

**ECONOMICS OF AUTOMOBILE RECYCLING**

by

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Bachelor of Science in Chemical Engineering  
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### **Abstract:**

The recycling of automobiles in North America represents one of the most successful -- if not the most successful -- examples of material recovery. This activity is sustained by a large industry constituted by several parties: consumers, dismantlers, remanufacturers, transportation companies, material recycling companies, metal recovery enterprises, landfills, and to certain extent, the automobile manufacturers.

It is estimated that approximately 94% of the vehicles being retired are processed by the recycling industry. From these, approximately 75% of the total mass is recovered. The other 25% is normally sent to the landfills. These recovery rates are even more impressive considering that approximately 10 million cars are disposed yearly in North America. This is an industry that processes almost ten million tons of material per year.

The fundament of this industry is that it works purely on the basis of economics. It is argued that the success of the industry is based on the structure of the system; parties taking profit self-optimizing decisions, are capable to efficiently deal with the recycling of cars.

However, the historic trends of reducing the vehicle weight and increasing the non-metal composition of cars pose serious doubts on the industry viability in the future. A significant portion of the economic benefits associated to automobile recycling comes from the recovery of metal materials. In addition, most of the non-metals represent a double cost to the industry; they have to be processed -- increasing the transportation and operation costs -- and, at the end, are sent to landfills at an additional cost.

Automobile manufacturers are concerned about these risks because they perceive -- in countries like Germany, governments are also understanding -- that they have a major impact in the recyclability of automobiles. The automobile manufacturers determine weight and composition, as well as the level of Design for Disassembly in vehicles. These factors have a major role in defining the dismantling and recycling that will take place on automobiles.

Recycling of automobiles involves two principal stages: disassembly and shredding. This work addresses both stages and explains a systematic approach to model them. The first part is focused on the detail complexity of the disassembly problem. The second deals with the industry as a whole including the shredding operation and the price dynamics governing the systems' behavior.

In the first part, the Disassembly Model Analyzer (DMA) tool is described. This is an optimization program based on a genetic algorithm. This tool is capable of interpreting the complex economic and physical information associated to the disassembly problem of a relatively large product (more than 500 parts). The DMA interprets this information and then returns, among other information, the profit-optimizing disassembly plan. The DMA was used to determine the potential impact on several dismantling drivers -- design, prices and costs -- on dismantling practices. The potential impacts were structured in the form of empirical equations using a design of experiments procedure.

The second part of this work includes the description and use of the Automobile Recycling Dynamic Model (ARDM). This industry model captures part of the most relevant interactions among parties in the industry and evaluates the effect of policy changes (such as weight, and vehicle composition), in the environmental impact of disposing and recycling automobiles. The ARDM uses the empirical equations generated by the DMA to model the dismantlers' behavior. In this sense, the ARDM includes optimization decisions (profit-maximizing) within a dynamic context. The ARDM has to be dynamic because prices depend on the different industry participants' decisions, which in turn, depend on the prices.

In the ARDM, the environmental impact of disposing automobiles is traced by determining the Automobile Shredder Residue (ASR) generation and the number of cars being left out of the recycling loop (abandoned cars).

The DMA and the ARDM are used to answer two fundamental questions: "Is there a major threat in the future for the industry recycling automobiles in North America?"; and "Is there something the automobile manufacturers can do to improve the situation?"

The answer to both questions is "Yes." Significant changes in vehicle weight and composition trends, or major changes in the industry structure have to be made if the industry recycling automobiles in North America is to exist in the future. However, automobile manufacturers have a good opportunity to deploy, in conjunction with other interested parties, a well-orchestrated strategy to sustain, at least, the current level of automobile recycling.

Sound strategies in this sense are not necessarily intuitive. Increases in the level of Design for Disassembly (DFD), for example, will not completely result in more recycling. This work shows how a structure based on parties seeking self-maximizing monetary goals will fail to convert DFD increases into additional recycling. The pollution externality argument is supported. It is also explained that certain types of coordinated intervention might be the optimum way to proceed.

Finally, this work explains how the DMA and the ARDM can be used inside the automobile manufacturers' organizations to evaluate and give relative priority to alternative projects in technological development and automobile design.

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I would also like to acknowledge the support and resources made available to me through the Leaders for Manufacturing Program, a partnership between MIT and major U.S. manufacturing companies.

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I am specially thankful to Larry Daniels who enthusiastically coordinated the interviews and participated in many hours of discussion during the modeling and writing stages. But certainly more important is the friendship and support he honored me with during this research.

To a significant extent, this work is the result of the joint research conducted by the author and Andrew Spicer. Andrew had worked in the area of disassembly to obtain a Master's Degree in Industrial Engineering from the University of Windsor, Canada. Upon my arrival at the VRDC, and having discussed extensively the implications and overlaps of his research area and mine, we decided to merge our projects into one. The key focus of his participation was on the disassembly complexity analysis, while mine was on the industry dynamics.



A special gratitude to Andrew for several reasons. This project benefited largely from his inquisitive and analytic mind. He helped extensively in proof-reading this thesis as well, and in the process, he has become a close friend.

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## **Disclaimer**

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

# Contents

## Introduction

1. Environmental Research	13
2. The Initial Steps	14
3. Vehicle Recycling Development Center	18
4. Understanding Automobile Recycling	19
5. Research Process	22
6. Relevance of this Work	23
• Dismantlers, Remanufacturers, Recyclers and Shredders	24
• Governmental Bodies	24
7. Project Objectives and Thesis Structure	25

## Part I. The Disassembly Problem 27

### Chapter 1. Disassembly Modeling 29

1. Relevant Information	31
• Physical Information	31
• Economic information	32
2. Disassembly Modeling Language	35

### Chapter 2. Disassembly Model Analyzer 40

1. Interpreting the DML information	40
2. Basic Structure Analysis	41

3. Disassembly Plan Analysis	43
4. Disassembly Plan Optimizer	44
• Identification of the Parts to be Resold	44
• Parts Which are Trivially Undesirable	46
• Grouping of the Remaining Parts	47
• Optimization by Enumeration	47
5. Optimization by Genetic Algorithms	48
• Genetic Algorithms applied to Disassembly Optimization	50
• Output of the DMA's Optimizer	54
<b>Chapter 3. Experimental Work at the Vehicle Recycling Development Center</b>	<b>56</b>
1. Dismantling and Time-studies	56
2. Economic Information	59
<b>Chapter 4. Analysis of "Car A"</b>	<b>62</b>
1. Economic information	62
2. DML file	65
3. Basic Structure Analysis of "Car A"	68
4. Optimization of the Disassembly Plan: Vehicle with All Parts Intact	69
5. Optimization of the Disassembly Plan: Vehicle with No Parts to be Sold	73
6. Experimental Design and Results	79
7. Sensitivity Analyses	88
• Plastic Prices	88
• Scrap Price	89
• Resale Price	90
• Labor Cost	90
• Landfill Cost	91
• The Optimistic Case	91

<b>Part II. The Automobile Recycling Dynamic Model</b>	<b>93</b>
• Dynamic Industry Models	94
• The Automobile Recycling Industry in North America	95
<b>Chapter II.1. Loops in the Environmental Arena</b>	<b>100</b>
1. Environmental degradation	101
2. Recycled materials	104
3. Regulation	106
4. The Automobile Manufacturers	108
<b>Chapter II.2. Introduction to the Automobile Recycling Dynamic Model (ARDM)</b>	<b>110</b>
1. Objective of the Model	111
2. The Case of a Dynamic Model	112
3. Main Feedback loops in Automobile Recycling	114
4. Model Boundary	118
5. Market of Used Parts	128
<b>Chapter II.3. The Automobile Recycling Dynamic Model</b>	<b>132</b>
1. <i>Automakers</i> Sector	133
2. <i>Aging</i> Sector	134
3. <i>Main</i> Sector	136
4. <i>Age</i> Sector	138
5. <i>Ini values</i> Sector	140
6. <i>x-levels</i> Sector	143
7. <i>Dismantling calculations</i> Sector	144
8. <i>Shredding calculations</i> Sector	147
9. <i>Properties</i> Sector	149

10. <i>Dismantlers' Forecast Sector</i>	151
11. <i>Dismantlers' Rates Sector</i>	152
12. <i>Dismantlers' Profit Sector</i>	154
13. <i>Dismantlers' Capacity Sector</i>	156
14. <i>Junk Car Price Sector</i>	158
15. <i>Shredder Forecast Sector</i>	159
16. <i>Shredding Rates Sector</i>	161
17. <i>Shredders Profit Sector</i>	163
18. <i>Shredder Capacity Sector</i>	164
19. <i>Hulk Price Sector</i>	165
20. <i>Autoscrap price Sector</i>	166
21. <i>Dismantling of new cars Sector</i>	170
22. <i>Control Sector</i>	170
<b>Chapter II.4. Initial Conditions</b>	<b>172</b>
1. <i>Automakers Sector</i>	173
2. <i>Aging Sector</i>	174
3. <i>Main Sector</i>	174
4. <i>Age Sector</i>	176
5. <i>x-levels Sector</i>	177
6. <i>Dismantling and Shredding calculation Sectors</i>	177
7. <i>Properties Sector</i>	178
8. <i>Dismantlers' and Junk Car Price Sectors</i>	179
9. <i>Shredders' and Hulk Price Sector</i>	182
10. <i>Additional initial information</i>	186
<b>Chapter II.5. Analysis from equilibrium</b>	<b>187</b>
1. <i>Changes in Plastic Usage</i>	188
2. <i>Changes in Sales</i>	205

---

3. Changes in <i>GDP</i>	210
4. Effect of Design for Disassembly ( <i>DFD</i> )	219
5. Simultaneous Changes in <i>x-variables</i>	225
6. An Overview of Policy Decisions	229
7. Integrating changes in <i>x-variables</i> , Policy Decisions and <i>GDP</i>	232
8. Monte Carlo Simulation on Retirement Fractions	238
<b>Chapter II.6. Analysis from historical conditions</b>	<b>240</b>

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<b>Part III. Conclusions and Recommendations</b>	<b>248</b>
1. The Disassembly Problem	248
• Disassembly Practices	249
• Disassembly for Material Recovery	250
• Areas for Future Research	252
2. Automobile Recycling Industry Analysis	253
• Industry Robustness	255
• Structural Deficiency	256
3. The Influence of the Automobile Manufacturers	259
• DFD	259
• Car Weight and Material Composition	260
• Scenarios Review	261
• Areas for Future Research	262
4. VRDC Reaction to Project	263
<b>Bibliographic Research</b>	<b>264</b>
<b>Appendix I: Car A. Physical Data</b>	<b>264</b>
<b>Appendix II: Results From the Design for Experiments</b>	<b>283</b>
<b>Appendix III: Complete Documentation of the Automobile Recycling Dynamic Model (ARDM)</b>	<b>285</b>



# Introduction

## 1. Environmental Research

At the end of the twentieth century, humanity faces immense problems. Despite unquestionable advancement in scientific and technological matters, and the corresponding increase in productivity, our world is not necessarily better off than, for example, ten centuries ago. It is true that antibiotics have been discovered and astronauts have walked on the moon. However, new and more resistant problems have been created. Man has developed and, sadly, has exercised an amazing destructive power as well. It is true that humanity have, on average, extended the life expectancy. However, “on average” can be a very misleading indicator. The distribution of life expectancy has probably changed in peculiar ways. It comes as no surprise that children in underdeveloped countries die at a faster rate than at the beginning of the century. To a certain extent, scientific development and technological advancement have become divorced from the general population.

Challenges in these times are not only about distribution. They involve, in a significant way, the hidden consequences of our technological development. Improvement in production systems has resulted in severe environmental damage. Worse, a major portion of the actual effects are still to be observed. We know little about the long-term effects of most of the chemicals in use. It will take decades before the already-emitted CFCs reach the ozone layer and further deteriorate this protective filter.

This is why a segment of the scientific community is starting to propose -- and some audience is starting to listen -- that societies need to redefine their long-term objectives. “Is it more

production that we need?" Some people would argue that there is no need to worry about distribution as long as there is not enough to distribute. Or perhaps it is continuing production that should attract our attention. At the pace we are using up our non-renewable resources we cannot expect to sustain our production and consumption rates. In recognition of the damage we are causing the environment, but more importantly, in recognition of the potential damage we can inflict, people are starting to think about "sustainability."

The pursuit of a society that makes decisions considering the long-term impact of its actions requires understanding of the processes creating environmental problems. This is an area where familiarity and knowledge is limited for several reasons. In terms of research, the environmental field is far behind most other research areas because, historically, small amounts of resources have been devoted to this area. In structural terms, the long delays associated with observing the environmental impacts of our actions complicate the analysis. There is a lack of empirical models to perform controlled experimentation, as in other fields. In addition, the economic foundation of our society has not proved capable of internalizing the true costs of pollution. Finally, there is an underdeveloped infrastructure to promote optimum use of our resources.

The intent of this work is to participate in developing an integrated framework to address environmental challenges. Many years will be required before we can see an extended use of such a framework. However, neither the difficulties nor the uncertainties associated with this enterprise should be deterrent enough to restrict this necessary evolution.

## **2. The Initial Steps**

Although in its initial stage, environmental research has been active in proposing systematic approaches for evaluating the environmental impact of technological alternatives. Life Cycle Analysis, for example, is a methodology that evaluates 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 problems -- it is time consuming and expensive, for example -- the life

cycle philosophy is a strong one for considering the tradeoffs associated with different industrial options.

The analysis, if any, was traditionally done focusing on each individual stage. This partial view would normally lead to a sub-optimal condition for the whole system. Instead, LCA proposes to consider alternatives in an integrated way: material extraction, manufacturing processing, usage and disposal should be evaluated for each alternative. In all stages, the air and water emissions, the solid waste, the energy use and other types of contamination should be identified and quantified. The foundation is that only by integrating the complete life cycle of a product can we aim to improve the whole system.

This work focuses on the disposal stage of durable goods. The application of the tools developed is done for automobiles, but the general approach can be extended easily to almost any other durable good. Since, the focus on disposal is also a partial view of the whole problem, it is not the intention of this work to suggest that disposal is the most critical stage of any particular product. The tools developed in this work should be used in conjunction with other instruments designed to evaluate the other stages of a product's life cycle.

As environmental threats become more significant, political and economic forces are pushing manufacturers and designers to produce products that are more "environmentally friendly". This has resulted in the creation of Environmentally Conscious Design and Manufacturing (ECDM). A research area of growing importance, ECDM tries to help companies design products that cause less harm to 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 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 efficiently, there must be a methodology for assessing a product in terms of its “enviro-friendliness”. This is where the emerging area of Life Cycle Analysis studies merge with the needs of manufacturers.

As mentioned, 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 are entirely driven by economics. That being the case, it is necessary that analyses regarding the retirement stage be based in this economic context.

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. As well, less waste implies that less space has to be reserved for landfill sites.

As the public awareness about environmental issues 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 problems. An example of

their response is the packaging legislation 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 facility 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 reduce the costs of raw materials and waste disposal, (2) the desire to cooperate with the government's environmental goals to discourage future legislation by being proactive, 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 consumers. As a result, companies have found it beneficial 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 for collecting and reprocessing the products at their own expense.

The "Extended Producers' Responsibility" theory is a response to this problem. According to this philosophy, the manufacturer of a durable good is in the best position to take responsibility for a larger portion of the product life cycle. In this context, Germany and other European countries, are considering legislation that will force automobile manufacturers to take back cars when the user is ready to dispose them. Under these conditions, they will be required by law to recycle these vehicles to an extent larger than current practice.

Part of the rationale is that under the “take-back legislation”, the automobile manufacturers will be incentivized to consider recycling in the design stages. It is assumed that the negative environmental impact of automobile disposal will be reduced as a consequence of this regulation.

This direction of European legislation is looked upon with skepticism in North America, where it is believed that mandated recycling could result in inefficiencies and increased costs.

Corporations generally would prefer to allow the disposal and recycling infrastructure to deal with the retirement of their products on its own.

In any case, because of potential legislation, or due to market forces, companies have an interest in studying how economic factors influence the process of recycling their goods.

Recycling and reuse of complex products are difficult activities to understand. This research focuses the analysis 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 dynamic model 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 of the retirement stage of a product’s life cycle.

### **3. Vehicle Recycling Development Center**

The Vehicle Recycling Partnership, a consortium of General Motors, Ford, and Chrysler was established in November, 1991, and is administered by the United States Council for Automotive Research (USCAR), the technical arm of the American Automobile Manufacturers Association (AAMA). The automobile manufacturers were joined by collaborators such as the Automotive Recyclers’ Association (ARA), the American Plastics Council (APC), and the Institute of Scrap Recycling Industries (ISRI), 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. The partnership was formed 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 center is a meeting place for people to discuss vehicle recycling issues. As well, it is an active research center where time-studies are conducted, and recorded, and materials are identified and sorted for recycling.

The VRDC, via General Motors, proposed a project to the Leaders for Manufacturing Program at the Massachusetts Institute of Technology. The proposal involved a general understanding of the issues associated with improving the recyclability of automobiles and identification of leverage points for the VRDC and the automobile manufacturers to improve the recyclability of automobiles. The author of this thesis worked at the VRDC for almost seven months during 1995. This work is the result of the research conducted during that time. The goal of this project was to create tools that would allow the automobile manufacturers to generate actionable learning in the area of automobile recycling.

#### **4. Understanding Automobile Recycling**

The creation of a dynamic industry model that would allow automobile manufacturers to test the potential impact of their decisions became a fundamental objective of this work. This simulation tool would allow the VRDC to give relative priority to alternative projects in terms of their potential benefits. The model captures the economic-driven foundation of the industry, as well as the actual stage of technology. It also incorporates the current industry practices.

Thus, understanding and modeling the critical decision processes of the entities involved in recycling automobiles became a core element for modeling the system. Contrary to the traditional view, the model incorporates a significant portion of the automobile's life cycle: automobile manufacturers, users, dismantlers, shredders, and part of the recyclers are represented in the model.

When automobiles get retired they can be abandoned or they can be acquired by the recycling industry. If they are to be recycled, they would normally be collected and brought to dismantlers. Dismantlers remove some parts for reuse or remanufacture, and some materials for recycling. What is left (the hulk) is then compacted and sent to a shredder. This entity processes the cars and recovers most of the metallic materials. The shredding technology is well established. The recovery yields do not vary significantly. Modeling the shredding step, therefore, required the study of established technology and its potential development.

Modeling the dismantling step, in contrast, is a more complex task. Dismantlers perform this activity based on experience and it responds to a variety of factors. Vehicles get into their facilities in very different conditions, the potential value of their parts vary according to a complex market dynamic that includes the level of their inventories, the exchangeability of parts, the level of demand, and the specific cost associated with dismantling the vehicles. This is a complex optimization process.

Mr. Andrew Spicer, a student of the University of Windsor, Canada, had done previous work in the disassembly area. For his Master of Applied Science Degree in Industrial Engineering, he proposed the development of a Disassembly Modeling Language and a Disassembly Model Analyzer. He made agreements with the VRP to do the experimental work at the VRDC.

Essentially, the author and Mr. Spicer managed to merge their projects into one. The project involved the study of 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.

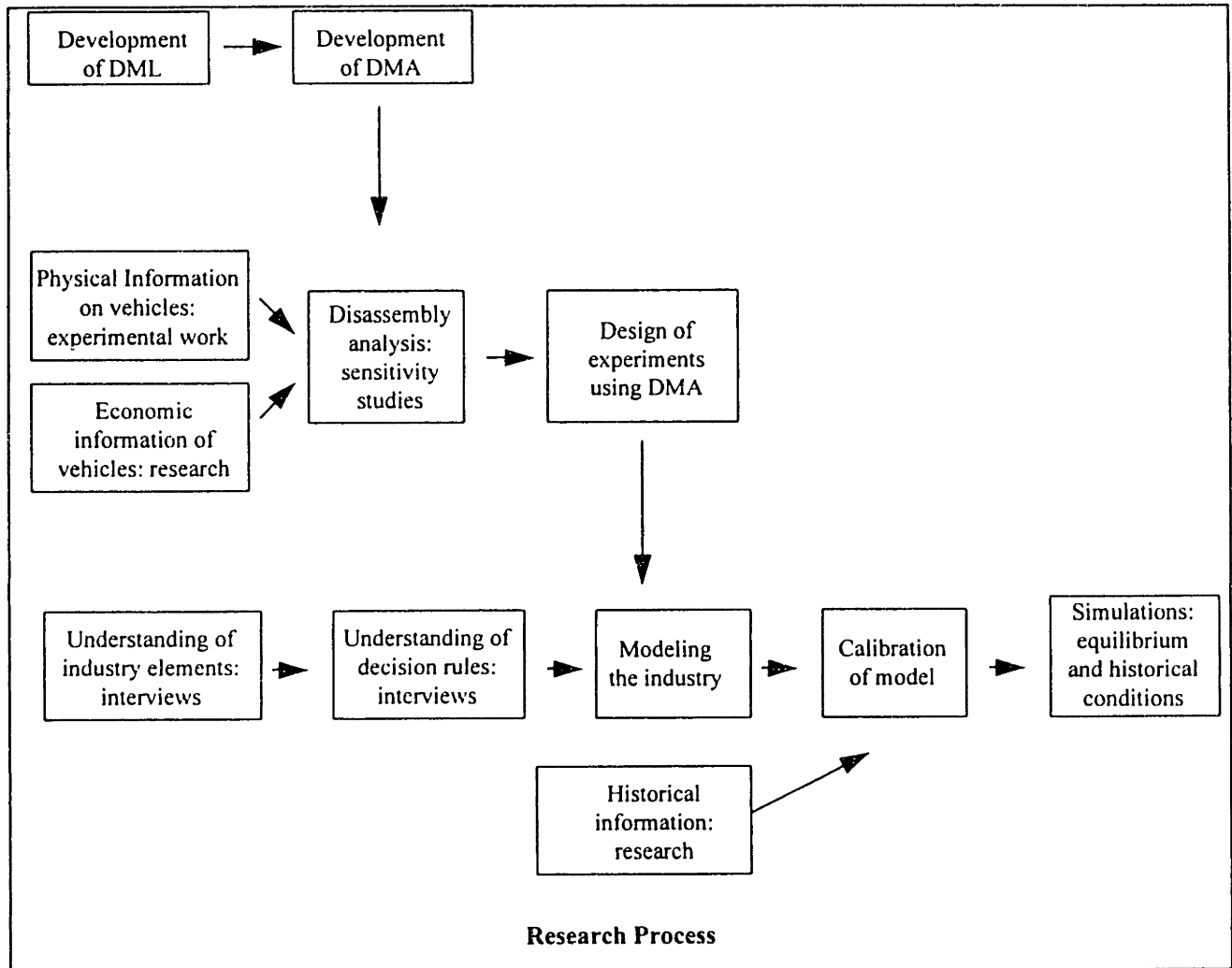
The macro level analysis involves the modeling of the interactions between the segments of the entire industry. This computer based model will allow the automobile manufacturers to use it as a “management flight simulator” to see how the variables they have control over can affect the system. They will also be able to study the potential impact of exogenous changes, such as sales rates, labor or landfill costs, for example.

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 behavior of the automotive recycling industry. This knowledge is an essential segment of the industry model.

For the research of this thesis, four vehicles were dismantled at the VRDC using a specially designed time-study. 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. A large number of interviews were conducted among many of the entities participating in the recycling of automobiles. Some of the information gathered was confidential and therefore, the specific source will not be cited.

The following section describes the main steps in gathering of data and information. Most of the activities here presented were carried out jointly by the author and Mr. Spicer, although the primary focus of Mr. Spicer was the disassembly modeling, and the primary focus of the author was the dynamic industry model.

**5. Research Process**



The figure above presents the overall flow of the research process for the project. The development of the Disassembly Modeling Language (DML) and the Disassembly Model Analyzer (DMA) merged with the research conducted at the VRDC on two types of vehicles. The research included physical and economic information for these particular vehicles. Once the initial analysis of the vehicles and the sensitivity runs were completed, some design of experiments was performed to obtain empirical equations about the disassembly process.

Extensive research was conducted to build the dynamic model. Direct interviews and research on reported trends were the primary source of information. Among other aspects, prices,

composition, flows of vehicles, and cost structures were investigated. The learning from the design of experiments was incorporated into the dynamic model to simulate the behavior of the dismantlers. Finally, some additional research was conducted to calibrate the dynamic model for historical conditions. Simulations under this and under the equilibrium stage were conducted.

The information for the disassembly modeling was gathered from the time-studies 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 Institute of Technology.

## **6. Relevance of this Work**

This work attempts to provide a systematic analysis of automobile recycling. It emphasizes the economic-driven structure and the complexity associated with the disassembly problem.

Therefore, it might be of interest to several concerned parties. However, the primary client of this research is the VRDC, in particular, General Motors, who sponsored the work.

Therefore, most of the analysis included in this thesis is oriented towards the automobile manufacturers. The hope is that the model, and the conclusions from this work, will be used to evaluate alternative projects. The ideal application would be to bring the model into the automobile manufacturers' processes. People at the design stages can use the model to simulate their decisions and understand their effects.

Specifically, automobile manufacturers, by using the tools developed in this work, can analyze the benefits (or pitfalls) associated with design changes and from the policies they implement to increase recyclability. This may help them to focus their efforts on the most beneficial areas. As well, they could determine how much potential legislation may cost them.

Although the thesis is written to that specific audience, other parties might find the tools here described interesting. With different levels of modifications and expansions, these tools can be used by dismantlers, remanufacturers, recyclers, and shredders. Government bodies might also

find these methodologies appealing. Following is a brief description of the types of issues these entities might be able to answer using the tools developed in this project.

### 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.

### 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. They intervene in the market by introducing taxes and subsidies to encourage the desired behavior. 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.

## 7. Project Objectives and Thesis Structure

In alignment with the project proposal from the VRDC, the goal of this research is to create a robust approach to understand the most relevant dynamics associated with automobile recycling in North America. This should allow the automobile manufacturers to understand their role and the potential impact of their policies in automobile recycling. This goal involves the development of a systematic approach to the problem as well as the application of these methodologies to create actionable learning. Following is the research agenda for this project:

- (1) Use of a comprehensive representation method capable of presenting all information relevant to the disassembly of a single product in a computer program. This modeling language should include both physical and economic information.
- (2) Participate in the development of 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 of products as complex as an automobile.
- (3) Apply the language and the analyzer to 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) Using experimental design techniques and the analyzer, generate relationships that can predict the market-driven dismantling practices under various economic and design-based conditions.
- (5) Create a dynamic model of the automobile recycling industry containing the most relevant information and physical flows to create a simulation environment for the manufacturers of

automobiles. The interactions and decisions of the principal participants should be endogenous to the model. This should include the dynamic determination of prices, as well as the determination of demand and supply of products along the recycling chain.

The objectives listed above can be broken into two categories: The disassembly problem (modeling and optimization) in automobiles and the dynamic model of the industry. That is why this thesis contains two major parts. In the first one, the general considerations of disassembly problems are explained in four chapters. An overview of the problem and the information requirements are described. Then the actual information used is presented with the corresponding analysis for one type of car. Sensitivity analysis on dismantling are also shared and Part I ends with the determination of the empirical equations that can simulate dismantling practices as a function of a series of relevant variables. These equations become an essential element of the dynamic model.

The second part of this thesis includes the description of the dynamic model in seven chapters. It contains an introduction to systems thinking using the area of environmental problems as a platform. It then explains qualitatively the major dynamics of the model. The following chapters present a detailed description of the model, its boundary and its initial conditions. One chapter is devoted to the analysis of the system starting at equilibrium condition and one more addresses policy alternatives starting at its current stage. The last chapter of this work summarizes the learning and proposes interesting areas for future work.

## Part I

# The Disassembly Problem

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 other assemblies and indivisible components.

The second category of necessary information involves the economic data. This category includes factors such as the cost of labor, 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. Analytical methods would also face serious constraints in their ability to solve this type of problems due to the non-linearity and integer nature of the disassembly problem. This research presents an optimization method which uses heuristics combined with a genetic algorithm for solving large disassembly optimization problems.

In this part of the thesis, a thorough methodology to perform analysis of this problem is presented. Chapter 1. presents an overview of the problem and describes the information necessary to conduct disassembly analysis. It also describes the Disassembly Modeling Language developed by Mr. Spicer. Chapter 2 explains the disassembly analysis in detail, while chapter 3 contains an explanation of the experimental work conducted at the VRDC. The final chapter of this part shares the information and the analysis completed in one of the two types of vehicles used in this research.



## Chapter I.1

# Disassembly Modeling

To understand the recovery process for complex products it is necessary to have an in-depth understanding of disassembly. Frequently, when the cost of repairing a durable good is large compared to its replacement value, the product has reached the end of its useful life. At this moment, the product as a whole is considered not useful. However, some of its components may still have value, and the only way to realize this value is to disassemble the product and recover the components.

Alternatively, the dismantling may reduce costs during the recovery process. Separation of components and materials have a value because if it is not done, contamination or material incompatibility may cause the recycling cost to increase dramatically.

Disassembly, of course, has costs to weigh against its benefits. The principal one is the cost of labor. Therefore, interested parties are faced with an optimization problem. Entities involved in the disassembly process need to analyze the benefits associated with incremental dismantling versus the marginal labor cost of doing it. From a life cycle analysis perspective, one may need to integrate the environmental impact associated with no-dismantling and the costs of improving the disassembly characteristics of a product.

Product designers and dismantlers are specifically faced with this problem. In the case of dismantlers, the expertise required to optimize the disassembly process has been passed down from one generation to the next because they are traditionally family businesses. In this case, there are several interesting questions associated with the accuracy of their optimization procedure.

Designers within the OEMs are faced with this issue in a very disadvantageous situation; they do not have a process to evaluate the impact of alternative designs. Secondly, the actual product disposal will occur many years into the future, adding a lot of uncertainty to the analysis. This work proposes a methodology that may allow designers to evaluate alternative designs in a systematic way.

Specifically, there are a variety of questions that they would like to have answered about the disassemblability of a product. These questions include:

- How long would it take to fully or partially disassemble the product for recycling?  
How much would it cost?
- Which components or materials can be economically removed and recycled (or reused or remanufactured)?
- What disassembly plan would optimize the profit of the dismantler?
- How can we predict what disassembly actions might take place at the end of the product's useful life?

Answering these questions require a thorough understanding of the disassembly problem. This chapter describes the information requirements for a systematic study of the disassembly problem and introduces a method for modeling that will form the foundation for tools used to answer disassembly questions.

## 1. Relevant Information

Studying the disassembly of a complex product requires information of 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 of the parts and materials contemplated.

### Physical Information

A product is 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 correctly marked to identify the materials, since materials which are not marked will take longer to sort and 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 time-study. 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.

### Economic Information

As explained, disassembly is a technical and an economic issue. This is because in many cases, such as automobile processing in North America, dismantling is done in search of economic benefits. However, even in jurisdictions that have enforced product recovery legislation, the business costs and benefits are of great interest to the companies involved. 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 is the resale value of parts. Within a product there are parts which can be sold for reuse or remanufacturing. 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. The information required here is the economic benefit that the dismantler would gain by removing the component and reselling it. Any component which has a value must be recorded.

The next information type concerns the benefits from the recycling of materials. Some materials, when removed from the product, can be sold to recyclers who will reprocess the material and sell it again for new uses. In this case the information should be quantified as potential revenue per unit of mass of material. The potential revenue per unit of mass of material should be used in the model for the recycling value of this material.

Finally, it is required to specify the potential benefits to dismantlers associated with shredding assemblies. Selling materials to shredders 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 sell them to shredders. Within the shredders' facilities, products are ripped into small pieces. Normally, shredders are designed for large metallic products and are equipped with magnets and other devices for separating as much of the metals as possible. They sell recovered metals and pay for the raw material ("disposed products") -- frequently to dismantlers.

In the disassembly analysis of a product, it is necessary to know what the “hulk” is and how much it is worth if it is to be shredded. Hulk in this context is what remains of the product after the chosen set of components has been removed. 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:

$$\begin{aligned}
 \text{shredding value of the steel} &= (0.05-0.02) * 800 = 24 \\
 \text{shredding value of the plastic} &= (-0.03-0.02) * 200 = -10 \\
 \text{total shredding value} &= 24 -10 = 14
 \end{aligned}$$

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

The second economic information category has to do with the costs involved. One type of costs are those associated with the landfilling of unwanted materials. Landfills typically charge a particular price per volume. In other cases, substances that are considered toxic or hazardous, have to pay a different, higher rate.

The other cost which needs to be included is the cost of the labor required for the disassembly. Within the physical information, removal times are already included. Therefore it is only necessary to add the marginal cost of labor per unit time. If different disassembly activities require labor of different skill levels these activities should receive a different cost per unit time.

The modeling proposed in this research recognizes that the order of disassembly is important by including the concept of precedence constraints. However, it does not allow for the effect of changing the sequence of actions in otherwise identical disassembly plans. 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. In the course of this work the effect of tool changes, for example has not been considered variable. 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 is to be allowed, the modeling problem becomes more complex and may require spatial considerations. Additionally, this would require defining a method to calculate what damaged components would be worth.

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. If disassembly is modeled to this level of detail, optimization for large and complex products becomes nearly impossible; these areas are left for future research.

The information included in the models presented in this thesis allows 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 has a relatively minor effect on the computation of disassembly costs, but makes the optimization procedure possible for large products. The inaccuracy associated with the simplification is quite small and is likely smaller than the inaccuracy caused by the estimation of prices.

## 2. Disassembly Modeling Language

It has been mentioned that the purpose of this work is to create a systematic approach to understand the disassembly problem. One needs to acknowledge the economics and physical constraints simultaneously because this task represents a major optimization problem. Thus, it is desirable to develop a format for explicitly recording the disassembly modeling information. By doing so: (1) disassembly modeling information can be accounted for without ambiguity, and (2) the information can be presented in a machine-readable way. The following paragraphs describe a language, developed by Mr. Spicer, for this purpose.

In addition to being capable of unequivocally representing the relevant information described above, 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 parts’ 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.

Attribute	Description
TIME	<ul style="list-style-type: none"> <li>The TIME attribute is used to indicate the time to remove the part in question from its parent.</li> </ul>
MASS	<ul style="list-style-type: none"> <li>The MASS attribute is used to indicate the mass of a part.</li> </ul>
MATERIAL	<ul style="list-style-type: none"> <li>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.</li> </ul>
MARKED	<ul style="list-style-type: none"> <li>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 textile since any dismantler can quickly determine this.</li> </ul>
BEFORE	<ul style="list-style-type: none"> <li>Used for precedence constraints. The BEFORE attribute is used to indicate that the object part must be removed before it is possible to remove the variable part.</li> </ul>
AFTER	<ul style="list-style-type: none"> <li>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”.</li> </ul>
RESALE_VALUE	<ul style="list-style-type: none"> <li>The RESALE_VALUE attribute is used to specify the value that a dismantler can realize by removing a part for resale.</li> </ul>
LABOR_COST_PER_TIME	<ul style="list-style-type: none"> <li>The LABOR_COST_PER_TIME attribute is used to identify a labor cost for the time invested in removing a particular part.</li> </ul>
RECYCLE_VALUE	<ul style="list-style-type: none"> <li>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.</li> </ul>
LANDFILL_COST	<ul style="list-style-type: none"> <li>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 cost to landfill a part.</li> </ul>

Most lines in a DML file are OAV triplets conveying information about parts. However, in order to differentiate between parts and materials in the file, material names are prepended with “\*.Material.” when they are objects. For example, the next two lines imply that the seat foam is made from PUR which is worth \$0.50 per kg.

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

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

Attribute	Description
RECYCLE_VALUE_PER_MASS	<ul style="list-style-type: none"> <li>This attribute is used to indicate how much a material is worth in the hands of a dismantler if they plan on recycling it.</li> </ul>
LANDFILL_COST_PER_MASS	<ul style="list-style-type: none"> <li>This attribute is used to indicate the cost of disposing of a material.</li> </ul>
SHREDDED_RECYCLE_VALUE_PER_MASS	<ul style="list-style-type: none"> <li>Indicates how much a material is worth in the hands of a dismantler if it is to be Shredded and recycled.</li> </ul>
SHREDDED_LANDFILL_COST_PER_MASS	<ul style="list-style-type: none"> <li>This attribute deals with the net cost to the dismantler for material which is sent through a shredder but is then disposed.</li> </ul>

It is known that landfills charge based on volume, however, 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.

To reduce the total number of 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 LABOR_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 “TIME\_FACTOR” attribute is 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 characteristics of the Disassembly Modeling Language described here make the language a capable completely describing all the relevant information for modeling the disassembly of a complex product. In the next chapter the disassembly analysis is studied. The software developed to analyze this issue uses DML files as the foundation. Among other possibilities, the analysis of the disassembly problem includes the determination of profit-optimizing dismantling plans.

## Chapter I.2

# Disassembly Model Analyzer

One of the goals of the analysis of disassembly models is to define disassembly plans that optimally satisfy a certain objective function. For example, it is believed that automobile dismantlers in North America make profit optimizing disassembly plans.

This type of analysis is a complex task, and attempting to do it 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 formulated for this purpose. Mr. Spicer, the main author, wrote the code using the C programming language.

### 1. Interpreting of the DML information

The DMA is capable of reading and interpreting a Disassembly Modeling Language (DML) file and performing various analyses of it. In addition to defining the optimization of the disassembly plan, the DMA analyzes the structure of the product. 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.

To start the DMA, the run command is given with the name of the DML file to be analyzed as the only command line argument. This instructs the DMA to begin reading the DML file and interpreting it line by line.

The DMA uses three data structures in interpreting the DML information. The first one holds the default values for the attributes that have been built in and can be changed by the user. The second and third structures are prepared to hold information about parts and materials. In reading the information, the DMA uses the default values and pre-determined properties and, by the end, the DMA has 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 without precedence constraints that can be removed with zero time.

## **2. Basic Structure Analysis**

The so called basic structure analyses comprise model reports, path and cumulative time reports, material breakdown reports, and precedence constraint reports. These analyses are relatively simple but can be revealing.

The main DMA menu allows the user to select any of these analyses and create reports of them on the screen or into a file. Following is a description of each of the basic analyses.

The model report is a summary of all the information included in the model. This report lists all the parts and for each it says what the mass, material, time to remove and marking status are. It 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 also includes the economic information -- such as resale value -- for each part. Following the parts, the report lists all the

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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. It 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 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. This analysis is also repeated specifically for parts with resale values.

Basic structure analyses are not very complicated, but they are useful in two ways. First, they can answer simple questions that might be of interest 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. Disassembly Plan Analysis

The DMA 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. It will then compute what the costs, benefits, and profit for the plan.

A disassembly plan is a list of the parts which will be removed from the product or from other parts. 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 labor costs are relatively easy to determine by multiplying removal time by the labor unit cost. This gives a cost for each part, and summing over all parts gives the total.

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 are four choices: resale, recycling, shredding, or landfilling. The DMA chooses the option with the greatest benefits for each piece. However, the determination of greatest benefit requires several calculations to avoid violation of constraints.

First, for resale to be a possibility, the DMA checks that the part in consideration has been removed, is complete, and has a resale value. Second, if one part has a RECYCLE\_VALUE or if the piece is comprised of a single material, then it can be recycled. 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 the previous chapter. Finally, any part can be landfilled. Again, the DMA can also calculate the value to do this.

For each piece that has been separated, these values are calculated. Of the possible values the highest 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 labor cost is subtracted then the profit is known.

The DMA's disassembly plan analysis, as a stand-alone tool, is not necessarily extremely useful. However, it is a fundamental part of the DMA's optimizer since its profit calculation represents the function to be optimized.

#### **4. Disassembly Plan Optimizer**

The DMA 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 disassembly plan profit-optimizer is the most significant part of The Disassembly Model Analyzer. The task it performs is quite difficult, but most useful.

Identification of some parts (and their precedence constraints) that should be resold in all instances, and definition of undesirable parts can reduce the size of the problem significantly. Following is a detailed description of these processes.

##### Identification of the Parts to be Resold

Some parts have a resale value much greater than the costs of disassembly. Thus, the problem can be simplified by identifying those parts and removing them from consideration. Importantly, 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. In other words, for some parts, a direct cost - benefit analysis is sufficient to conclude that they should be removed and sold.



When a part is to be sold, the precedence constraints for that part have to be met and as well the components that comprise the part must be left intact. These conditions imply costs of two types. The first set of costs involve the labor 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 refers to 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. As well, 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 identifies all parts which meet the condition described above and marks them for removal. These parts are kept intact by noting that their components must not be removed from them. It also makes sure to mark the precedence constraint parts for removal.

### Parts Which Are Trivially Undesirable

In this case, parts are in the opposite situation than when those parts are so valuable that it is easy to see that they should be removed. There are some parts which are worthless and should obviously never be removed. These parts are trivially undesirable.

In general, there are two potential benefits to removing a part. The part itself may have some value, or the part may be part of a precedence constraint for another part that has value. When this second possibility is ruled out because it is not a constraint for any other part, 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.

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.

### Grouping of the Remaining Parts

So far it has been explained that the DMA reduces the number of parts from consideration because it identifies parts (and their precedence constraints) that should be removed and resold in any event, and because the DMA identifies as well parts that are worthless (or lead to only worthless parts) and should never be removed. The next step for the DMA is to separate the remaining parts into independent groups.

Using simple rules, the DMA assigns parts to groups with the hope of creating as many small independent groups as possible. If groups are independent, they can be optimized separately. The creation of groups essentially breaks the problem into a number of smaller problems.

Let us illustrate the power of analyzing smaller independent groups. A product that has 16 parts may have up to 65,536 disassembly plans ( $2^{16}$ ). If this product is reduced to two independent problems with 10 and 6 parts only, the total number of possibilities is reduced to only 1,088 ( $2^{10} + 2^6 = 1,024 + 64 = 1,088$ ). Although the DMA optimization process is not based on any exhaustive search, clearly the time required to evaluate a smaller problem would be shorter.

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, and all the components of a part with a resale value belong in the same group. The third condition which governs the creation of groups, is 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.

### 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.

It is important to remember that a solution for a group is simply represented by a series of ones and zeros corresponding to the parts in the group, where a zero means that for this solution, the corresponding part will not be removed, and 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, because the time necessary to evaluate larger groups grows exponentially. Thus, once the smaller groups have been optimized, an alternative non-exhaustive method should be used. The DMA deals with larger groups using an optimization procedure based on a genetic algorithm.

