Sensitivity Analysis

The sensitivity analyses that were performed for Car DfR1 and Car DfR2 were the same as those for Car A and Car B. The sensitivity to changes in the recycling values were investigated in a range from -50% to +800%. The sensitivity to changes in the disassembly costs were investigated in a range from -100% to +50%.

The results of these sensitivity analyses are presented in graphs similar to those for Car A and Car B. Bars are plotted that show the composition and amount of material to be sent to the landfill based on the profit-maximizing disassembly plan that corresponds to the value on the x axis. The following four graphs will be presented and then discussed. The first two illustrate the sensitivity to changes in recycling values for

Cars DfR1 and DfR2. The second pair of graphs are concerned with the sensitivity to changes in the disassembly costs.

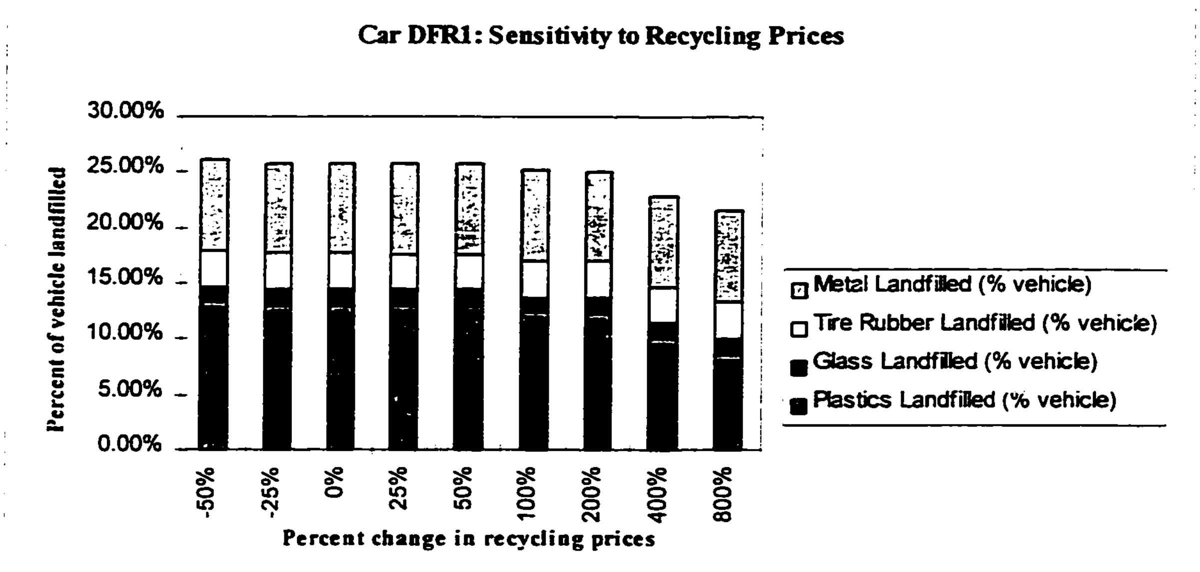

Figure 4.16 Car DfR1: Sensitivity to Changes in Recycling Values

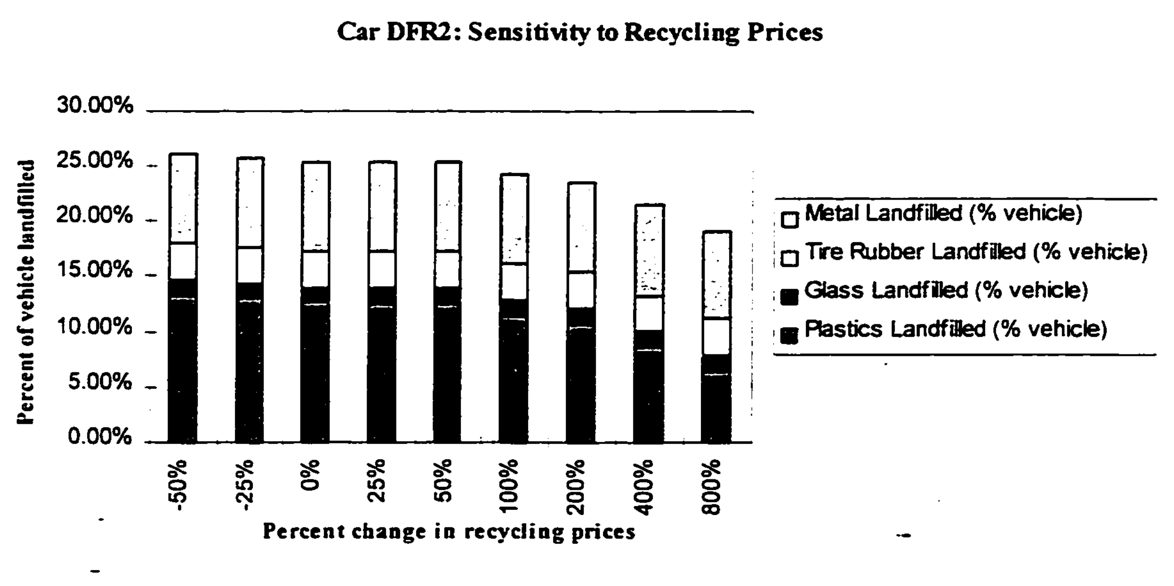

Figure 4.17 Car DFR2: Sensitivity to Changes in Recycling Values

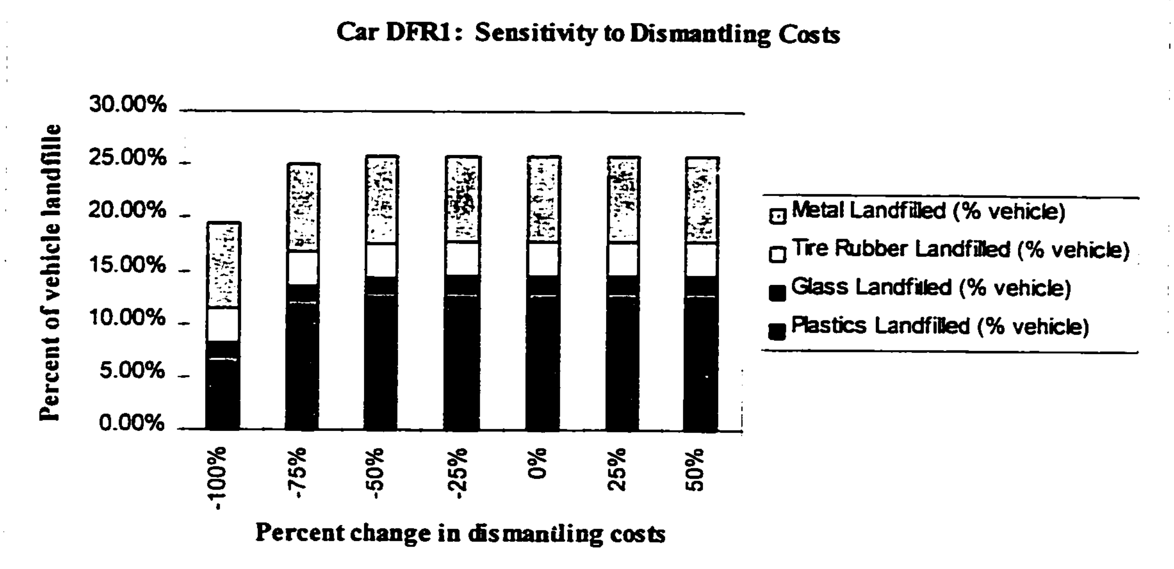

Figure 4.18 Car DFR1: Sensitivity to Changes in Dismantling Costs

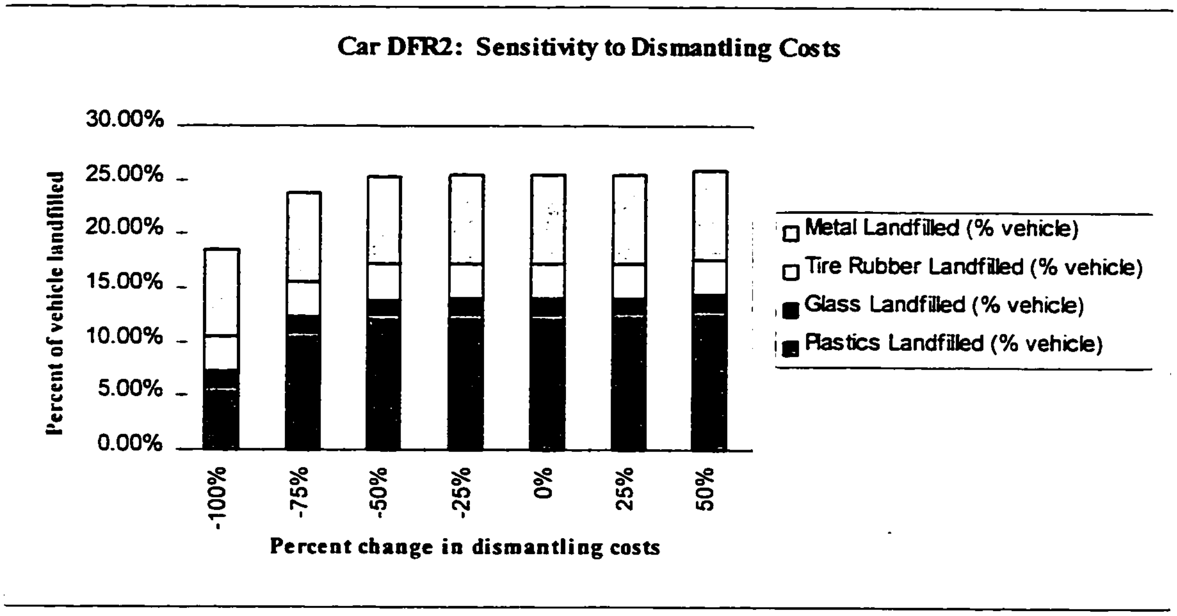

Figure 4.19 Car DFR2: Sensitivity to Changes in Dismantling Costs

The sensitivity analyses for Car DFR1 were not very different from those for Car B. There was little change in the amount of material going to landfill except in the extreme cases, such as when the disassembly costs are reduced 100% or the recycling values are increased 400% or 800%. In other words, the design changes that were made did not make a big enough difference to make dismantling for recycling attractive. The extreme cases for which there was an improvement were arguably unrealistic (because the changes from the status quo were too large) and the improvements were not very large.

The sensitivity analyses for Car DFR2 show the same results as for Car B and Car DFR1 except at the extreme cases. When the disassembly costs are reduced 100% or the recycling values are increased 400% or 800%, the amount of material being sent to the landfill is moderately reduced. These reductions occur at the unrealistic fringes of the sensitivity analysis, and furthermore, the reductions are not very large. When disassembly is free, the landfill rate is reduced to 18.5%. When recycling values are increased to nine times their current value this Design for Recycling concept car is projected to have a landfill rate of 19.2%. When it is considered that free disassembly or recycling values greater than virgin material prices are not practical, it is clear that the recycling rate will not improve within any reasonable range of economic changes, despite maximum DfR effort.

4.5 Conclusions

The application of disassembly modeling and analysis using *The Disassembly Modeling Language* and *The Disassembly Model Analyzer* to the automotive industry has been thoroughly undertaken and is revealing. The question of whether the current free-market automotive recycling infrastructure can be expected to improve the amount of recycling has been considered.

First, a pair of automobiles that were recently produced in high volume were studied. This pair can be taken to represent the pool of automobiles currently in use, and are likely not significantly different from those being produced now. It was found that despite potential changes in recycling prices for non-metals or potential changes in disassembly costs, there would likely be no change in the current practice of dismantlers and no increase in the amount of disassembly for recycling.

Second, a pair of virtual Design for Recycling concept cars were modeled to study the potential for future design changes to improve the amount of dismantler recycling.