## **5. Optimization by Genetic Algorithms**

Since the time required to optimize a group grows exponentially with the number of parts, when the groups have hundreds, or even tens, of parts the problem cannot be optimized by enumeration. A different method is needed. 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. Disassembly problems are not only integer optimizations, but are highly non-linear because of the subassembly structure and the precedence constraints. It was decided, therefore, to apply genetic algorithms to the problem.

Genetic algorithms (GA) are a class of search mechanisms based on the principle of survival of the fittest. 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 a value associated with the objective function being optimized. 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.

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; a string of ones and zeros. The most common methods of reproduction are crossover, mutation, and replication. 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 single crossover point is indicated by the asterisk, the children are shown below in the second pair of chromosomes. Crossover with multiple crossover points is also possible.

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

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 behind 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.

### Genetic Algorithms Applied to Disassembly Optimization

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 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 above. 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. 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, than 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 reasons to leave individual's genetic information unchanged. 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 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 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.

### 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.

Next, the optimization parameters that the user specified are summarized. 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. 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. As well, the values for the options considered by the disassembly plan analyzer (e.g., resale, recycling, etc.) are 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 useful analysis of the optimal disassembly plan for the product. As such, they are essential 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 disposal treatment of the item in a free market economy without regulation of the dismantling and recycling industries.

## Chapter I.3

# Experimental work at the Vehicle Recycling Development Center

### 1. Dismantling and Time-studies

Two cars were fully dismantled for this project during the summer of 1995. A family-sized sedan was selected ("Car A"), and two cars were disassembled. The first one was carefully studied in an in-depth time-study. The second car was used as a control experiment, which is discussed later in this chapter. Out of consideration for the wishes of the sponsors, the make and model of the car will not be identified. The following segments provide more details on the work involved.

The time-studies 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 time-study and involved the removal and break-down of more components.

For each car 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 time-studies 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 on any car before being sent to the shredder.

During these operations there was 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 were 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 mid-range infrared 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 by comparing the reflected spectrum to a stored computerized library, 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 complete 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, were 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. The discrepancy, according to the experienced dismantlers was a result of a "non-business environment". In principle, when dismantling is done for economic -- as opposed to research -- purposes, dismantlers are under high pressure to work more efficiently.

## 2. 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 performs a search beginning in the local area and expanding until a good sample of parts at various dismantlers has been investigated. A further description of this system is included in the second part of this thesis (chapters II.1 and II.2).

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. In other words, the relevant price is the actual economic benefit that dismantlers would capitalize if they sold each material type at their site. 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 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 1,250 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 dismantling workers may earn up to twenty US dollars an hour. This value was used as the cost of labor for the models. This cost may not represent the actual marginal cost of incremental dismantling because costs such as inventory, handling, and sales force expenses might be also marginal. Additional discussion of this cost is presented in chapter II.4.

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 behavior 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.

The third stage of analysis based on the disassembly model of the vehicles revolves around development of a mathematical model to approximate the results of the optimal disassembly sequence under various combinations of the variables. This can be accomplished using a design of experiments to guide the optimizations to be made with the analyzer in generation of data points.

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.

In the next chapter the specific information about "Car A" is presented. As well the analysis of this data using the DMA is explained. Finally, the results of two design of experiments are included. The equations obtained from the design of experiments represent the fundamental link between the first part of this work and the dynamic model presented in the second part.

## Chapter I.4

### Analysis of "Car A"

"Car A" is a mid-sized family car. Two vehicles of "Car A" were dismantled. Both were manufactured in 1993. The previous chapter described the work completed on these vehicles in detail. This chapter describes and interprets the results of the analyses of this model.

#### 1. Economic Information

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. Figure I.4.1 summarizes the results.

Part -- DML Name	Resale value (US\$)
.DoorFrontRight	430.00
.DoorFrontLeft	525.00
.DoorRearRight	425.00
.DoorRearLeft	425.00
.SeatRearBottom	25.00
.SeatRea.Back	25.00
.SeatbeltFrontRight	40.00
.SeatbeltFrontLeft	40.00
.SeatbeltRearRight	40.00
.SeatbeltRearLeft	40.00
.SteeringColumnAssembly	200.00
.SteeringColumnAssembly.Base	50.00
.TailLightCoverRight	65.00
.TailLightCoverLeft	65.00
.TailLightCoverCenter	50.00
.FasciaRearLower	200.00

Part -- DML Name	Resale value (US\$)
.EnergyAbsorberRearLeft	40.00
.EnergyAbsorberRearRight	40.00
.DeckLid	163.00
.Battery	20.00
.AirCleanerAssembly	113.00
.HeatBoxAssembly	20.00
.HeatBoxAssembly.Motor	28.00
.BrakeBooster	45.00
.CoolingFanShroudAssembly	70.00
.CruiseServo	48.00
.WheelRearRight.Cover	33.00
.WheelRearRight.Rim	85.00
.WheelRearLeft.Cover	33.00
.WheelRearLeft.Rim	85.00
.WindshieldWiperMotor	40.00
.WindShieldFront	50.00
.FrontClip	2115.00
.FrontClip.RadiatorHeatExchanger	85.00
.FrontClip.ACCondensor	135.00
.FrontClip.MarkerLightFrontLeft	17.00
.FrontClip.MarkerLightFrontRight	17.00
.FrontClip.LightFrontAssembly.HeadLightLeft	60.00
.FrontClip.LightFrontAssembly.HeadLightRight	60.00
.FrontClip.LightFrontAssembly.Center	100.00
.FrontClip.FasciaFrontLower	225.00
.FrontClip.EnergyAbsorberFrontRight	43.00
.FrontClip.EnergyAbsorberFrontLeft	43.00
.FrontClip.Hood	200.00
.DriveTrain.ACCompressor	138.00
.DriveTrain.Alternator	75.00
.DriveTrain.PowerSteering	230.00
.DriveTrain.Starter	35.00
.DriveTrain.Engine	730.00
.DriveTrain.Transmission	478.00
.DriveTrain.WheelRight.Cover	33.00
.DriveTrain.WheelRight.Rim	85.00
.DriveTrain.WheelLeft.Cover	33.00
.DriveTrain.WheelLeft.Rim	85.00
.DriveTrain.CradleSuspensionAssy	459.00
.InstrumentPanel.Radio	125.00
.InstrumentPanel.Cluster	125.00
.CatalyticConvertor	50.00

Figure I.4.1. Non-metal recycle values.

The non-metals<sup>1</sup> recycling values were determined based on an 80% discount from the reported prices for recycled materials. Figure I.4.2 lists the values that were used. The value "M" refers to a very large number. The non-metals have no shredder recycling value. In other words, they receive the value "-M".

Non-metal Material	Recycle value per mass (US\$/kg)
ABS	0.1474
Carpet	0.1430
Elastomer	0.1650
PC	0.2002
PC-ABS	0.5632
PE	0.1342
PET	0.1936
PP	0.1122
PUR	0.1870
TPO	0.3784
Xenoy	0.4400
Any other non-metal	-M

Figure I.4.2. Non-metal recycle values.

In the case of 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 in shredding and the losses therein.

Material	Recycle value per mass (US\$/kg)	Shredded recycle value per mass (US\$/kg)
Aluminum	0.2991	0.2622
Copper	0.7169	0.6591
Ferrous	0.0600	0.0982
Lead	0.0902	0.0637
Magnesium	0.9496	0.8801

Figure I.4-3. Metal recycle values.

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

<sup>1</sup> In this work the terms "non-metals" and "plastics" are used indifferently. They both refer to textiles, rubber, glass and plastic.

The final costs are those which were used for landfilling and for labor. The landfill cost for any materials sent by the dismantler to the landfill was 0.0484 US\$/kg. The landfill cost for materials shredded and then landfilled was 0.0440 US\$/kg. The cost of labor used was twenty US dollars per hour. Since the times used in the model were in seconds, this cost was converted to 0.005556 US\$/s.

## 2. DML File

As the time-studies were conducted as described in chapter five, all the data was recorded in a spreadsheet using *Microsoft Excel 5.0*. Each part was represented by a row, and there were columns for the name, the time, the material, whether or not it was marked, the before, and the fasteners. Each part was also assigned a number to help keep track of the parts.

The DML modeling of some parts involved some tricks. 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 analyzer 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. During the dismantling of cars A and B, it was necessary to estimate the material content of some parts (which could not be disassembled) and to model them in this way

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". For metal pieces which are not identified, "SKOM" should be used, which is an acronym for "some kind of metal". 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. Finally, bolts and unclassifiable material should be referred as "SKOS", which stand for "some kind of stuff".

The shredder recycling and landfill values described in the previous section 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. In the North American automotive recycling industry, shredders pay dismantlers a flat rate per unit mass. It is possible to model this 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 per kilogram. On the other hand it is necessary for the analyzer to be able to determine which

materials will go to the landfill and which will be recovered. Therefore, the other criteria is that for shredder-recyclable materials the recycle value should be higher than the net landfill value, and vice versa for non-shredder-recyclable materials. This can be accomplished by assigning shredder recycle values of 0.06 for metals, and also giving them M for a landfill cost. To model the non-metals, -M should be used for the shredder recycle value and -0.06 should be used for the landfill cost. With these values, the dismantler will get paid six cents for every kilogram, but the analyzer will still be able to know that the non-metals should be landfilled. Figure I.4.4 presents the shredder recycling and landfill values used in the model.

Material	Shredder recycle value (US\$/kg)	Shredder landfill cost (US\$/kg)
Aluminum	0.06	M
Copper	0.06	M
Ferrous	0.06	M
Lead	0.06	M
Magnesium	0.06	M
ABS	-M	-0.06
Carpet	-M	-0.06
Elastomer	-M	-0.06
PC	-M	-0.06
PC-ABS	-M	-0.06
PE	-M	-0.06
PET	-M	-0.06
PP	-M	-0.06
PUR	-M	-0.06
TPO	-M	-0.06
Xenoy	-M	-0.06
Any others	-M	-0.06

Figure I.4.4. Shredder recycling and landfill values.

Once the spreadsheet was completed, the next step was to create the DML file. A program was written in C which could take the data from a text file saved by Excel and create the DML file from it. The economic information not included in the spreadsheet was added into the file, and then the file was loaded into the analyzer to check for errors. A number of small errors -- mostly spelling errors -- were corrected and then the DML file was ready for analysis.

The DML file for car A was 98 kilobytes. It had 2,357 lines which referred to 553 parts. Appendix I presents most of the information of the Car A, in a spreadsheet.

### 3. Basic Structure Analysis of Car A

The first step in the analysis of the car was the basic structure analysis. In this step, the Disassembly Model Analyzer was used to gather statistics on the mass and materials of car A, on the precedence constraints and cumulative removal times for parts, and on the marking of materials.

The total mass of car A as modeled was about 1,377 kilograms. 21.2% of the vehicle was non-metals, and 9.5% of the vehicle was non-ferrous metal. The remainder was steel or iron. 76% of the materials did not require identification, but of those that did, only about 8% were marked.

One of the most interesting basis structure analyses that the DMA performs has to do with the possibilities in terms of the material destination. Assuming that the recovery yields at the shredding process are perfect, it is easy to determine the minimum amount of material that would end up in the landfill. In other words, all the non-metal material that is contaminated or is not marked is not suitable for

dismantling, because it has no economic value. By the same token, the metal content of the vehicle will either be dismantled or get recovered after shredding. Therefore, this part of the car can be expected to get recycled. The difference between these two amounts cannot be defined by this simple calculation because it depends on the dismantling

procedure. The plastic parts that are not contaminated, have their

composition identified and have a positive economic value could be dismantled. The optimization process will define the destination for this part of the vehicle. Figure I.4.5 presents this preliminary analysis for Car A. As explained, Car A has 68% ferrous material and 3% non-

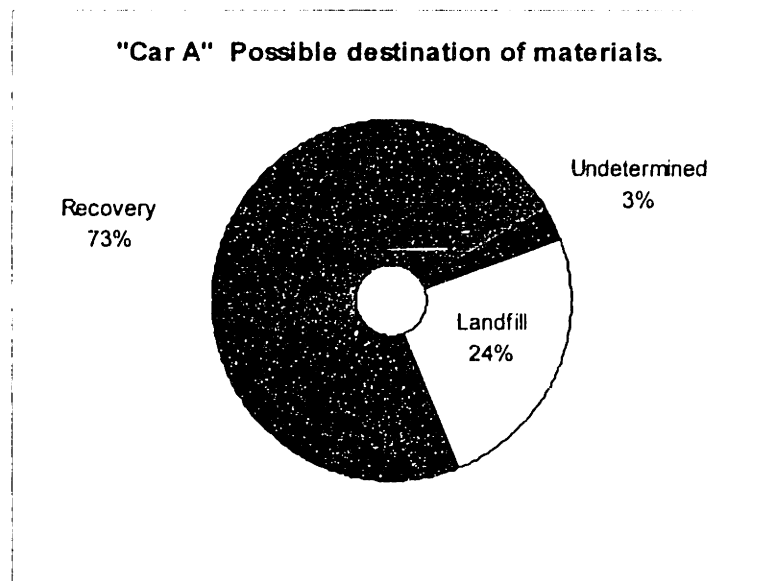


Figure I.4.5.



ferrous metals. These two materials represent the "certain recovery fraction" (72%). Given the level of contamination and the lack of material identification, 24% of the vehicle can safely be expected to end up in the landfill. It is a major finding to observe that the "undetermined" fraction is approximately 3%.

There was a total of 432 precedence constraints in the model. Of the 553 parts, only 133 had no constraints, and 69 had one constraint. One part had as many as 26 constraints. Figure I.4.6 shows a histogram of precedence constraints.

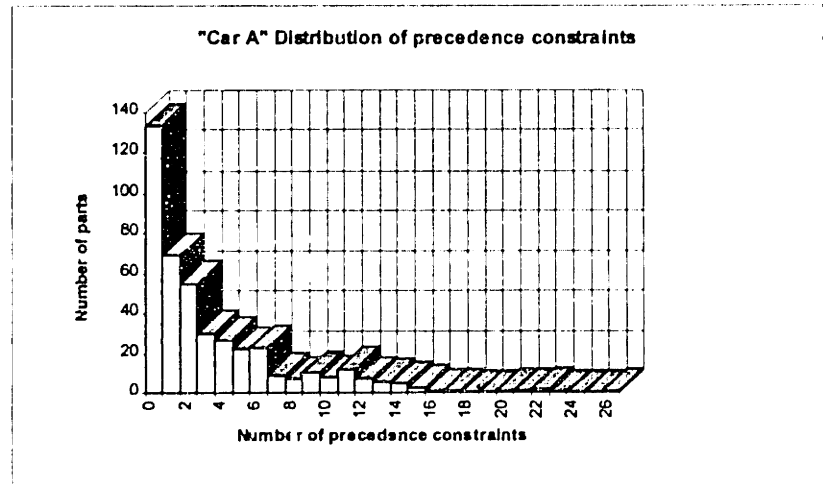


Figure I.4.6.

#### 4. Optimization of the Disassembly Plan: vehicle with all parts intact

When the DML file was interpreted by the analyzer and the optimizer was started, a large number of parts were immediately identified for resale. An additional number 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. This group 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 this group were as follows. The generation size was 150 individuals and there were a total of 250 generations. Sixty five percent of all children were produced by regular mutation, and the rest by resale mutation. The probability of a mutation for children being produced by regular mutation was one per ten parts. The probability of a resale mutation was one per ten resellable 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 a 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, and the time is in seconds.

```
*****
Resale:
45 parts were reused, with a total mass of 876.651855.
These parts were resold for $8276.000000.
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: 37.394001
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: 77.339996
Core_product: 31.818001
PET: 2.450000
Copper: 4.732000
PC: 0.380000
Magnesium: 1.723000
PUR_contaminated: 1.200000
Zinc: 5.554000
PC-ABS: 0.400000
```

The parameter settings which were used for optimization of this group were as follows. The generation size was 150 individuals and there were a total of 250 generations. Sixty five percent of all children were produced by regular mutation, and the rest by resale mutation. The probability of a mutation for children being produced by regular mutation was one per ten parts. The probability of a resale mutation was one per ten resellable parts.

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ABS: 6.240000
Shoddy: 0.240000
Ferrous: 598.411987
SKOS: 39.573002
Glass: 20.042000
Aluminum: 37.394001
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: 77.339996
Core_product: 31.818001
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 (recycled)  
 SKOS: 30.701994 (landfilled)  
 Aluminum: 2.016000 (recycled)  
 PUR: 6.420000 (landfilled)  
 Polyester: 0.240000 (landfilled)  
 PP: 3.500000 (landfilled)  
 PC\_contaminated: 0.040000 (landfilled)  
 Rubber: 4.727000 (landfilled)  
 Carpet: 12.820000 (landfilled)  
 Elastomer: 9.960000 (landfilled)  
 SKOR: 35.545002 (landfilled)  
 SKOM: 0.020000 (landfilled)  
 PET: 2.240000 (landfilled)  
 Copper: 1.908000 (recycled)  
 PC: 0.200000 (landfilled)  
 PE: 0.960000 (landfilled)  
 PPO\_contaminated: 0.500000 (landfilled)  
 PPO: 0.510000 (landfilled)

Total shredder recycling: 358.315948  
 Total shredder landfilling: 140.207001

## Dismantler Landfilling:

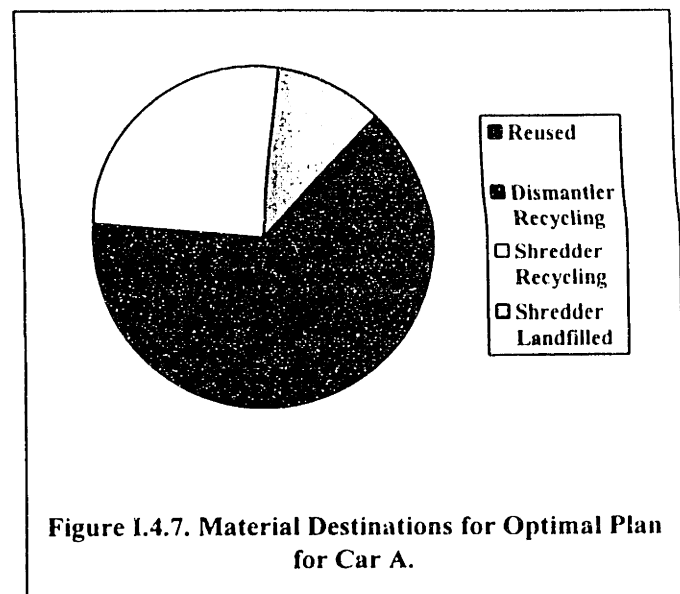
No material was landfilled by the dismantler.

The total dismantling time was 21086.000000.  
 The total dismantling cost was \$117.145393.

Total dismantler profit is \$8189.502552

\*\*\*\*\*

Figure I.4.7 illustrates how much material ends up being reused, recycled, and landfilled. Note that this analysis is on the extreme of an optimistic situation: only 10% of the material is sent to the landfill. This is achieved by investing less than 6 hours in dismantling, and the dismantler realizes a profit of almost \$8,200 per car. The amount of dismantler recycling is imperceptibly small however. Under this condition the major portion of the vehicle is reused. An in-depth analysis of these results is provided below.



According to this plan, it is economical for the dismantler to resell forty-five parts. On closer analysis, it can be shown that no resellable parts are left on the vehicle. Any resellable parts which have not been 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 for 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.

It is evident that there is very little material recycling (less than 4 kilograms) by the dismantler. In fact, the material recycling by the dismantler is only worth seventy four cents! While recycling these materials may have an incremental profit, doing 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

access to 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 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 also eliminates the financial incentive for recycling for the dismantler and allows him to save landfill costs.

Note that more than 877 kilograms are resold as parts, this implies the astronomical revenue of \$8,276. The corresponding hulk is extremely light (less than 500 kilograms) and yields a minute revenue of \$30 to the dismantler.

These results obtained from this first optimization are interesting, but not very realistic. That is because a two year old car in perfect running condition would not frequently find its way into the dismantler's hands -- unless that dismantler is part of a car theft organization.

## 5. Optimization of the Disassembly Plan: vehicle with no parts to be sold

To study the same problem on the other extreme, 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  
 39: Part #435: .WireHarnessCover

\*\*\*\*\*

Group 15

45 members:

0: Part #264: .LowerIP  
 1: Part #267: .LowerIPReinforcement  
 2: Part #268: .LowerIPReinforcement2  
 3: Part #269: .SteeringColumnSupport  
 4: Part #270: .InstrumentPanel  
 5: Part #271: .SteeringColumnSupport.Electrical  
 6: Part #272: .SteeringColumnSupport.Case  
 7: Part #273: .SteeringColumnSupport.Bracket  
 8: Part #274: .SteeringColumnTurnSignal  
 9: Part #275: .SteeringColumnLowerPanel  
 10: Part #276: .SteeringColumnAssembly  
 11: Part #312: .WiringHarnessCloseOut  
 12: Part #331: .HeatBoxAssembly  
 13: Part #332: .HeatBoxAssembly.EC  
 14: Part #333: .HeatBoxAssembly.LateralCover  
 15: Part #334: .HeatBoxAssembly.Elastomer  
 16: Part #335: .HeatBoxAssembly.Filter1  
 17: Part #336: .HeatBoxAssembly.SpringHeater  
 18: Part #337: .HeatBoxAssembly.Panel1  
 19: Part #338: .HeatBoxAssembly.Panel1.Sponge  
 20: Part #339: .HeatBoxAssembly.Panel1.PP  
 21: Part #340: .HeatBoxAssembly.Duct1  
 22: Part #341: .HeatBoxAssembly.Duct1.Pump  
 23: Part #344: .HeatBoxAssembly.Duct1.Structure  
 24: Part #345: .HeatBoxAssembly.Duct1.Structure.Steel  
 25: Part #346: .HeatBoxAssembly.Duct1.Structure.PP  
 26: Part #347: .HeatBoxAssembly.Duct1.Structure.SKOS  
 27: Part #348: .HeatBoxAssembly.Elastomer2  
 28: Part #349: .HeatBoxAssembly.Fan  
 29: Part #350: .HeatBoxAssembly.Motor  
 30: Part #354: .HeatBoxAssembly.Duct2  
 31: Part #355: .HeatBoxAssembly.Duct2.SKOS  
 32: Part #356: .HeatBoxAssembly.Duct2.PP



```

33: Part #357: .HeatBoxAssembly.Box
34: Part #359: .HeatBoxAssembly.Box.Filter2
35: Part #360: .HeatBoxAssembly.Box.PP
36: Part #517: .InstrumentPanel.DuctWork
37: Part #518: .InstrumentPanel.EvapDuct
38: Part #519: .InstrumentPanel.DuctWork2
39: Part #520: .InstrumentPanel.Hoses
40: Part #521: .InstrumentPanel.WireHarness
41: Part #529: .InstrumentPanel.Radio
42: Part #532: .InstrumentPanel.TrayAssembly
43: Part #541: .InstrumentPanel.Ashtray
44: Part #544: .InstrumentPanel.CenterBezel
*****
    
```

Figure I.4.8 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. The computation time for this model was about nine hours on the same SGI Indy.

Group	Size	Number of Generations	Generation Size	Percent children by mutation	Mutation rate per part
1	16	175	100	100%	1/10
2	16	175	100	100%	1/10
7	40	350	200	100%	1/20
15	45	350	200	100%	1/22

Figure I.4.8. Optimization parameters for optimization without resale.

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 51.875004.
These materials were sold for $27.729977.
Breakdown by mass of materials in dismantler recycled parts.
ABS: 3.960000
Aluminum: 28.895000
Xenoy: 18.240002
PC: 0.380000
PC-ABS: 0.400000
    
```

Shredding:

The dismantler sent a mass of 1324.799683 to the shredder.

The shredder paid the dismantler \$79.489235 for this.

Breakdown by mass of materials in shredded parts.

- SKOP: 30.528006 (landfilled)
- Textile\_contaminated: 5.370000 (landfilled)
- Textile: 0.420000 (landfilled)
- ABS\_contaminated: 1.020000 (landfilled)
- ABS: 3.420000 (landfilled)
- Shoddy: 11.187000 (landfilled)
- Ferrous: 954.424011 (recycled)
- SKOS: 70.275002 (landfilled)
- Glass: 20.042002 (landfilled)
- Aluminum: 10.515000 (recycled)
- PUR: 11.420000 (landfilled)
- Polyester: 0.840000 (landfilled)
- PP: 8.719999 (landfilled)
- TPO: 1.700000 (landfilled)
- Lead: 0.080000 (recycled)
- PC\_contaminated: 0.040000 (landfilled)
- Rubber: 4.727000 (landfilled)
- Carpet: 12.820000 (landfilled)
- Elastomer: 10.052000 (landfilled)
- SKOR: 36.065002 (landfilled)
- SKOM: 77.360001 (landfilled)
- Core\_product: 31.818001 (landfilled)
- PET: 4.690000 (landfilled)
- Copper: 6.640000 (recycled)
- PC: 0.200000 (landfilled)
- Magnesium: 1.723000 (recycled)
- PUR\_contaminated: 1.200000 (landfilled)
- Zinc: 5.554000 (landfilled)
- PE: 0.960000 (landfilled)
- PPO\_contaminated: 0.500000 (landfilled)
- PPO: 0.510000 (landfilled)

Total shredder recycling:

973.382080

Total shredder landfilling:

351.437988

Dismantler Landfilling:

No material was landfilled by the dismantler.

The total dismantling time was 2764.000000.

The total dismantling cost was \$15.355678.

Total dismantler profit is \$91.863527

\*\*\*\*\*

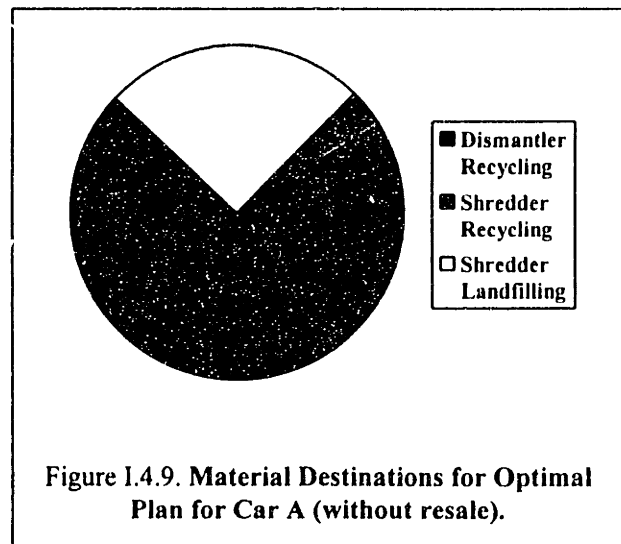


Figure I.4.9 shows a pie chart with the relative magnitudes of the material flows resulting from this disassembly plan. It is clear that this is a completely different dismantling procedure than the one presented in the previous section. For comparison reasons, figure 1.4.10 summarizes part of the results for both conditions.

	Car with all parts intact	Car with no parts to be sold
Mass in parts sold	876.5 kg	0 KG
Dismantler revenue from parts	\$8,276	\$0
Dismantler revenue from recycling	\$0.73 (0% of total revenue)	\$27.72 (25.8% of total revenue)
Dismantler revenue from hulk	\$29.91 (0.4% of total revenue)	\$79.5 (74.2% of total revenue)
Dismantler time/cost	5.8 hours / \$117.2	0.77 hours / \$15.3
Dismantler profit	\$8,189.50	\$91.86
Landfill	140 kg (10.2% of vehicle mass)	351 kg (25.5% of total vehicle mass)

Figure I.4.10. Comparison of key results from optimizations.

The profit in this case is, of course, much less than in the previous situation. The dismantler of this type of vehicle is oriented around recycling. Compare, for example, the 52 kilograms of material recycled by the dismantler to the less than 4 kilograms in the previous case. The revenue from recycling accounts now for almost 26% of the total dismantlers' revenue.

When one compares the economics of these two types of dismantling, it becomes evident that they are caused by being extremely different vehicles. This dismantling practice differentiation is consistent with the industry segmentation. Some dismantlers, for example process only late-model vehicle ("new cars"). Their major source of cars are auctions where they acquire the vehicles at very competitive prices (in the order of thousands of dollars per car). On the other end, "old cars" are bought at extremely low prices -- tens of dollars. These cars are processed rapidly by the dismantlers, who rely on the income generated by selling the hulks to shredders.

Notice that in the case of "old cars" (no parts to be resold), the shrinkage factor for the shredders is more than 25%. This shrinkage factor is a close approximation to the Automobile Shredder Residue and is the percent of the hulk mass that ends up in the landfill.

The total weight of the vehicle as modeled is 1,377 kilograms. In the optimization with no resale 75% of the vehicle was recycled. This is the same as the figure 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.

So far, 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.

## 6. Experimental Design and Results

Although a single variable sensitivity analysis is normally clear and intuitive, it does not represent a good way of studying the behavior of a system that has several variables, because it does not capture the combined effects of simultaneous changes to the values of the key variables. Remember that a fundamental part of the objectives of the DMA studies is to provide a way to estimate dismantling practices under changing environments. The optimum way to do so is to perform a design of experiments aiming to obtain empirical equations that describe the observed results.

The design of experiments work performed for this analysis was aided by the software tool *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 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-ferrous usage
- $(x_3)$  the level of non-metal usage
- $(x_4)$  recycled non-ferrous prices
- $(x_5)$  recycled non-metal prices
- $(x_6)$  landfill cost
- $(x_7)$  labor cost
- $(x_8)$  resale prices.

Once the relevant variables ("x-variables") have been chosen, the next step is to specify the range of values that they will have during the experimental runs. This is commonly referred as the levels of the x-values. In this case, the levels chosen were -1, 0, and 1. Figure I.4.10 indicates the meanings of these levels.

x	Variable name	-1	0	1
1	Level of DFD	Same as Car A except no parts marked	Same as Car A	Less before, fewer materials, parts 100% marked
2	Non-ferrous usage	Less	Car A	More
3	Non-metal usage	Less	Car A	More
4	Non-ferrous prices	Car A	100% more	200% more
5	Non-metal prices	50% less	Car A	50% more
6	Landfill cost	20% less	current	100% more
7	Labor cost	20% less	\$20/hour	50% more
8	Resale price	10% of Car A	15% of Car A	20% of Car A

Figure I.4.10. Values for experiment variables

The experimental matrix defines a series of experiments to be performed which will be used in the analysis. In this case, the experimental matrix was defined using the *DOE Expert* software tool, which proposed the matrix displayed in figure I.4.11. The matrix is of type L12.

Experiment #	x <sub>1</sub>	x <sub>2</sub>	x <sub>3</sub>	x <sub>4</sub>	x <sub>5</sub>	x <sub>6</sub>	x <sub>7</sub>	x <sub>8</sub>
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

Figure I.4.11. Experimental matrix

For the second set of experiments, with no resale values, the columns representing x<sub>1</sub> through x<sub>7</sub> are identical to those in the matrix above.

To run the experiments the DML original file was modified to reflect the new level of the x-variables. In some cases, making the changes was as simple as changing a number -- for example when changing the labor cost. For others, however, the changes to the DML file represented design changes to the vehicle.

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 be reduced in number to 57%. The number of non-metal materials was also halved. This was done by changing TPO, PBT-PC, 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, 1994]. 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. Figure I.4.12 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.

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

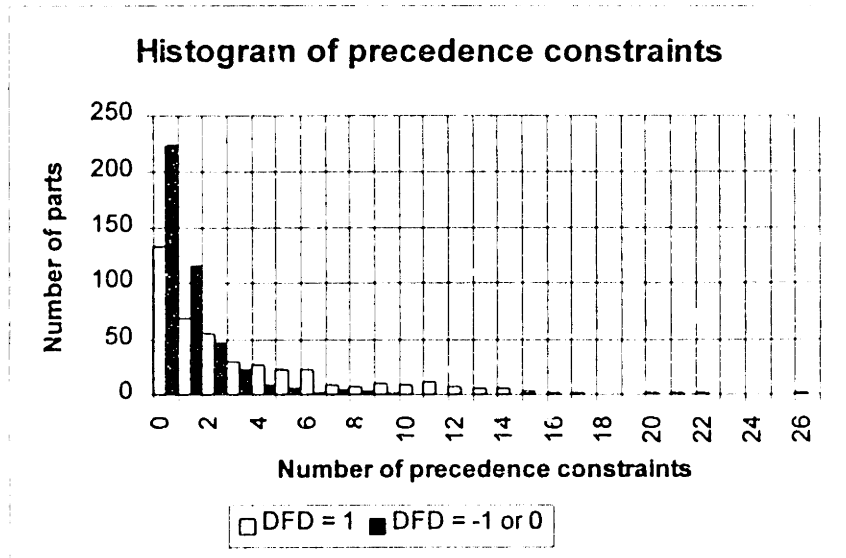


Figure I.4.12 Histogram of precedence constraints, based on DFD level.

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. Figure I.4.13 illustrates the resulting vehicle compositions based on these DML changes.

$x_2$	$x_3$	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%

Figure I.4.13. Effect of  $x_2$  and  $x_3$  on vehicle composition.

The potential effect of the DFD changes is illustrated in figure I.4.14. The interpretation of the "undetermined destination fraction" is the same than the one explained in the basic structure

analysis. The diagram presents the experiment conducted under conditions  $x(\text{DFD}) = 1$ ,  $x(\text{nonferrous fraction}) = 1$  and  $x(\text{plastic fraction}) = 1$ . Note that even though the plastic composition has increased, the percent undetermined has increased. This is an encouraging situation, because, under an ideal situation the landfill percent could be reduced to 15% (compared to 24% minimum in the base case).

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*. A table summarizing the results of the experiments executed for both sets is in Appendix II.

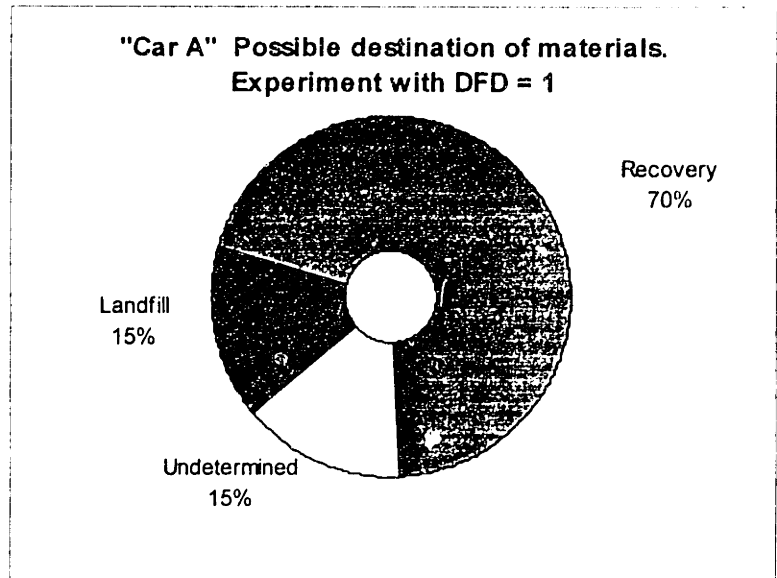


Figure I.4.14

Based on the results of the experimental runs, the coefficients for the empirical equations were calculated. These include: 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. Some of these equations are used in the second part of this thesis when evaluating the dismantling practices. Coefficients are calculated by performing the dot-function of the experimental result vector (appendix B) by the  $x$ -value vector. Equations  $f_i(\mathbf{x})$  refer to the scenario of no resale parts. Equations  $g_i(\mathbf{x})$  consider the scenario with resale. The meanings of these equations for the various  $i$ 's are listed in figure I.4.15 below.



i	Meaning of equation $f_i(x)$ or $g_i(x)$
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.

Figure I.4.15. Meanings of equations  $f_i(x)$  and  $g_i(x)$

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

Figure I.4.16. Equations produced experimentally

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. Figure I.4.16 summarizes the equations which were created using the *DOE Expert*.

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. The following figure summarizes the results.

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-ferrous composition ( $x_2$ )	Lookup graph	Figure I.4.18.
Non-metal composition ( $x_3$ )	Lookup graph	figure I.4.19.
Non-ferrous price ( $x_4$ )	$(\text{Nonferrous\_price\_index} + 100)/100 - 2$	Where Nonferrous price index is the percent change in the recycling values of non-ferrous metals compared to the current values.
Non-metal price ( $x_5$ )	$\text{Non-metal\_price\_index}/50$	Where Non-metal price index is the percent change in the recycling values of non-metals compared to the current values.
Landfill cost ( $x_6$ )	$\text{Landfill\_cost\_index}/60 - 2/3$	Where Landfill cost index is the percent change in the landfill costs compared to current values.
Labor cost ( $x_7$ )	$\text{Labor\_cost\_index}/35 - 3/7$	Where Labor cost index is the percent change in the labor costs compared to current values.
Resale price ( $x_8$ )	$(\text{Resale\_price\_index} + 100)/5 - 3$	Where Resale price index is the percent change in the resale prices compared to current (new) prices.

Figure I.4.17 Equations to produce  $x$ 's.

Most of the equations in figure I.4.17 are simply derived from the definitions of the  $x$ 's at -1, 0, and 1. However, the relationships to generate  $x_2$  and  $x_3$  from the material compositions of the vehicles are based on extrapolation of the 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*. Figures I.4.18 and 19 present these relationships.

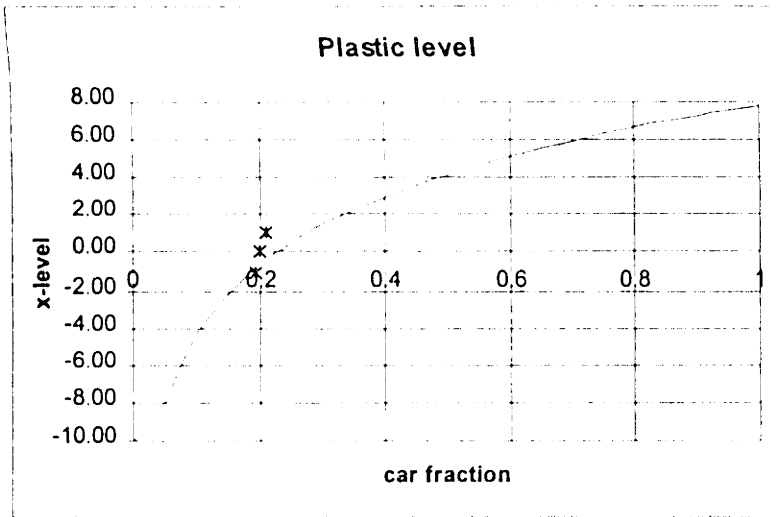


Figure I.4.18

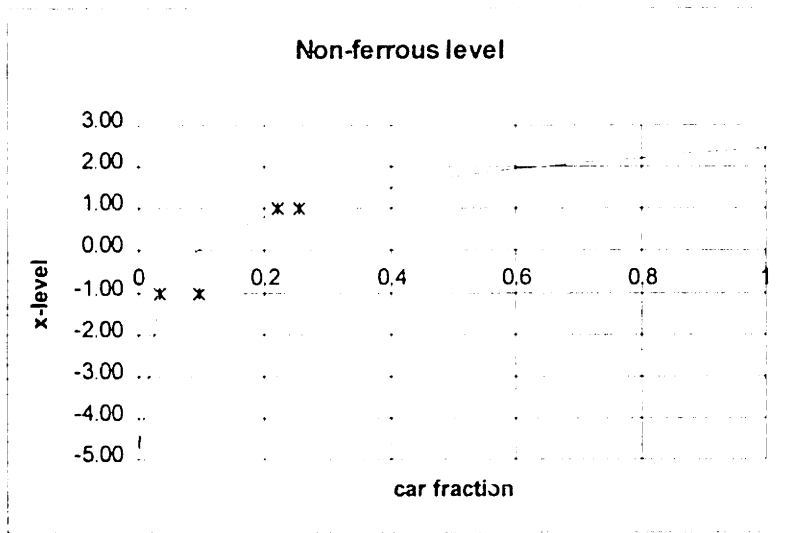


Figure I.4.19

Using figures I.4.16 to 19 it is possible to estimate the material and financial flows associated with the dismantling practices. The required inputs are the  $x$ -variable levels. In order to estimate these flows for an entire fleet of vehicles, it is necessary to understand the effect of the age of the vehicle, the effect of the probability of parts being undamaged, and a portion of the effect of the supply and demand relationship of the parts.

As vehicles age, they tend to have fewer good parts. In addition, the value of the parts may also change as a function of age as determined by the supply and demand relationship. Dismantlers frequently choose to not recover parts that might have value based on their current inventory and their expected rate of sales. As well, the demand for used parts varies over time.

When a vehicle is first introduced, the only cars being retired have been involved in accidents.

Their remaining good parts can not be sold immediately because the other cars of the same age are still under warranty and insurance rules require new parts at this time. As the cars age more and more parts become available, and the demand also increases. After a particular age, the supply of parts from old cars retiring surpasses the potential demand because the vehicle can

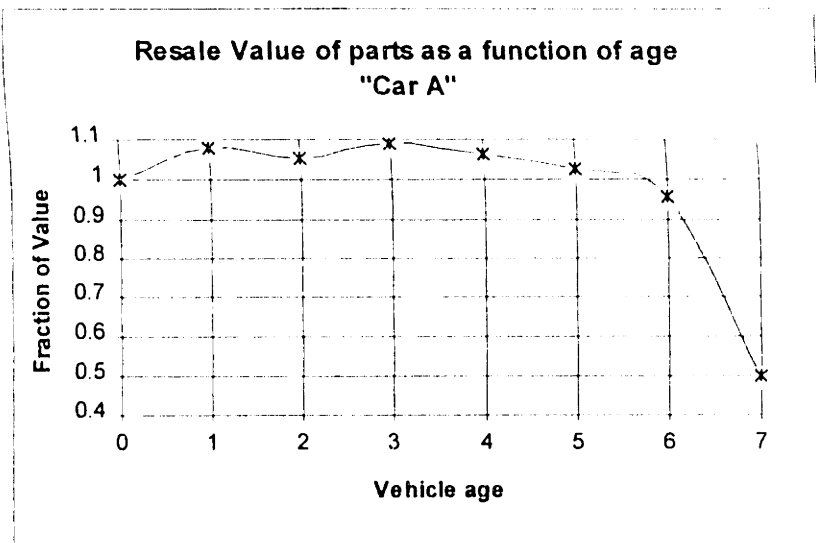


Figure I.4.20

be discontinued or the market can reach saturation. Generally speaking, we can expect that, in the long-run, the value of parts goes down. In the extremely long run, (more than 15 years), it is possible to observe an increase in the value of parts. Again, this is a result of the demand-supply balance. Cars of that age are starting to be considered antiques and their value is increasing. At the same time, there is probably no more supply of those used parts. Figures I.4.20 and 21 present evidence of this dynamic.

In both cases, research was conducted, using the Hollander system, to gather a sample of prices for a basket of parts at different ages of the same car. Figure I.4.20 presents the results for "Car A". Since the current design of "Car A" was fairly recent, there was no information on values of parts after 7 years.

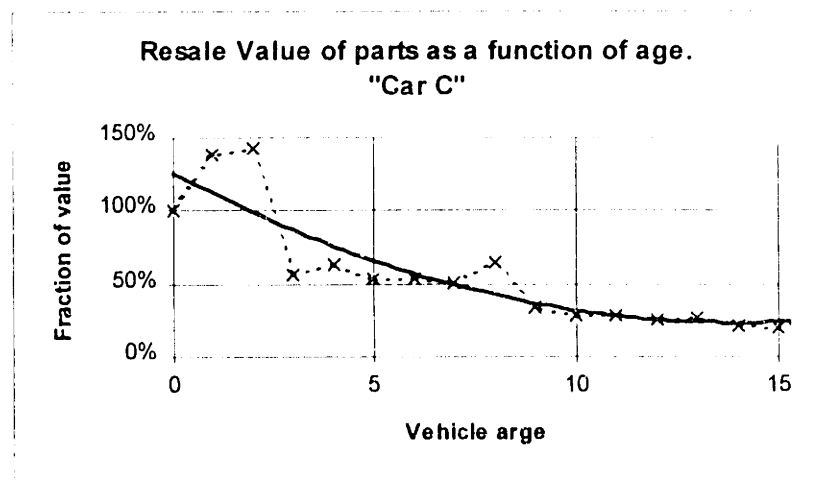


Figure I.4.21

"Car C" is a vehicle that has been offered to the market for a long time without major

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modifications. Information for this vehicle was obtained up to 15 years. Figure I.4.21 includes a trend line to suggest the long-term path. Both graphs were built by comparing prices at different ages to the prices of a 1995 model. The basket of parts was: right front door, tail light, engine assembly, headlamp, park lamp, radiator, front seats, power steering pump. For each of them between 5 and 20 prices were researched.

Part II of this work includes a detailed description of the use of equations in figures I.4.16 and 17. The assumptions on condition, supply, demand and value of parts is also explained later.

## 7. 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 scrap price of steel, the resale prices of parts, labor costs (for scenarios with and without resale) and on landfill costs. 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.

### Plastic prices

Sensitivity analysis was carried out on the values for plastics recycling. This was done by changing these values in the DML file and optimizing the disassembly plan many times. The values were investigated between 100% and 800% of the current recycling values. Materials that are currently not recyclable remained that way throughout the analysis. This is, contaminated material, parts without material identification and materials lacking a market were not affected during this simulation.

Figure I.4.22 illustrates the results.

The percent of non-metals recovered climbs from about 5% to over 15% as the recycling prices rise to four times their current values. This only results in a small change in the percent of the vehicle landfilled, however. By the time recycling values reach 800% they are certainly beyond the virgin prices for the same material, which is quite unrealistic, but it conveys the point that pure economic forces (without government intervention) would not necessarily result in much more recycling.

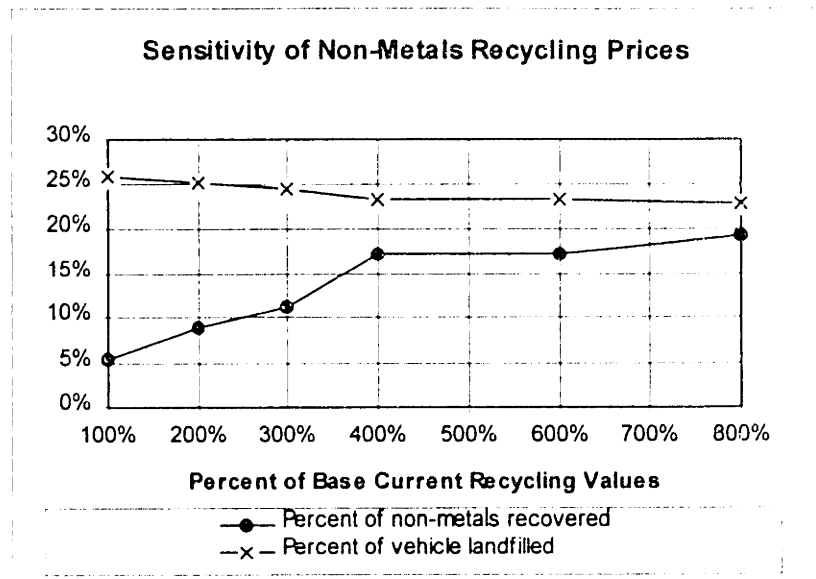


Figure I.4.22. Sensitivity of Non-Metals Recycling Prices for Car A

### Scrap Price

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. As explained in the case of the optimization without resale parts, most of the dismantlers' revenues come from the hulks. Therefore, this price is of paramount importance to the recycling infrastructure. However, the hulk price does not help to differentiate in terms of the dismantling practices.

Resale Prices

The optimal disassembly plans were not sensitive to resale prices of parts, 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.

Labor Cost

A study of the effect of labor prices was conducted for scenarios both with and without resale of parts. The case without resale showed virtually no increase in the amount being landfilled as the labor price was raised. Again, labor cost could jeopardize the viability of the whole industry, but does not define the dismantling process. In the case of no resale parts, a minor improvement in the landfill rate was witnessed as labor costs were reduced to zero. Figure I.4.23 illustrates the results.

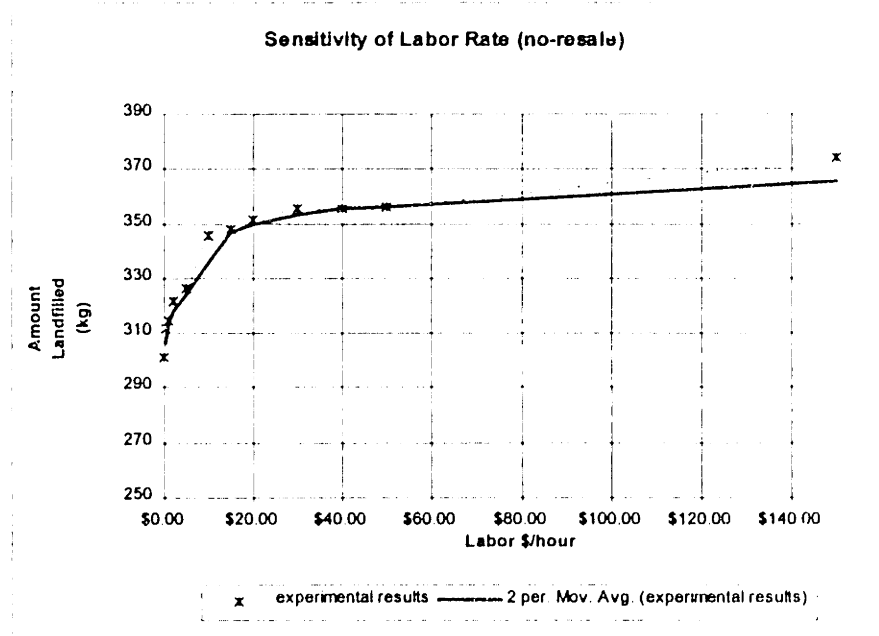


Figure I.4.23. Sensitivity of Labor Cost for Car A (with no resale)

The investigation into the effect of the labor cost on the disassembly of cars with parts for resale had a similar result. The labor costs did not change the amount to be landfilled by a large percentage, even when pushed beyond reasonable limits. The next figure illustrates the outcome.

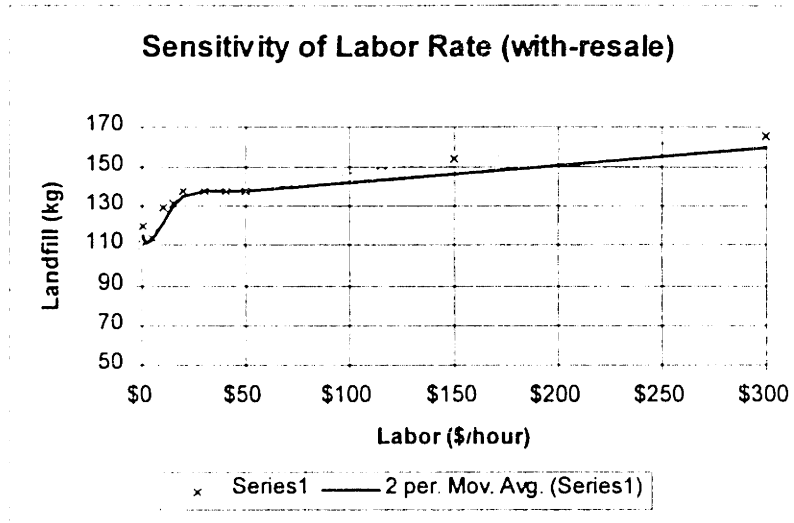


Figure I.4.24. Sensitivity of Labor Cost for Car A (with resale)

Landfill Cost

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 a very small sensitivity was observed. The dynamic effect of a lower shredder’s profitability is studied in the second part of this thesis.

The Optimistic Case

A final analysis was performed based on the virgin material prices. In this case, all the recycling values for the non-metals were set to that of the virgin prices. As well, contaminated materials and unidentified materials were also given recycling values. The DML file corresponding to this



analysis was then optimized. The following pie graph illustrates the material destinations for this scenario.

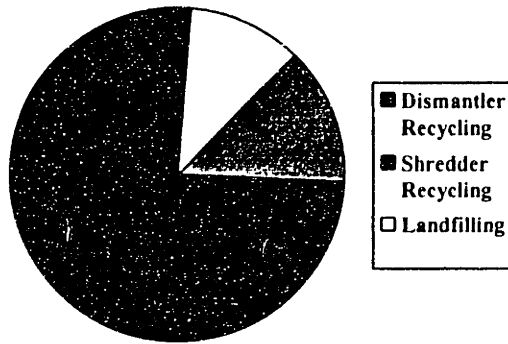


Figure I.4.24. Optimistic Scenario

In this case, the landfilled amount drops to about 11%, which is an excellent improvement over the current estimate of 25%. Of course, it is entirely unrealistic for these material prices to be equal to the virgin prices. As well, this scenario benefited greatly by having all materials identified, recyclable, and uncontaminated.

## Part II

# The Automobile Recycling Dynamic Model

“While the web of interdependencies tightens, our capacity for thinking in terms of dynamic interdependencies has not kept pace.” This is why “the problems that we currently face have been stubbornly resistant to solution, particularly unilateral solution” [Barry Richmond, 1993]. Systems Thinking, and in particular System Dynamics, is a methodology well suited to help decision makers close this gap. This methodology has at its core the ability to deduce behavior patterns rather than seeking to predict events. “It combines the human’s ability for making meaningful structure with the computer’s ability for correctly tracing out the dynamic behavior patterns implied by that structure” [Barry Richmond, 1993].

Accordingly to the founder of System Dynamics, Prof. J. Forrester from the Massachusetts Institute of Technology, in a “dynamic information-feedback system, decision makers have access to much less than the total existing information, but more importantly, much less than the information available is actually used” [Forrester, 1994]. Accordingly, System Dynamics accepts the “bounded rationality” interpretation of policy in which decisions are based on limited information and action is directed toward local goals [Morecroft 1983, Simon 1979, Simon 1972]

System Dynamics is a methodology that captures the processes in which managers convert their available and selected information into actions. This involves the use of explicit policy rules; the knowledge and the mental data of policy makers [Morecroft and Sterman, 1994]. In identifying the processes to choose a course of action, System Dynamics acknowledges the feedback and the delays associated with managers' actions and decisions. Thus, a dynamic model contains the decision rules for managers and simulates their access to information. It also evaluates how managers' actions change their environment and how corresponding changes in the information are incorporated into the next round of decisions. The evaluation of this type of dynamic problem is handled using computers and software specifically designed for dynamic modeling.

### Dynamic Industry Models

Dynamic industry models are computer tools that reassemble the major interactions among entities in the industry being contemplated. In general, they are used to generate learning and leverage points for policy makers. They consider the feedback loops and delays in the system. These two characteristics make alternative approaches seem relatively inefficient. In a dynamic model, a series of simultaneous differential equations are evaluated using numeric methods. During the simulation, the values of each variable are recorded and their structural behavior is studied.

Interactions between industry participants may include transfers of "things" (products or money, for example) or transfers of information. Entities perceive trends or changes in their inputs, or in their environment. They base their expectations on their perception of reality and make decisions accordingly. The dynamic complexity is simply the result of the fact that, while parties base their decisions on the image they have of how reality works for them, it is also true that by taking actions in their context they change their environment.

Decisions by industry participants normally have to do with the speed at which they decide to react to changes in the environment - this is why, these variables are generally called *rates*. They can include, for example, the rate at which they decide to buy raw materials, or sell finished products.

The rate at which they expand (or contract) capacity is another example of decisions made by entities in an industry model.

In this type of models some variables are treated as *stocks*. Stocks represent variables that accumulate (or de-accumulate) over time. Capacity, inventories, and backlog are examples of stocks. The inflows and outflows from a particular stock are rates.

Generally, transfer prices constitute a fundamental part of models because entities have economic objectives. In the pursuit of profitability, each entity would make decisions differently when they perceive there are opportunities or when they perceive threats in the future.