These cars were designed to be as favourable as possible to dismantlers wishing to disassemble and recycle automobiles. It was found that within a reasonable range of changes in recycling prices for non-metals or in disassembly costs there was no significant improvement in the amount of disassembly for recycling. In other words, if cars were redesigned very aggressively for recycling and the recycling prices were tripled or the disassembly costs were quartered, there would still be no noticeable increase in the amount of recycling done as a result of disassembly (according to the profit-optimizing disassembly plan). Furthermore, if these redesigned cars faced a market with recycling prices nine times greater than today, or with free disassembly, there would be only a small change in the amount of recycling, despite the unrealistically optimistic nature of these conditions.

Therefore, the conclusion of the author with respect to the application of disassembly modeling and analysis to the automotive recycling question, is that recycling of non-metals via traditional dismantling procedures (i.e., disassembly) will not be economically feasible despite attempts at Design for Recycling or changes in the marketplace. If non-metals are to be recycled through disassembly, it must be paid for by the customers, the automakers (shareholders), or the government (taxpayers). It is recommended, therefore, that the automakers investigate the possibilities for new technologies to be used to solve the automotive shredder residue problem. These potential new technologies include methods for automatically shredding and sorting parts comprised of multiple non-metal materials, methods of automated, destructive disassembly, or methods for recycling or reusing automotive shredder residue directly.

Chapter 5

Conclusions and Future Work

5.1 Conclusions

In this thesis, a method for analyzing the economics of disassembly for recycling was presented. The method that was developed includes a modeling language, a software tool for analysis, and an optimization methodology. The premise behind this work is that economics drive disassembly and recycling and are therefore crucial to understanding of these issues.

The disassembly modeling and analysis method proposed can be useful in assessing the possibilities for recycling or reusing materials or components of durable goods. As a first step it can be used to assess current designs in the current economic environment. Sensitivity analysis can be used to investigate how changes in the economic environment can affect the results. The effect of design changes can also be explored by simulating these changes by altering the original model.

These methodologies have been tested in an industrial case study. This application involved automobiles and is discussed fully in Chapter 4. Conclusions regarding the automotive recycling industry can be found there. The case study was a success and demonstrated the usefulness of the disassembly modeling and analysis methodologies proposed.

5.2 Future Work

The following opportunities for future research in the area of disassembly modeling and analysis have been identified:

1. Expansion of the disassembly modeling method to include the opportunity for multiple types of shredders (for different material types).

2. Expansion of the disassembly modeling method to include the opportunity for multiple methods of disassembling various parts. (For example, part *a* can be removed before part *b* with one set of times and values, or part *b* can be removed before part *a* with a second set of times and values.)

3. Alternative objective functions for the analysis:

    - Maximize the amount of material recycled, while the profit is greater than or equal to *x*.

    - Maximize the profit, while the disassembly time is greater than or equal to *x*.

    - Maximize the profit, while the disassembly time is less than or equal to *x*.