### The Automobile Recycling Industry in North America

In this, the second part of the thesis, the Automobile Recycling Dynamic Model (ARDM) is presented. The ARDM captures the major interactions between the automobile manufacturers, consumers, dismantlers and shredders. Automakers are responsible for the material selection, the car weight and other design characteristics. Consumers of vehicles are the general public, who buy and later dispose of the automobiles. Dismantlers normally acquire deregistered cars and process them by removing some parts for reuse and some for remanufacture. They could potentially dismantle vehicles to recover specific types of materials as well.

What is left after the dismantling is complete is called the *hulk*, and is sold to shredders. There are about two hundred shredders in North America and they are said to process about 94% of vehicles that are deregistered. 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 hammer mill (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, as well as some leftover metals. This mixture is known as *Automotive*

*Shredder Residue* (ASR) or auto fluff. Most of the fluff is sent to landfills. ASR represents one of the major environmental concerns associated with disposing of automobiles.

The figure below illustrates the main physical flow in the automobile recycling industry. Notice that there is a relationship between the recovered materials back to production. The ARDM tries to close this loop by linking the key stimuli of sales (and production) of automobiles to the drivers of scrap demand.

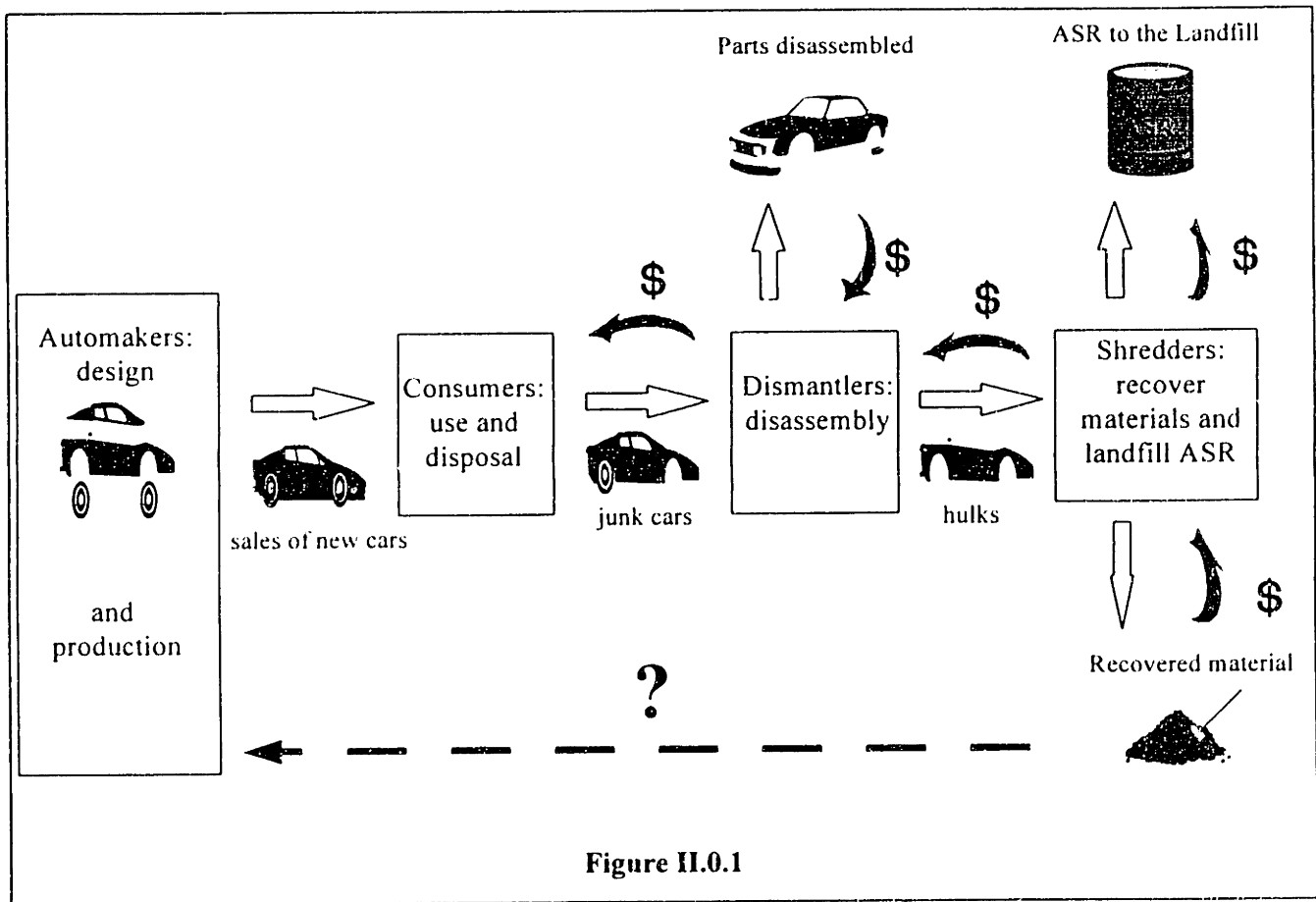


Figure II.0.1

The ARDM was built based on direct bibliographic research and interviews conducted mostly in the Detroit Metropolitan area. The VRDC coordinated a series of talks with different parties involved in recycling automobiles in North America. The following list illustrates the breadth of the research.

## Automobile manufacturers' organizations

- GM: development and design groups
- Ford: development and design process
- Chrysler: vice-president and corporate staff for environmental issues
- GM: senior managers in corporate are for environmental research and corporate objectives
- GM: new parts division
- GM: pyrolysis research group
- GM: North American Marketing
- Ford: statistical analysis groups (customer behavior)

## Dismantlers

- Schram Auto & Truck Parts: Hollander System
- Schram Auto & Truck Parts: operation procedures, dismantling practices for "new cars"
- Olson's Auto Parts: U-pull it yard practices
- D&R Auto Parts: dismantling practices for "new cars"
- Fox Auto Parts: dismantling practices for "new cars"
- Highway Auto Equipment: dismantling practices for "old cars"
- Schram Auto & Truck Parts: disassembly process
- Lindell Co: disassembly process
- T. Lindell (dismantlers' consultant): dismantling industry

## Shredders

- Mason Iron
- Huron Valley Steel
- Sam Allen (now called "TBS Recycling")
- David J. Joseph Co

## Repair Shops

- Automotive Service Association
- Westborn Collision

## Landfill

- City Management

## Government Institutions

- Department of the Interior: Bureau of Mines

## Materials Industry

- Aluminum Association
- American Iron and Steel Institute
- Steel Recycling Institute
- Broker: David J. Joseph Co
- American Plastics Council

## Car registration (flows)

- MI State Police
- National Insurance Crime Bureau
- L. Polk

The majority of the interviews were conducted during the first half of the internship, however, some others were conducted after having started modeling the industry. In conjunction with the bibliographic research, they represent the source of the information that is contained in the ARDM. The author wants to extend a sincere appreciation to all the people that spent time sharing their experience and points of view.

The automotive recycling industry in North America dates back to times long before recycling and environmental consciousness were in vogue. Today it represents probably the most successful recycling story [Field, Eherenfeld, Ross and Clark 1994]. The industry is processing retired cars and trucks at a rate of ten to twelve million per year. It is commonly recognized that this industry works extremely efficiently because it is economically driven. In other words, each participant makes decisions seeking to optimize their monetary benefit. In the course of this part of this work it will be argued that it is not only the economic foundation what makes this industry a success. Rather, it can be shown that technological development has been a fundamental success driver, by creating the conditions for economical recovery of metals. The development of the electric-arc furnace and the shredding technology solved the abandoning problem observed in the late 60s and early 70s.

The ARDM explores other areas of interesting questions about the future of the industry. A major portion of the non-metal (plastic) composition of the vehicles is not recovered in any way today and ends up in the landfill. This is a pure cost to the recycling industry and has a double negative impact: it increases processing costs (transportation and shredding) and requires an outflow of resources (disposal fee).

In addition to an increase in plastic usage, the average weight of the vehicles has been a continuously reduction over time. These trends pose severe concerns on the future viability of the industry. Interestingly, they are to a significant extent, the response to legislation for fuel efficiency, another environmental goal.

“What would happen if suddenly, shredders find themselves operating at a loss because the plastic content of the vehicles is too large?” “What if the dismantlers see their profits diminished because shredders cannot afford to pay them higher prices for the hulks?” “Would Design for Disassembly (DFD), an emerging concept in Environmentally Conscious Design and Manufacturing, save the industry?” Clearly, removal times are also a cost to the industry (labor cost), but “Can we expect DFD savings to offset the additional costs caused by more plastic usage?”

“What about changes in landfill tipping fees?” “Would it be enough to make the industry collapse, or alternatively, is this an efficient incentive to encourage more dismantling and recycling?” “What are the consequences of a continuously increasing rate of sales of vehicles, if any?” These and other questions are addressed in the rest of this section of the thesis.

Any dynamic model can be used for several purposes. Although the original intention defines a lot of what the model includes, it is frequently the case that upon completion of the model, it represents a major source of additional learning. This work includes only the initial manipulation of scenarios and learning that the ARDM can generate.

More importantly than forecasting, the model can be the basis for hypothesis testing and for discussion. As it has been explained, the environmental impact of disposing durable goods is not an area with which companies are familiar. Neither is the scientific community an expert on this field. From the definition of what is *recyclable* to the implementation of strategies, there is a lot of miscommunication that prevents constructive dialogue. The ARDM, because it is explicit in every aspect, can bring people together and promote constructive discussion. Nothing will satisfy the author more than knowing that industry participants disagree with some of the model’s assumptions and simplifications, and accordingly they would work on restructuring and expanding the model.



## Chapter II.1

# Loops in the Environmental Arena

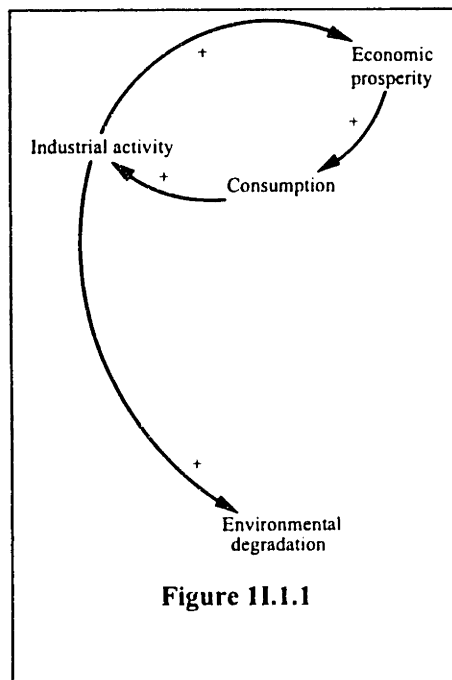
The first activity towards building the dynamic model of the automobile recycling industry was to present the basic principles of Systems Thinking to the people working at the VRDC and to some other individuals working in environment-related groups within the automakers. Although, the people invited to these introductory talks were individuals that could contribute later to building the model, the initial focus of these presentations was not to identify specific dynamics of automobile recycling, but to introduce the Systems Thinking mind frame.

Three presentations were offered describing the concepts behind mental models, feedback loops, traditional linear interpretation of reality versus dynamic causal loops, etc. The initial reaction was very positive and some groups asked for additional presentations to some other internal groups working on LCA and other pollution prevention topics.

As a second step several workshops were coordinated to stimulate the participation of individuals with the objective of identifying feedback loops in the context of environmental problems, in particular on pollution sources and material recycling. In this chapter some of the major areas explored during these discussions are presented. The loops presented here do not represent a comprehensive group of issues associated with this topic. Rather, they are a sample of the

discussions conducted. Neither do they represent the personal opinion of the writer, nor the automobile manufacturers. They are just an introduction to the complexity associated with the environmental challenge and with automobile recycling. In the following chapters several hypotheses presented in this section are challenged and additional relationships proposed.

### 1. Environmental degradation



The figure II.1.1 presents one of the initial relations recognized during the workshops. An increase in the economic conditions of a region stimulate consumption. This additional consumption is met by incremental production. And it is production which is a main driver of economic prosperity. The side effect of this is that pollution, or environmental degradation, is also caused by industrial activity.

This relationship suggests that a system that is improving in its economic position would damage its environment incrementally. Optimists explained later that if the

environment gets hurt, people perceive more clearly the benefits of a clean planet. This increase in the value people would place in environmental protection would result in an increase in undertaking projects to protect the environment. These projects would contribute to decrease the level of environmental damage. Figure II.1.2 illustrates this cause-effect relation.

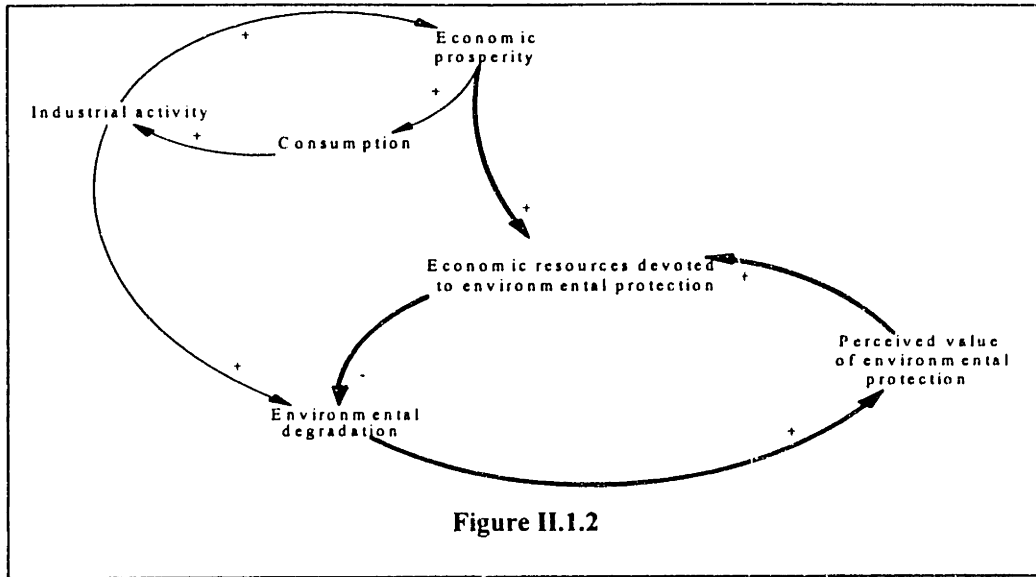


Figure II.1.2

Furthermore, some participants also explained that economic prosperity would cause people to associate a higher value to the environment. The mechanism proposed is that if the region prospers, people would have more disposable income, and this would increase the number of parameters that are critical when making purchase decisions (purchase differentiators).

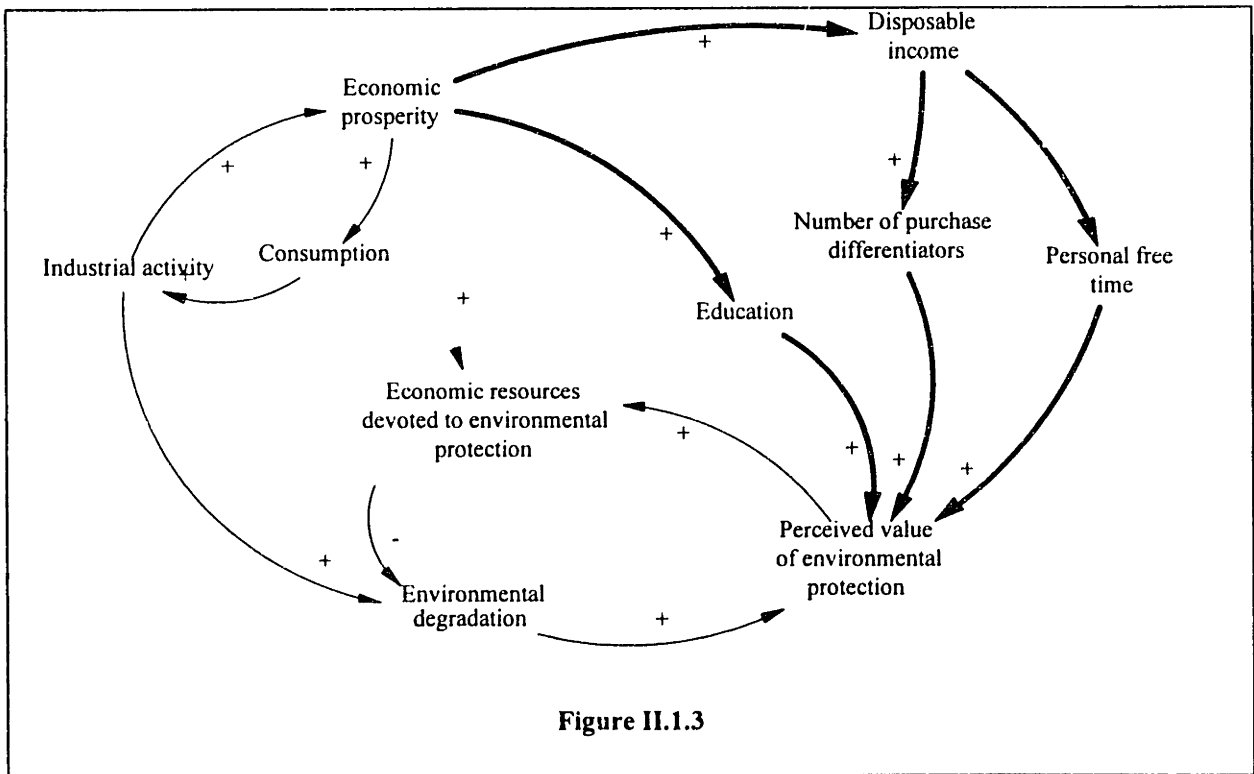


Figure II.1.3

Additional disposable income would give people the opportunity of incorporating environmental parameters when deciding what to buy. Additionally, an increase in disposable income can

generate more personal free time, which will also result in people taking the time to enjoy, and therefore value a better environment more. Economic prosperity can result in more education which again would contribute to increase the perceived value of the environment. Figure II.1.3 illustrates this series of positive influences of economic prosperity on the perceived value of the environment.

Some people argue that devoting resources to environmental projects would have an effect on economic prosperity. The reason is that, even when some environmental projects may have a potential positive monetary pay back, this is not the case for all environmental projects. The “low-hanging-fruit” will not be there forever. This means that the more environmental projects are undertaken, the less monetary return one can expect from them. At the end, environmental protection is a real cost, and not always an additional source of income. Internalizing this cost may have a decelerating effect on economic prosperity. The figure II.1.4 incorporates this effect. As one can see, the less the pay back is on an environmental project the less interest there may be in investing in environmental projects.

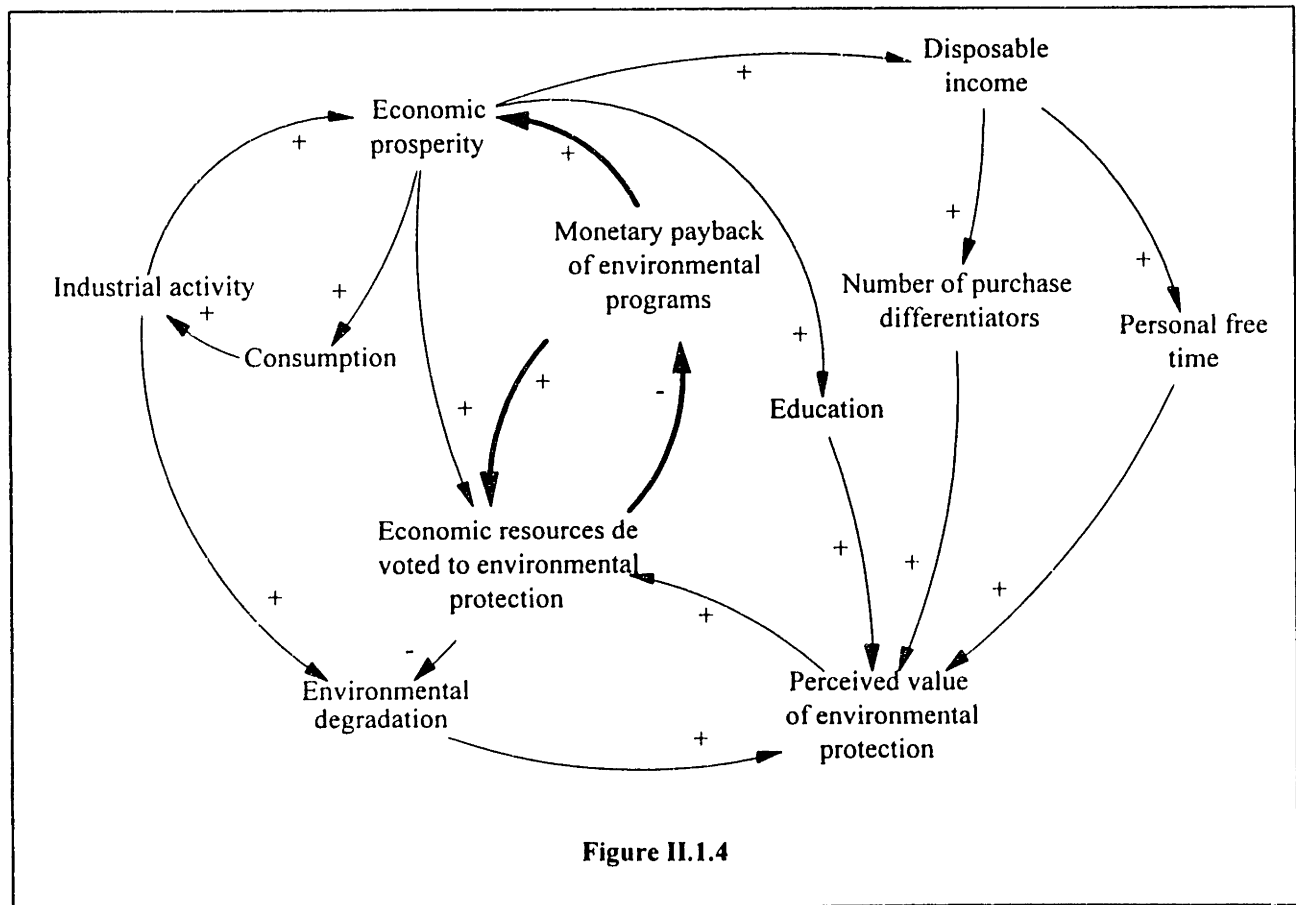


Figure II.1.4

The final discussion on this area was centered in the recognition that even when most of these relationships certainly exist in reality, the combined effect of them was difficult to estimate because of the uncertainty of the relative strength of these relationships and the significant delays associated to some of these connections.. Environmental degradation as a result of industrial activity is something that probably happens faster than the process of internalizing this degradation into a higher perceived value of the environment. The effect of environmental protection projects on environmental degradation was also considered to be a slow effect.

## 2. Recycled materials

Figure II.1.5 presents the main interaction that would foster the use of recycled materials. As the

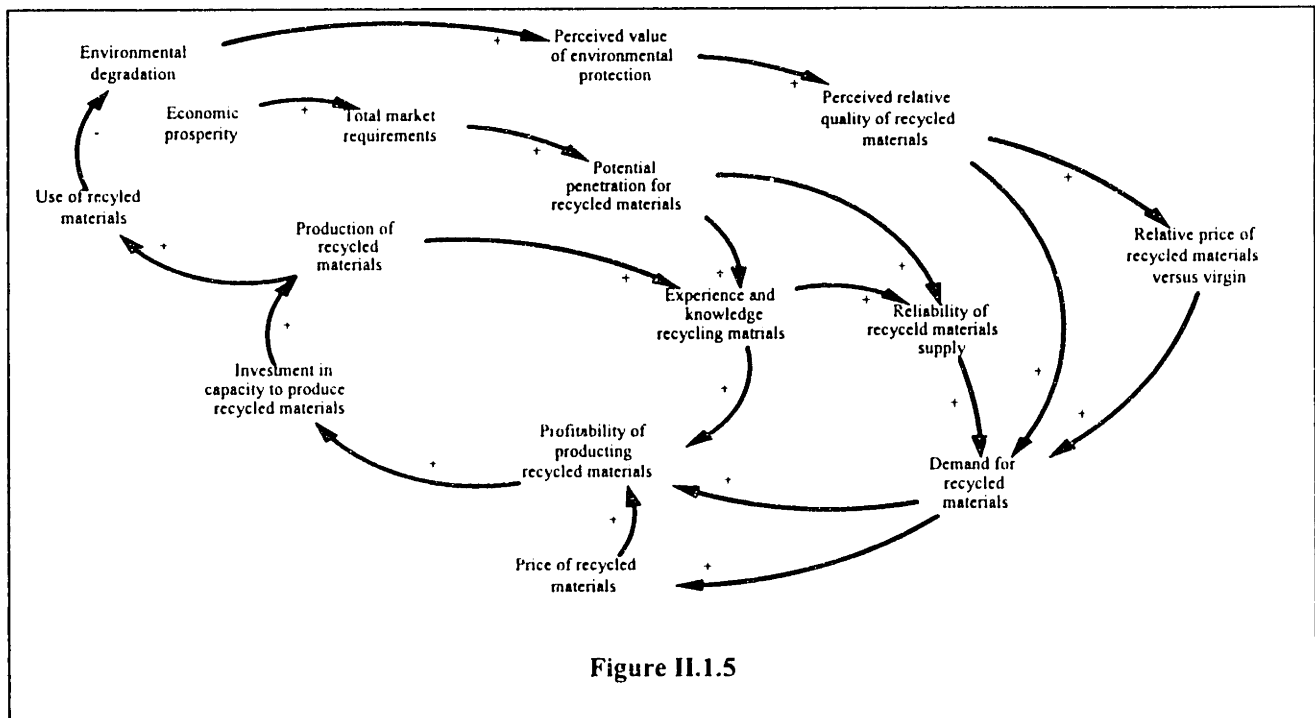


Figure II.1.5

perceived value of environmental protection increases the relative quality of recycled material to virgin increases, because people consider recycled materials to be more environmentally friendly. In addition, economic prosperity increases the total market demand for materials, which would increase the potential market for recycled materials. These two effects contribute to increase the demand for recycled materials, which in turn, would bid their price up and increase the profitability of recycling. As this activity becomes more profitable, more capacity is put in place

to recycle materials and thus, more materials are recycled. The additional benefit of increasing recycling is that variable costs would be reduced as a consequence of the conventional “learning curve” effect. More production of recycled materials increases the level of reliability that industry perceives in the supply of recycled materials, resulting in higher demand. As demand goes up and production goes up, the use of recycled material would also increase. Finally, an increase in use of recycled material would turn into reducing environmental degradation.

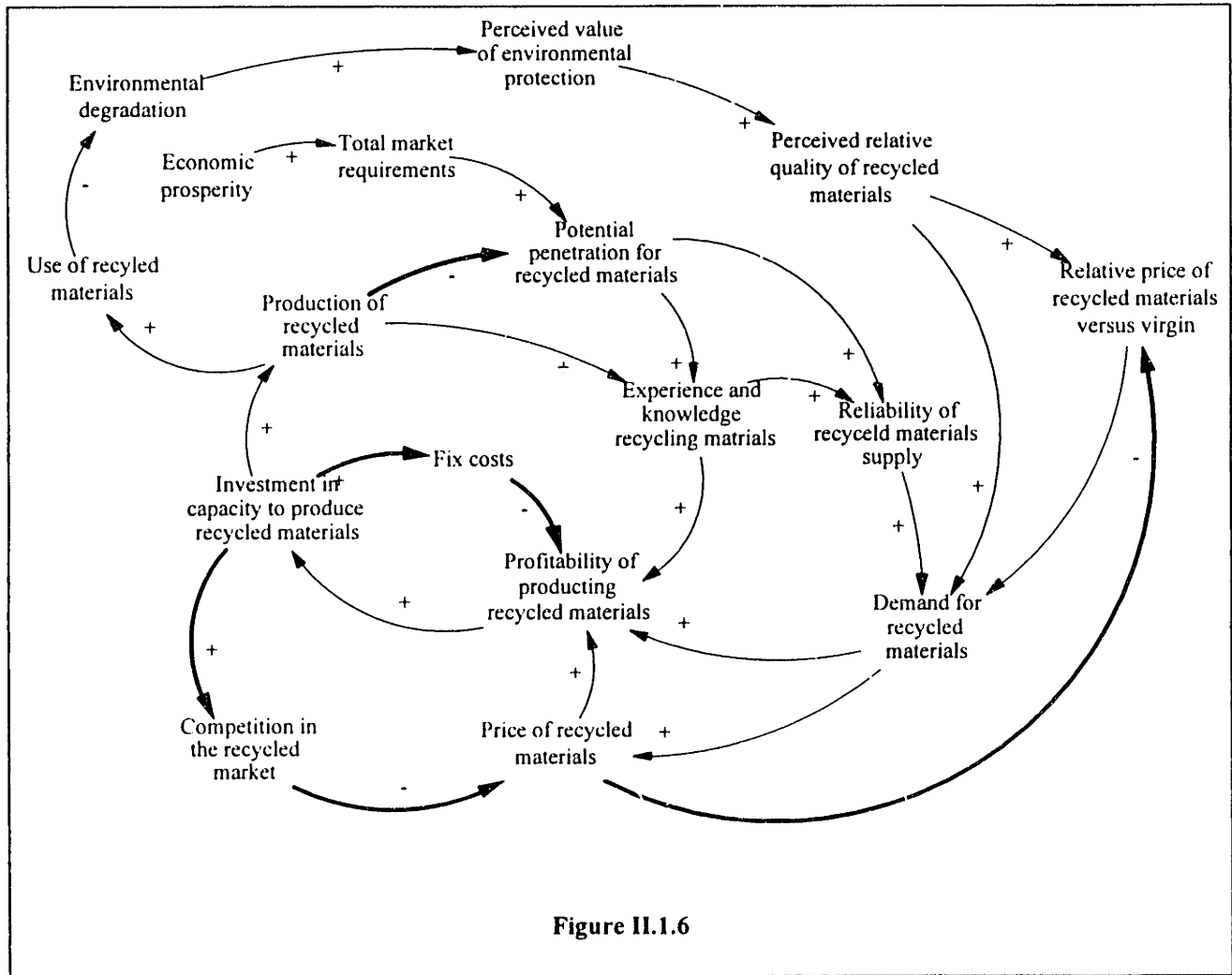


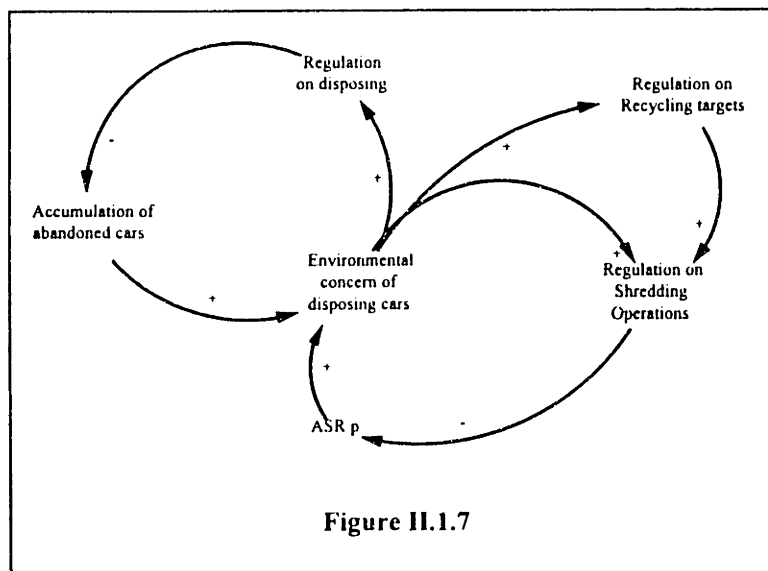
Figure II.1.6

So far this is a happy story where economic prosperity causes society to increase the use of recycled materials. Furthermore, this use would increase exponentially based on the dynamics described. There are some caveats in this story.

Some additional relations may contribute to the opposite: less use of recycled materials. The simplest one is that as the price of the recycled material goes up, the relative price of recycled to virgin material decreases, and this reduces demand. Additionally, increases in capacity would most likely result in an increase in competition, and this may tend to lower the price of recycled material. Therefore, profitability and overall attractiveness of recycling would go down. Finally, the more that recycled materials are produced the less potential for additional demand there is and therefore the less growth you can expect on demand. These relations are presented in the figure II.1.6.

This extended view is closer to the real world: economic prosperity has produced an increase in the use of recycled materials, but this change has not been dramatic. Sometimes it has not even caused the use of recycled materials.

### 3. Regulation



Disposal of durable goods has a negative impact on the environment. The two primary indicators of this, in the case of automobiles, are the accumulation of abandoned (or deregistered) cars in public or private places, and the generation of Automotive Shredder Residue (ASR).

It is argued that the purpose of

regulating the disposal of automobiles is to reduce the number of cars that are abandoned and accumulate in “the woods” without being recycled.

The second objective is to force the industry to recycle more, and therefore reduce the ASR. It is thought that this can be achieved by direct regulating shredding operations and dismantling practices. This argument has merit, as the future “take-back” regulation in Germany would suggest. However, there are additional considerations to be made.

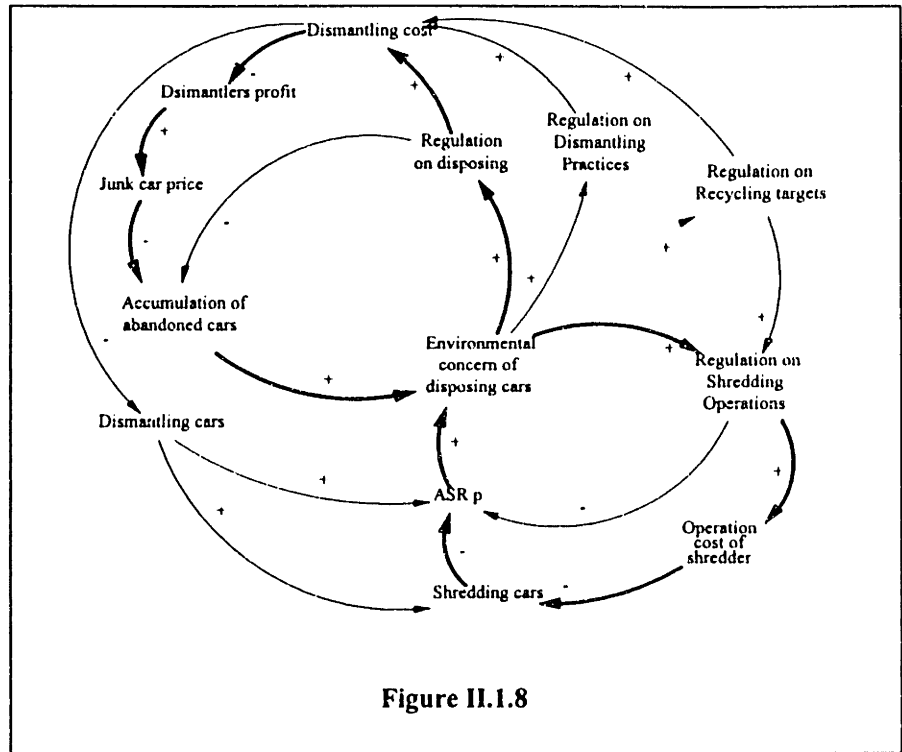


Figure II.1.8

The more complete figure

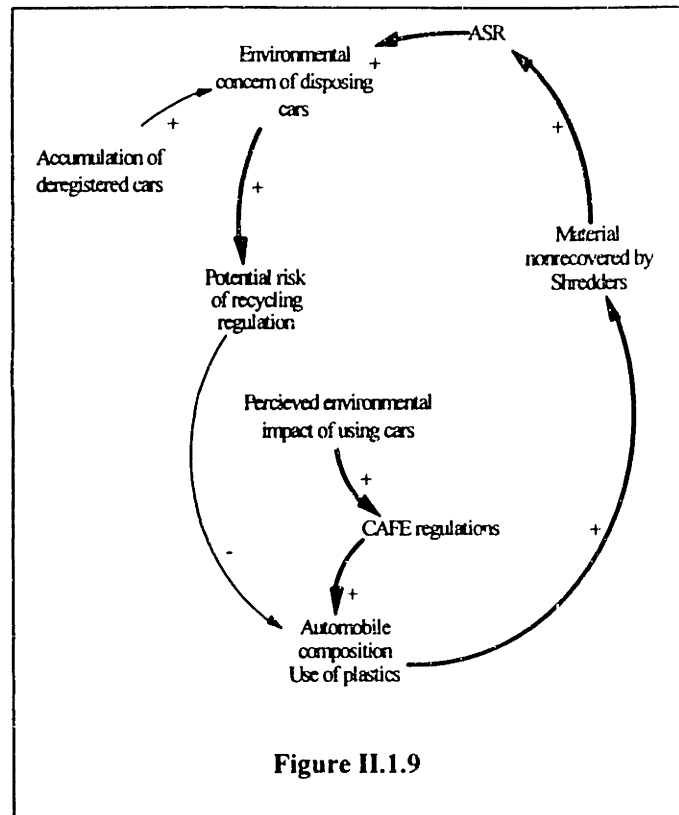
II.1.8 shows part of the concerns that the automobile manufacturers have associated with regulation on this area.

Regulation of dismantling practices and of disposal would have the negative effect of increasing the operation cost of dismantlers. As a result, the price they would be willing to offer for the cars would go down and less cars would be brought to the recycling industry (causing an accumulation of cars “to-be-recycled”). Additionally, mandated recycled targets can have a negative impact on shredders’ profit, and by the same token, fewer cars would be shredded. According to this point of view, less dismantling done in cars and a constrained shredding operation would result in more ASR measured as a fraction of the material flows handled by the industry.



#### 4. The Automobile Manufacturers

Figure II.1.9 presents part of the dynamics generally associated to the automakers' role in recycling automobiles. CAFE regulations are a result of an increase in the awareness of the environmental impact associated to driving cars, burning of oil and the corresponding air emissions. CAFE regulations have driven automakers to incorporate more plastics into the automobiles because they are, in general, lighter materials. The increase in plastics turns into less material being recovered by shredders, which translates into higher levels of ASR.



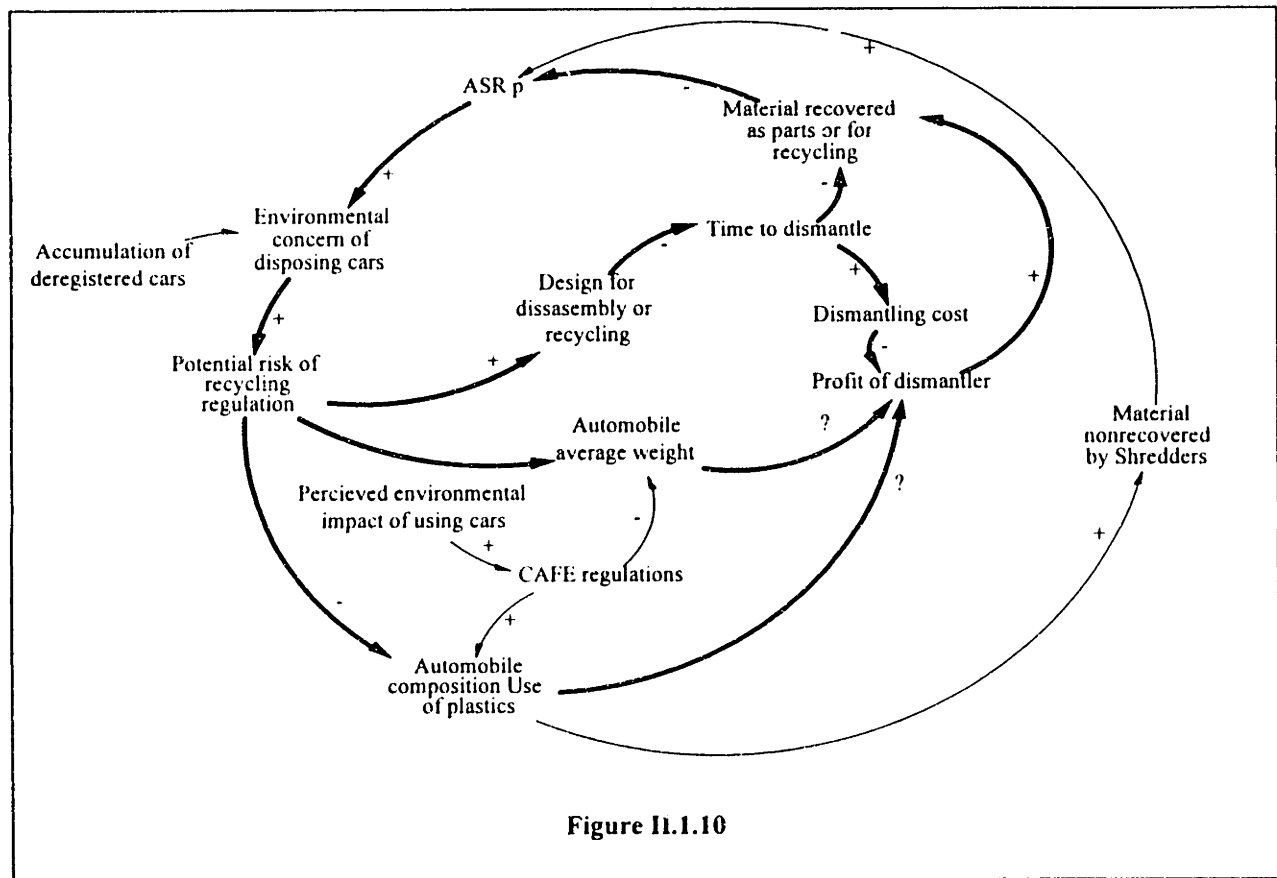
Some people explain that increases in accumulation of abandoned (deregistered) automobiles and in ASR are resulting in higher levels of concern about the environmental impact of disposing vehicles. This raising concern might result in new regulation, in this case, regulation of recycling. This might have an effect on the plastic composition of cars.

But can the automakers do something else than balancing the plastic composition to improve recyclability? It seems that the CAFE regulations are generating a problem that politicians want to solve by imposing more regulations. Figure II.1.10 presents part of what some people believe can help to solve this puzzle.

The argument is that if the automakers incorporate more Design for Disassembly, the “time to dismantle” cars and the “dismantling cost” would be reduced. This implies that dismantlers would see their profitability increase and therefore the amount of material recycled would

increase, as they dismantle more material. If more material is recovered by the dismantlers, less would end up in the landfill (less ASR).

This is a compelling argument. However, there are some areas of uncertainty on what can the automakers do to foster recycling. What would be the effect of changes in automobile weight in dismantlers' profit, if any? What about the effect of automobile composition? Or more importantly perhaps, what is the mechanism that would convert less "time to dismantle" into more recycling?; or is the landfill cost a strong control mechanism on ASR generation?; can economic incentives, such as taxes or recycling deposits, help? These and some other relevant questions are discussed in detail in the following chapters.



## Chapter II.2

# Introduction to the Automobile Recycling Dynamic Model (ARDM)

The objective of the Automobile Recycling Dynamic Model (ARDM) is for the Vehicle Recycling Partnership and more specifically, decision makers within the automakers to use the model to test hypothesis and learn about the potential impact of their policies on automobile recycling. The first section of this chapter expands on the goal of the ARDM. The second contains a discussion about the fundamental reasons behind the complexity of this problem and argues that it can only be systematically studied using a dynamic approach.

As described in the previous chapter, understanding the dynamics of the interactions between the parties involved in any environmental problem is a major task. Some simplification is required to generate actionable learning. In this chapter the major dynamics included in the Automobile Recycling Dynamic Model (ARDM) will be qualitatively introduced. It will also be indicated what areas have been left outside the model and what is the potential impact associated with simplifications. Interesting areas of future development will be discussed as well.

## 1. Objective of the model

The model covers two major areas of interest: The industry robustness and the automakers ability to increase automobile recycling. It is convenient to list some of questions posed about the automobile recycling industry.

Is automobile recycling in North America a robust industry? Serious doubts have been raised in regards to what is the industry's capability to manage the decreasing car weight and the increasing level of non-metal composition. If the industry is not robust enough, some people would argue, we will see accumulation of abandoned cars in woods and lots all across the region in a similar fashion as during the 60's. In that period, automobile recycling was not a profitable activity, and nothing was being done with the old cars that got retired. In that case, a technical innovation solved the problem. The invention of shredding machinery capable of processing complete automobiles at a reasonable cost has served as the basis for an industry that is prosperous. This prosperity has resulted in an extremely high level of recycling of automobiles.

However, non-metals in cars represent a pure cost to the industry. These materials have a double negative effect. They have to be processed through the system, generating costs, and at the end, they are sent to the landfills at a cost. To aggravate the situation further, the composition of cars is not only increasing the content of what we call in this work generically *plastics*, but is also reducing the metal content. Thus, sources of income are being reduced while cost drivers are increasing. The analysis of this problematic situation is one of the objectives of the ARDM.

The automobile manufacturers do not participate in the automobile recycling activity. From their perspective this is more efficiently done by specialized companies. However, they recognize they have not only a significant influence in recycling, but they also see that society is increasingly associating a certain level of responsibility to the original producers of durable goods in regards to how friendly products are to the environment when used and disposed.

Therefore, there are several incentives for the automakers to think about and act on the basis of improving the recyclability of automobiles. The immediate question is then “How?”. Material selection and weight are part of the possible areas to consider. But then, what would be the effect of, let us say, a reduction in the car weight of 10%, while increasing the plastic content by 2% and the non-ferrous metals by 5%? Or are there other means to achieve more recycling?

Design for Disassembly is a new concept that, in principle, would result in more recycling. Easier-to-dismantle cars and trucks designed with high levels of material compatibility are examples of the potential effects of incorporating DFD in the design process. But again, how can one quantify the expected effects of undertaking this activity. At the end, the automakers have to balance a variety of objectives and cost, when designing cars. We can not expect DFD to be more than a "nice-to-have" attribute if the automakers can not estimate the potential benefit of it.

And then, we can add to the discussion the extremely controversial area of self-motivated enterprises. What would be the effect of automakers effort to improve recyclability when the industry is constituted by parties making self-optimizing profit decisions? Would Design for Recycling, as opposed to Design for Disassembly make any difference? These questions are addressed by the ARDM.

## **2. The case for a dynamic model**

To be able to provide answers for the two issues described above, the ARDM should be able to estimate the automobile shredder residue flow and the fraction of cars being recycled (compared to the total number of cars being “discarded”). To do so, the model should be capable of quantifying the material flows, and their composition at any point in time in the system. This can be estimated using material accounting balances.

However, the fundamental operating structure for the industry is economic. The number of cars being brought to the recycling industry depends on the price offered for junk cars. The

junk car price is a function of the profitability of the dismantlers. In addition, profits for the dismantlers depend on the price they get for hulks. And this, in return, is a function of the flows of hulks they sell to the shredders because the more hulks they offer (supply) to the shredders, the less money shredders need to offer to get the quantity they require (demand).

The same structure works for the shredders. In this case the relevant prices are those of the hulks and the autoscrap<sup>1</sup>. As it will be described in detail in the next section, this pricing cascade is a fundamental link among the entities in the system, and is dynamic.

In addition, one can estimate with precision, using accounting procedures only, what is the composition of the flows in the system *if* the flows of cars are given. But the flows of cars are a function of the prices and therefore they are subject to profitability variations on each entity in the system, which depend, in return, on the composition of the flows. The loop that links composition to profitability, to prices, to flows, and back to composition is another key element that makes this system highly dynamic.

Assuming constant prices, and therefore constant flows, would represent a major flaw in the analysis because it would overlook the fact that this industry functions on the basis of economics: every entity in the system is trying to maximize its own profit. It would also forget that the price level of any item in a competitive environment is what will cause the market to clear.

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<sup>1</sup> Autoscrap is an iron and steel scrap classified and quoted by the American Metal Market. It refers to the scrap obtained from shredding automobiles and some other durable good (home appliances).

### 3. Main Feedback Loops in Automobile Recycling

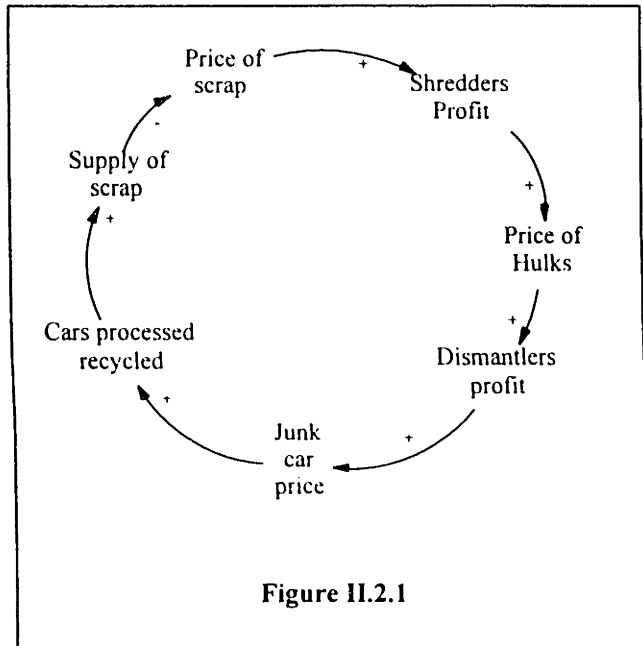


Figure II.2.1

The simplest representation of the main dynamics associated to automobile recycling is presented in figure II.2.1. Let us suppose, for explanation purposes, that the autoscrap price suddenly increases. This would cause the shredders' profit to improve. As their profit increases, they would be in the position to offer higher prices for the hulks they buy to ramp up production. This will have a similar effect in the profit of dismantlers, who now will be willing to pay more for the

junk cars they buy. However, as more cars are bought into the recycling industry, more material is recovered and more scrap is supplied to the steel industry. The effect of this increase in scrap supply will tend to reduce the price of the autoscrap. The reader can easily observe that the speed at which these interactions occur may vary significantly.

Figure II.2.2 represents part of the dynamics of what the model captures. GDP is an exogenous input that stimulates sales of automobiles. An increase in car sales would result in more cars on the road. This increase in the fleet of cars being used will eventually result in more cars being

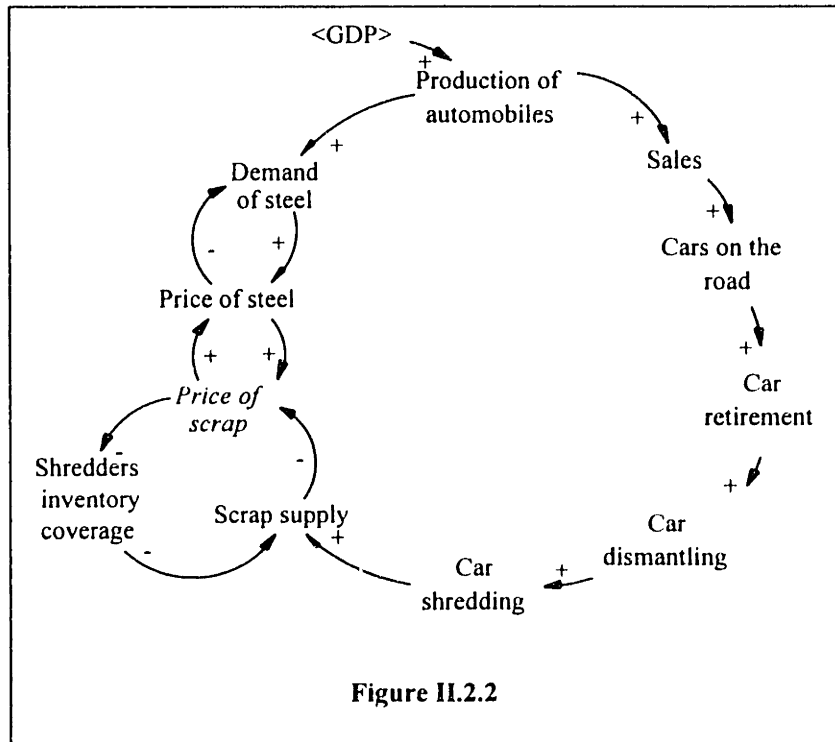


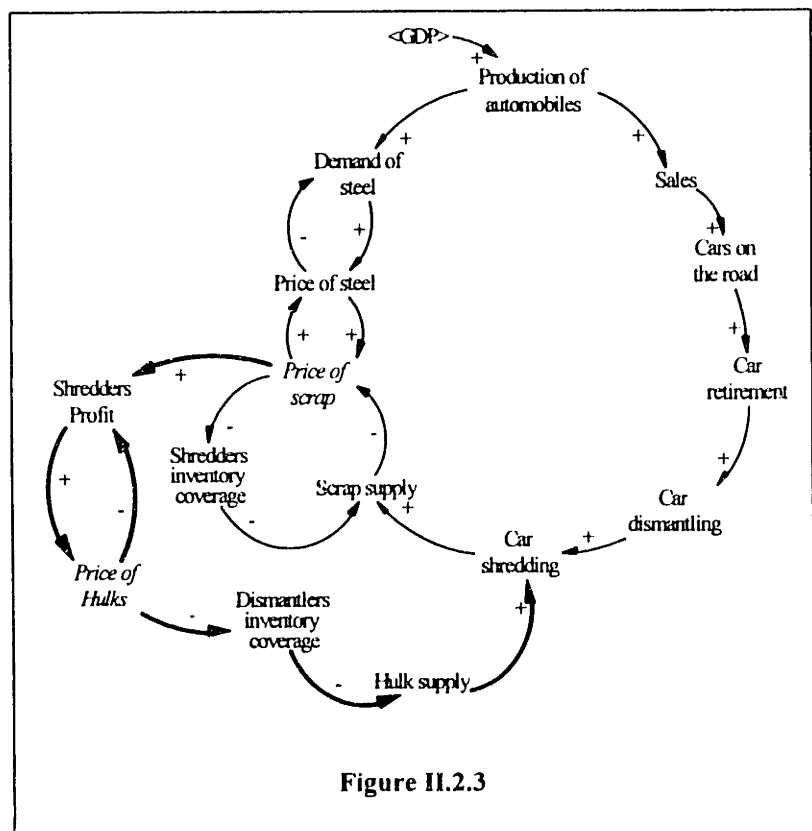
Figure II.2.2

retired. Retired cars end up in the dismantlers' hands, who dismantle them and sell them to the shredders as hulks. Hulks are then shredded and ferrous materials are recovered from this process. As more scrap is recovered, more will be offered to the steel industry (increase in scrap supply). This will cause a reduction in the scrap price. Since the price of the scrap and the price of the steel are directly correlated, one can expect the steel price to go down as the scrap price goes down. In principle, a decrease in steel price would stimulate the demand of steel because it becomes a relatively more attractive material.

Production of automobiles is correspondingly associated with sales. Increases in GDP also increases demand for steel.

It is important to emphasize the mechanism for the scrap supply to increase as a response to an increase in scrap price. Shredders decide how much they sell as a function of the price they can get for the scrap. If the market is depressed and the scrap price is low, they will

accumulate material. Some shredders, for example, explained that they have had up to one year of material accumulated on their property when they thought the scrap price was too low. During the summer of 1995, when the auto scrap price reached a historical high, shredders were selling as fast as they could. It is estimated that during this period they were carrying less than two months of inventory.





Modeling this mechanism involves the use of the *coverage* variable. This variable quantifies how many months of sales of material are desired in inventory and is inversely proportional to the price. In other words, if the price of product *x* increases, the desired *coverage* for *product x* is reduced.

An increase in the price of scrap results in an increase in

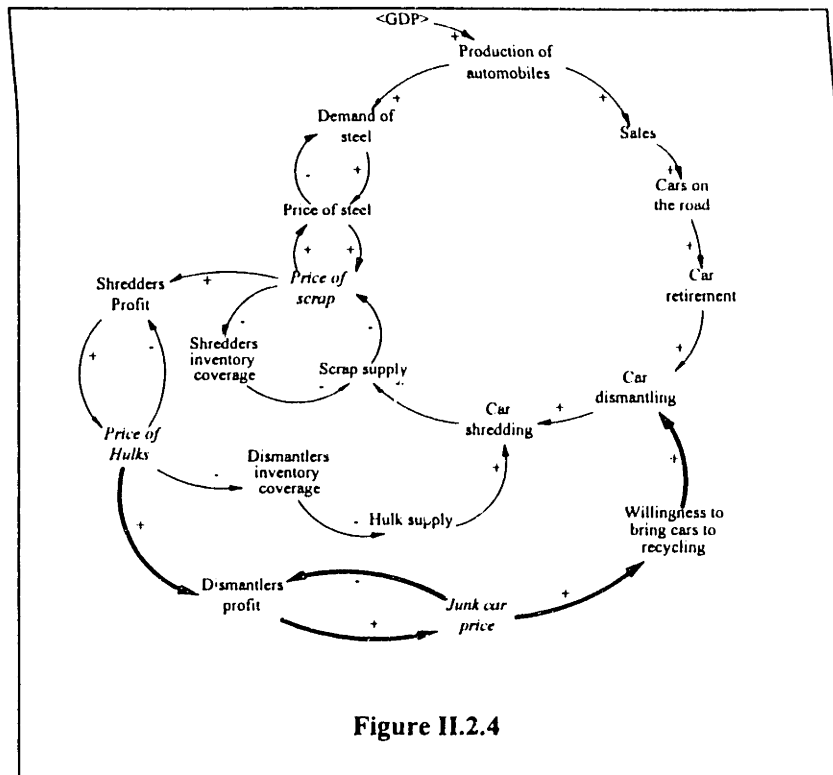


Figure II.2.4

shredders profit because that is one of their main sources of income. An increase in shredders' profitability allows them to increase the price they are willing to pay for the hulks. As it is represented in figure II.2.3, this increase in price has three effects; it decreases profits because hulks represent the basic raw material; it increases profit for the dismantlers because hulks are their primary final products; and accordingly, dismantlers decrease their desired inventory coverage for the reason explained above.

People familiar with the dismantlers' practice describe this coverage adjustment in a colorful way: "Walking along a dismantlers' yard allows you to easily see how good the price of hulks is. You just have to look at the fence; if you can see piles of cars above the level of the fence, the price is low. If you do not see any cars above the fence level, the hulk price is high". This accumulation (or de-accumulation process) has a direct effect on the level of cars that are shredded because they will influence the rates at which hulks are transferred to the shredders.

When the profit of dismantlers increase, they are willing to pay more for the junk cars because they want to process more cars and increase their throughput. Again, this causes their profitability to be reduced, but it also causes the rate at which cars are brought to them to

increase because owners are more interested in bringing cars to the dismantlers when they know that they will get more money for them. Additionally, entrepreneurs currently bringing cars to the dismantlers would increase the radius of their operations, having access to more cars and contributing to the increase in the inflow of cars into the recycling industry.

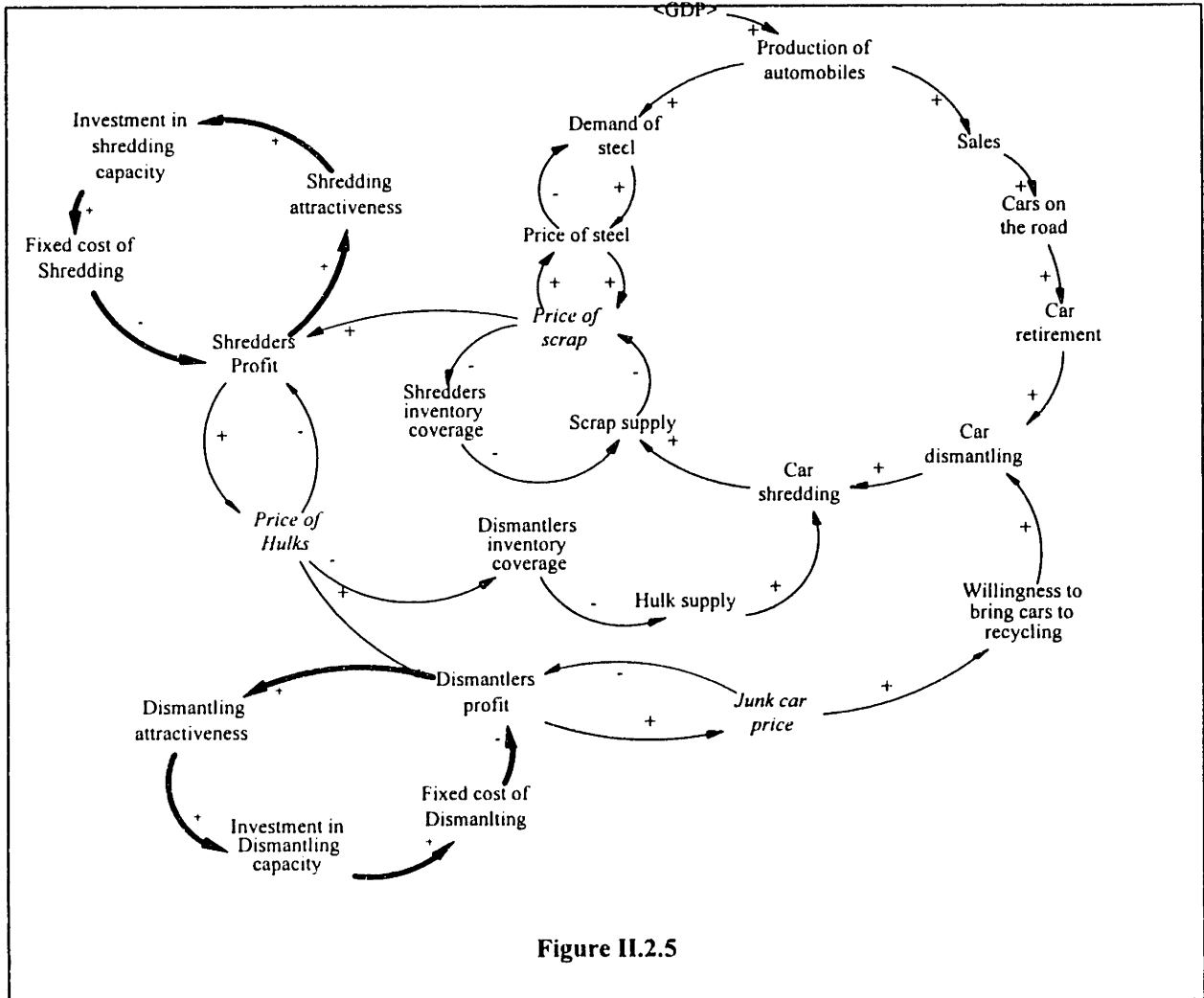


Figure II.2.5

Finally, two similar loops are considered in the model. Figure II.2.5 illustrates the effect of competition and over-capacity acquisition in the industry cycle. If shredders become more profitable, the activity becomes more attractive, and more business people would be interested in participating on it. As more investment is devoted to this activity, capacity and fixed costs increase. The effect of an increase in costs is a reduction in profits. The same structural

relationship applies to dismantlers. Since the capacity acquisition process involves long delays associated with ordering and setting up the facilities, one can expect a long-term cycle<sup>2</sup>.

The feedback loops described in this section are contained in the Automobile Recycling Dynamic Model. However, there are many more in the real automobile recycling industry. In the next section a clear distinction is made between what is and what is not incorporated in the model.

#### 4. Model Boundary

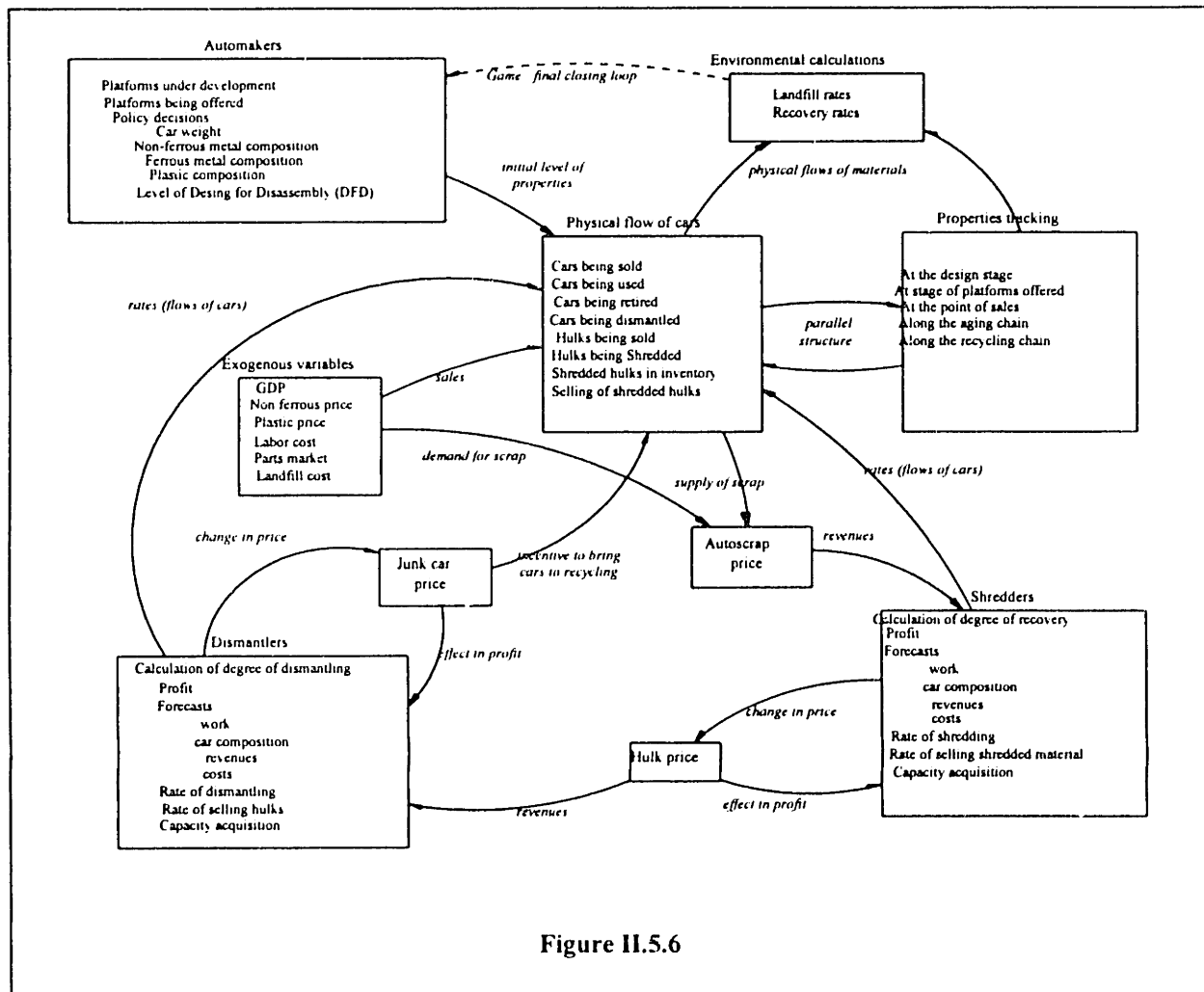


Figure II.5.6

<sup>2</sup> It is assumed that both dismantlers and shredder have adaptive expectations.

We can group the model into several areas: *Automakers*; *Physical Flow of Cars* and the corresponding *Properties*; *Dismantlers* and *Shredders*; prices for *Autoscrap*, *Hulks*, and *Junk cars*; and *Environmental calculations*. Figure II.5.6 contains an overview of the different sections of the ARDM, which are represented by boxes. The arrows reflect the key information exchanged by the different areas of the model. In addition, the model also considers some external inputs (exogenous variables) such as GDP, cost of labor and cost of landfills, among others.

By properties, the reader should understand characteristics of the cars under analysis: total weight, ferrous composition, nonferrous metal composition, plastics (non-metals) composition and level of design for disassembly (DFD). These properties are measured in kilograms per car. Units in the case of DFD do not have a physical meaning, they represent only a heuristic relative index.

In the automakers area, the design stages are presented -- the number of platforms being developed and offered to the market, and the level of properties in these stages form part of this sector.

The physical flows of cars and properties start with sales of automobiles. Cars are tracked during the stages of use and deregistration, through the dismantling and shredding processes until they end up (as material) back in the metal industry. Along this chain, it is of fundamental importance to be able to determine the level of each property because these levels influence many of the rates in the system. To carry out these calculations a parallel structure is incorporated which, with the use of subscript's, does the material accounting along the recycling chain.

The *Dismantlers* and *Shredders* areas are similar, having the same sectors: determination of rates (at which they process cars and sell their output); capacity acquisitions activities; estimation of forecasts; activity-specific calculations; and determination of profit. Figure II.5.7, which is a blow-out of figure II.2.8, illustrates this structure in the case of dismantlers.

Prices are calculated based on the fact that each entity desires to protect certain profitability.

The model includes the effect of inventory adequacy and utilization rates in the pricing mechanisms. In addition, some calculations are carried out to determine recyclability indicators such as percentage of ASR, or the fraction of cars being processed, compared to the number of vehicles being discarded.

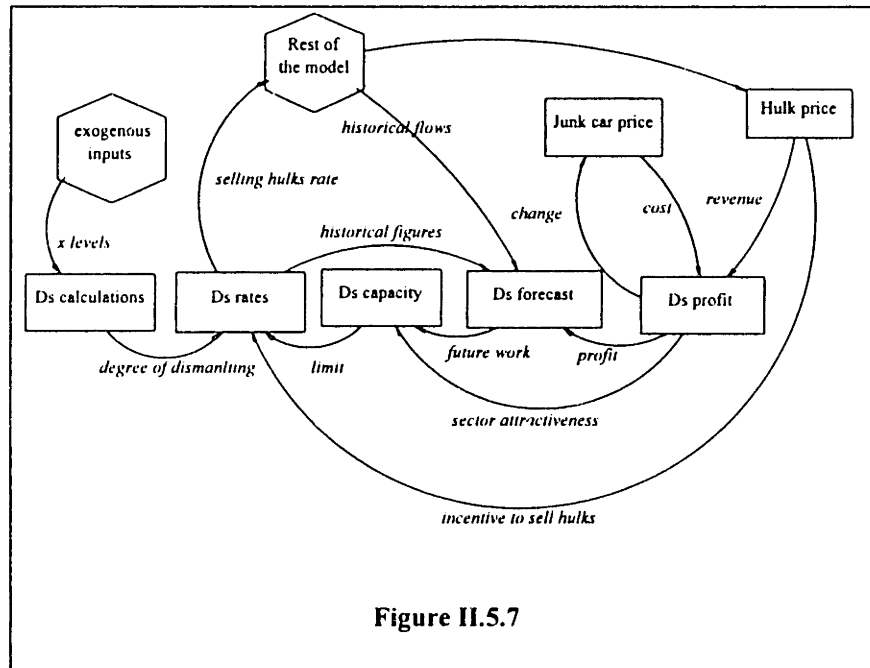
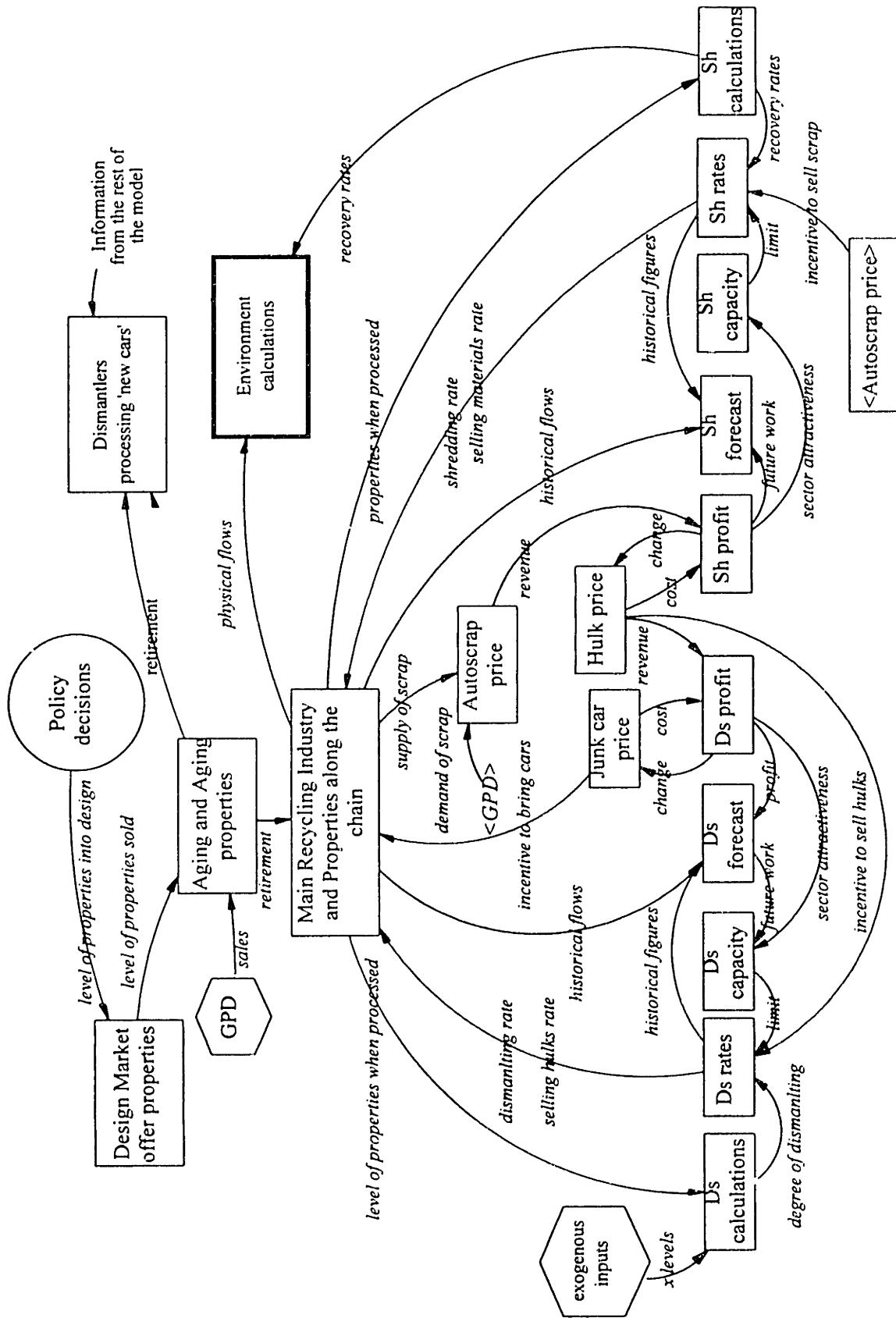


Figure II.5.7

A distinction is made between cars being recycled. The so called "new cars" are vehicles that the dismantlers buy at a competitive price. A significant portion of these cars are dismantled and sold as parts. The "old cars" are acquired at a very low cost and are processed only for the material value they have. Since the price differential between these two types is substantial they are treated differently in the model.



"New cars" are generally retired because they suffered a major accident. Dismantlers would normally buy all of these cars and process them for the intrinsic value of their parts. Therefore they are not subject to the ferrous-price dynamics of the old vehicles; the junk car price calculated in the model has no impact on how these cars are processed. Although the focus of this work is not on the market for used parts, we need to include the flows of material associated with this activity because the hulks generated after dismantling "new cars" also go to the shredders.

In order to simplify the model, it is assumed that all the vehicles retired with the age range of 0 to 9 years old (approximately 20% of total car attrition) are processed as "new cars".

The equations describing the dismantling practices on "new cars" were estimated assuming that all parts in them were in good condition. However, we know that they are recycled because they are partially damaged. The correction for this fact is introduced by the variable *FREQUENCY OF PARTS*. This is a fraction that simplifies this problem by assuming that some cars would be completely damaged and others would be completely intact.

The following table presents the key variables by sector. The table indicates as well what are the most important exogenous variables and what has been left outside of the model. The variables in bold represent the automobile manufacturers' policy variables.

Sector	Dynamic variables	Exogenous variables	Variables excluded
1. <i>Automakers</i> . Presents the automobile design process.	<ul style="list-style-type: none"> <li>• Platforms under development.</li> <li>• Platforms in market.</li> <li>• Property levels of platforms under development.</li> <li>• Property levels of platforms in the market.</li> </ul>	<ul style="list-style-type: none"> <li>• <b>Target properties: weight, ferrous composition, non-ferrous composition, plastic composition, and level of design for disassembly.</b></li> <li>• Development time.</li> </ul>	<ul style="list-style-type: none"> <li>• Desire to reduce the number of platforms offered to the market.</li> <li>• Desire to reduce development time.</li> <li>• Modifications of platforms already being offered to the market.</li> </ul>

Sector	Dynamic variables	Exogenous variables	Variables excluded
2. <i>Aging.</i> Sales, and use of cars, including vehicle attrition are described.	<ul style="list-style-type: none"> <li>• Equilibrium number of cars in the road.</li> <li>• Sales.</li> <li>• Cohorts of cars being used at different ages: from 0 to 3, from 3 to 6, from 6 to 9, from 9 to 12, from 12 to 15, from 15 to 18, from 18 to 21 years old.</li> <li>• Aging rates.</li> <li>• Retirement rates.</li> <li>• New cars being deregistered.</li> <li>• Old cars being deregistered.</li> </ul>	<ul style="list-style-type: none"> <li>• GDP.</li> <li>• Retirement fractions.</li> </ul>	<ul style="list-style-type: none"> <li>• Effect of GDP in retirement fractions.</li> <li>• Imports and exports of cars.</li> <li>• Thefts of vehicles.</li> </ul>
3. <i>Main.</i> The automobile recycling chain is modeled.	<ul style="list-style-type: none"> <li>• Old cars deregistered.</li> <li>• New cars deregistered.</li> <li>• Dismantled hulks.</li> <li>• Shredders raw material inventory.</li> <li>• Shredded hulks FGI.</li> <li>• Supply fraction of old cars.</li> </ul>	<ul style="list-style-type: none"> <li>• Relative supply fraction (of old cars) as a function of relative junk car price: price sensitivity of supply of "old cars" (lookup graph).</li> <li>• Time to perceive junk car price.</li> <li>• Time to dismantle new deregistered cars.</li> </ul>	<ul style="list-style-type: none"> <li>• Dynamics of dismantling "new cars".</li> </ul>
4. <i>Age.</i> Is a parallel structure to calculate the average age when retired.	<ul style="list-style-type: none"> <li>• Cohorts accumulating model-years corresponding to every age cohort.</li> <li>• Average age of "new", and "old cars" when retired.</li> </ul>	<ul style="list-style-type: none"> <li>• Initial model.</li> </ul>	<ul style="list-style-type: none"> <li>• Sales of one model-make in the immediate next or previous year.</li> </ul>
5. <i>Ini values.</i> Is the sector to initialize the model stocks at the adequate level.		<ul style="list-style-type: none"> <li>• Initial values of every stock in the model.</li> </ul>	<ul style="list-style-type: none"> <li>• There is no difference in the automakers' stocks between historical and equilibrium conditions.</li> </ul>
6. <i>x levels.</i> The exogenous variables used in the empirical equations are calculated.		<ul style="list-style-type: none"> <li>• Non-ferrous price index.</li> <li>• Plastic price index.</li> <li>• Landfill cost index.</li> <li>• Labor cost index.</li> <li>• Parts price index.</li> </ul>	<ul style="list-style-type: none"> <li>• Steel cost index.</li> </ul>



Sector	Dynamic variables	Exogenous variables	Variables excluded
7. <i>Dismantling calculations.</i> Performs material balances by evaluating the DOE empirical equations.	<ul style="list-style-type: none"> <li>• Mass being recycled in old cars, and composition.</li> <li>• Mass being recycled in new cars, and composition.</li> <li>• Mass and composition of parts being resold in new cars.</li> <li>• Property of hulks after dismantling.</li> </ul>	<ul style="list-style-type: none"> <li>• Frequency of complete parts.</li> </ul>	
8. <i>Shredding calculations.</i> Defines material balances based on recovery fractions.	<ul style="list-style-type: none"> <li>• Landfill rates, by property.</li> <li>• ASR fraction calculations.</li> <li>• Dismantlers recovery rate, compared retirement and to processing flows.</li> <li>• Shredders' shrinkage factor.</li> </ul>	<ul style="list-style-type: none"> <li>• Recovery fractions.</li> </ul>	<ul style="list-style-type: none"> <li>• Material balance associated to the replacement and use of parts.</li> <li>• Required dismantling.</li> <li>• Alternative use of ASR based on technological innovation: Combustion, pyrolysis, etc.</li> </ul>
9. <i>Properties.</i> Parallel structure that follows the level of properties at all levels of the recycling chain.	<ul style="list-style-type: none"> <li>• Property levels at any age cohort.</li> </ul>		
10. <i>Dismantler forecast.</i> Evaluates expectations of dismantlers.	<ul style="list-style-type: none"> <li>• Expected future labor into cars.</li> <li>• Expected future retiring of old cars.</li> <li>• Expected future <math>D_s</math> profit.</li> </ul>	<ul style="list-style-type: none"> <li>• Time to perceive profit.</li> <li>• Average time to forecast.</li> <li>• Dismantlers' time horizon.</li> </ul>	
11. <i>Dismantler rates:</i> Calculates dismantling rate and rate at which dismantlers sell hulks to shredders.	<ul style="list-style-type: none"> <li>• Dismantling rate.</li> <li>• Selling hulks rate.</li> <li>• Desired months of <math>D_s</math> inventory.</li> <li>• Dismantlers' storage usage.</li> </ul>	<ul style="list-style-type: none"> <li>• Relationship between relative hulk price and relative number of months in desired inventory (lookup graph).</li> <li>• Dismantlers' storage capacity.</li> </ul>	<ul style="list-style-type: none"> <li>• Acquisition of storage capacity.</li> <li>• Dismantlers' inventory of junk cars.</li> <li>• Independent, material-specific flows.</li> </ul>
12. <i>Dismantler profit.</i> Is the financial accounting for dismantlers.	<ul style="list-style-type: none"> <li>• Variable labor into dismantling.</li> <li>• Dismantlers from recycling and from hulks.</li> <li>• Dismantlers' monthly profit.</li> <li>• Dismantlers' average semester profit.</li> </ul>	<ul style="list-style-type: none"> <li>• Unit energy cost.</li> <li>• Unit labor cost.</li> <li>• Unit capacity cost.</li> <li>• Standard time to process cars.</li> </ul>	<ul style="list-style-type: none"> <li>• Economics of required (forced) dismantling.</li> </ul>

Sector	Dynamic variables	Exogenous variables	Variables excluded
13. <i>Dismantler capacity.</i> Contains the Dismantlers acquisition process for capacity.	<ul style="list-style-type: none"> <li>• Dismantlers capacity on order.</li> <li>• Dismantlers' capacity in place.</li> <li>• Dismantlers utilization rate.</li> </ul>	<ul style="list-style-type: none"> <li>• Relative effect of Ds profit in desired relative Ds capacity (lookup graph).</li> <li>• Lifetime of dismantlers capacity.</li> <li>• Time to complete dismantlers capacity.</li> </ul>	
14. <i>Junk car price.</i> Proposes a pricing structure that dismantlers follow to buy junk cars.	<ul style="list-style-type: none"> <li>• Target Junk car price to protect margin.</li> <li>• Dynamic Junk car price.</li> </ul>	<ul style="list-style-type: none"> <li>• Dismantlers desired margin per car.</li> <li>• Effect of adequacy of dismantlers' inventory as a function on the Junk car price.</li> <li>• Relative effect of dismantlers' utilization rate on the Junk car price (lookup graph).</li> </ul>	
15. <i>Shredder forecast.</i> Evaluates the expectations of shredders.	<ul style="list-style-type: none"> <li>• Expected future weight of hulks.</li> <li>• Expected future compositions of hulks.</li> <li>• Expected future cost per car.</li> <li>• Expected future hulks transferring (from dismantlers to shredders).</li> <li>• Expected future profit.</li> <li>• Expected income per car.</li> </ul>	<ul style="list-style-type: none"> <li>• Time to perceive weight.</li> <li>• Time to perceive Sh accounting information.</li> <li>• Average time for forecasts.</li> <li>• Shredders time horizon.</li> </ul>	