    - Maximize the profit, while the recycling rate is greater than or equal to *x* per cent.

4. Application of disassembly modeling to many other types of durable products. Use of disassembly modeling and analysis to help develop design guidelines or assess research priorities.

5. Complete the integer programming model discussed in Appendix E. Compare the results of this model to those for the *Disassembly Model Analyzer*.

6. Create a better set of equations to predict automotive dismantler activities for use in an industrial model. (See Appendix F.)

7. Expand the methodology to include assessment of alternative technologies such as automated destructive disassembly or systems for shredding and sorting mixed plastics.

Appendix A

Car A Sensitivity Analysis Data

Car A -- Sensitivity to Recycling Values

Percent change in recycling values	-50%	-25%	0%	25%	50%	100%	200%	400%	800%
Dismantler recycling (kg)	46.960	47.740	47.740	54.520	56.760	57.040	61.890	64.690	87.010
Dismantling revenue	$ 22.72	$ 24.95	$ 27.03	$ 30.51	$ 33.53	$ 38.68	$ 51.46	$ 76.39	$ 148.53
Dismantling costs	$ 8.84	$ 8.98	$ 8.98	$ 9.71	$ 10.21	$ 10.39	$ 12.32	$ 14.38	$ 35.37
Ferrous	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.700
Non-ferrous	28.720	28.720	28.720	28.720	28.720	28.720	28.720	28.720	28.720
Non-metal	18.240	19.020	19.020	25.800	28.040	28.320	33.170	35.970	55.590
Shredded (kg)	1297.900	1297.117	1297.117	1290.337	1288.097	1287.817	1282.967	1280.167	1257.875
Shredding revenue	$ 77.87	$ 77.83	$ 77.83	$ 77.42	$ 77.29	$ 77.27	$ 76.98	$ 76.81	$ 75.47
Ferrous	954.584	954.584	954.584	954.584	954.584	954.584	954.584	954.584	951.884
Non-ferrous	96.413	96.413	96.413	96.413	96.413	96.413	96.413	96.413	96.413
Non-metal	246.903	246.120	246.120	239.340	237.100	236.820	231.970	229.170	209.578
Total shredder recycling	945.897	945.897	945.897	945.897	945.897	945.897	945.897	945.897	943.467
Total shredder landfilling	352.003	351.220	351.220	344.440	342.200	341.920	337 070	334.270	314.408
Profit	$ 91.75	$ 93.80	$ 95.88	$ 98.22	$ 100.61	$ 105.56	$ 116.12	$ 138.82	$ 188.63
Landfill Pct	26.17%	26.12%	26.12%	25.61%	25.45%	25.42%	25.06%	24.86%	23.38%
Non-metal recycle Pct	6.88%	7.17%	7.17%	9.73%	10.58%	10.68%	12.51%	13.57%	20.96%

Car A -- Sensitivity to Disassembly Cost

Percent change in dismantling time/cost	-100%	-75%	-50%	-25%	0%	25%	50%
Dismantler recycling (kg)	123.000	69.730	64.680	54.520	47.740	47.740	47.740
Dismantling revenue	$ 42.46	$ 32.30	$ 31.33	$ 28.15	$ 27.03	$ 27.03	$ 27.03
Dismantling costs	$ -	$ 4.18	$ 7.34	$ 7.28	$ 8.98	$ 11.22	$ 13.47
Ferrous	9.368	4.068	4.068	0.000	0.000	0.000	0.000
Non-ferrous	36.670	31.820	31.820	28.720	28.720	28.720	28.720
Non-metal	76.962	33.842	28.792	25.800	19.020	19.020	19.020
Shredded (kg)	1221.935	1275.127	1280.177	1290.337	1297.117	1297.117	1297.117
Shredding revenue	$ 73.31	$ 76.51	$ 76.81	$ 77.42	$ 77.83	$ 77.83	$ 77.83
Ferrous	945.216	950.516	950.516	954.584	954.584	954.584	954.584
Non-ferrous	88.463	93.313	93.313	96.413	96.413	96.413	96.413
Non-metal	188.256	231.298	236.348	239.340	246.120	246.120	246.120
Total shredder recycling	930.311	939.446	939.446	945.897	945.897	945.897	945.897
Total shredder landfilling	291.624	335.681	340.731	344.440	351.220	351.220	351.220
Profit	$ 115.77	$ 104.63	$ 100.80	$ 98.29	$ 95.88	$ 93.64	$ 91.39
Landfill Pct	21.68%	24.96%	25.34%	25.61%	26.12%	26.12%	26.12%
Non-metal recycle Pct	29.02%	12.76%	10.86%	9.73%	7.17%	7.17%	7.17%

Appendix B

Car B Sensitivity Analysis Data

Car B -- Sensitivity to Recycling Values

Percent change in recycling values	-50%	-25%	0%	25%	50%	100%	200%	400%	800%
Dismantler recycling (kg)	1.840	1.840	1.840	2.720	2.720	8.620	9.020	19.843	31.750
Dismantling revenue	$ 0.52	$ 0.78	$ 1.04	$ 1.42	$ 1.70	$ 4.22	$ 6.46	$ 19.49	$ 52.41
Dismantling costs	$ 0.11	$ 0.11	$ 0.11	$ 0.18	$ 0.18	$ 1.51	$ 1.58	$ 8.19	$ 21.82
Ferrous	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.998	1.747
Non-ferrous	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Non-metal	1.840	1.840	1.840	2.720	2.720	8.620	9.020	18.845	30.003
Shredded (kg)	1263.710	1263.710	1263.710	1262.832	1262.832	1256.932	1256.530	1245.709	1233.801
Shredding revenue	$ 75.82	$ 75.82	$ 75.82	$ 75.77	$ 75.77	$ 75.42	$ 75.39	$ 74.74	$ 74.03
Ferrous	939.297	939.297	939.297	939.297	939.297	939.297	939.297	938.299	937.550
Non-ferrous	97.708	97.708	97.708	97.708	97.708	97.708	97.708	97.708	97.708
Non-metal	226.705	226.705	226.705	225.827	225.827	219.927	219.525	209.702	198.543
Total shredder recycling	933.305	933.305	933.305	933.305	933.305	933.305	933.305	932.406	931.732
Total shredder landfilling	330.406	330.406	330.406	329.528	329.528	323.628	323.226	313.303	302.069
Profit	$ 76.23	$ 76.49	$ 76.75	$ 77.01	$ 77.29	$ 78.13	$ 80.27	$ 86.04	$ 104.62
Landfill Pct	26.11%	26.11%	26.11%	26.04%	26.04%	25.57%	25.54%	24.76%	23.87%
Non-metal recycle Pct	0.81%	0.81%	0.81%	1.19%	1.19%	3.77%	3.95%	8.25%	13.13%