16. <i>Shredder rates.</i> Calculates shredding rate and rate at which shredders transfer out material.	<ul style="list-style-type: none"> <li>• Shredding rate (in cars and ton units).</li> <li>• Selling of recovered materials (in cars and ton units).</li> <li>• Shredders' storage usage.</li> <li>• Shredders' desired months of inventory.</li> </ul>	<ul style="list-style-type: none"> <li>• Relative effect of autoscrap price in relative number of months in Sh inventory desired (lookup graph).</li> <li>• Shredders' storage capacity.</li> </ul>	<ul style="list-style-type: none"> <li>• Shredding other durable goods or construction material.</li> </ul>
17. <i>Shredder profit.</i> Is the financial accounting for shredders.	<ul style="list-style-type: none"> <li>• Hulk cost.</li> <li>• Operational cost.</li> <li>• Landfill cost.</li> <li>• Fixed cost.</li> <li>• Autoscrap revenue.</li> <li>• Sh nonferrous revenue.</li> <li>• Sh monthly profit</li> <li>• Shredders' average semester profit.</li> </ul>	<ul style="list-style-type: none"> <li>• Unit transportation cost.</li> <li>• Unit energy cost.</li> <li>• Unit maintenance cost.</li> <li>• Unit capacity cost.</li> <li>• Unit nonferrous price.</li> </ul>	<ul style="list-style-type: none"> <li>• Economics of composition-related pricing.</li> <li>• Economics of alternative uses of ASR.</li> </ul>

Sector	Dynamic variables	Exogenous variables	Variables excluded
<p>18. <i>Shredder capacity.</i> Contains a capacity acquisition structure for shredders.</p>	<ul style="list-style-type: none"> <li>• Shredder capacity in place.</li> <li>• Shredder capacity in order.</li> <li>• Shredder capacity utilization rate.</li> </ul>	<ul style="list-style-type: none"> <li>• Effect of profit on shredder desired capacity (lookup graph).</li> <li>• Lifetime of shredder capacity.</li> <li>• Time to complete shredders' capacity.</li> <li>• Desired capacity utilization.</li> <li>• Relative effect of Sh capacity utilization in desired Sh capacity (lookup graph).</li> </ul>	
<p>19. <i>Hulk price.</i> Proposes a pricing mechanism that shredders follow to buy hulks.</p>	<ul style="list-style-type: none"> <li>• Target price to protect Sh margin.</li> <li>• Dynamic Hulk price.</li> </ul>	<ul style="list-style-type: none"> <li>• Base Sh margin per car.</li> <li>• Effect of Sh utilization rates on the Hulk price (lookup graph).</li> <li>• Effect of adequacy of inventories on the Hulk price (lookup graph).</li> </ul>	<ul style="list-style-type: none"> <li>• Economics of material composition pricing.</li> </ul>
<p>20. <i>Scrap price.</i> Evaluates the scrap price that would sustain constant ratio of virgin to scrap produced steel.</p>	<ul style="list-style-type: none"> <li>• Corrected automobile demand for steel.</li> <li>• Deviation of scrap fraction of steel.</li> <li>• Dynamic scrap price.</li> </ul>	<ul style="list-style-type: none"> <li>• Time to perceive scrap fraction.</li> <li>• Base scrap fraction of steel demand.</li> <li>• Effect of relative deviation of scrap fraction on the Autoscrap price (lookup graph).</li> <li>• Base demand of scrap.</li> <li>• Equilibrium price.</li> </ul>	<ul style="list-style-type: none"> <li>• Alternative, non-automotive sources of scrap.</li> <li>• Composition-based (grades) pricing.</li> <li>• Alternative uses of scrap.</li> <li>• Technological limits on desired scrap fraction.</li> <li>• Post industrial scrap.</li> </ul>
<p>21. <i>New cars.</i> Includes the material and financial accounting of dismantling "new cars".</p>	<ul style="list-style-type: none"> <li>• Processing cost of new cars.</li> <li>• Revenue form recycling in new cars.</li> <li>• Revenue from parts in new cars dismantled.</li> </ul>	<ul style="list-style-type: none"> <li>• Frequency of new cars.</li> <li>• Unit non-ferrous price.</li> </ul>	

Sector	Dynamic variables	Exogenous variables	Variables excluded
22. Control. Switches and general information variables.	<ul style="list-style-type: none"> <li>• Complete set of switches to control conditions for simulation and to isolate sectors of the model for testing purposes.</li> <li>• Comparison of profitability between dismantlers of new and old cars.</li> <li>• Comparison of profitability between shredders and dismantlers.</li> </ul>		

The market of scrap analyzed in the model includes the effects of automobile recycling only. We know that a significant portion of the scrap produced in North America is obtained from automobiles. However, there are other sources, such as construction scrap and scrap obtained from other durable goods. This work pretends to isolate the dynamics of the scrap price and the recycling of automobiles. Therefore, it is not recommended interpreting the model-calculated scrap price as a good representation of the real scrap price. Instead, it should be interpreted as the scrap price one can expect if the only source of scrap was the recycling of cars. By the same token, the demand for steel estimated in the model, although triggered by changes in GDP, include a correction for steel usage in automobiles. This structuring suggests a closed system where the autoscrap would be used in automobile production. This simplification ignores the degradation effect associated with recycling and the technical limitations of steel mills. We know that the possible use of scrap for many automobile applications is limited by technological constraints. It is considered that the effect of this simplification is not significant because GDP is a good indicator (or driver) of overall steel demand. Again, the correction of automobile steel demand causes the scrap price calculated in the model to be a virtual price; the price that would prevail *if* the automobile steel/scrap cycle was closed. This price in reality, is one of several components of the real scrap market price.

It is important to emphasize that the model does not include the dynamics associated with the prices of non-ferrous metals, nor with the market of parts. These represent potential additions

to this work for further research. In the next section some characteristics of the market of parts are discussed.

## 5. Market of Used Parts

Dismantlers used to be called junk yards. For many years their operations have been considered "dirty" and unsophisticated. Nothing is further from the truth. Today, dismantlers use complex information systems that allow them to perform highly complicated tasks.

First, they have to keep a strict control of their inventory. Some parts are very profitable, but because their turnover is long, they have to store them for months before selling them. In addition, there is a complex net of interchange-ability information that is of paramount importance to their operation.

If a customer wants to buy a front left door for a 1988 Taurus, for example, it is indispensable to know that a front left door of a 1987 Sable may fit. This relationship applies not only to different makes, but to different models as well; they would need to know that this door is the same in all 1987-Taurus than, let us say, in all 1990-Taurus. The information system in use allows them to recognize all of these possibilities. During the research one of these systems (The ADP Hollander System) was used extensively. There are two conventional applications of the information system.

The first is to create a list of all parts that can be sold by model to analyze cars before processing them. When a car enters the dismantling facility, an experienced manager enters the make and the model. The system would then create a list of all the parts that are normally sold from this vehicle. It will also present the number of similar items that the dismantler has already in stock. With this information, the expert analyzes the vehicle, considers the state of the attractive parts, and trying to optimize profits, defines a disassembly plan. Note that this optimization is more complicated than the one the Disassembly Model Analyzer performs because it considers more parameters. In addition to the physical structure, the removal times,

the composition and the static price of all parts, dismantlers also consider the level of inventory, the likelihood of selling an additional part and the estimated time to sales.

The second conventional application is when a customer calls asking for a specific part. The system tells the dismantler whether they have it in stock, the part condition is and which type of car it came from (make and model). It will also present, to the sales representative, the suggested price range.

There is one less frequent application. When one dismantler does not have in stock the part under request, he can look for the part in the inventory of other dismantlers in the region. This is accessed on-line and displays the same information described above. Additionally, the dismantler can request the system to look for the part in the centralized database. This search would include all dismantlers affiliated with the system in North America. Because the system shows suggested price, and number of parts in stock, there is an opportunity to do competitive analysis<sup>3</sup>.

The Hollander System includes many more features, it keeps track of a significant part of the accounting and can produce reports of a variety of activities. Within this research it was tried to estimate, for example, how many front seats were sold on average in one specific dismantling operation. It was an easy task for an expert user of the system. We obtained numbers for the previous 5 years. When we compared these values to the number of vehicles processed by this facility, we concluded that they sold, on average 50% of the front seats that they received. This number was significantly higher than what the dismantler originally estimated. At this moment the VRDC is working on trying to determine these type of fractions in several dismantling facilities for the most frequently sold parts. As explained, for the purpose of this work we used 50% in all cases.

There is one other feature that the Hollander System is trying to incorporate; activity reports. The idea is to generate a report that would tell dismantlers how frequently customers look for

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<sup>3</sup> Note, for example, the asymmetry in the information when a customer calls. The sales representative has in the computer monitor the number of similar parts available in the whole region and the suggested prices. The potential customer on the other extreme does not have anything similar.

each possible part. This information analysis may allow them, accordingly to the interviews conducted, to more closely monitor demand.

All these interactions of information and supply and demand form part of the pricing dynamics of used parts. As the reader may conclude this is a fascinating area. The rule of thumb says that the price of a used part is 50% of the new part price. However, this is only true on average, one would frequently observe used parts with prices that range from 70% to 20%.

To complicate the analysis even more, there is the effect of marginal costs. The Disassembly Model Analyzer used a labor cost of 20 dollars per hour. Most dismantlers considered this number too low. They proposed to use something on the order of 50 to 150 dollars per hour. On the other hand, we observed that many cars were compacted and shredded with many parts that could be used. However, dismantlers explained they had not dismantled these cars any further because they could not sell these parts... at the price they wanted.

These facts raise a significant number of interesting questions: "Is their real marginal cost much higher than the hourly market cost of labor?"; "Are the costs of storage and inventory control responsible for the difference?"; "Is this a case of asymmetrical information where dismantlers are constraining supply of used parts using the information system in place to foster coordination?", but then, "How is it possible that more than 12,000 dismantlers to collude harmonically over time?". "How is demand for used parts determined?" "Is consumer preference the underlying reason for so many parts being shredded in good condition?". These represent only some of the interesting questions for further research.

Finally, the impact of DFD on the market for used parts represents another area of significant interest. DFD is very attractive to dismantlers, because it reduces their operational cost, but this would not necessarily result in more recycling. It may only result in more profits for dismantlers.

On the other hand, if the dismantling time is reduced by DFD, one can speculate that more parts would be disassembled and offered to the public. This increase in used parts supply

would certainly create a pressure on the parts price to go down and therefore the profitability of the dismantlers would also be diminished. The combined effect of these events is hard to estimate without undertaking a closer analysis of the dynamics of the market of used parts. Answering these questions is beyond the scope of this work, however they are clearly an area of interesting future research.



## Chapter II.3

# The Automobile Recycling Dynamic Model (ARDM)

This section describes the basic structure of each of the 22 sectors of the Automobile Recycling Dynamic Model (ARDM). A detailed formulation is presented in Appendix III.

The model is built under the following general considerations:

- Time horizon: 50 years.
- Time unit: Month.
- Time step: 1 month.
- Basic units:
  - ◊ Automobiles: cars
  - ◊ Platforms: vehicles
  - ◊ Level of properties in automobiles: kg/car
  - ◊ Price of scrap and hulks: \$/kg
  - ◊ Price of junk cars: \$/car

### 1. Automakers Sector

The structure of the design process of the automobile manufacturers is modeled in this sector.

There are two basic stocks and three flows. The first stock represents the number of vehicles or platforms being designed by the automakers. These platforms are not currently offered to the market. The second stock is the number of different platforms offered to the market.

There is a flow at which new platforms are incorporated into the design process and another one associated with the design rate, which quantifies how many platforms are launched per month. The third flow is the rate at which platforms are discontinued. The model uses a unit of *vehicle* to quantify platforms, as opposed to *car* that is used to quantify automobiles.

In parallel, a property-tracking structure was built. The purpose is to follow the level of each of the 5 properties under study at each of the stages of the design chain. The average level of the property in the stock of platforms being offered to the market is the property level at which cars are sold. They represent the dynamic values for the variables that go into the aging chain described in the next section.

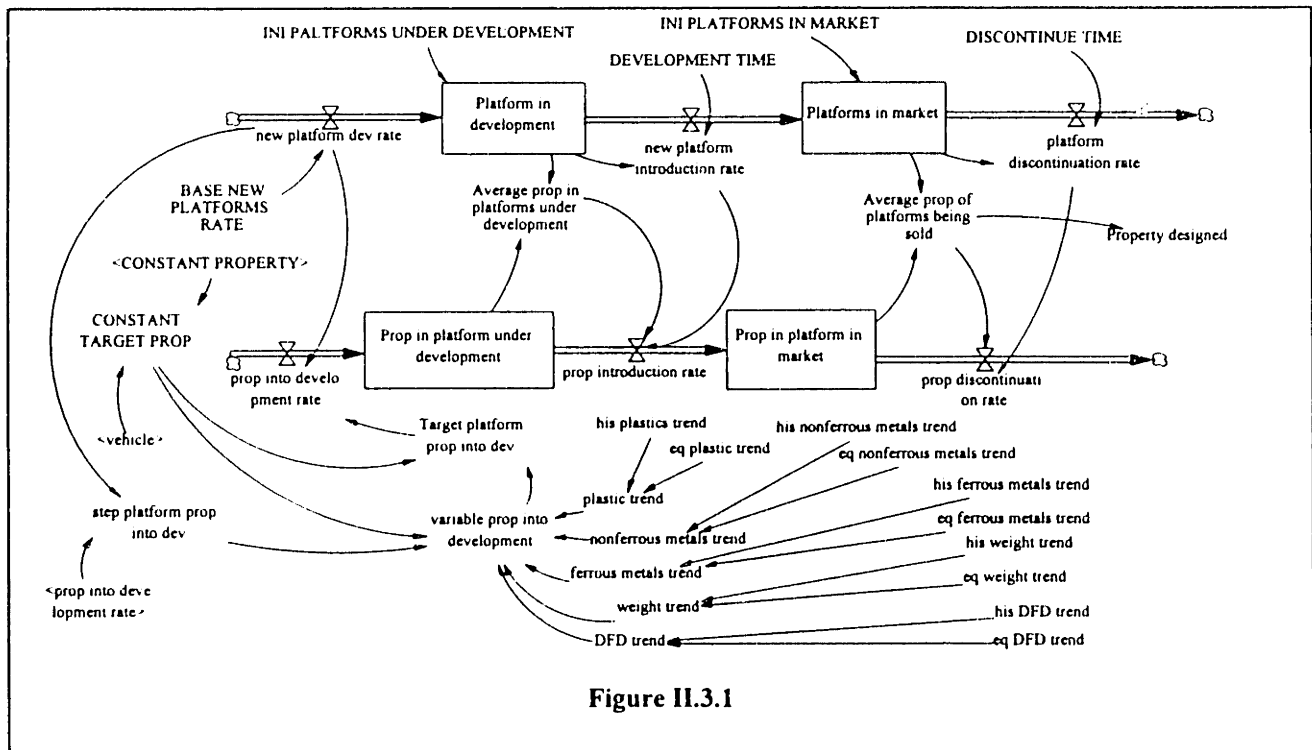


Figure II.3.1

As explained, there are 5 properties under study: total weight of cars, ferrous content, nonferrous content, plastic content, and level of DFD. These properties represent the core of the policy decisions. It is clear that the automakers can define policy only for the new cars being developed. In other words, they do not have immediate control on the average property level at the point of sales.

Decisions about these policies can be made using the variables *trend* which allow one to define the targets for the complete time horizon before running the simulation. On the other hand, if the simulations will be run intermittently (as in a game mode) the *CONSTANT TARGET PROP* variable would be used to define policy.

### 2. Aging Sector

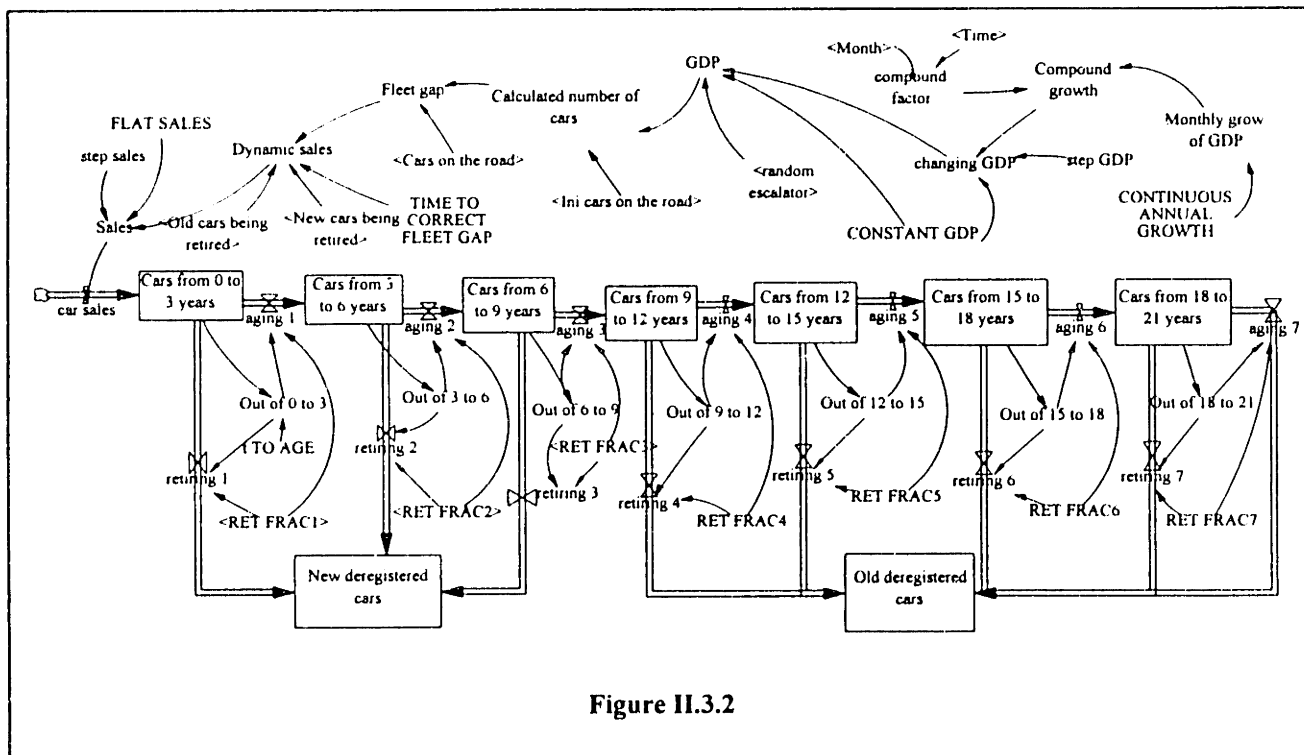


Figure II.3.2

This sector simulates the aging chain. It represents the vehicles usage sector. The upper part of the sector contains the structure that generates sales, which are calculated based on GDP. It is estimated that the elasticity of cars in the road (fleet of cars) to GDP is 1.0. The stock adjustment period *TIME TO CORRECT FLEET GAP* is estimated as 66 months [Pindyck 1994].

When cars are sold they go into the aging chain, which is a series of seven age cohorts that accumulate cars. Cars move from one age cohort to the next as time elapses. Since each of the age cohorts corresponds to 3 years, the variable  $t$  TO AGE is 36 months. The outflow of cars from each cohort is calculated dividing the number of cars in the cohort by the  $t$  TO AGE.

This outflow is then divided into two different flows; one ages (into the next age cohort) and then another gets retired (the car will no longer be used). The fraction of cars that will be retired is estimated based on the Liberty calculations [Liberty 1993]. The figure II.3.3 below shows a detailed view of this process. The retirement fractions in the model are kept constant. However, they could incorporate dynamics associated with income per capita, consumer preferences and driving behavior. This is a possible area for future research.

As explained in the previous chapter, dismantlers treat automobiles that provide sellable used parts differently from those that represent a material opportunity only. Thus, when automobiles get retired they can go into two different stocks: *New deregistered cars* and *Old deregistered cars*. This classification is used because the two types of automobiles are processed differently.

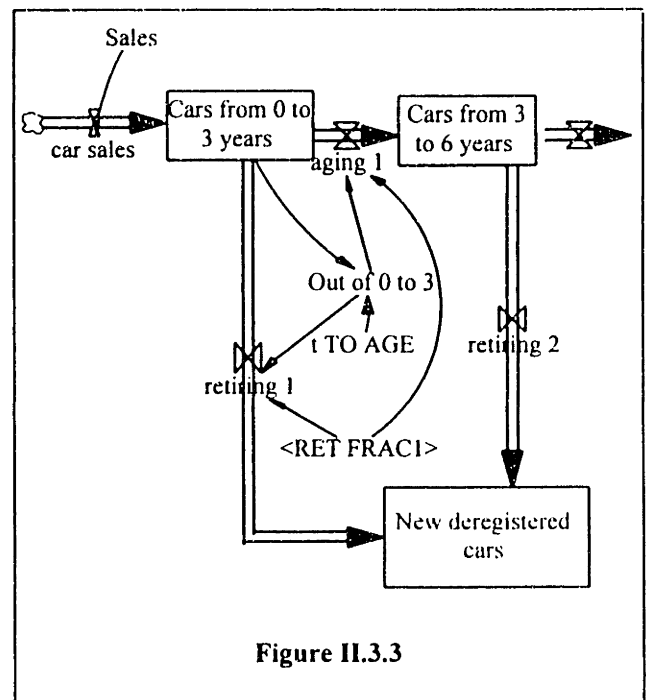


Figure II.3.3

### 3. Main Sector

The backbone of the model consists of the *Aging* and *Main* sectors. In this sector cars are recycled. The units in these sectors are cars for the stocks and cars/month for the flows. The rest of the model is comprised of either parallel flows of these two, support and decision sectors that evaluate the rate at which cars are processed by the recycling industry, or auxiliary sectors that calculate information variables.

This sector starts with two stocks: *Old and New deregistered cars*. They represent the cars that

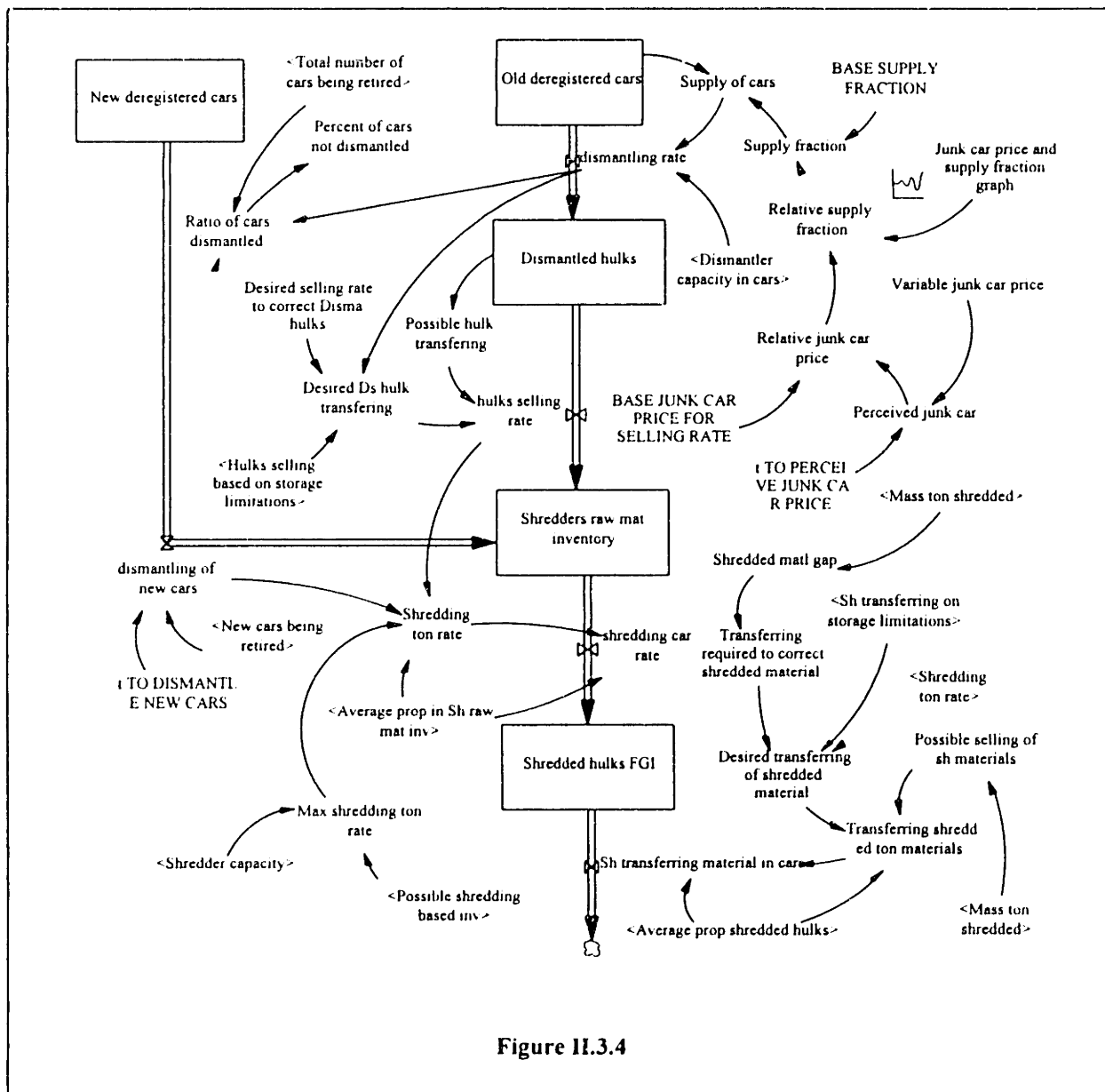


Figure II.3.4

can potentially be recycled. In the case of new cars, the process is simple: they have had a major accident and were declared a total loss by the insurance companies. These cars will be auctioned to dismantlers. Typically, the value of the parts in these vehicles is high and the auctions are highly competitive. As was discussed in the previous chapter, the dynamics of this part of the industry are dominated by the market for used parts. Between 20% and 27% of the vehicles being processed would be “new cars”, depending on the state of the model -- equilibrium or non-equilibrium. In the model, “new cars” are processed as they get deregistered (a time delay is also included in the formulation).

In the case of the “old cars”, the process is dynamically determined. First, “old cars” are deregistered and go into a zone where, if the price is attractive enough, the last user (or a self-motivated intermediary) would take the cars to the dismantlers and obtain the *Junk car price* for them. Note that this is a material-conserved structure: cars do not leave the system. The rationale is that if the price was high enough, even cars in the woods, or on islands would be brought to the recycling industry.

The supply formulation evaluates the relative price of cars, comparing the price offered to a standard. This relative price generates a flow that is a fraction of the stock of *old deregistered cars*, as it is presented in figure II.3.5.

Cars are processed by the dismantlers as soon as they receive them (assuming they have enough capacity). Dismantlers take some parts and some material and store the remaining hulks in their inventory (*Dismantled hulks*). As dismantlers decide to sell hulks, they transfer them to the *Shredders' raw material inventory*.

Shredders take hulks from this inventory and process them. As hulks are shredded, they become part of the final material inventory of shredders (*Shredded hulks FMI*). The final flow represents the rate at which shredders decide to sell

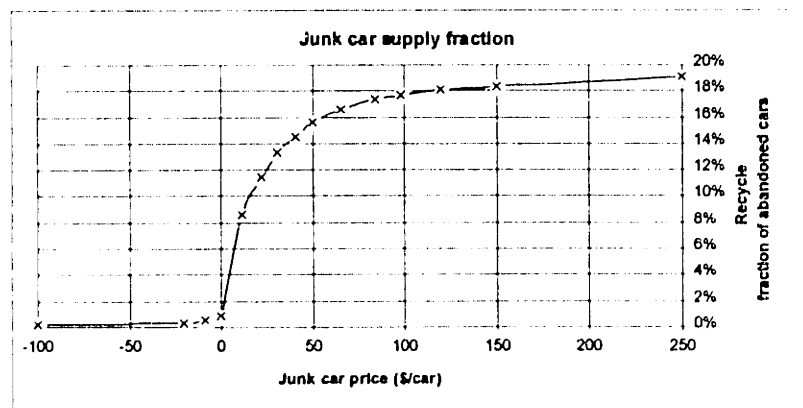


Figure II.3.5

recovered material, and landfill the corresponding ASR.

The flows presented in this sector are calculated in other parts of the model and will be explained in the following sections.

#### 4. Age Sector

In this sector the average age of automobiles being retired is calculated. This is a parallel structure based on the aging sector. The input into the chain is defined by sales of new automobiles and by the purchase date. *Purchase date* is calculated adding the variable *Time* (in year units) to the *INITIAL MODEL* variable, which is the date at which the simulation starts, namely, 1995.

The flows are calculated, based on the Aging sector. For example, the variable *model transf 1*, which is a flow from the first to the second cohort, is calculated based on the variable *aging 1* and on the *Average Model* in the first model-stock. The *Average Model* in each stock is calculated dividing the model cohort by the corresponding car cohort. This is a virtual variable that estimates the average model of the vehicles in the corresponding cohort. Figure II.3.6 presents a detailed structure for the first set of flows. The stocks in this sector have units of *year\*car* and the flows have units of *(year\*car)/Month*.

The average age in each model-cohort is calculated by subtracting the *Purchase date* from the *Average Model*. The average age of “new” and “old cars” is then calculated as a weighted average of ages and the relative size of each flow.

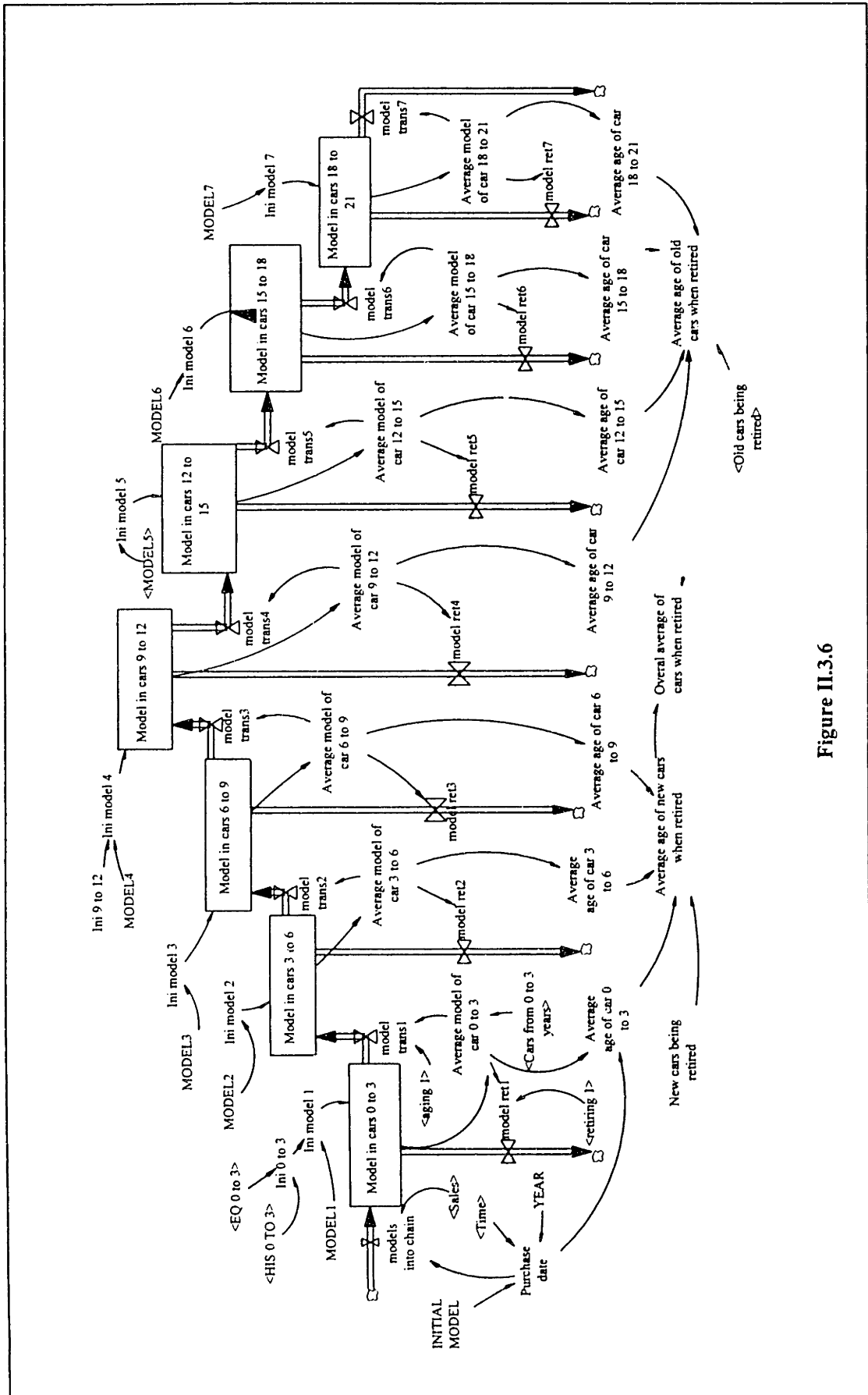


Figure II.3.6



**5. Ini values Sector**

The model can be initialized under equilibrium or historical conditions. These initial stages are different because sales and property levels have been changing continuously and significantly in the past: they have never become constant. The only difference between these stages is the level of the stocks in the model when the simulations start. In this sector the alternative values are selected based on the values of two switches.

The equilibrium condition is used to test the model during the building process and to understand single policy effects, discussed in chapter I.5. Historical conditions are used in chapter II.6 to

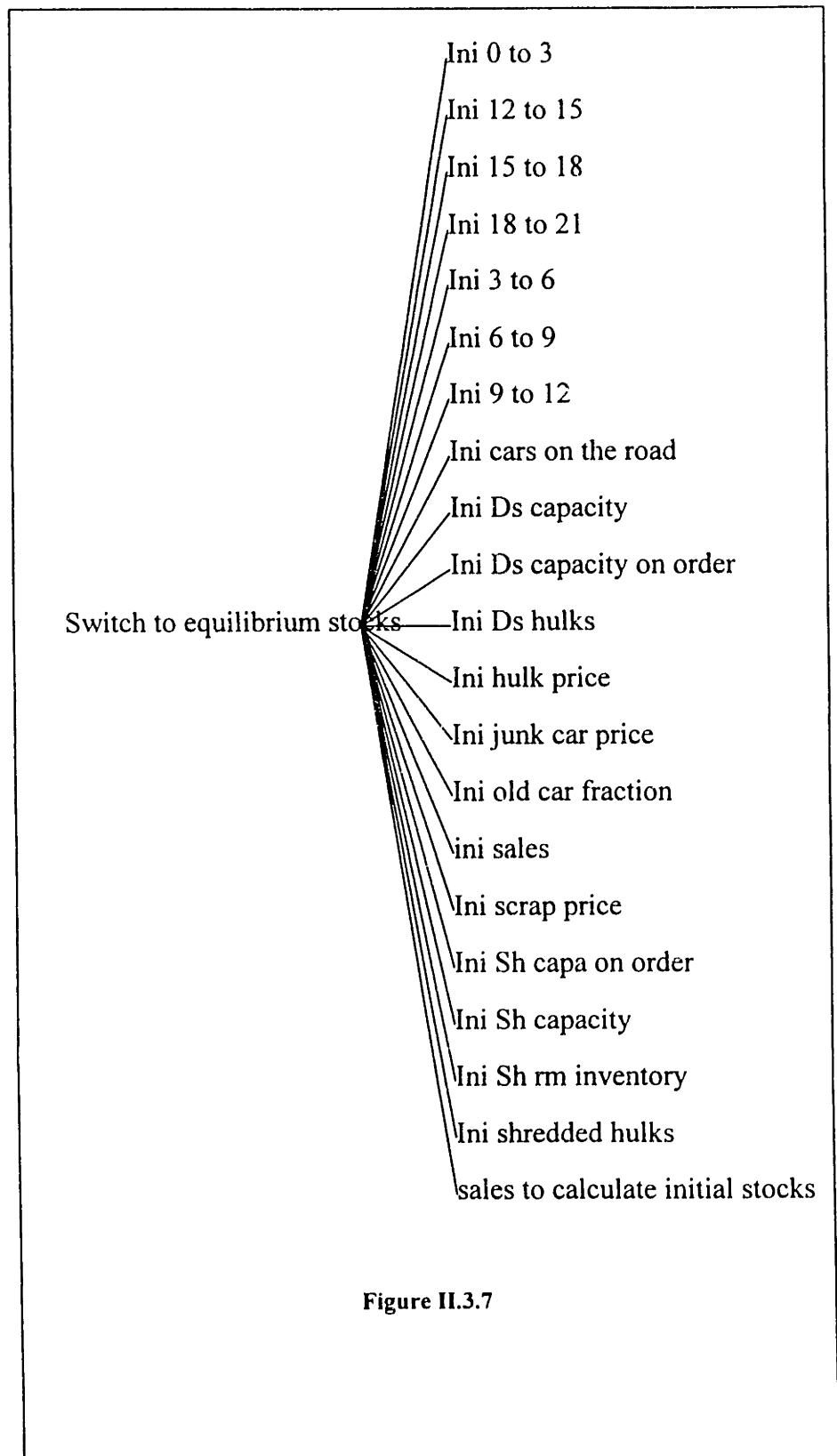
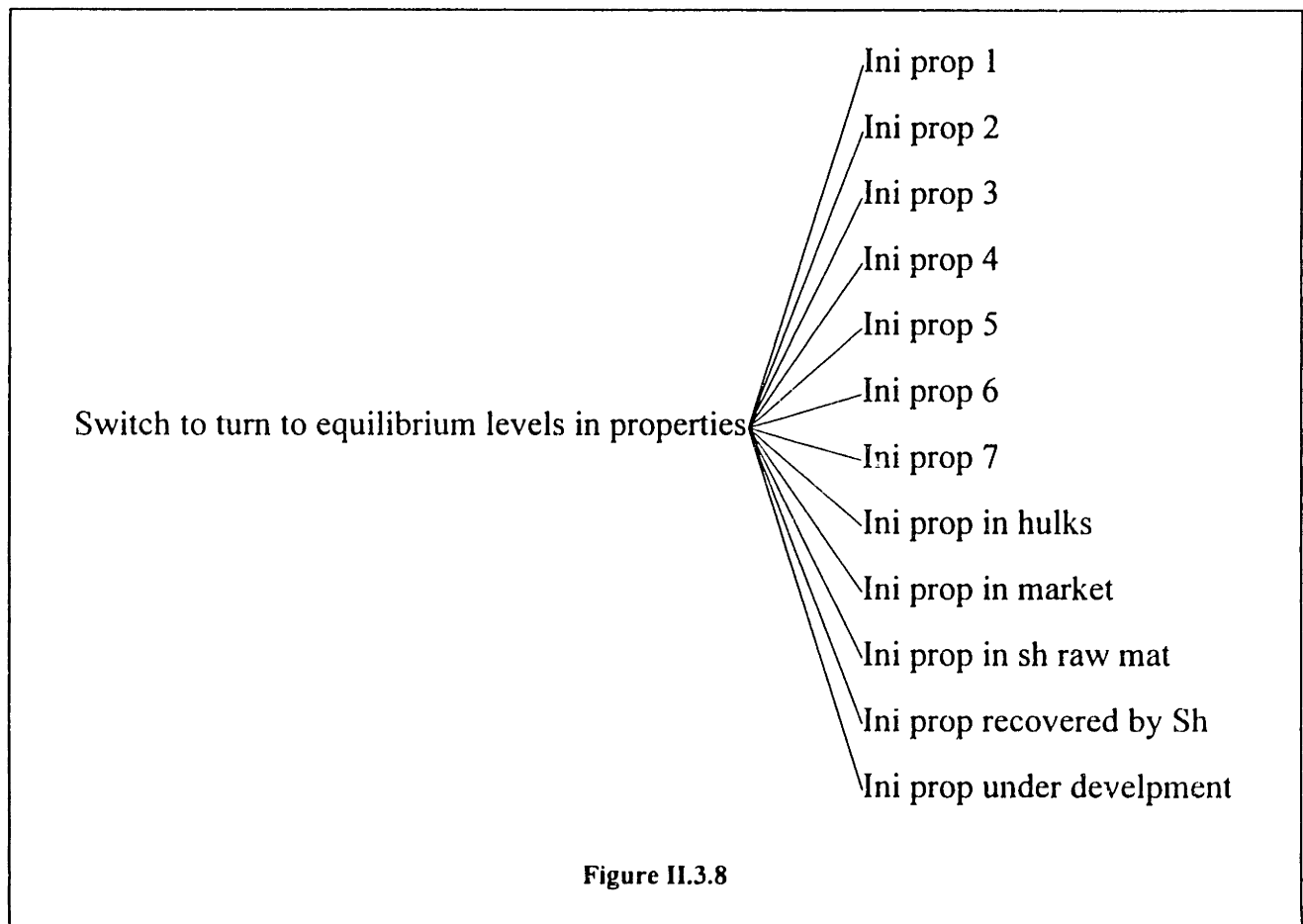


Figure II.3.7

evaluate the potential impact of policy decisions given the actual conditions of the system.

The switches that control the values of the variables in this sector are *Switch to equilibrium stocks* and *Switch to turn equilibrium levels in properties*. The first is a control for the initial condition of the stocks of cars, the second defines the initial level of the stocks of properties.

Their control structure is presented in figures II.3.7 and II.3.8.



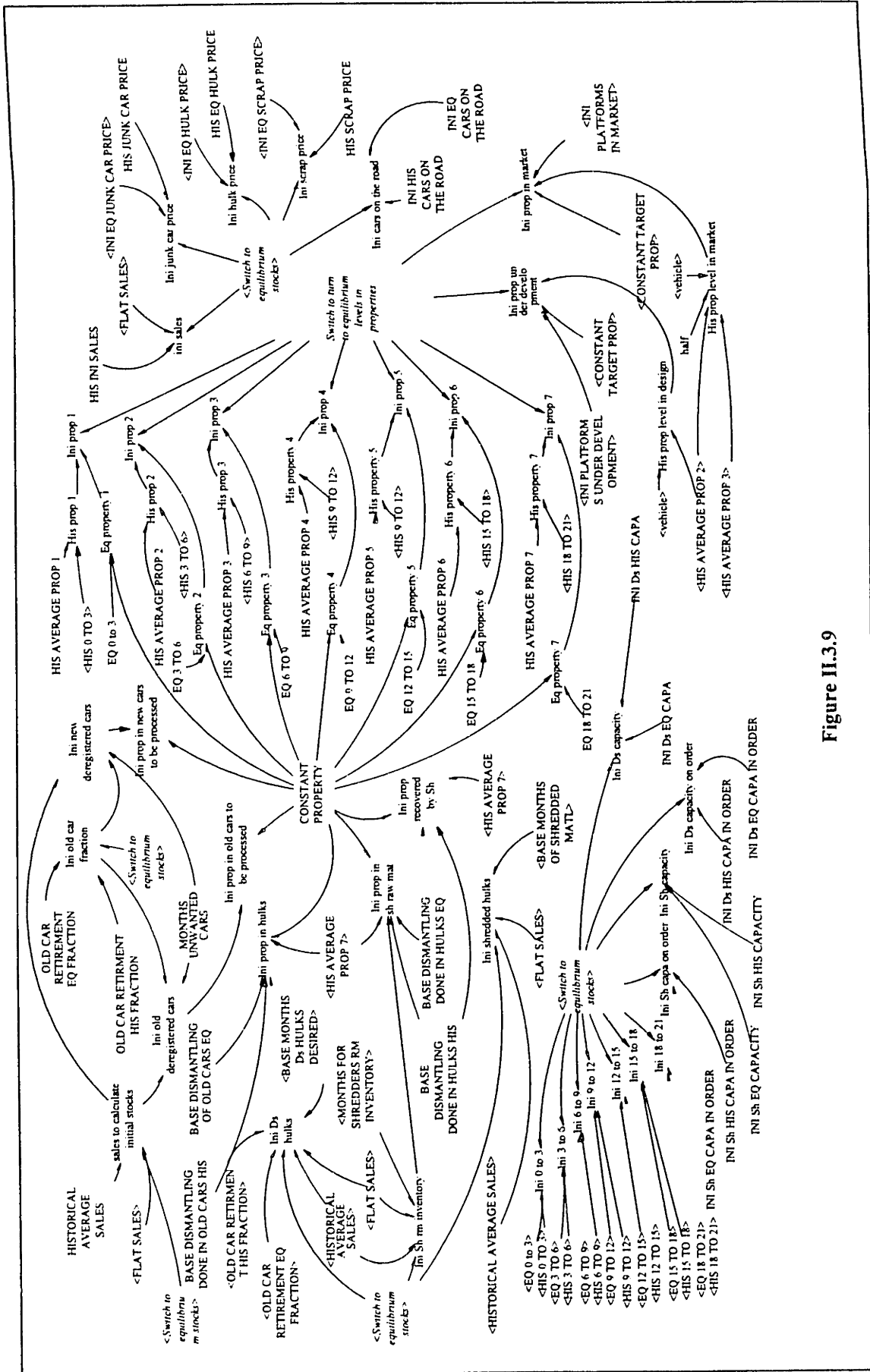


Figure II.3.9

6. x-levels Sector

This auxiliary sector presents the level of the exogenous variables used to define the dismantling procedure. This set of independent variables corresponds to the variables used in the DOE described in Part I of this work. When these variables are based on a property level, the distinction is made between “new” and “old cars”.

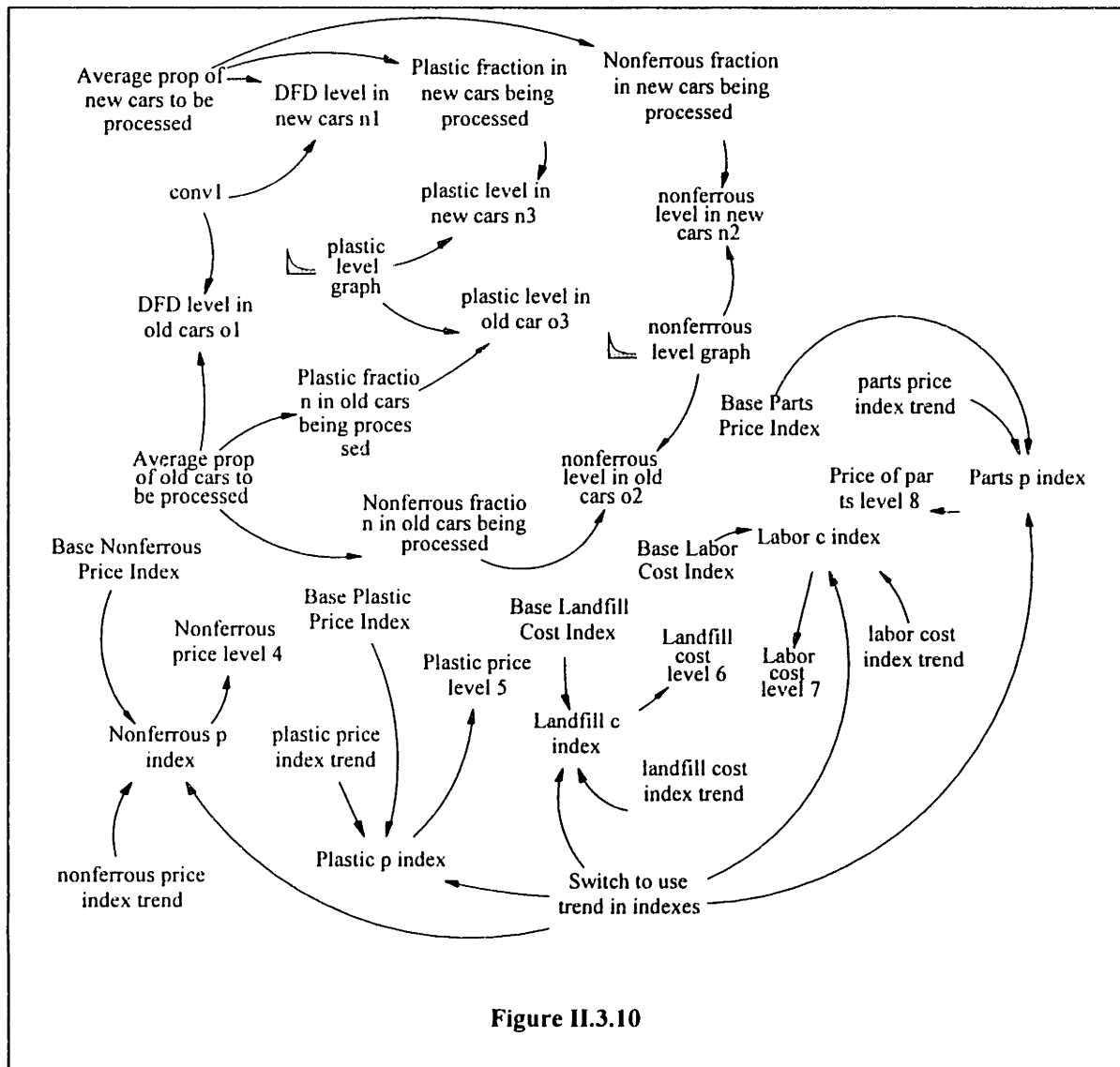


Figure II.3.10

These variables have real values, defined exogenously or by policy. However, these real values have to be converted into the numbers within the scale used during the experimental designs. In

this sector these conversions are calculated: from real values (denominated *index*) to the so called, “*x-levels*”. The *trend* variables allow the user to change the index values during the simulations.

In most of the cases the conversion from real values to x-levels is done using simple mathematical equations. In the case of the material content this is somewhat more complicated. The conversion has to be done based on what was done during the experimental designs, when the DML files were manipulated (“changing the automobile design”) to obtain different levels of each component. Figures I.4.18 and 19 in the first part of this thesis contain the conversion relations proposed. In both cases the level to be used in the corresponding equation is a function of the material composition fraction of the automobile under analysis.

### **7. Dismantling calculations Sector**

This sector presents most of the calculations of the Dismantling procedure. The levels of the variables, calculated in the previous sector, are used here to evaluate the level of dismantling on “new” and “old cars”. The objective of this sector is to quantify the amount of material recycled in both types of vehicles, and the amount of material dismantled in parts in the case of “new cars”. In addition, the composition of these materials is also monitored.

In the case of material recovery, the following variables (for both types of cars) are evaluated using the equations found in the automakers’:

- Fraction of nonferrous recycled in new cars
- Fraction of plastics recycled in new cars
- Fraction of mass recycled in new cars

Since these three equations are calculated independently, there is the possibility of estimating infeasible solutions (when the sum of the fraction of plastics and non-ferrous exceeds the total mass fraction). Therefore, some additional calculations are added to prevent impossible solutions. The correction rules are the following: If the sum of the fractions (nonferrous plus plastics) does not exceed the total fraction, then do not correct; if the sum of the fractions is greater than the total fraction, then correct for the difference (reducing one of the fractions) on the larger individual fraction; in the case of no correction required, the ferrous fraction balances the sum of individual fractions making them equal to the total recycling fraction.

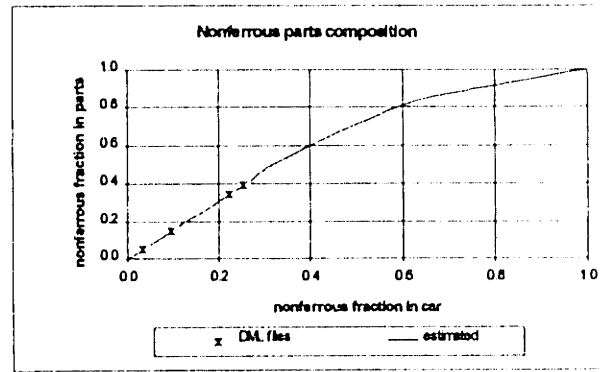


Figure II.3.11

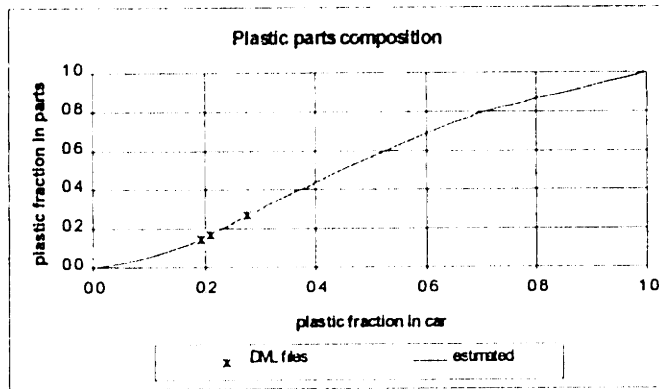


Figure II.3.12

The relevant property level to be used to evaluate the dismantling process is the property level at the "deregistered" stage. In the case of "new cars", the material dismantled is to be added to the material in the parts recovered to produce the variables called: *kg of material x reused or recycled*.

The exogenous variable *FREQUENCY OF COMPLETE PARTS*, as explained, represents the fact that "new cars", when

retired, have a significant level of damage, and therefore not all parts can be sold. It is estimated that this fraction is approximately 50%.

The composition of the parts dismantled is estimated based on the following relationships shown in figures II.3.11 and 12.

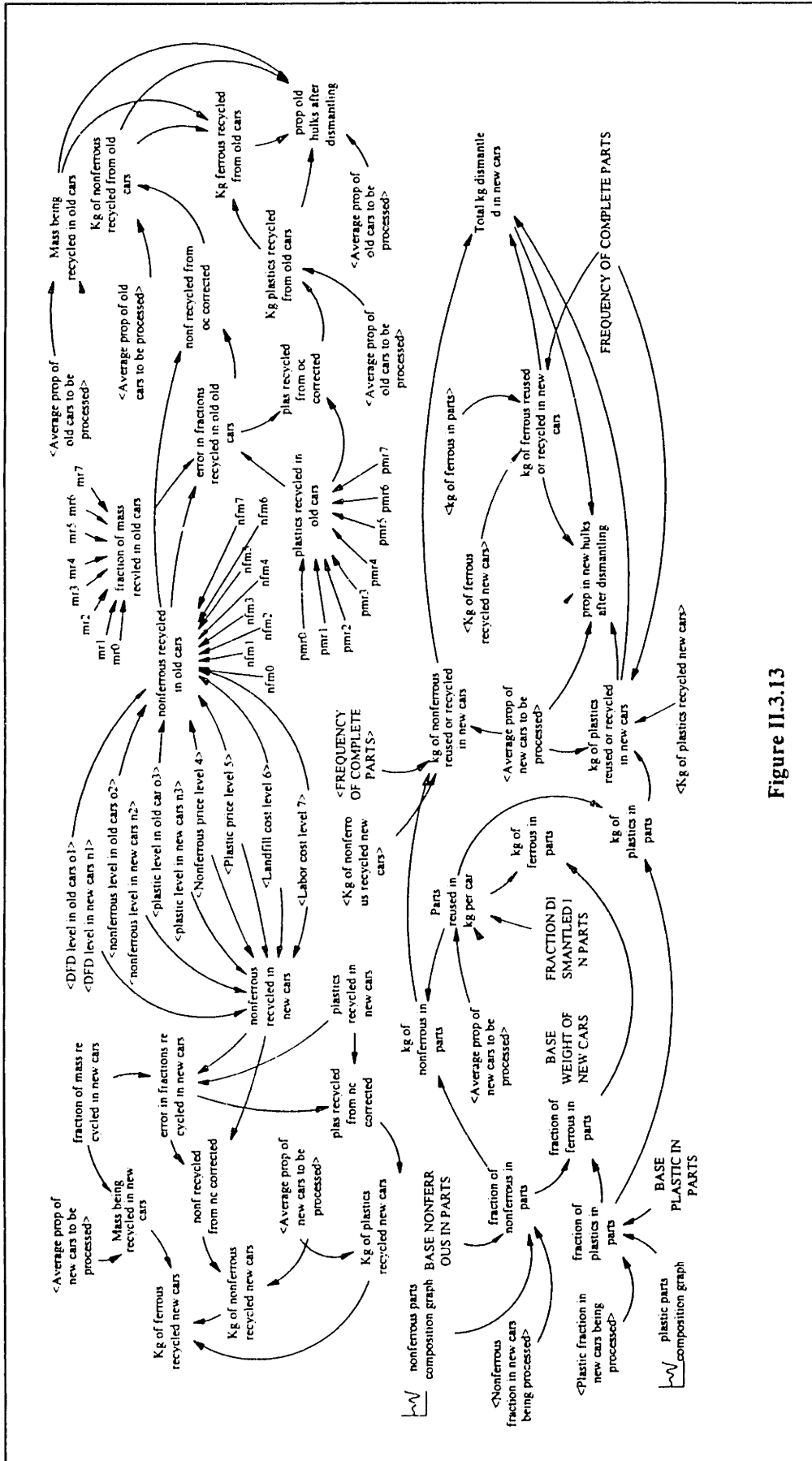
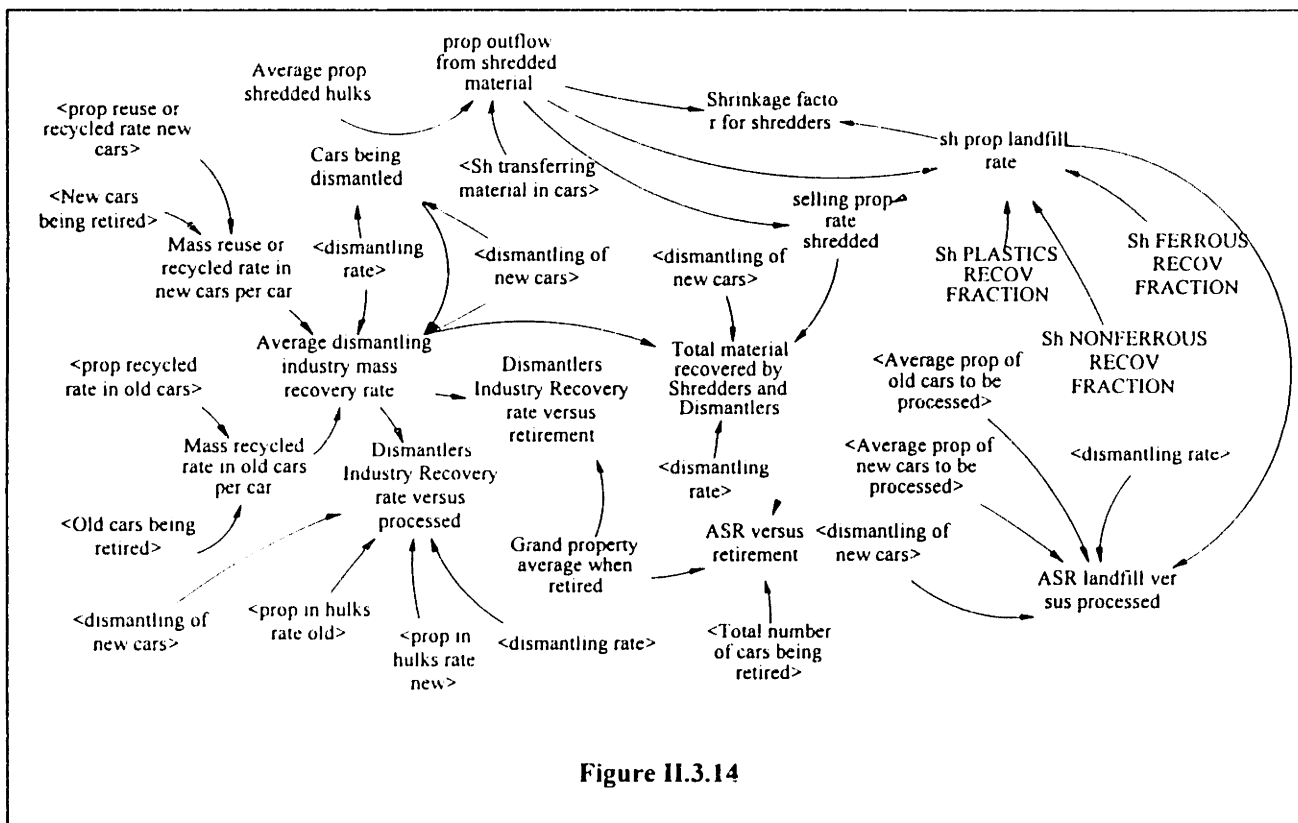


Figure II.3.13

8. Shredding calculations Sector



This sector contains the calculation necessary to model the shredding process. Its objective is to evaluate the composition-specific flow of material that shredders sell and the material and composition of the flows to landfills.

Shredders decide to sell material by reacting to the price they can obtain for their products. This mass flow is converted to car units by dividing the mass flow by the average weight of the shredded hulk. The rate of “equivalent-cars” being sold is then converted into net, material-specific outflows from the shredders. Outflows from shredders’ facilities involve both flows of materials sold and the flows to the landfill. The fraction of materials that is not recovered by the shredders constitutes the Automotive Shredder Residue (ASR). This frequently referred to environmental indicator is normally measured as a percentage.



During the course of this research it was impossible to find a consistent definition for ASR. Therefore, two calculations are made. In both cases that are reported, the fraction of ASR is calculated by dividing the flow of materials to the landfills by another flow. In the first case, the total flow of materials being retired is used in the denominator. The second calculation uses the total flow of materials to the dismantlers. In the case of a sudden accumulation of cars in the stage of *Old cars to be processed* these two calculations may differ.

Some other environmental calculations are included in this sector, such as *Shrinkage factor*. This refers to the fraction of hulks that goes to the landfill. The variable *Average dismantlers Industry Recovery rate versus retirement* calculates the amount of material that the dismantlers recover as a fraction of the material per car being retired. *Dismantlers Industry Recovery rate versus processed* calculates the amount of material that the dismantlers recover as a fraction of the material per dismantled car.

## 9. Properties

This sector evaluates the level of each property along the physical chain described in sectors *Aging* and *Main*. In these two sectors, vehicles are sold, are retired, and may eventually be incorporated into the recycling infrastructure. Dismantlers process cars and store hulks in the corresponding inventory. When hulks are sold to shredders they keep them in a temporary inventory and process them later. The material obtained is kept in the Finished Material Inventory. From there, recovered material is sold and ASR is sent to the landfill. This structure is based on 7 age stocks, 2 retirement stocks and, 1 stock associated with the dismantlers' inventory and 2 shredders' inventories.

The *Properties* sector tracks the level of 5 properties (weight, ferrous content, non-ferrous content, plastic content and level of DFD) from the point of sales to the dismantlers' operation. Afterwards, only four properties are evaluated. The property level of Design for Disassembly (DFD) has no meaning after the vehicles have been dismantled.

For each stock the *Average property* is calculated by dividing each property stock by the corresponding stock of cars. Therefore *Average properties* are always measured in kg/car. It is assumed that vehicles moving from one stock to the next carry with them the level of the *Average property* on that stock. The flow of properties is calculated by multiplying the flow of cars by the *Average property* in the stock.

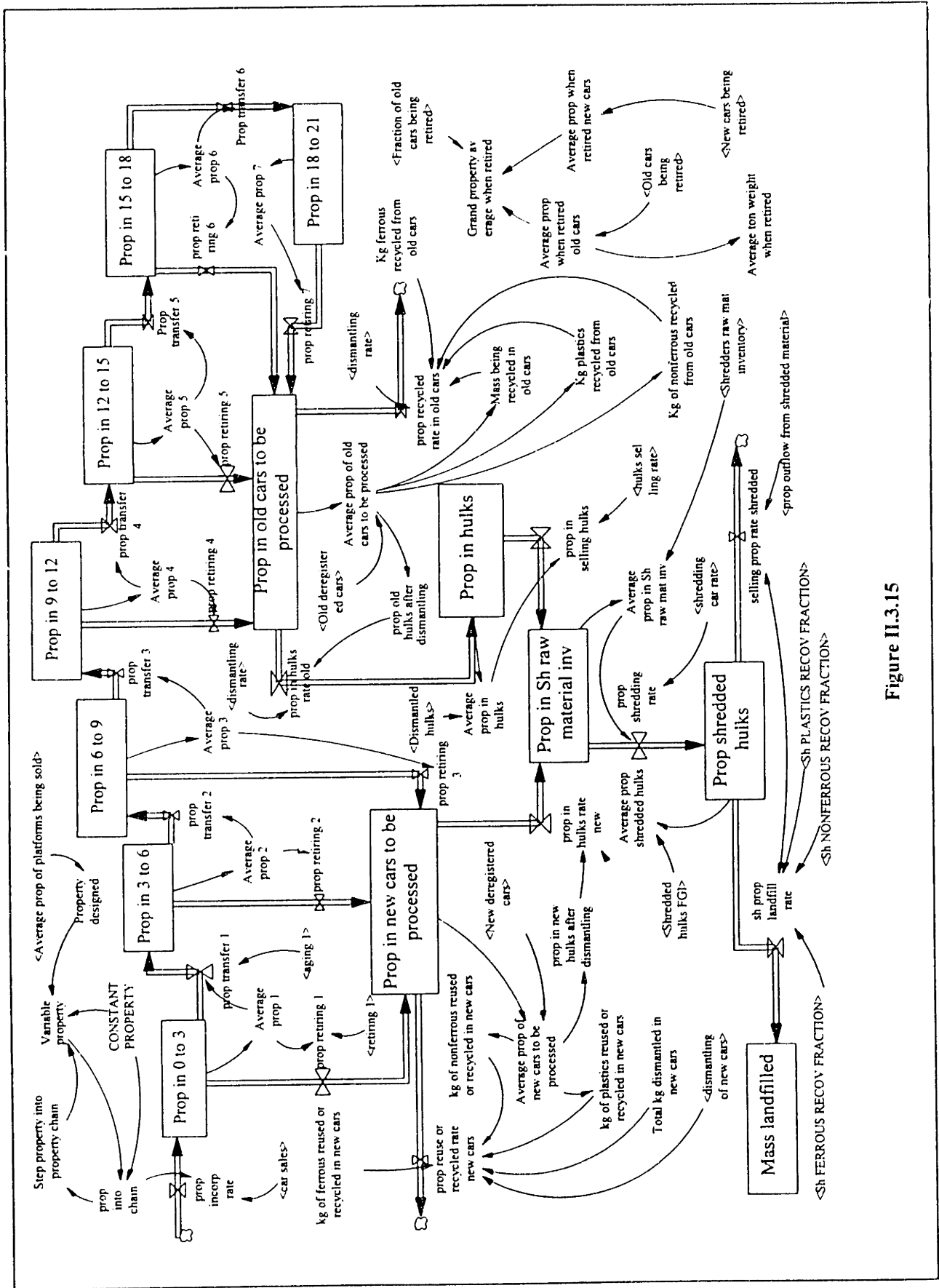


Figure II.3.15

**10. Dismantlers' Forecast Sector**

In this sector the expectations of the “old car” processing dismantlers are estimated. These include:

- Expected future retirement: Based on actual retirement of old cars.
- Expected future labor into cars: Based on labor devoted to dismantling (old cars).
- Expected future profit: Based on *Perceived semester profit*.

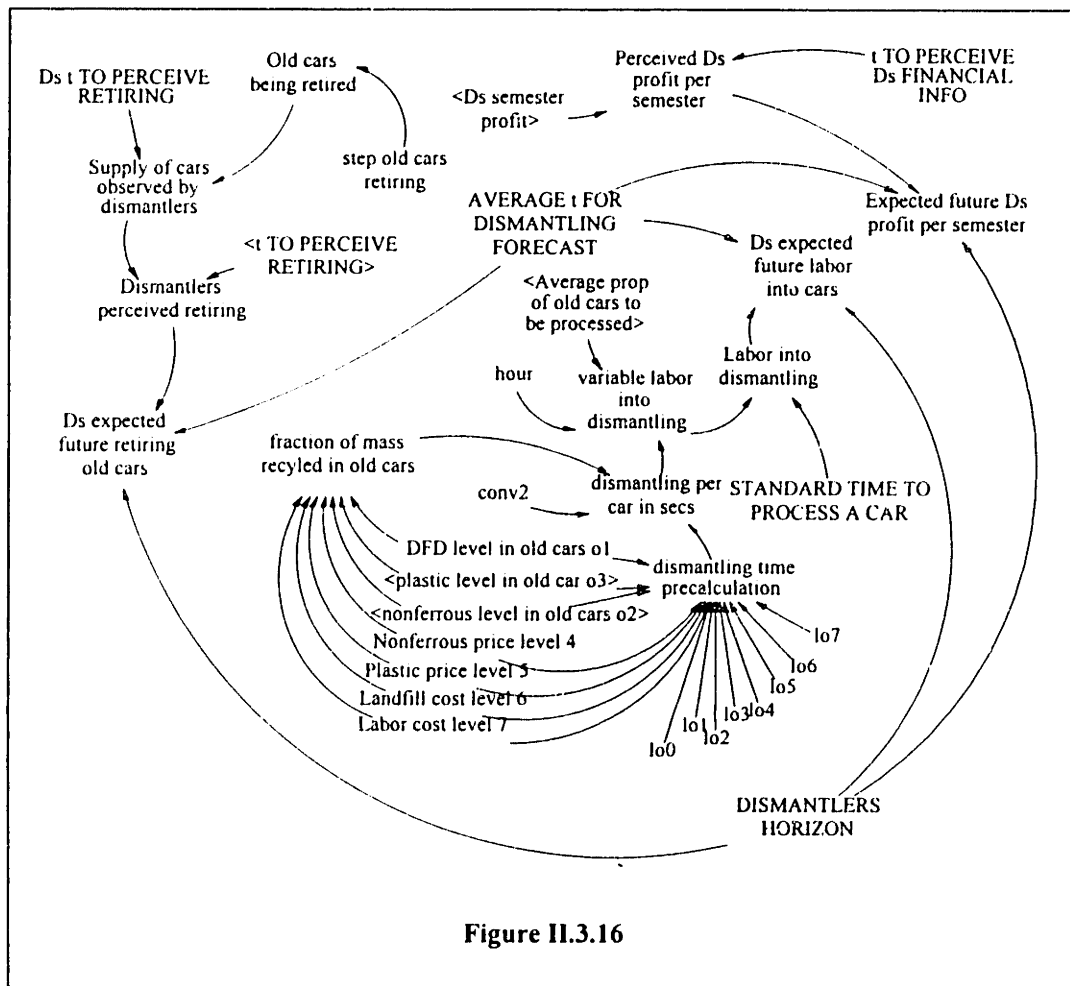


Figure II.3.16

It is assumed that dismantlers take into consideration the last 12 months and look 12 months into the future when forecasting.

The empirical equation to determine labor being spent in dismantling is evaluated here. The level of the *x-variables* determine the time per car dismantlers spend on average disassembling it. This initial calculation represents the time to optimize their profit. Then a fixed amount of time is added per car. This additional time is due to regulations or shredders' requirements. Gas tanks and batteries, are examples of parts that have to be removed.

**11. Dismantlers' Rates Sector**

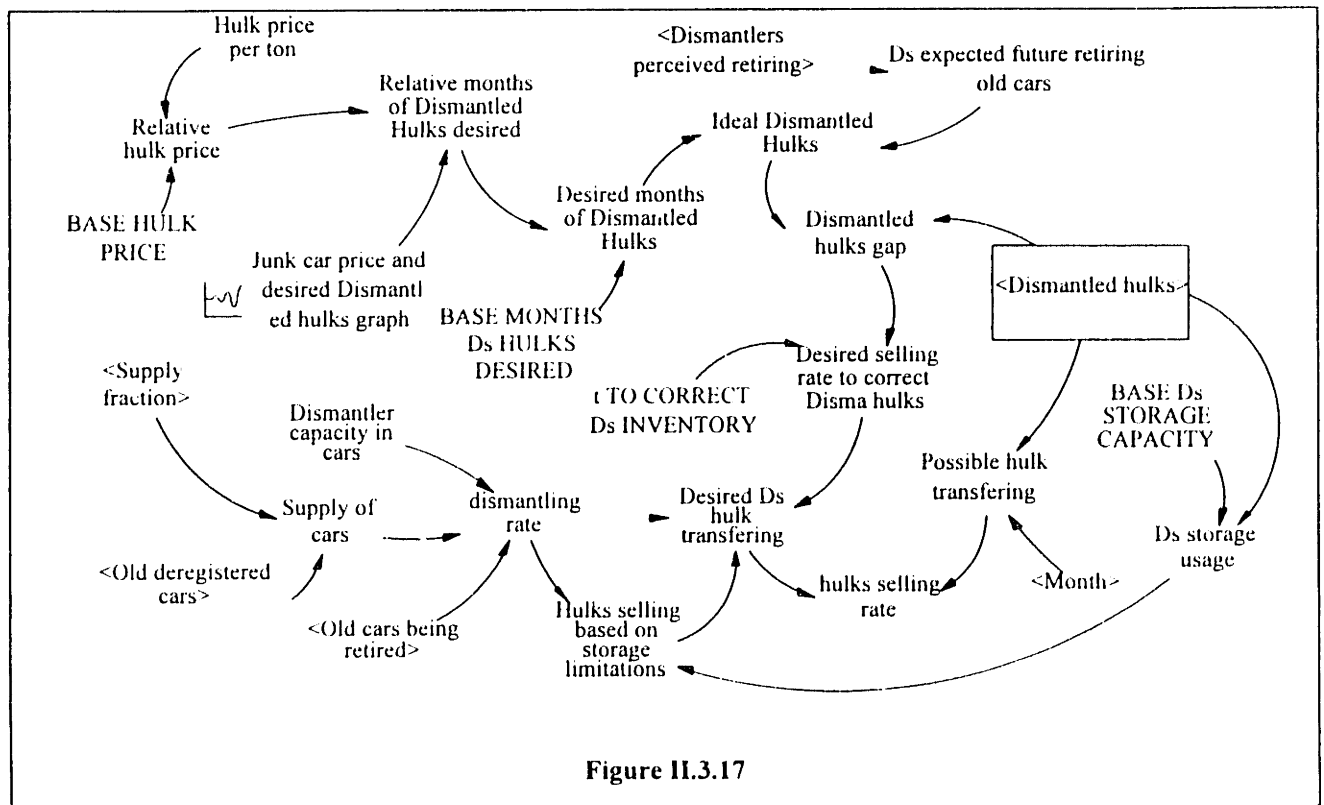


Figure II.3.17

This sector models the decision making process of dismantlers . They have to decide on two flows: the rate at which they process cars and the rate at which they sell hulks to shredders.

The decision rule for the first rate is simply, “process all the cars you get, as soon as you receive them, provided that you have the capacity to do so. Otherwise, work at capacity”. As it will be

explained later, dismantlers use the *Junk car price* to regulate the rate at which cars get into their facilities.

The decision rule for selling hulks is a little more complex. It is based on the "inventory coverage" principle. Dismantlers desire to hold certain inventory coverage, quantified as the number of months of cars to be processed. For example, if dismantlers believed that the number of cars they will receive per month is 100, and their desired inventory coverage is 10 months, the target level of inventory is 1,000 cars. Therefore, they would sell the amount of cars they dismantle, plus a fraction of the excess or deficit of the actual inventory level, minus the target level.

Additionally, the inventory coverage is a function of the hulk price they observe. The actual hulk price is compared to a standard and the resulting relative price determines the relative number of months to be kept in inventory. Figure II.3.18 presents this relationship.

Once the desired level of inventory is defined, this level is compared to the actual inventory to define a gap. The selling rate is then defined by adding or subtracting a portion of the gap to the dismantling rate.

There are two final considerations. The first is a result of the fact that the storage area is finite. If the storage capacity is used completely, then the selling of hulks equals the dismantling rate, regardless of the inventory coverage.

Finally, the formulation includes a section that prevents the model from deciding to sell more hulks than what are available in the inventory.

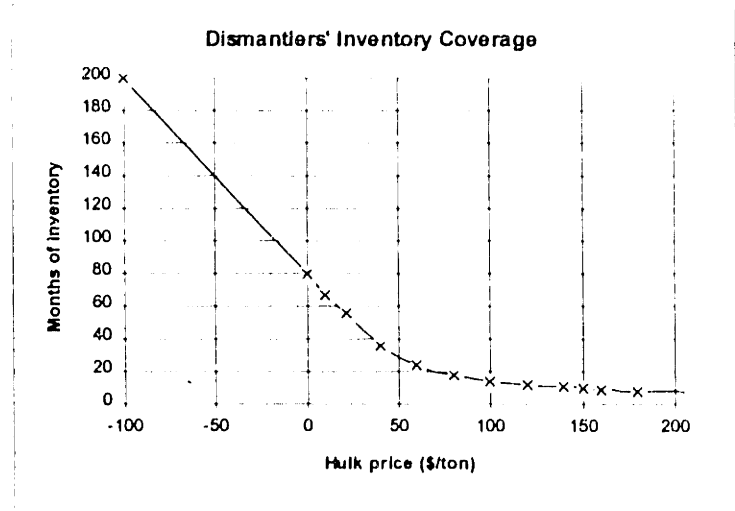


Figure II.3.18

### 12. Dismantlers Profit Sector

This sector represents the financial structure for dismantlers. The monthly and semester profits of this entity are evaluated here. One additional equation from the DOE is evaluated here:

*Revenue from recycling.*

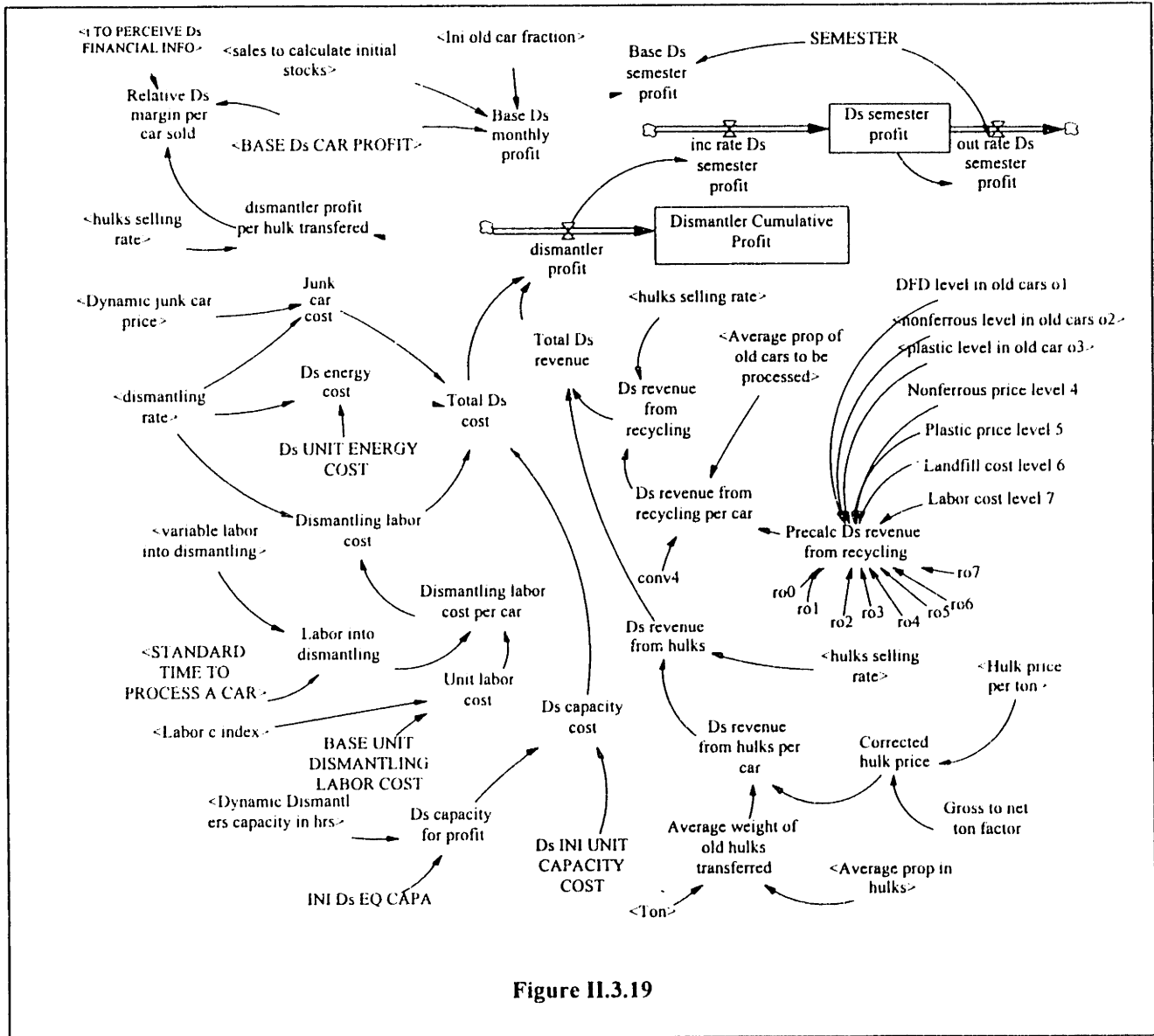


Figure II.3.19

The dismantlers' costs has four elements: junk car acquisition, energy, labor and capacity costs. The latter is based on an estimated unit fixed cost; the rest are variable. The estimation of the capacity cost is described in detail in the next section.

Revenue is generated by selling hulks and by selling materials recovered from vehicles (recycling). It is assumed that the recycling revenue is obtained at the same relative rate as the hulks.

There is an auxiliary stock accumulating profits, during the simulations, for reporting purposes. In addition, a semester profit stock is also evaluated. This structure estimates the average semester profit and reduces the noise in monthly profit associated with changes in sales. For example, a sudden decrease in hulk sales for one month, as a response to a change in hulk price, may cause a very negative one-month profit. This one-time value is a poor indicator of economic performance; instead the semester profit is a smoother indicator. The average profit is used to define capacity targets.

It is important to note that the market Hulk Price, in dollars/ton is corrected to reflect the industry practice: shredders pay dismantlers on the basis 2000 lb/ton, while they get paid based on 2,240 lb/ton.

### **13. *Dismantlers' Capacity Sector***

In this sector dismantlers define, order, and build the capacity they would like to have. The indicated (or target) capacity is a function of the expectations they have in the future level of dismantling per car and the future rate of processing cars.

Orders for capacity become actual capacity as the projects are completed. The completion rate, based on *t TO COMPLETE CAPACITY*, includes activities such as permit approval, construction, equipment acquisition, installation, training and start up.

When dismantlers place orders for capacity they consider three factors:



- *Ds capacity indicated increment*: Quantifies the expected deviation of actual capacity from the desired future capacity considering expectations.
- *Ds correction for capacity on order*: Dismantlers would take into consideration *capacity on order*, correcting the desired capacity increment to prevent over-ordering.
- *Ds aging rate*: The order for capacity includes the replacement of the capacity that is retired.

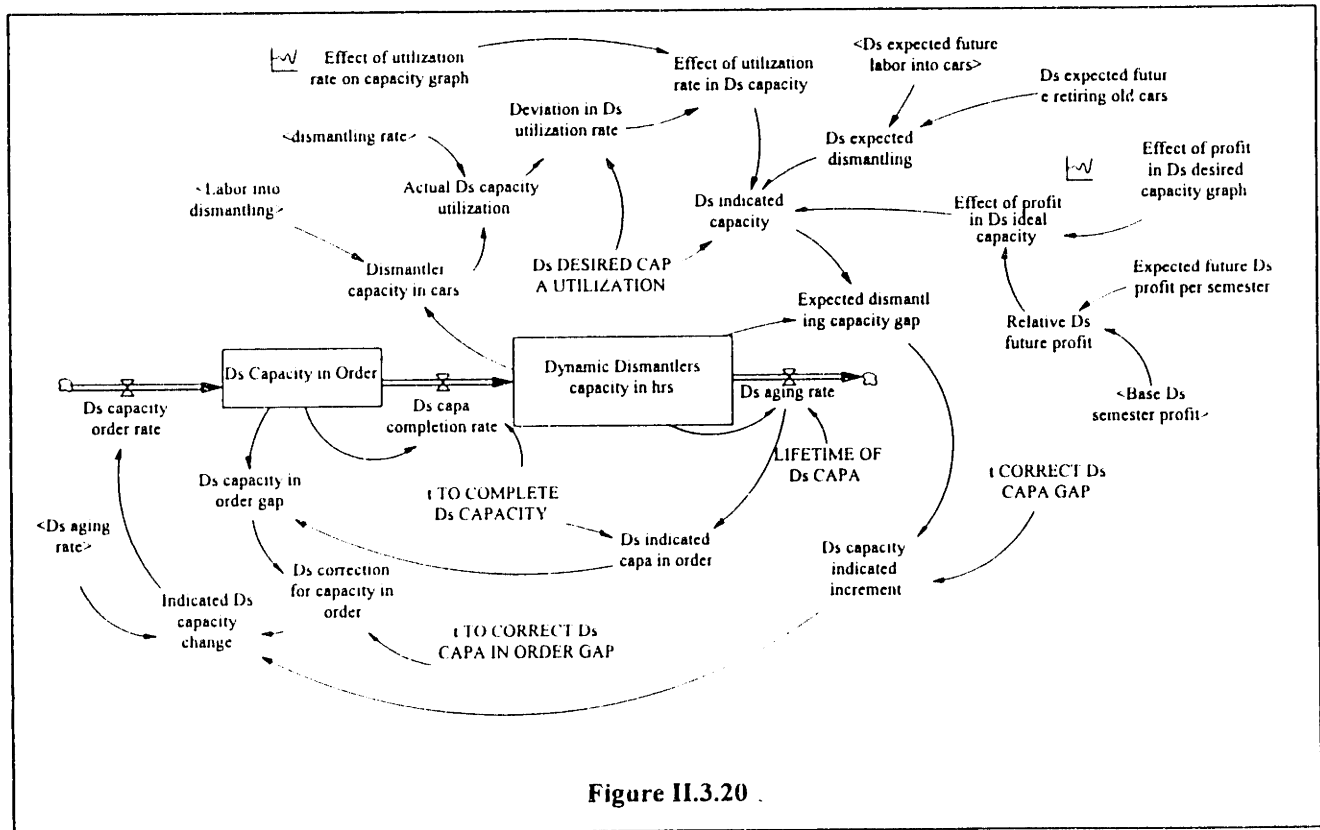


Figure II.3.20 .

When the dismantler industry is experiencing good times (making good profits), presumably people would like to participate in the activity. The *Effect of profit in Ds ideal capacity* captures this dynamic. Figure II.3.21 presents the relationship estimated.

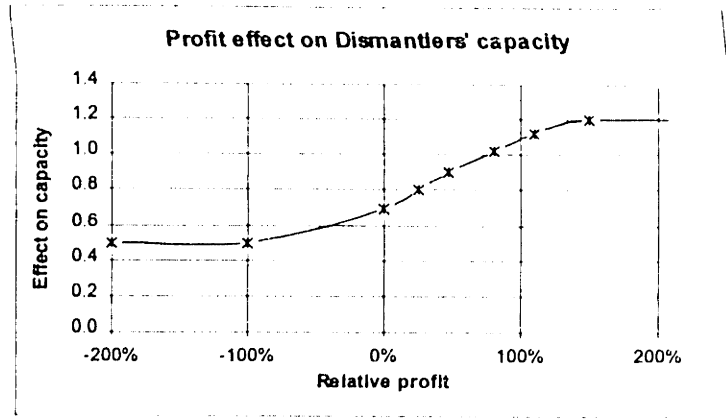


Figure II.3.21

Dismantlers incorporate as well the effect of the actual utilization rate in the *indicated capacity*. In general, dismantlers would like to operate at 80% utilization rate. The variable *Deviation in Ds utilization rate* is calculated by subtracting the actual utilization rate from the desired, it is reported as fraction of the desired level.

Figure II.3.22 presents the effect of the deviation in utilization rate on indicated capacity.

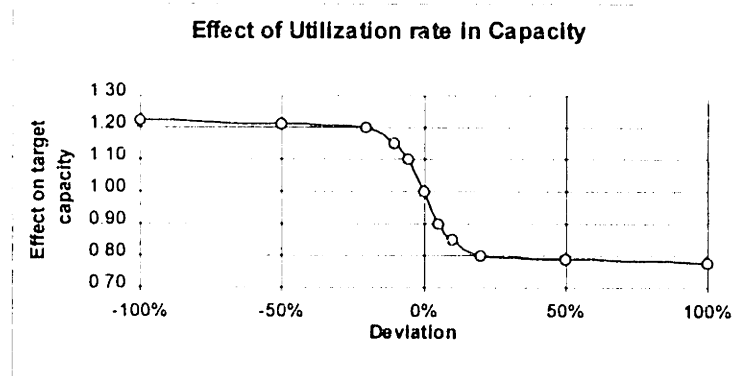


Figure II.3.22

14. Junk Car Price Sector

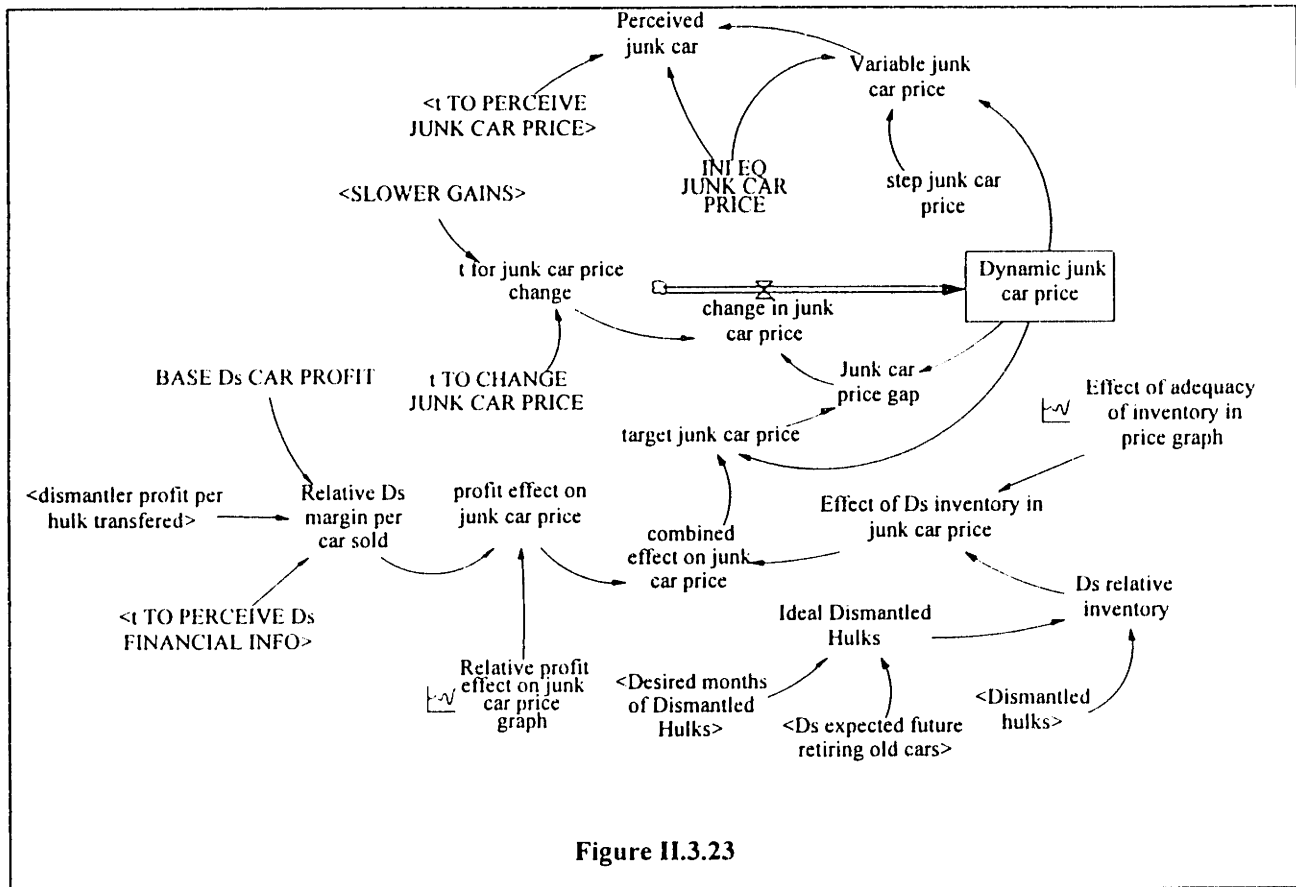


Figure II.3.23

This sector presents the mechanism for dismantlers to set the price of junk cars. This formulation proposes a structure in which dismantlers perceive the price for hulks as exogenous, defined by the shredders. Dismantlers then internalize perceived profit and modify their target junk car price trying to maximize their profit.

This decision rule is modeled by calculating a relative profit per car. This relative profit determines a direct effect on the target junk car price, as presented in figure II.3.24. Note that if the

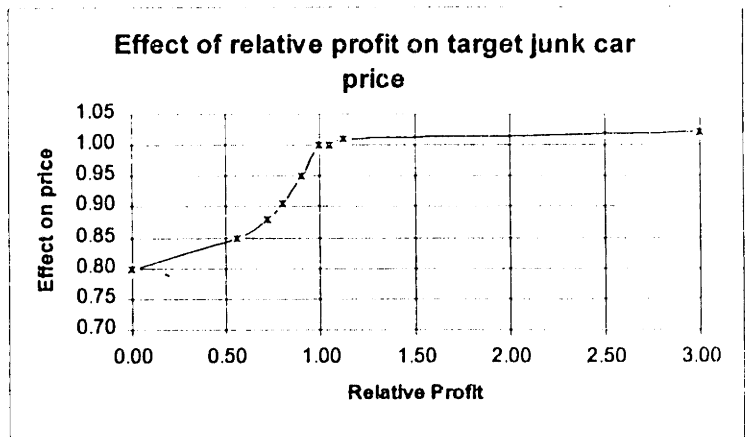


Figure II.3.24

dismantlers' profit goes down they would reduce the junk car price. However, the opposite is not

necessarily true. If they are doing well the direct incentive to increase the junk car price would not come from this structure, but from the inventory control explained below.

The adequacy of the level of dismantlers' inventory is also considered in the pricing mechanism. The rationale is that dismantlers perceive their inventories to be lower than desired, they would increase the junk car price to stimulate the incoming flow of cars. Figure II.3.25 presents the effect of this factor on the target pricing structure.

After defining the target price, dismantlers compare it to the actual price and a gap is calculated. It is this gap, and a desired time to correct the price, that defines the increase or decrease in the offered price.

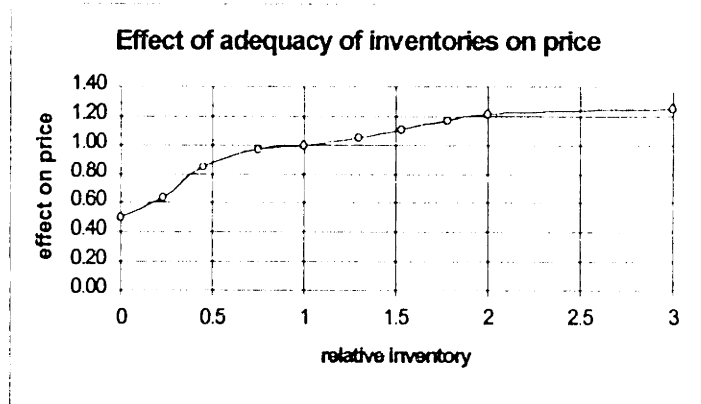


Figure II.3.25

This pricing structure includes the consideration of fixed costs. Based on

the interviews conducted, it is believed that dismantlers would incorporate this cost element, with certain delay, in their expectations. This is specially true when considering a long term horizon.

### 15. Shredder forecast Sector

Shredders' expectations about the future are calculated in this sector. The key parameters are:

- *Future shredding rate* (ton/month): This is a function of the shredders' beliefs about the future weight of hulks and the rate at which they will receive them. This expectation is used to calculate the ideal level of inventory and the capacity requirements.

- *Expected future profit*: This is a forecast based on their profit per semester and has an effect on desired capacity.

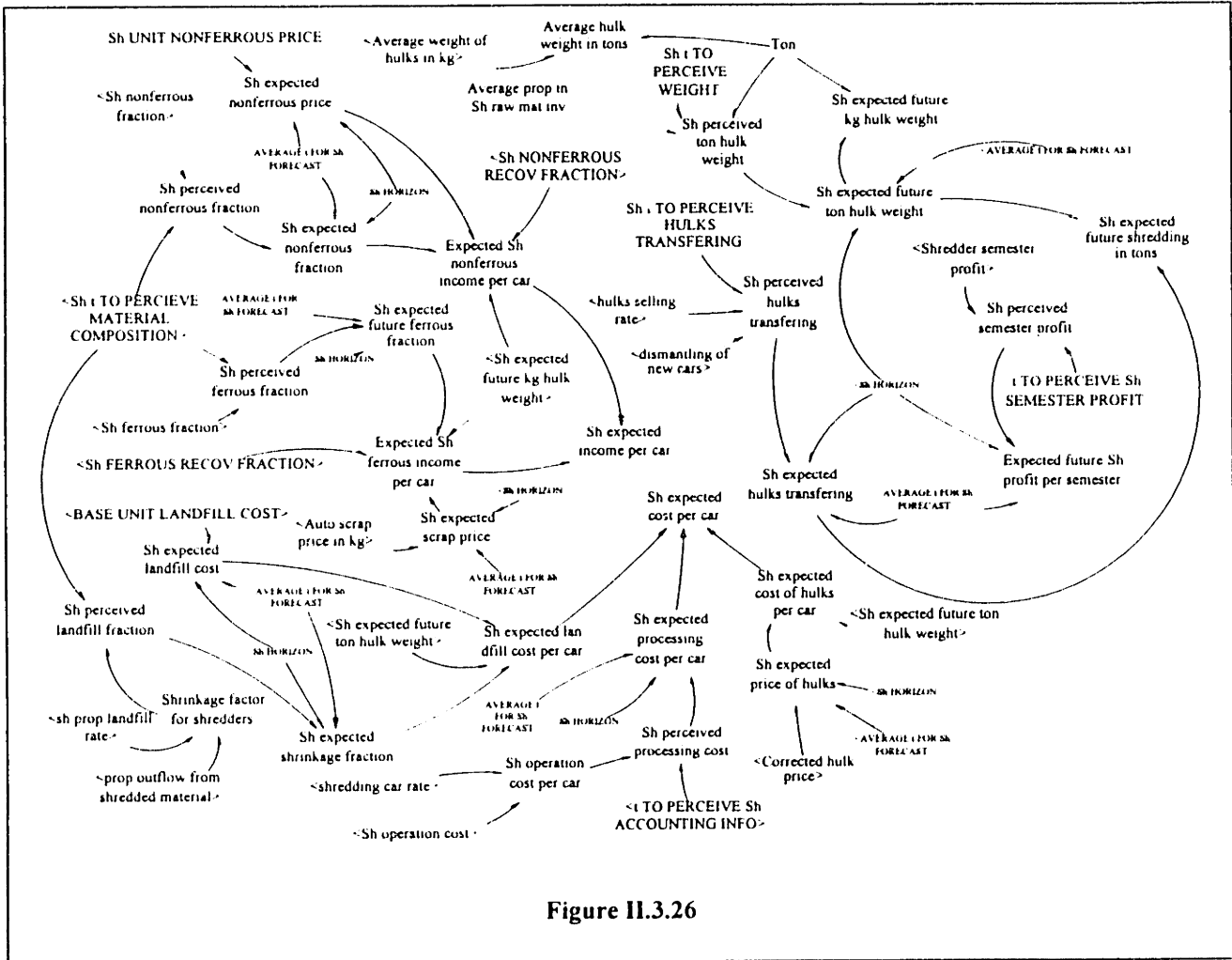


Figure II.3.26

- *Expected cost per car*: This value is used to determine the hulk price that protects the desired margin in the *Hulk price* sector. To forecast this, shredders have to estimate the future of the key cost elements: unit landfill cost, shrinkage fraction and processing cost. Capacity cost is not included in this calculation because it is unlikely that the shredders internalize this component in their expectations.
- *Expected income per car*: This variable is also used in defining the target hulk price. To be able to forecast this, shredders have to forecast the components of income: the hulk weight; the metal fractions, and future prices of ferrous and nonferrous metals.

It is assumed that the shredders would consider the last 12 months and look 12 months into the future when forecasting.

### 16. Shredding Rate Sector

In the same manner as dismantlers, shredders make two decisions: the rate at which they process hulks (*shredding rate*) and the rate at which they sell recovered materials and send the ASR to the landfills (*transferring of materials*). The term “transfer” is used for this flow, because it comprises two different actions: selling materials and disposing of waste.

A simplifying assumption is used when modeling this decision: when shredders decide to sell recovered materials they also send the corresponding amount of ASR to the landfill.

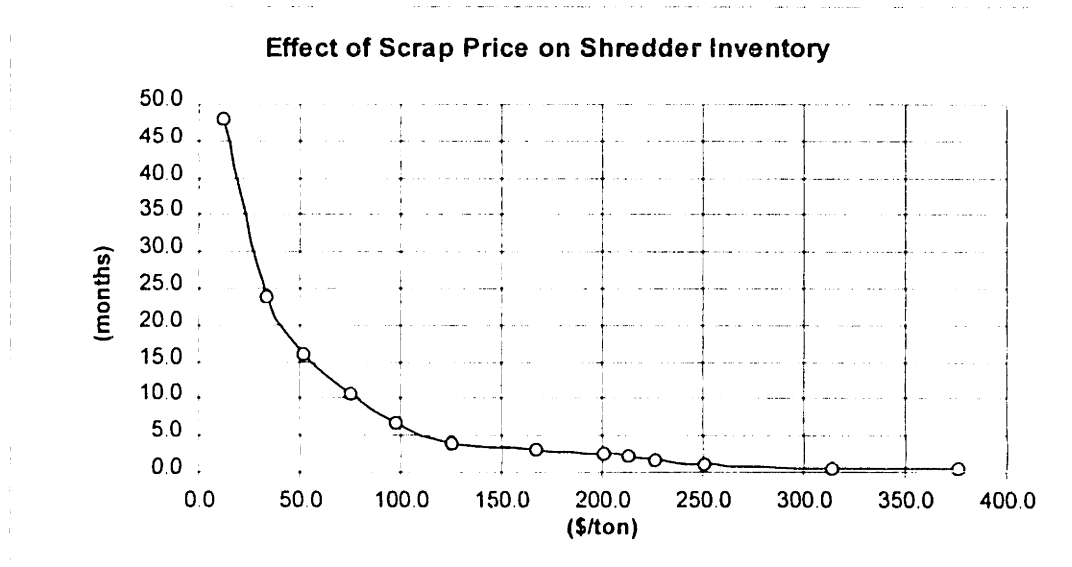


Figure II.3.27

The decision rule for shredding is, “Process all hulks received, as fast as possible, provided that there is capacity to do so. Otherwise, work at capacity”. This decision rule, similar to the dismantling rate, resembles closely what happens in the industry. An element to avoid infeasible decisions, such as processing more hulks than what are available, is also incorporated.

In the same manner that dismantlers decide on the ideal coverage, shredders perceive the price they can get for the scrap and modify their ideal level of inventory.

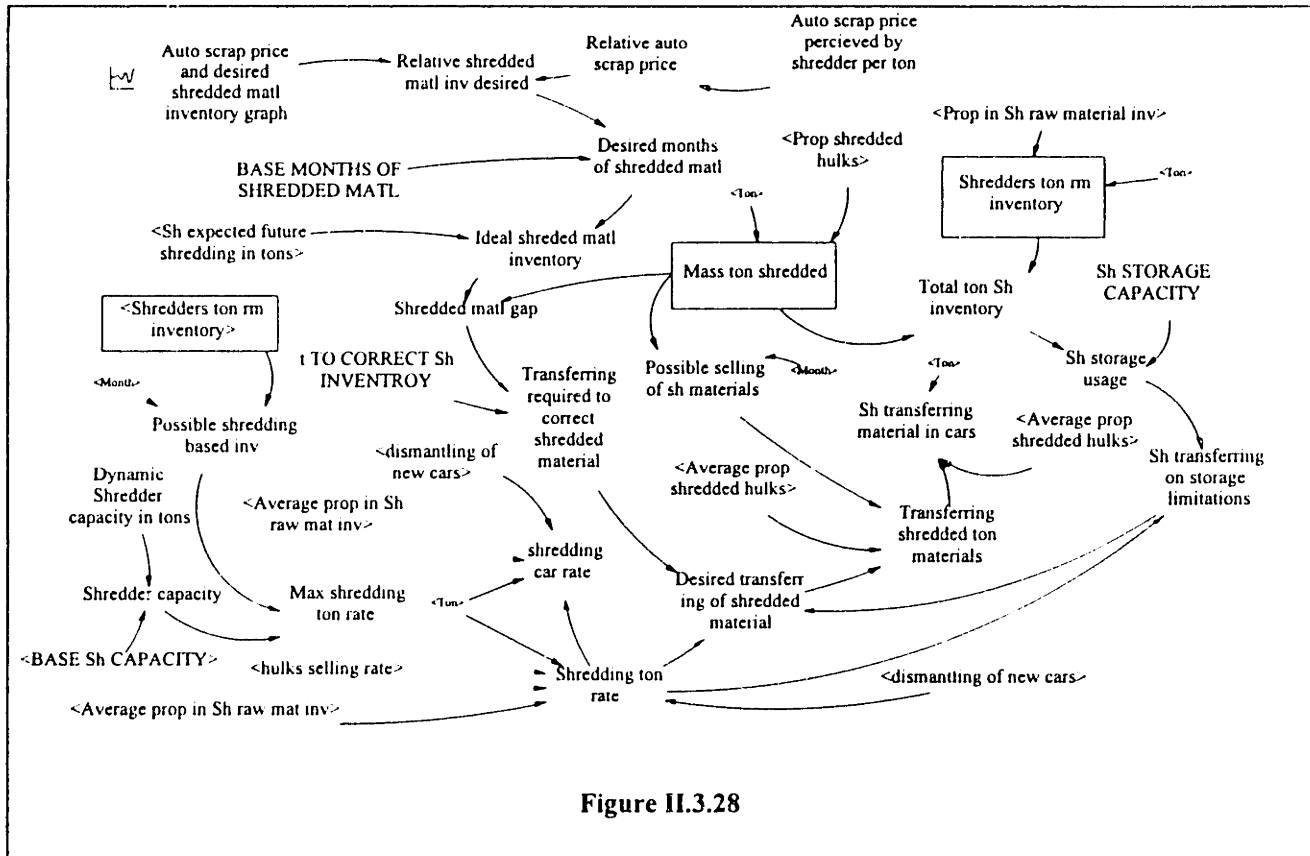
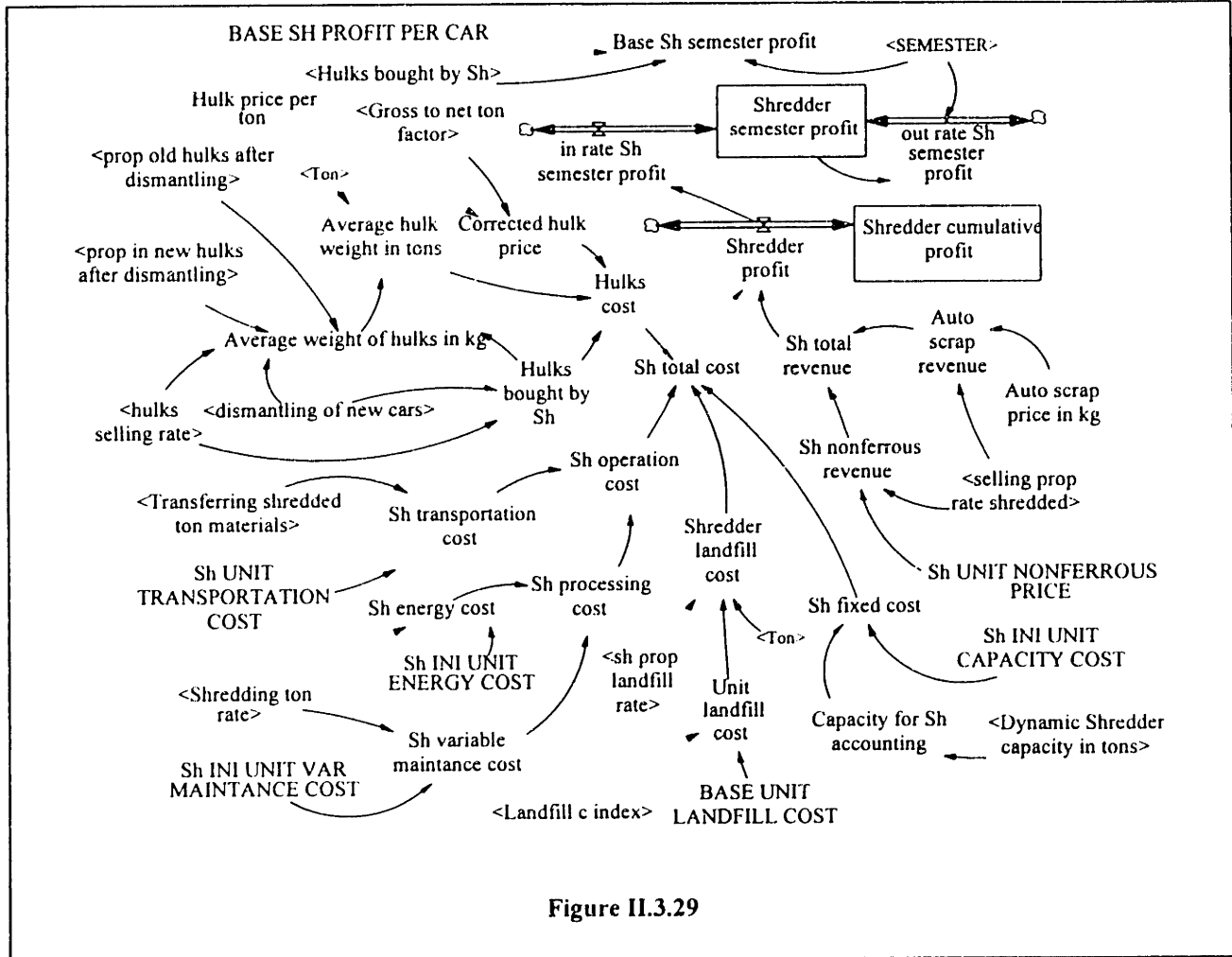


Figure II.3.28

Given that the shredders have two inventories (raw material and shredded product) the storage limit effect of *transferring materials* considers both. Again, for the transferring rate decision there is a provision to prevent infeasible (negative) flows of stocks.

### 17. Shredders Profit

This sector represents the financial structure of shredders. The monthly and semester profits are evaluated.



The cost in this case has four constituents: hulk acquisition cost, operation cost, landfill cost and capacity cost. The first three are variable costs. The operation cost is the sum of processing cost and transportation cost. The processing cost has two components: variable maintenance and energy.

There are two sources of revenue: autoscrap (ferrous metals) and nonferrous metals recovered. Both are variable and therefore depend on the rate shredders sell recovered materials.



In the same way as in the financial sector for dismantlers, there is an auxiliary stock accumulating profits during the simulation. Semester profit is used to smooth out the profit noise associated with drastic changes in buying and selling. This profit is an input when deciding target capacity.

**18. Shredder Capacity Sector**

The structure for this sector is the same as the dismantlers capacity sector. The only difference is the rates at which decisions are taken: shredders' facilities are longer lasting and projects to increase capacity take longer to complete.

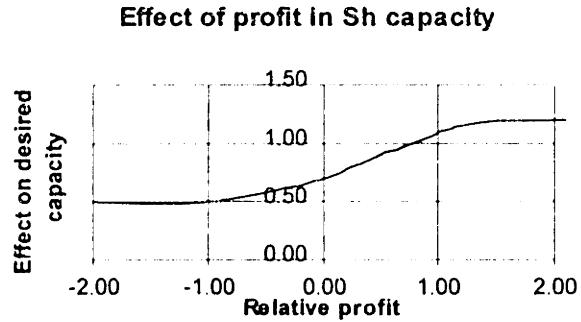


Figure II.3.30

The effect of utilization rates on capacity acquisition decisions follows the same structure as the one explained for dismantlers (figure II.3.22). The effect of profitability follows the relationship presented in figure II.3.30.

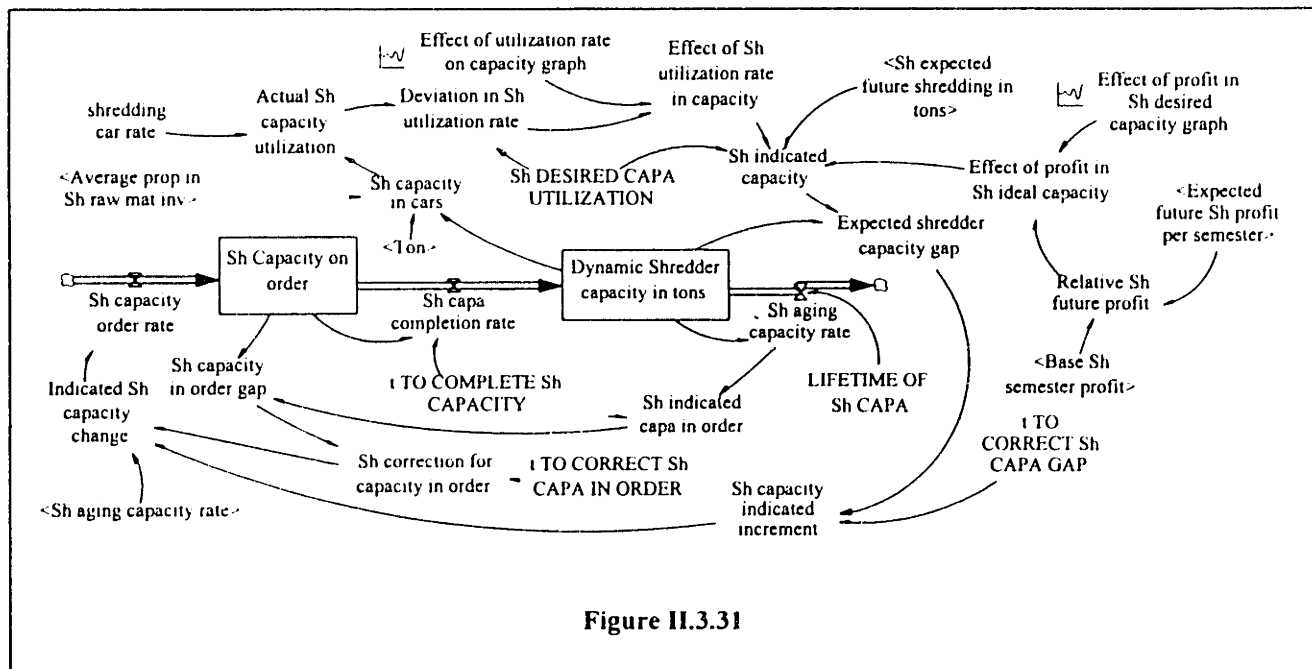


Figure II.3.31

### 19. Hulk Price Sector

This sector is similar to where dismantlers set the price they are willing to pay for the junk cars. In this case, shredders consider the autoscrap price as a given; they internalize this price and their operation cost and try to protect certain margin per car.

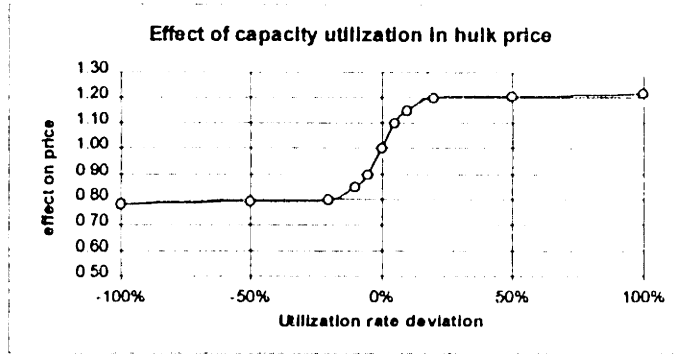


Figure II.3.32

The adequacy of the inventory level has the same type of effect as in the case of junk car prices (figure II.3.25). Additionally, the utilization rate is considered to help fine-tune the pricing decision, figure II.3.32 presents the relationship used.

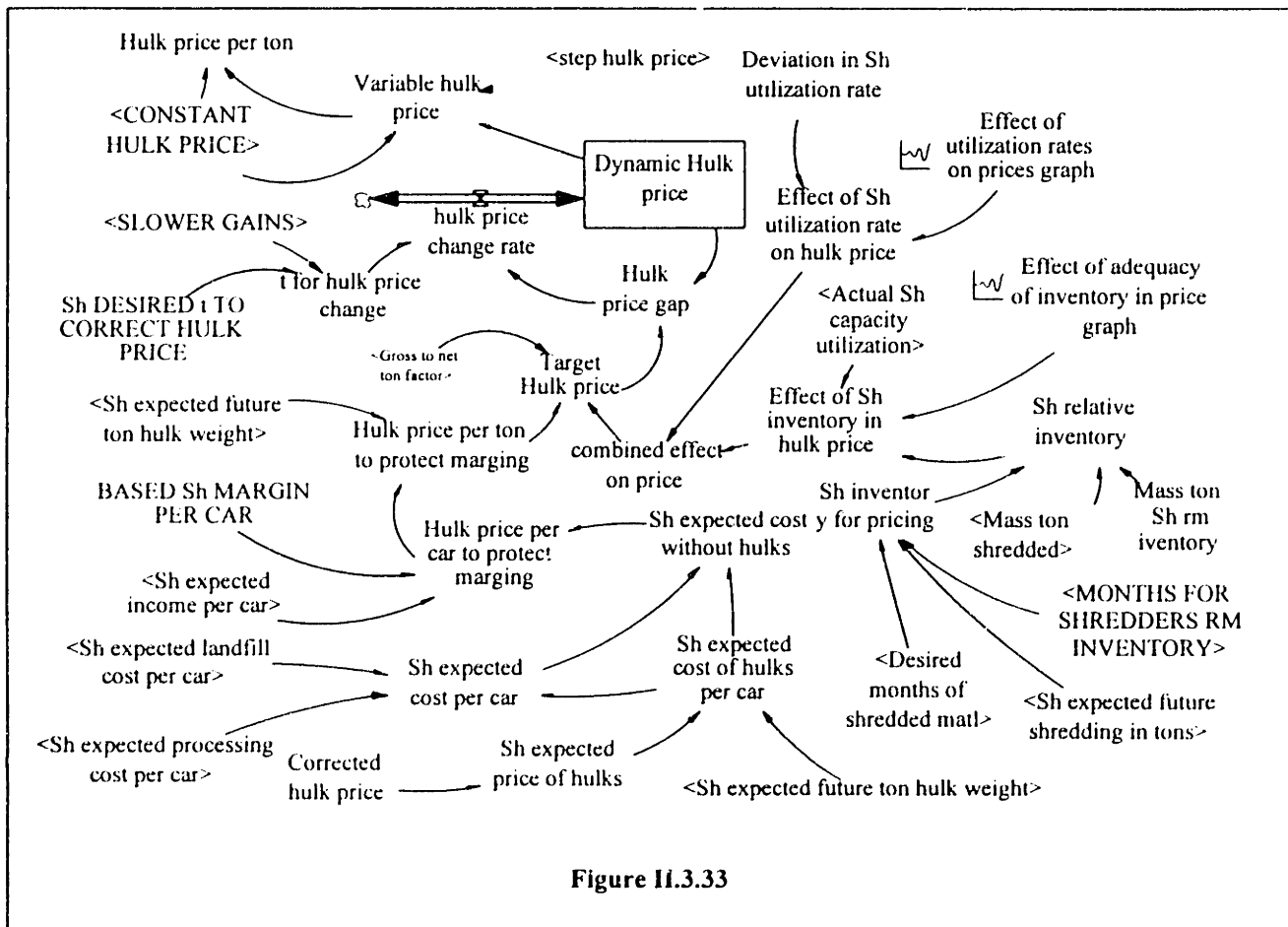


Figure II.3.33

There are three important differences between this and the *Junk car price* sector. First, the costs and revenues used to change price are future expectations. The rationale is that the shredders look further into the future than dismantlers because their execution time (capacity related) is longer. Second, there is no consideration of fixed costs in determining the target price. Instead, an operation margin is used. Third, this pricing mechanism tries to protect a constant margin per car. As a consequence, savings (or increases in costs) in shredders' operations would be completely passed on to dismantlers. The structure in this sector is based on the interviews conducted among shredders.

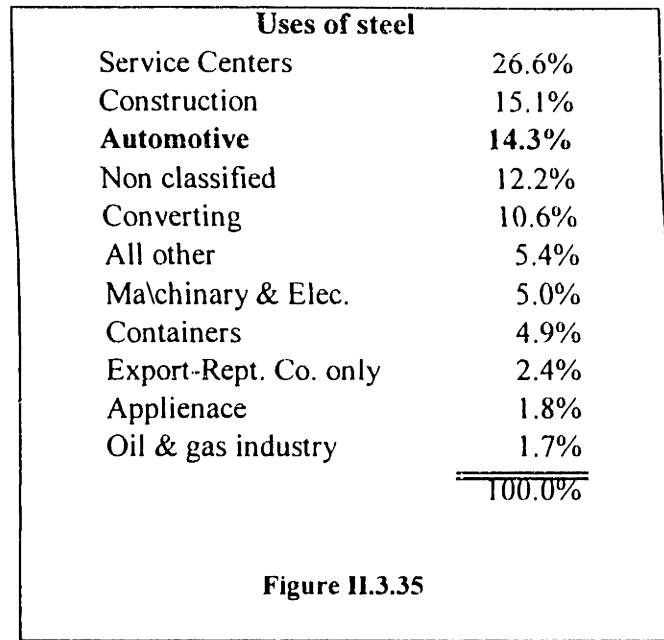
## 20. Aut scrap Price Sector

	1993	1992	1991	1990	1989
(Thousands of Net Tons)					
Total Scrap Used	58,515	55,274	53,768	59,924	58,128
Shipments of Steel	89,022	82,241	78,846	84,981	84,100
Scrap fraction	0.657	0.672	0.682	0.705	0.691
Average	0.682				
Standard deviation	0.018				
Variation coefficient	2.67%				

Figure II.3.34