Car B -- Sensitivity to Disassembly Costs

Percent change in dismantling time/cost	-100%	-75%	-50%	-25%	0%	25%	50%
Dismantler recycling (kg)	77.913	18.166	6.680	1.840	1.840	1.840	1.840
Dismantling revenue	$ 16.99	$ 7.74	$ 3.46	$ 1.04	$ 1.04	$ 1.04	$ 1.04
Dismantling costs	$ -	$ 3.18	$ 1.53	$ 0.08	$ 0.11	$ 0.14	$ 0.17
Ferrous	17.859	0.000	0.000	0.000	0.000	0.000	0.000
Non-ferrous	9.274	8.079	3.489	0.000	0.000	0.000	0.000
Non-metal	50.780	10.087	3.191	1.840	1.840	1.840	1.840
Shredded (kg)	1187.640	1247.386	1258.872	1263.710	1263.710	1263.710	1263.710
Shredding revenue	$ 71.26	$ 74.84	$ 75.53	$ 75.82	$ 75.82	$ 75.82	$ 75.82
Ferrous	921.438	939.297	939.297	939.297	939.297	939.297	939.297
Non-ferrous	88.434	89.629	94.219	97.708	97.708	97.708	97.708
Non-metal	177.768	218.460	225.356	226.705	226.705	226.705	226.705
Total shredder recycling	908.885	926.033	930.164	933.305	933.305	933.305	933.305
Total shredder landfilling	278.755	321.353	328.708	330.406	330.406	330.406	330.406
Profit	$ 88.25	$ 79.40	$ 77.46	$ 76.78	$ 76.75	$ 76.72	$ 76.69
Landfill Pct	22.03%	25.39%	25.97%	26.11%	26.11%	26.11%	26.11%
Non-metal recycle Pct	22.22%	4.41%	1.40%	0.81%	0.81%	0.81%	0.81%

Appendix C

Car DfR1 Sensitivity Analysis Data

Car DFR1 -- Sensitivity to Recycling Values

Percent change in recycling values	-50%	-25%	0%	25%	50%	100%	200%	400%	800%
Dismantler recycling (kg)	1.840	5.540	5.540	6.420	6.420	13.800	14.880	44.160	62.356
Dismantling revenue	$ 0.52	$ 1.09	$ 1.45	$ 1.94	$ 2.32	$ 5.41	$ 9.27	$ 35.94	$ 92.80
Dismantling costs	$ 0.11	$ 0.13	$ 0.13	$ 0.20	$ 0.20	$ 1.76	$ 2.48	$ 17.64	$ 36.74
Ferrous	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.998	1.620
Non-ferrous	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Non-metal	1.840	5.540	5.540	6.420	6.420	13.800	14.880	43.162	60.736
Shredded (kg)	1263.460	1259.760	1259.760	1258.880	1258.880	1251.500	1250.420	1221.141	1202.940
Shredding revenue	$ 75.81	$ 75.59	$ 75.59	$ 75.53	$ 75.53	$ 75.09	$ 75.03	$ 73.27	$ 72.18
Ferrous	938.230	938.230	938.230	938.230	938.230	938.230	938.230	937.232	936.610
Non-ferrous	97.709	97.709	97.709	97.709	97.709	97.709	97.709	97.709	97.709
Non-metal	227.521	223.821	223.821	222.941	222.941	215.561	214.481	186.200	168.621
Total shredder recycling	932.345	932.345	932.345	932.345	932.345	932.345	932.345	931.447	930.887
Total shredder landfilling	331.115	327.415	327.415	326.535	326.535	319.155	318.075	289.694	272.053
Profit	$ 76.22	$ 76.55	$ 76.91	$ 77.27	$ 77.65	$ 78.74	$ 81.82	$ 91.57	$ 128.24
Landfill Pct	26.17%	25.88%	25.88%	25.81%	25.81%	25.22%	25.14%	22.90%	21.50%
Non-metal recycle Pct	0.80%	2.42%	2.42%	2.80%	2.80%	6.02%	6.49%	18.82%	26.48%

Car DFR1 -- Sensitivity to Disassembly Cost

Percent change in dismantling time/cost	-100%	-75%	-50%	-25%	0%	25%	50%
Dismantler recycling (kg)	110.254	25.108	10.380	5.540	5.540	5.540	5.540
Dismantling revenue	$ 21.50	$ 9.30	$ 3.88	$ 1.45	$ 1.45	$ 1.45	$ 1.45
Dismantling costs	$ -	$ 3.88	$ 1.54	$ 0.10	$ 0.13	$ 0.17	$ 0.20
Ferrous	17.103	0.110	0.000	0.000	0.000	0.000	0.000
Non-ferrous	9.274	8.539	3.489	0.000	0.000	0.000	0.000
Non-metal	83.877	16.459	6.891	5.540	5.540	5.540	5.540
Shredded (kg)	1155.046	1240.192	1254.920	1259.760	1259.760	1259.760	1259.760
Shredding revenue	$ 69.30	$ 74.41	$ 75.30	$ 75.59	$ 75.59	$ 75.59	$ 75.59
Ferrous	921.127	938.120	938.230	938.230	938.230	938.230	938.230
Non-ferrous	88.434	89.169	94.219	97.708	97.708	97.708	97.708
Non-metal	145.485	212.903	222.471	223.822	223.822	223.822	223.822
Total shredder recycling	908.605	924.560	929.204	932.344	932.344	932.344	932.344
Total shredder landfilling	246.441	315.632	325.716	327.416	327.416	327.416	327.416
Profit	$ 90.80	$ 79.83	$ 77.64	$ 76.94	$ 76.91	$ 76.87	$ 76.84
Landfill Pct	19.48%	24.95%	25.74%	25.88%	25.88%	25.88%	25.88%
Non-metal recycle Pct	36.57%	7.18%	3.00%	2.42%	2.42%	2.42%	2.42%

Appendix D

Car DfR2 Sensitivity Analysis Data

Car DFR2 -- Sensitivity to Disassembly Cost

Percent change in dismantling time/cost	-100%	-75%	-50%	-25%	0%	25%	50%
Dismantler recycling (kg)	122.729	40.778	19.176	18.296	14.036	10.076	6.380
Dismantling revenue	$ 23.60	$ 12.00	$ 7.66	$ 7.57	$ 4.79	$ 2.47	$ 1.77
Dismantling costs	$ -	$ 3.68	$ 3.01	$ 4.47	$ 2.62	$ 0.78	$ 0.43
Ferrous	17.293	0.110	0	0.000	0	0	0
Non-ferrous	9.274	8.919	7.749	7.749	3.489	0.000	0.000
Non-metal	96.162	31.749	11.427	10.547	10.547	10.076	6.380
Shredded (kg)	1142.571	1224.562	1246.124	1247.004	1251.264	1255.224	1258.920
Shredding revenue	$ 68.55	$ 73.47	$ 74.77	$ 74.82	$ 75.08	$ 75.31	$ 75.54
Ferrous	920.937	938.120	938.230	938.230	938.230	938.230	938.230
Non-ferrous	88.434	88.789	89.959	89.959	94.219	97.708	97.708
Non-metal	133.200	197.653	217.935	218.815	218.815	219.286	222.982
Total shredder recycling	908.434	924.218	925.370	925.370	929.204	932.344	932.344
Total shredder landfilling	234.137	300.344	320.754	321.634	322.060	322.880	326.576
Profit	$ 92.15	$ 81.79	$ 79.42	$ 77.92	$ 77.25	$ 77.00	$ 76.88
Landfill Pct	18.50%	23.74%	25.35%	25.42%	25.45%	25.52%	25.81%
Non-metal recycle Pct	41.93%	13.84%	4.98%	4.60%	4.60%	4.39%	2.78%

Car DFR2 -- Sensitivity to Recycling Values

Percent change in recycling values	-50%	-25%	0%	25%	50%	100%	200%	400%	800%
Dismantler recycling (kg)	5.329	9.500	14.036	14.916	14.916	28.456	37.690	66.148	103.576
Dismantling revenue	$ 2.79	$ 3.40	$ 4.79	$ 5.54	$ 6.20	$ 11.20	$ 20.37	$ 54.99	$ 136.75
Dismantling costs	$ 2.11	$ 2.13	$ 2.62	$ 2.69	$ 2.69	$ 5.24	$ 8.32	$ 21.28	$ 45.80
Ferrous	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.621	10.904
Non-ferrous	3.489	3.489	3.489	3.489	3.489	3.489	3.489	3.489	4.304
Non-metal	1.840	6.011	10.547	11.427	11.427	24.967	34.201	61.038	88.368
Shredded (kg)	1259.971	1255.800	1251.264	1250.384	1250.384	1236.844	1227.610	1199.152	1161.724
Shredding revenue	$ 75.60	$ 75.35	$ 75.08	$ 75.02	$ 75.02	$ 74.21	$ 73.66	$ 71.95	$ 69.70
Ferrous	938.230	938.230	938.230	938.230	938.230	938.230	938.230	936.609	927.326
Non-ferrous	94.219	94.219	94.219	94.219	94.219	94.219	94.219	94.219	93.404
Non-metal	227.522	223.351	218.815	217.935	217.935	204.395	195.161	168.324	140.994
Total shredder recycling	929.204	929.204	929.204	929.204	929.204	929.204	929.204	927.745	918.657
Total shredder landfilling	330.767	326.596	322.060	321.180	321.180	307.640	298.406	271.407	243.067
Profit	$ 76.28	$ 76.62	$ 77.25	$ 77.87	$ 78.53	$ 80.17	$ 85.71	$ 105.66	$ 160.65
Landfill Pct	26.14%	25.81%	25.45%	25.38%	25.38%	24.31%	23.58%	21.45%	19.21%
Non-metal recycle Pct	0.80%	2.62%	4.60%	4.98%	4.98%	10.89%	14.91%	26.61%	38.53%

Appendix E

Mathematical Modeling and the Disassembly Problem

Appendix E

Mathematical Modeling and the Disassembly Problem

E.1 Introduction

The profit-maximization method proposed in this research relies on genetic algorithms. Genetic algorithms cannot be guaranteed to deliver an optimal solution. There is, however, potential to use a mathematical modeling approach to generate optimal solutions. In the past, attempts to do so have not resulted in methods that were capable of solving large problems in a reasonable amount of time. This appendix will discuss the mathematical model developed by Johnson [1994] and propose a framework for a new integer programming method.

E.2 Johnson's Two-Commodity Network Approach

Johnson's model of disassembly placed a greater significance on the specific order of disassembly operations. For example, if two parts were fastened similarly, there could be a benefit gained from removing them consecutively. In contrast, the model proposed in this work does not attempt to specify the order of disassembly. Rather, it specifies a set of parts to remove, and ensures that this set is not in violation of any precedence constraints.

With disassembly modeled as in Johnson, the disassembly sequence problem was formulated as scheduling *n* disassembly operations on a single worker. The problem was solved by using a two-commodity network formulation.

The disadvantages to this model revolve around the decision to place such an importance on the specific order of disassembly operations. It is true that this specific order matters, but the problem becomes too difficult to solve for complex products. For large problems what is needed is a method to simply select which parts to remove, and that is what is done by the proposed methodology of this thesis. The following section discusses the potential for developing a mathematical model for generating optimal disassembly plans -- i.e., sets of parts to be removed.

E.3 Integer Programming Possibilities

It may be possible to model the disassembly problem as formulated in this thesis using integer programming. This integer programming formulation has not been fully developed, but the framework is explained below.

Notation

X_i	= 1 if the ith part is removed. = 0 if the ith part is not removed. *X* is the decision variable. It tells us whether a part should be removed or not.
C_i	= 1 if the ith part is complete. = 0 if the ith part is not complete. *C* is used to let us know whether a part is complete or not, based on the plan determined by the *X*'s.
F_i	= 1 if the ith part is fully disassembled. = 0 if the ith part is not fully disassembled. *F* is used to let us know whether a part is fully disassembled or not, based on the plan determined by the *X*'s.
P_i	= 1 if the ith part is partially disassembled. = 0 if the ith part is not partially disassembled. *P* is used to let us know whether a part is partially disassembled or not, based on the plan determined by the *X*'s.
D_i	Disassembly cost for removing part i.
$MRO_{max,i}$	The maximum material recovery opportunity value for part i. This depends on the plan determined by the *X*'s. For example, a part can only be resold if the part is complete.
RS_i	Resale value for part i.
RC_i	Recycle value for part i.
S_i	Shredder value for part i.
L_i	Landfill cost for part i.

Objective Function

$$Z = \sum_i (X_i (C_i \cdot MRO_{\max,i} + P_i \cdot MRO_{\max,i}) - D_i X_i)$$

Constraints and Other Defining Equations

$X_i \leq X_j$	Example precedence constraint: Part j must be removed before part i.
$C_i + F_i + P_i = 1$	(For all i.) Each part is either complete or fully disassembled or partially disassembled.
$C_i = 1$	iff all $X_k=0$ and all $C_k=1$, for the set of $k=k_1..k_K$ representing the children of part i. (A part is complete if none of its children have been removed, and all of its children are also complete.)
$F_i = 1$	iff $\sum_k \max(X_k, F_k) \geq (K-1)$ (A part has been fully disassembled if all, or all but one of its children have been removed or fully disassembled.)

There are a couple equations above that have not been written in rigorous detail. For example two of the equations are not constraints at all, but are rather in the form of "if" statements.

The more difficult problem depends on the *MRO*'s. The *MRO* value for a part is defined not only by the subcomponents of the part and the *RS*, *RC*, *S*, and *L* values for the part and its subcomponents, but also by the state of the *X*'s for the part and all its subcomponents. For example, if a part is comprised of a number of subcomponents, and some of these subcomponents are of one material, and the rest are of others, then the part can be recyclable if subcomponents of different materials have been removed. The part would not be recyclable if any of the subcomponents of different materials are remaining. This can be further complicated when it is realized that this part could have three or more groups of subcomponent materials that could be recyclable if the other groups were removed.

So, the *MRO* for a part would be the greater of the four options that may be available -- resale, recycling, shredding, and landfill. The resale is not too tricky; if the part is complete, resale is possible. Recycling is complicated by the difficulties outlined in the above paragraph. Keep in mind that any part can have subcomponents that in turn have their own subcomponents, and so on. The shredder values and landfill costs for a part are not too difficult, and can be specified in a single equation, specific to each part. The following equations demonstrate how this can be done for the shredder, and the landfill costs work the same.

$S_i = \sum_{k=1}^{K} (1 - X_k) \cdot S_k$	For parts with subcomponents, the shredder value is simply the sum of the shredder values for the subcomponents that have not been removed. (Note, this equation is therefore recursive.)
$S_i = N$	For parts with no subcomponents, the shredder value can be defined by a number from the beginning.

In conclusion, the framework for an integer programming solution to the disassembly problem has been presented. The formulation has not been completely drawn up. Although some complicated problems remain, the foundation has been laid and the problem remains a good project for future work.

Appendix F

The Automotive Recycling Dynamic Model

Appendix F

The Automotive Recycling Dynamic Model

F.1 Introduction

It has been previously mentioned that the work of the author for this thesis was done while working closely with Mr. Pável Zamudio-Ramirez of the Massachusetts Institute of Technology. Mr. Zamudio-Ramirez carried out research toward his thesis for the degrees of master of science in civil and environmental engineering, and master of science in management. This appendix will not attempt to repeat what has been published in his thesis, but will explain the basic idea of Mr. Zamudio-Ramirez's work and will give details on how the work of the author was related to Mr. Zamudio-Ramirez's.

F.2 The Concept

Business today can be viewed as a network of flows of information and resources. System dynamics is a modeling method that essentially uses simulation to study how these flows of information, money, and materials interact given the structures of the system, including the inherent time delays.

The *Automotive Recycling Dynamic Model* is a dynamic model that has been developed for the Vehicle Recycling Partnership. It is difficult to explain such a large model in few words, but its purpose is to test hypotheses and learn about the potential impact of policies on the recycling infrastructure. The ARDM models the flow of cars from the design stage through usage and into the recycling system. Once the cars have been retired the dismantlers and shredders make decisions about what to do based on the information that they are receiving. All of these things have been modeled in the ARDM and so it is possible to investigate things such as how steel scrap prices will affect the price that dismantlers are willing to pay for junk cars.

The ARDM is a complex and powerful tool. It is, however, beyond the scope of this thesis. It is worth noting the connection between the ARDM and the work involving disassembly modeling and analysis. The following section explains how disassembly modeling was used to develop one of the core segments of the *Automotive Recycling Dynamic Model.*

F.3 The Interaction with Disassembly Modeling and Analysis

In order for the ARDM to be able to properly determine the material flows, it is necessary for it to be able to simulate the decision making processes of the automotive dismantler. The dismantlers make decisions about which parts to remove for resale or recycling while minding the goal of maximizing their profit. For this reason, the *Disassembly Model Analyzer* and its ability to generate profit-maximizing disassembly plans was a natural tool to be used in developing the ARDM.

What the Automotive Recycling Dynamic Model required was essentially a "black box" that could be used to determine the dismantlers decisions based on information about the economic environment and about the vehicle design. This black box was created by using the Car A disassembly model and generating a series of equations that would take the input (economic and physical information) and deliver the amounts of materials to be sent to the various material destinations.

This work was performed in the fall of 1995, and was incorporated into the ARDM at that time. Since then, the two research projects have diverged. During 1996, the Automotive Recycling Dynamic Model was completed, while the disassembly model of Car A was revised. (As well Car B and the DfR cars were studied during 1996.) As a result, the Car A model that was used in this project is slightly different than what is discussed in chapter 4.

The process of creating the "black box" equations could have been quite difficult. The task called for running a series of optimizations through the *Disassembly Model Analyzer* to see what affect the interactions between various variables would be. In order to make the most efficient use of time and resources, Design of Experiments was used to guide the process by selecting which optimizations should be run with which variables changed.

The design of experiments work performed for this analysis was aided by a software tool called *DOE Expert*. The *DOE Expert* is an add-on to *Microsoft Excel 5.0* which guides a user through the experimental design and analysis process.

Two sets of experiments were conducted. The difference between the two sets was that the in the second the parts had no resale values. The variables being studied were: (x_1) the level of design for disassembly (DFD), (x_2) the level of non-metal usage, (x_3) the level of non-ferrous usage, (x_4) recycled non-metal prices, (x_5) recycled non-ferrous prices, (x_6) landfill cost, (x_7) labour cost, and (x_8) resale prices.

It is necessary when performing an experimental analysis of this type to specify the specific meanings of the x's. For example, each of the x's needs to be defined at -1, 0, and 1. In this case, a two-level experiment is intended. Therefore it is necessary to define x's at the -1 and 1 values. The 0 values are also defined to allow extra experiments to be run to test the validity of the equations once they have been generated. Table F.1 shows the meaning of each of these variables for each of those values. Restricting the analysis to these x values amounts to linearizing the problem. In other words, it is assumed that the relationship between the set of the x's and any of the functions is linear. Whether or not this simplification is reasonable for this case is debatable, however.

The variables x_1, x_2, and x_3 are not explicitly defined in the table. The exact meaning of "less non-metal usage" or "more non-ferrous usage" was not decided *a priori*. Rather, the disassembly models were modified first, and then examined to see the exact result. For example, the disassembly models that represented "less non-metal usage", (i.e., $x_2 = -1$), had a non-metal fraction of 19.4%, compared to a base case of 21.2%. For more information, refer to Figure F.1 and Table F.3, and to the accompanying paragraphs.

Table F.1 Values for experiment variables

x	variable name	-1	0	1
1	Level of DFD	Same as Car A	Same as Car A	Less befores, fewer materials
2	Non-metal usage	Less	Car A	More
3	Non-ferrous usage	Less	Car A	More
4	Non-metal prices	Car A	100% more	200% more
5	Non-ferrous prices	50% less	Car A	50% more
6	Landfill cost	20% less	current	100% more
7	Labour cost	20% less	$20/hour	50% more
8	Resale price	10% of Car A	15% of Car A	20% of Car A

The experimental matrix defines a series of experiments to be performed which will be used in the analysis. Choosing the proper matrix (i.e., experimental design) is normally a difficult task. In this case, the decision was left up to the *DOE Expert* software tool, which created the matrix displayed in table F.2. The *DOE* Expert uses the Taguchi method and the matrix is of type L12.

It is obvious that since there are two points required for each x (due to the linearity assumption) that there should totally be 256 combinations of experiments. The purpose of the experimental matrix is to simplify the problem by reducing the number of experiments to be run, while at the same time ensuring that interesting interactions between variables are not missed.

The L12 matrix that was used accomplishes this as it is an orthogonal array. The columns are pairwise orthogonal; i.e., in every pair of columns, all combinations of variable levels occur an equal number of times. For example, consider columns one and two. The possible pairs are -1 and -1, -1 and 1, 1 and -1, and 1 and 1. Each of these pairs is found in these columns, and each pair is found three times. This is true no matter which two columns are compared. In this way, the number of experiments has been reduced, but there is still some reason to be confident that variable interactions will not be missed.

Table F.2 Experimental matrix

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8
1	-1	-1	-1	-1	-1	-1	-1	-1
2	-1	-1	-1	-1	-1	1	1	1
3	-1	-1	1	1	1	-1	-1	-1
4	-1	1	-1	1	1	-1	1	-1
5	-1	1	1	-1	1	1	-1	1
6	-1	1	1	1	-1	1	1	-1
7	1	-1	1	1	-1	-1	1	1
8	1	-1	1	-1	1	1	1	-1
9	1	-1	-1	1	1	1	-1	1
10	1	1	1	-1	-1	-1	-1	1
11	1	1	-1	1	-1	1	-1	-1
12	1	1	-1	-1	1	-1	1	-1

For the second set of experiments, with no resale values, the columns representing x_1 through x_7 are identical to those in the matrix above. (x_8 is omitted from the second set of experiments because resale price is not relevant.)

Modified DML files were created for each experiment to be run. For some of the variables, making the changes was as simple as changing a number. For others, however, the changes to the DML file represented design changes to the vehicle. These modifications are described in the following paragraphs.

To create a DML file which emulates a higher level of Design for Disassembly the concentration of precedence constraints was reduced, as was the variety of non-metal materials. The precedence constraints were reduced randomly. That is, half of the constraints were removed, but thirty were then reinstated because without them some parts could be removed in zero time. In the end, the precedence constraints had been reduced in number to 57%. The number of non-metal materials was also halved. This was done by changing TPO, PC/PBT, PET, PE, and PPO into PP. PP was chosen because it is cheap and is a material of growing importance in the automotive industry. [Ward's Auto World] As well, any contaminated materials were changed to be non-contaminated. The goal of all these changes was to create a DML file which represented a vehicle that had been designed with the intention of improving the recyclability. The following chart illustrates the effect of the DFD on the number of precedence constraints. The chart is a histogram of the cumulative number of constraints for the parts. The case where DFD is improved has fewer precedence constraints overall, and there are many fewer parts with high counts of constraints.

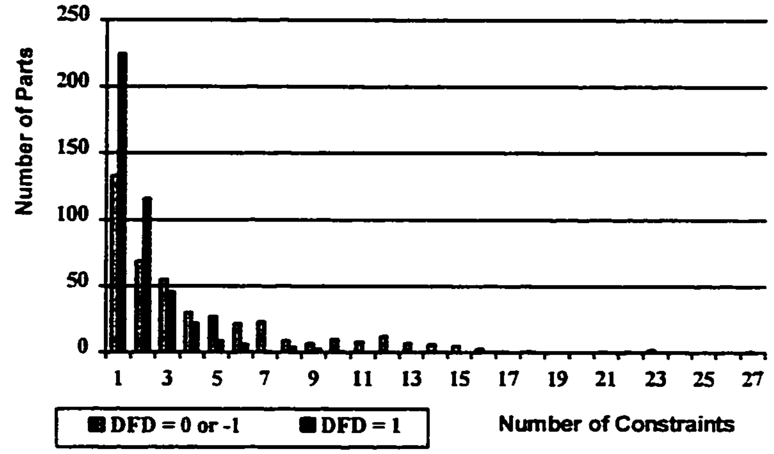

Figure F.1 Histogram of precedence constraints, based on DFD level.

To create a DML file which represented an increase in the amount of non-metal usage or non-ferrous usage, some materials in car A which are currently ferrous were changed to a non-metal material or a non-ferrous metal, respectively. The parts which were changed were parts which are frequently predicted to no longer be ferrous metal in the future. Examples would be body panels or some engine components. To create a DML file which represented a decrease in the amount of non-metal usage or non-ferrous usage, some materials in car A which are not currently ferrous -- but historically were ferrous -- were changed back to ferrous. The following table illustrates the resulting vehicle compositions based on these DML changes.

Table F.3 Effect of x_2 and x_3 on vehicle composition.

x_2	x_3	Non-metal fraction	Non-ferrous fraction
-1	-1	19.4%	3.4%
-1	1	19.4%	25.5%
1	-1	27.8%	3.4%
0	0	21.2%	9.5%
1	1	27.8%	22.2%

Each of the DML files created to represent one of the experiments for either set of runs was loaded into the Disassembly Model Analyzer and a corresponding optimal disassembly plan was generated. The statistical output from these optimal plans was then used to generate equations using the *DOE Expert*.

Based on the results of the experimental runs, the *DOE Expert* was able to produce the coefficients for equations to determine the number of parts to be resold, the revenue from parts resale, the fraction of mass in parts to be resold, the material composition of those parts, the income from material recycling, the fraction of mass to be recycled by the dismantler, the composition of that mass and the dismantling time. These equations were essentially produced by choosing coefficients to minimize the error of the equations. Equations $f_i(\mathbf{x})$ deal with the scenario of no resale parts. The equations $g_i(\mathbf{x})$ consider the scenario with resale. The meanings of these equations for the various i's are listed in the table below.

Table F.4 Meanings of equations $f_i(\mathbf{x})$ and $g_i(\mathbf{x})$

i	Meaning of equation $f_i(\mathbf{x})$ or $g_i(\mathbf{x})$
1	Number of parts resold.
2	Revenue from parts.
3	Fraction of vehicle mass reused as parts.
4	Income from material recycling (by dismantler).
5	Fraction of vehicle mass recycled.
6	Fraction of vehicle mass recycled as non-ferrous metals.
7	Fraction of vehicle mass recycled as non-metals.
8	Dismantling time.

Other information about the dismantling or recovery practices can be generated based on these equations. The only other required information is the material composition of parts, and the mass of the vehicle being considered. The following table summarizes the equations which were created.

Table F.5 Equations produced experimentally

Eq'n	Right Hand Side
$f_1(\mathbf{x})$	0
$f_2(\mathbf{x})$	0
$f_3(\mathbf{x})$	0
$f_4(\mathbf{x})$	$(14.028 -1.95x_1 -4.845x_2 +13.293x_3 -2.937x_4 +10.467x_5 +1.09x_6 -3.587x_7)$ * Vehicle_weight / 1377
$f_5(\mathbf{x})$	$(18.517 +0.804x_1 -5.641x_2 +17.604x_3 -2.304x_4 +8.054x_5 -2.662x_6 -4.059x_7) / 1377$
$f_6(\mathbf{x})$	$f_5(\mathbf{x})$ * Non-ferrous_fraction_of_parts
$f_7(\mathbf{x})$	$f_5(\mathbf{x})$ * Non-metal_fraction_of_parts
$f_8(\mathbf{x})$	$2f_5(\mathbf{x}) * (11.373 -1.543x_1 +0.575x_2 +6.077x_3 -1.671x_4 +7.934x_5 -0.713x_6 - 4.804x_7)$ * Vehicle_weight
$g_1(\mathbf{x})$	$43.25 +0.417x_1 -0.083x_2 -0.083x_3 +0.083x_4 -0.083x_5 -0.083x_6 -0.250x_7 +0.250x_8$
$g_2(\mathbf{x})$	$1163.575 +70.108x_1 -69.075x_2 -68.068x_3 -68.242x_4 +68.242x_5 -69.075x_6 +66.942x_7 +344.075x_8$
$g_3(\mathbf{x})$	0.621
$g_4(\mathbf{x})$	$(0.296 +0.246x_1 +0.044x_2 -0.046x_3 +0.036x_4 +0.016x_5 +0.088x_6 +0.018x_7 +0.026x_8)$ * Vehicle_weight / 1377
$g_5(\mathbf{x})$	$(1.278 +0.468x_1 +0.203x_2 +0.203x_3 +0.068x_4 +0.338x_5 -0.338x_6 +0.203x_7 - 0.068x_8) /1377$
$g_6(\mathbf{x})$	$g_5(\mathbf{x})$ * Non-ferrous_fraction_of_parts
$g_7(\mathbf{x})$	$g_5(\mathbf{x})$ * Non-metal_fraction_of_parts
$g_8(\mathbf{x})$	$2* (g_3(\mathbf{x}) + g_5(\mathbf{x})) * (8.842 -0.423x_1 +0.121x_2 +0.121x_3 +0.184x_4 -0.189x_5 +0.124x_6 -0.251x_7 +0.250x_8)$ * Vehicle_weight

In order to use the equations to learn about the dismantling practices for x values other than -1, 0, and 1, it was necessary to create equations to generate the x's from variables which are more realistic. For example, equations are required to produce x_2 and x_3 from the material composition of a vehicle. The following table summarizes the results.

Table F.6 Equations to produce x's.

Variable	Equation	Explanation
DFD (x_1)	DFD_Level - 2	Where DFD_Level is an index ranging from 1 to 3 which indicates the designed level of DFD in the vehicle.
Non-metal composition (x_2)	$-6.6516 + 22.1569y_2 + 27.8410y_3 - 23.4176y_2y_3 - 60.968y_2^2 - 7.2318y_3^2$	Where y_2 is a number between 0 and 1 representing the fraction of non-metal material in the vehicle and y_3 is a number between 0 and 1 representing the fraction of non-ferrous material in the vehicle.
Non-ferrous composition (x_3)	$-1.9375 + 21.9649y_2 + 2.07124y_3 + 1.1299y_2y_3 - 45.411y_2^2 - 4.4701y_3^2$	Where y_2 and y_3 are as above.
Non-ferrous price (x_4)	(Nonferrous_price_index +100)/100 -2	Where Nonferrous price index is the percent change in the recycling values of non-ferrous metals compared to the current values.
Non-metal price (x_5)	Non-metal_price_index/50	Where Non-metal price index is the percent change in the recycling values of non-metals compared to the current values.
Landfill cost (x_6)	Landfill_cost_index/60 -2/3	Where Landfill cost index is the percent change in the landfill costs compared to current values.
Labour cost (x_7)	Labour_cost_index/35 -3/7	Where Labour cost index is the percent change in the labour costs compared to current values.
Resale price (x_8)	(Resale_price_index + 100)/5 -3	Where Resale price index is the percent change in the resale prices compared to current (new) prices.

Most of the equations in the table above are simply derived from the definitions of the x's at -1, 0, and 1. The equations to generate x_2 and x_3 from the material compositions of the vehicles are based on the actual DML files that were created. The material compositions from the DML files were compared to the x values, and a curve of best fit was created using the *Solver* tool in *Microsoft Excel 5.0*.

It is possible, therefore, to use these equations to create an estimate for the material and financial flows of one vehicle based on the x values. In this way the learning from the *Disassembly Model Analyzer* and the work with Car A was incorporated into the *Automotive Recycling Dynamic Model*. The following section explains how this work could be improved in the future.

F.4 Possibilities for Improved Interaction

The present set of equations generated by the *DMA* for the *ARDM* are less than perfect for a number of reasons. The equations were generated based on only one car and they did not have the advantage of having the virtual DfR concept cars available for study, either. Some of the x values, such as for the landfill cost, turned out to be quite unimportant and could have been eliminated. As well, the equations are all in the form:

$$f(\mathbf{x}) = a_0 + \sum a_i x_i$$

In other words, the equations are linear when in fact it may be better to have non-linear terms in the equations. This linearity assumption makes it difficult to trust the results of the equations, particularly when an x value falls outside the -1 to 1 range. If a new set of equations were required, these changes could be made to the model and a better result could be expected.

Vita Auctoris

Andrew Spicer was born in Windsor, Ontario on the 1st of August, 1972. He has attended the University of Windsor since 1990, completing a B.A.Sc. degree in Industrial Engineering in 1994. Since that time he has been studying towards his M.A.Sc. degree in the Department of Industrial and Manufacturing Systems Engineering.

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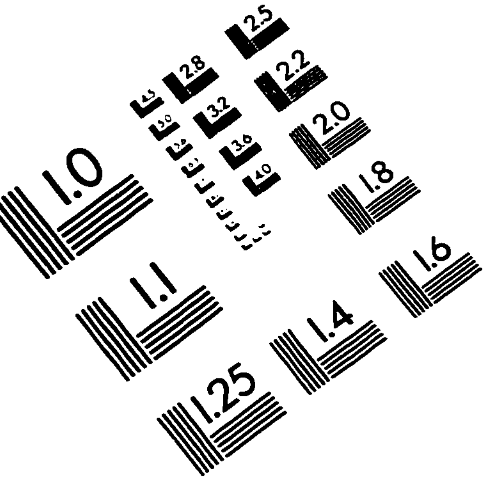

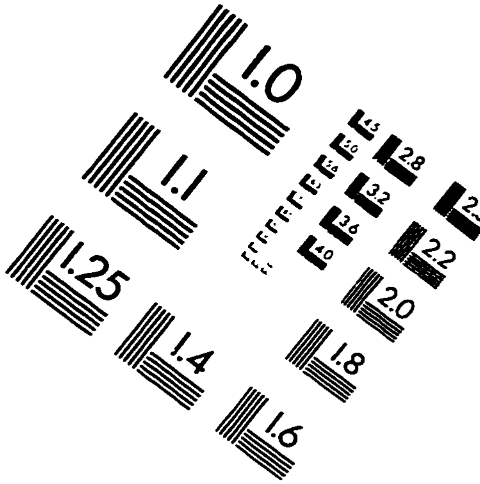

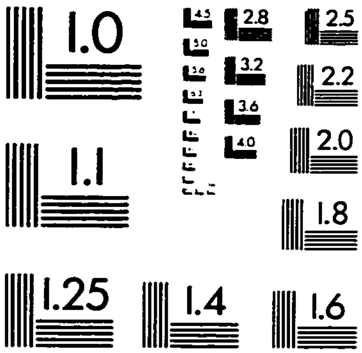

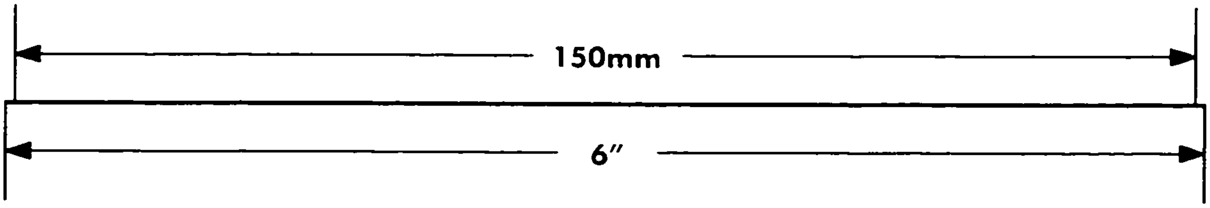

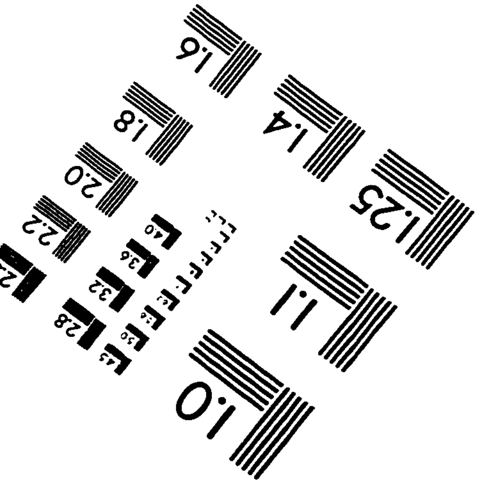

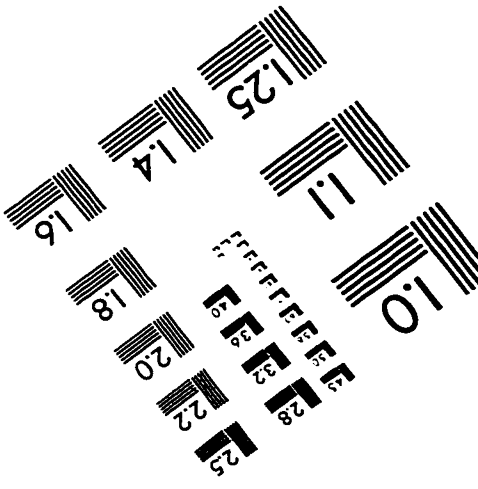

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