In this sector the price of the autoscrap is dynamically calculated. In principle, this price is set by the steel industry. The basic principle is that the steel industry would try to maintain a constant ratio of scrap-produced steel to ore-produced. Since this ratio is a profit optimizing decision made by the steel mills, the underlying assumption is that the relative processing cost of producing ore-based-steel and scrap-based-steel will not change significantly. Figure II.3.34 presents some historical values of this ratio. In the final chapter, a sensitivity analysis is done on this critical value.

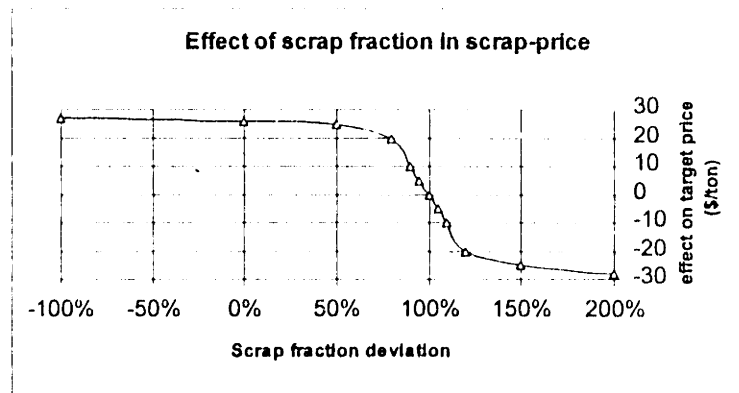
If the fraction of steel produced from scrap is below the desired fraction, the Steel Industry would be willing to pay more for the scrap. As the price of the autoscrap increases, the desired coverage from shredders decreases, and as a consequence the amount of scrap sold would increase. This balancing mechanism corrects the scrap fraction to the desired level. The effect of the deviation of scrap fraction to price of scrap is presented in figure II.3.36 [American Iron and Steel Institute, 1993].



Total demand for steel is calculated here as a function of GDP. It is estimated that the demand for steel is has an GDP-elasticity of 1. The demand for automotive steel demand is calculated based on a fixed (14.3%) usage of steel in automobiles, based on the statistics presented in figure II.3.36 [American Iron and Steel Institute, 1993].

In reality there is no difference between autoscrap and scrap obtained from other durable goods. Sometimes construction scrap is even mixed with automobile scrap. However, given that the purpose for this model is focused on an analysis of the automobile recycling industry and the dynamics associated with this activity, the scrap price calculated here should be interpreted as the automobile scrap price that one can expect in isolation from the rest of the scrap sources.

A correction for the demand for steel is introduced as a result of the steel content in automobiles. If, for



**Figure II.3.36**

example, the average ferrous content in cars sold drops 10%, the total demand of automotive steel would be reduced by 10% as well.

The actual ratio of scrap to virgin production of steel is calculated by dividing the flow of scrap going into the steel industry -- as a result of the shredders sale of recovered material -- by the demand for automotive steel.

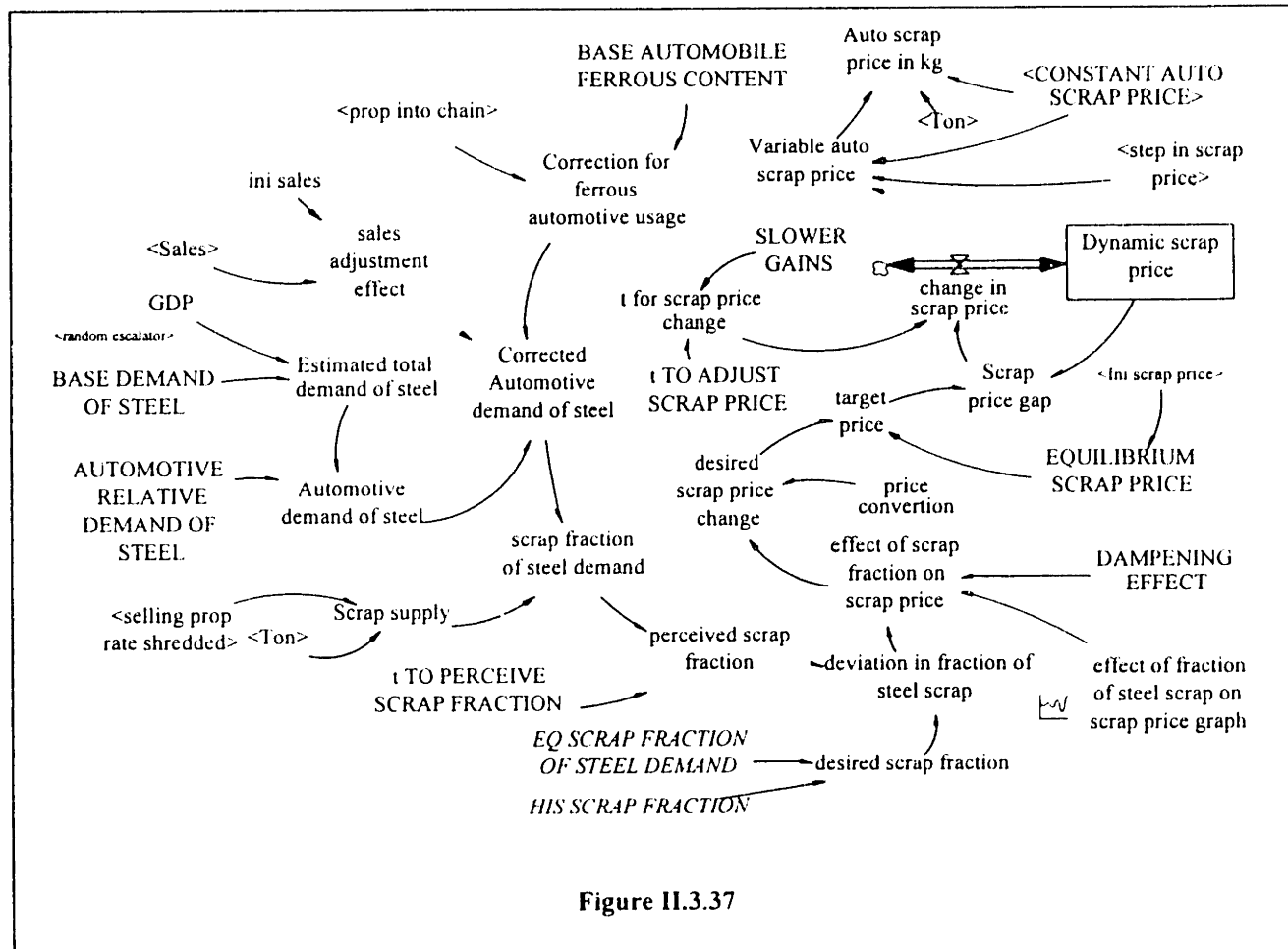


Figure II.3.37

This perceived scrap fraction is compared to the desired fraction and an effect on the price of autoscrap is calculated. Note that the impact of scrap price on demand for steel is not incorporated. It is assumed that the selection of steel versus other materials considers cost as a secondary decision factor. This is not to say that automobile manufacturers do not closely monitor the material cost. However, steel price is significantly lower than most of the alternative materials. The decision to replace steel by another material represents a cost. Automobile manufacturers would need to justify this additional cost with other parameters, such as

performance, safety or weight. In summary, steel is considered the primary material for building automobiles. The price differential between this and alternative materials will remain large, and as a consequence the price influence in steel demand is relatively slow. It is recommended that this assumption be relaxed in future work.

Finally, note that an increase in demand for steel associated with an increase in GDP produces an instantaneous increase in demand beyond the long-run equilibrium level, because of the stock adjustment effect. The proposed formulation accounts for this by correcting the demand for automotive steel based on the sales level. On the other hand the total demand for steel reacts one-to-one with GDP.

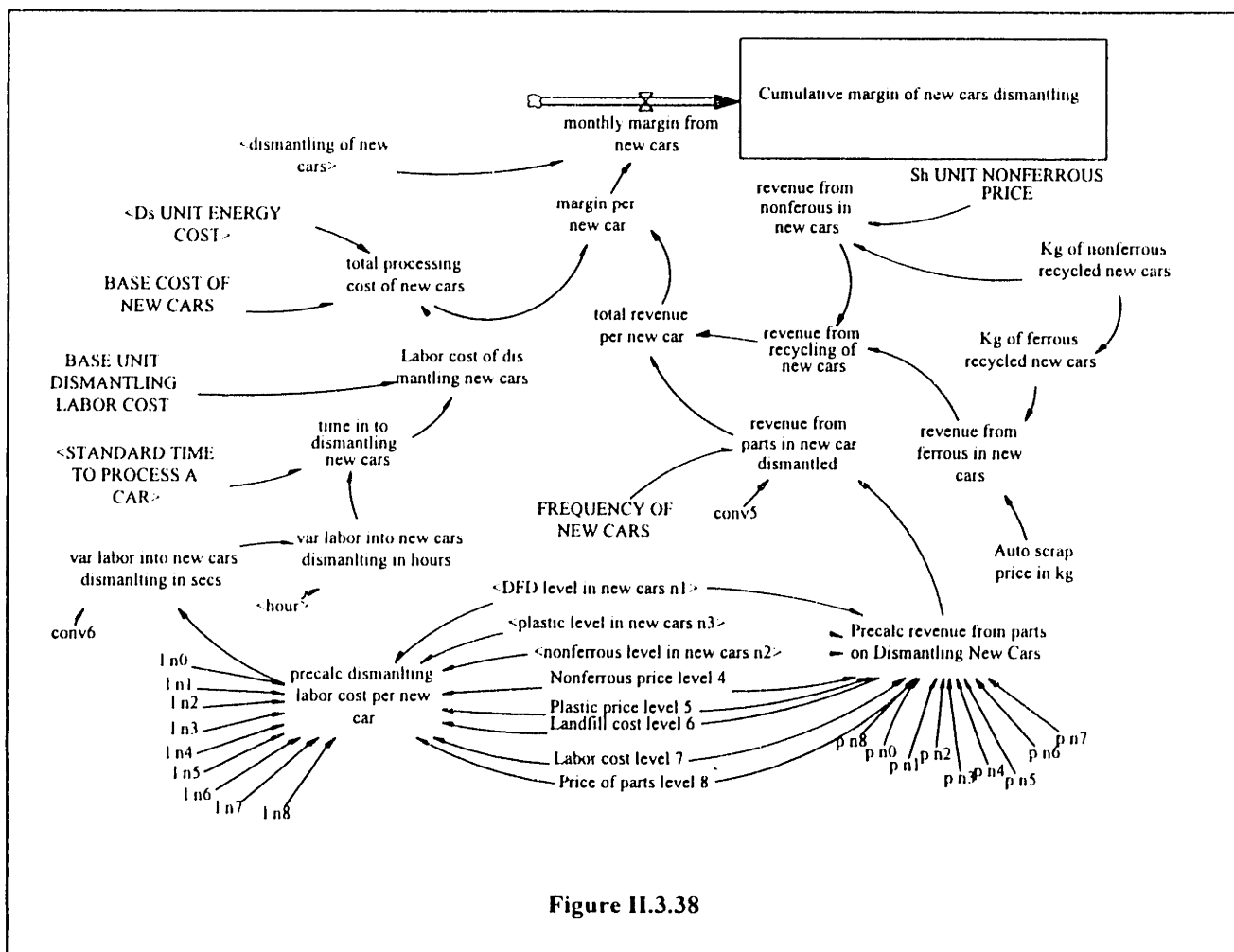


Figure II.3.38

*Slower gains* and *Dampening effect* are two variables introduced to study the sensitivity of the model to changes in the speed of balancing the gains and to changes in the elasticity of price

responsiveness. These variables may allow for calibration. For further research, it is recommended that actual historical prices and steel flows be used to fine-tune the model.

### **21. Dismantling of new cars Sector**

In this sector some calculations are carried out to observe the effect of policy decisions on the profitability of dismantling “new cars”. Two additional equations from the automobile manufacturers are evaluated here: *Dismantling labor in new cars* and *Revenues from parts*.

However, as it was mentioned in the previous chapter, the dynamics of the parts market -- where most of the profits are made -- are not included in the model. Therefore, the calculations in this sector should be considered with care.

The variable *monthly margin from new cars* is equivalent to the variable *dismantler profit* presented in sector 12. In this case, however, the unit fixed cost is not included in the calculation. Car acquisition, labor for dismantling on this type of cars, and energy are the relevant costs. Parts and some material recycling are the key sources of revenue.

### **22. Control Sector**

This sector includes the most relevant variables from the whole model. These variables and the complete set of switches are centralized here to facilitate running the simulation under different conditions.

General purpose variables are presented here, such as *fraction of old cars being processed* or *perceived average property*. In addition, new information variables are also evaluated in this sector. These new variables were created to compare policy effects on relative profitability. dismantlers of “new” and “old cars” are compared as well as dismantlers' and shredders' operations.

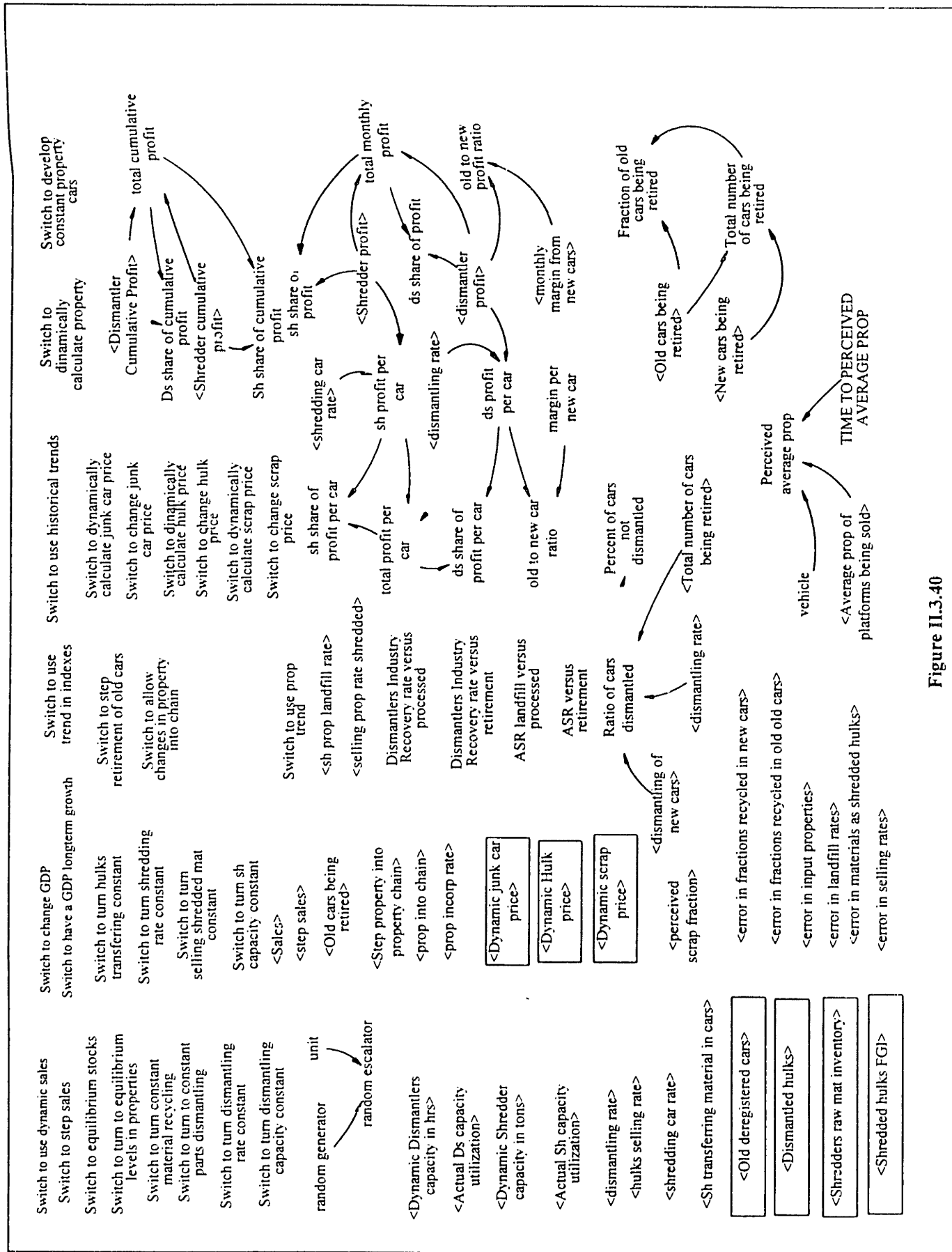


Figure II.3.40



## Chapter II.4

### Initial conditions

In this chapter the initial levels of the stocks will be described for both the equilibrium and the historical conditions. The equilibrium is defined based on sales of automobiles of 1,000,000 per month. The equilibrium property levels are based on the physical characteristics of Car A, as discussed in the first part of this thesis. The historical levels were researched directly. In some cases the information was found in magazines or other types of bibliography, in other instances, the information is estimated based on the interviews conducted with the different parties participating in the recycling of automobiles. When a variable is introduced and there is a significant lack of information, a detailed discussion is presented.

Equilibrium condition is important for two reasons. First, this is the stage used to test the model. As explained at the beginning of the previous chapter, each sector was built independently and tested extensively. Sector testing involves the analysis of the sector behavior to changes in its inputs. To understand this it is necessary to initialize the testing under equilibrium conditions.

Second, once the model is complete, learning is achieved by running simulations under different conditions. It is desirable that the model user establish hypothesis and test them against the model output. If the simulations are started under a condition far from an stable equilibrium, it is

extremely difficult to differentiate the effects of the policies under analysis and the behavior caused by the initial conditions. Therefore, the initial analysis of the structural dynamics is more clear if performed by starting the simulations at equilibrium conditions. Chapter II.5 is completely devoted to this type of analysis.

Historical conditions are relevant because they allow the model user to confront learning from the model. They represent a good ground for evaluating policies as well. In principle, if the model is robust in structural terms, simulations starting at historical conditions may provide the basis for a predictive (forecasting) model. Chapter 6 discusses these conditions for the automobile recycling industry in North America.

### 1. Automakers Sector

Figure II.4.1 presents the initial level of the key variables contained in the *Automakers* sector for both the equilibrium and the historical conditions. These levels correspond to 1995 historical data [Automotive News, 1995].

	Chrysler	11 vehicles
	Ford	11 vehicles
	GM	18 vehicles
	Total	40
Average lifetime of platforms		7 years
		84 months
discontinue rate		0.476 vehicles/month
Platforms under development		22.86 vehicles
DEVELOPMENT TIME		48 months
development rate		0.476 vehicles/month
New vehicles introduction rate		6 vehicle/year
		0.83 vehicle/month
INI VEHICLES IN MARKET		40 vehicles
DISCONTINUE TIME		48 months

**Figure II.4.1**

## 2. Aging Sector

The initial level of the age-cohorts are presented in the table 4.2. Historical values are based on Polks' reports [R. L. Polks & Company, 1995]. One can see that the equilibrium condition, based on million cars per month sold, results in a total number of cars on the road that is higher than the actual level. This is consistent with the fact that sales of 1 million cars per month is higher than the historical average. The retirement fractions are based on the Liberty calculations [Liberty 1993].

As explained in the previous chapter, *sales* are estimated based on an elasticity to GDP equal to 1 and a *time to adjust fleet gap* equal to 66.6 months [Pindyck 1994].

	Vehicles on the road		Retirement
	Historical (cars)	Equilibrium (cars)	Fraction (%)
Cars 0-3 years	21,175,281	36,000,000	0.01500
Cars 3-6 years	27,300,914	35,460,000	0.06497
Cars 6-9 years	27,834,415	33,156,000	0.14976
Cars 9-12 years	18,118,460	28,190,700	0.36489
Cars 12-15 years	11,921,399	17,904,240	0.57960
Cars 15-18 years	4,635,568	7,526,917	0.79781
Cars 18-21 years	59,432	1,521,860	1.00000
Total	<u>111,045,469</u>	<u>159,759,717</u>	

Figure II.4.2

## 3. Main Sector

The initial number of vehicles in stocks *Old deregistered cars* and *New deregistered cars* is calculated by multiplying a sales rate times a fraction of "old-cars" (or "new cars"), times a number of months of sales. The sales rate for the equilibrium condition is 1 million per month. The historical case is estimated using the data in figure II.4.3 [AAMA Motor Vehicle Facts and Figures 1994].

The fraction of “old cars” is estimated based on the retirement flows as shown in figure II.4.4.

Due to the lack of data for the stocks of deregistered cars, this variable was estimated from interviews. It has been chosen to use 6.382 months of sales for both, the equilibrium and the historical conditions. However, this value and the supply fraction curve described in the previous chapter (figure II.3.5) could be defined in a more precise form. As a recommendation for future work, one could search for more precise information or estimate this variable using more sophisticated methods. The Monte Carlo simulation presented in the next chapter analyzes the effect of this simplifying estimation.

Year	New cars registered
1978	11,032,068
1979	9,603,185
1980	8,817,281
1981	7,949,799
1982	8,336,651
1983	9,732,363
1984	10,372,287
1985	11,048,203
1986	10,684,054
1987	10,424,490
1988	10,220,604
1989	9,414,552
1990	8,616,179
1991	8,213,315
1992	8,074,309
1993	8,765,117
Annual average	9,456,529
Average sales per month	788,044

**Figure II.4.3**

Age cohort	Fleet Analysis				Retirement Analysis				Historical	Equilibrium
	Historical		Equilibrium		Historical		Equilibrium			
	#	%	#	%	#	%	#	%	new cars	new cars
0-3	21,175,281	19%	36,000,000	23%	8,823	1.3%	15,000	1.5%	173,885 26.6%	216,925 21.7%
3-6	27,300,914	25%	35,460,000	22%	49,274	7.5%	64,000	6.4%		
6-9	27,834,415	25%	33,156,000	21%	115,788	17.7%	137,925	13.8%	old cars 479,962 73.4%	old cars 783,075 78.3%
9-12	18,118,460	16%	28,190,700	18%	183,645	28.1%	285,735	28.6%		
12-15	11,921,399	11%	17,904,240	11%	191,935	29.4%	288,259	28.8%		
15-18	4,635,568	4%	7,526,917	5%	102,731	15.7%	166,807	16.7%		
18-21	59,432	0%	1,521,860	1%	1,651	0.3%	42,274	4.2%		
total	111,045,469		159,759,717		653,846		1,000,000			

**Figure II.4.4**

The initial levels of the rest of the stocks are calculated following the same basic structure. The main difference is that the number of months considered is more precise. Although these variables are also based on direct research, in this case the people interviewed had a more precise idea of the inventory levels they normally carry. Figure 11.4.5 presents the values considered. Note that the difference between historical and equilibrium conditions results from using a different sales rate.

Number of months in deregistered cars	6.8 months
Base (number of) months of hulks desired (for Dismantled hulks)	18.0 months
Months for Shredders' raw material inventory	2.0 months
Base (number of) months for shredded material	4.0 months

Figure 11.4.5

#### 4. Age Sector

The initial levels of the stocks in this sector are calculated by multiplying the initial level of cars in the age cohorts times a series of model years denominated *MODEL 'X'*. Since the starting date of the simulation is 1995 and each of these constants corresponds to a 3-year age cohort, their values are: 1992, 1989, 1986, 1983, 1980, 1977, and 1974.

**5. *x*-levels Sector**

Figure II.4.6 presents the initial level of the *x-values* for both conditions. It is also mentioned in the table whether the variables are completely exogenous or depend on policy decisions. In the next chapter, a sensitivity discussion is included.

Index	Equilibrium	Historical	Behavior
1 Level of DFD	1	1	Policy and sales related
2 Nonferrous content	5%	9%	Policy and sales related
3 Plastics content	25%	19%	Policy and sales related
4 Nonferrous price	0	0	Exogenous
5 Plastics price	0	0	Exogenous
6 Landfill cost	0	0	Exogenous
7 Labor cost	0	0	Exogenous
8 Parts price	20	20	Exogenous

**Figure II.4.6**

**6. *Dismantling and Shredding calculation Sectors***

Figure II.4.7 presents the exogenous variables in the *Dismantling and Shredding calculation* sectors. Except for the sensitivity analysis, these variables are kept at these levels during all simulations of both conditions.

Variable	Value
Fraction dismantled in parts for "new cars"	62.1%
Frequency of complete parts for "new cars"	50.0%
Sh plastics recovery fraction	0.0%
Sh nonferrous recovery fraction	98.0%

**Figure II.4.7**

## 7. Properties Sector

As explained, the variable *Switch to turn to equilibrium properties* changes the initial level of all property stocks. To do so, initial levels of the age-cohorts and the stocks in the *Main* sector (stocks of cars) are multiplied by a property level (kg/car). Therefore, the property levels have units of kilograms (kg). The difference between historical and equilibrium conditions is caused by the property levels used, which are exogenous.

In the equilibrium condition the level used is the variable *CONSTANT PROPERTY[property]*, which represents the Car A discussed in the first section of this work. In the case of the historical conditions, information on material composition and weight is used from AAMA Fact and Figures, 1994. Figure II.4.8 presents the values used.

	Age cohort	Age	weight	ferrous	nonferrous	plastic	DFD
HIS AVERAGE PROP 1 (kg/car)	0 to 3 years	1.5	1,352.5	974.1	121.1	257.3	1.0
HIS AVERAGE PROP 2 (kg/car)	3 to 6 years	4.5	1,238.2	890.2	111.8	236.2	1.0
HIS AVERAGE PROP 3 (kg/car)	6 to 9 years	7.5	1,285.6	938.5	109.1	238.0	1.0
HIS AVERAGE PROP 4 (kg/car)	9 to 12 years	10.5	1,343.7	1,011.8	98.2	233.7	0.5
HIS AVERAGE PROP 5 (kg/car)	12 to 15 years	13.5	1,325.8	1,000.0	93.7	232.1	0.5
HIS AVERAGE PROP 6 (kg/car)	15 to 18 years	16.5	1,445.1	1,124.1	91.7	229.4	0.3
HIS AVERAGE PROP 7 (kg/car)	18 to 21 years	19.5	1,445.1	1,124.1	91.7	229.4	0.3
CONSTANT PROPERTY (kg/car)	Equilibrium	All	1,400.0	980.0	70.0	350.0	1.0

Figure II.4.8

## 8. *Dismantlers' and Junk car price Sectors*

The sectors *Dismantlers' forecast* and *Dismantlers' rates* include no additional values that change depending on equilibrium or historical information. The sector *Dismantlers' profit* uses the variable *Ini old car fraction* that changes according to the scenario. This fraction represents is calculated by comparing the number of "old cars" being retired by the total number of vehicles disposed. Figure II.4.4 indicates that these fractions, under historical and equilibrium conditions, are 73.4% and 78.3%, respectively.

The stock *Dismantler cumulative profit* starts from zero in both scenarios because it is a reporting variable. The *Ds semester profit* stock is initialized using the corresponding sales rate, initial old car fraction and a BASE DS PROFIT PER CAR. The last variable does not change in scenarios and is equal to \$43.76/car. Figure II.4.9 shows a snapshot of the dismantlers' financial information at equilibrium. This information is based on interviews with dismantlers. The unit costs are estimated based on a hypothetical facility that processes 700 cars per year.

Figure II.4.10 shows the calculations done to define the operation margin dismantlers would like to protect when making pricing decisions. The calculations for the non-equilibrium runs are done using the same structure and the same unit prices.

Figure II.4.11 presents the initial values of the stocks of capacity in place and in order, as well as the calculations behind them



Dismantlers Profit Calculation					
Total deregistration	1,000,000	car/mo	Fraction of old cars	78.31%	
Capacity	978,844	car/mo			
Utilization	80%				
Dismantling rate	783,075	car/mo	26,103	car/day	
<b>Variable costs</b>					
Junk car	Junk car price	50.00	\$/car		
Dismantling time	Optimized time	1,426	sec/car	0.39610 hr/car	
	Forced dismantling	900	sec/car	0.25000 hr/car	
	Total time	2,326	sec/car	0.64610 hr/car	
	Total time in hours	0.64610	hr/car		
	Labor cost	20	\$/hour		
	Labor cost per car	12.92	\$/car		
Energy cost	Energy cost per car	0.64610	\$/car		
<b>Total variable costs</b>		<b>63.57</b>	<b>\$/car</b>		
<b>Revenue</b>					
Material recycling	Material unit revenue	22.11	\$/car		
Hulks revenue	Hulk weight	1,363.85	kg/car		
	Hulk weight in tons	1.36385	ton/car		
	Hulk price per ton	71.43	\$/ton		
	Hulk revenue	97.42	\$/car		
<b>Total Income</b>		<b>119.52</b>	<b>\$/car</b>		
<b>Operation Margin</b>		<b>55.9557</b>	<b>\$/car</b>		
<b>Fixed costs</b>					
Capacity replacement cost	Base capacity used	700	car/year	58.33 car/mo	
	Base time into dismantling			0.65 dism hr/car	
	Capacity in hrs			37.69 dism hr/month	
	Lifetime of capacity	15.00	year		
	Base cost	2,500,000	\$		
	Yearly cost	166,667	\$/year	13,889 \$/mo	
	<b>Replacement cost</b>			<b>368.51 \$/dism hr</b>	<b>6.32 \$/car</b>
Insurance	10% of capa replacement cost		10%	36.85 \$/dism hr	0.63 \$/car
Administrative	\$100,000 year	100,000	\$/year	8,333 \$/mo	
				221.11 \$/dism hr	3.79 \$/car
Maintenance	\$50,000 year	50,000	\$/year	4,167 \$/mo	
				110.55 \$/mo	1.90 \$/car
Total Capacity Cost at 100% utilization				737.02 \$/mo	12.63 \$/car
	Utilization	80%			
<b>Total Capacity Cost at 80% Utilization</b>				<b>921.27 \$/mo</b>	<b>15.79 \$/car</b>
Calculation of energy cost	\$100,000 year	100,000	\$/year	8,333	\$/mo
				37.69	\$/mo
<b>TOTAL COST</b>				<b>79.36</b>	<b>\$/car</b>
<b>PROFIT</b>				<b>40.1625</b>	<b>\$/car</b>
Industry Profit	31,450,233				(if working at capacity)

Figure II.4.9

Capacity	978,844	car/mo	632,435.67	hr/mo			
Dismantling rate	783,075	car/mo	505,948.53	hr/mo			
Junk car cost	Junk car price	50.00	\$/car	39,153,750	\$/mo	50.00	\$/car
Energy cost	Energy cost per car	0.646105	\$/car	505,949	\$/mo	0.65	\$/car
Labor cost	Labor into dismantling	0.64610	hr/car	10,118,971	\$/mo	12.92	\$/car
	Labor cost	20	\$/hr				
Capacity cost at 80%		15.79	\$/mo	15,459,104	\$/mo	19.74	\$/car
<b>Total Dismantling Industry cost</b>				<b>65,237,773</b>	<b>\$/mo</b>	<b>83.31</b>	<b>\$/car</b>
Unit capacity cost		24.44375708	(\$/mo)/(hr/mo capa)				
Capacity cost at 80%		15,459,104	\$/mo				
Material Revenue	22.11	\$/car		17,310,662	\$/mo	22.11	\$/car
Hulk Revenue	97.41790138	\$/car		76,285,523	\$/mo	97.42	\$/car
<b>Total Dismantling Industry revenue</b>				<b>93,596,185</b>	<b>\$/mo</b>	<b>119.52</b>	<b>\$/car</b>
<b>TOTAL INDUSTRY PROFIT</b>				<b>28,358,412</b>	<b>\$/mo</b>	<b>36.21</b>	<b>\$/car</b>
Ds unit cost per car	Energy cost per car	0.65	\$/car				
	Labor into dismantling	12.92	\$/car				
	Junk car price	50.00	\$/car				
	Subtotal	63.57	\$/car				
Revenue	Material Revenue	22.11	\$/car				
	Hulk Revenue	97.42	\$/car				
	Subtotal	119.52	\$/car				
<b>Operation Margin per car</b>		<b>55.96</b>	<b>\$/car</b>				

Figure II.4.10

	Units	Equilibrium	Historical
t TO COMPLETE Ds CAPACITY	mo	24	24
LIFETIME OF Ds CAPACITY	mo	180	180
t TO CORRECT Ds CAPA GAP	mo	12	12
Ds CAPACITY UTILIZATION		80%	80%
Labor into cars	hr/car	0.6461	0.2898
Dismantling rate	car/mo	783,075	1,000,000
Future dismantling	hr/mo	505,948.53	289,800.00
Profit effect on Ds capacity		1.00	1.10
Indicated capacity	hr/mo	632,435.67	398,475.00
Ds aging rate	hr/(mo*mo)	3,513.53	2,213.75
Indicated capacity on order	hr/mo	84,324.76	53,130.00

Figure II.4.11

## 9. Shredders' and Hulk Price Sectors

By the same token as the dismantlers', the sectors *Shredders' forecast* and *Shredders' rates* include no variables that change from equilibrium to historical conditions. In this case the sector *Shredders' profit* does not refer to a sales rate to evaluate semester profits because it is possible to refer to dismantling rates. The fraction of "old" cars is not relevant to any shredders' calculations due to the fact that shredders process both the "new" and the "old cars".

Again, the stock *Shredder cumulative profit* starts from zero in both scenarios because it is a reporting variable. The *Shredder semester profit* stock is initialized using the dismantling rates for "new" and "old" cars, and a *BASE Sh PROFIT PER CAR*. Figures II.4.12 to 15 contain some of the principal calculations behind the unit prices and profit, the key capacity variables, and the estimation of *BASE Sh MARGIN PER CAR*. Most of this information was obtained from a series of interviews with shredders.

Figures II.4.13 and II.4.14 are based on a hypothetical facility that shreds automobiles and other durable goods. Note that the *Hulk* and *Junk car* prices are those of equilibrium. The unit cost estimated in these calculations is used for the simulations starting with historical values.

Total volume	16,000 ton/mo	<u>Hulk cost:</u>	
Shredder volume	7,000 ton/mo	Hulk price	80.00 \$/ton
	43.8%	Transportation cost	- \$/lb
<u>Metal distribution</u>			- \$/ton
ferrous	95.9%	Corrected junk car price	71.43 \$/ton
non ferrous	4.1%	<u>Final Product prices:</u>	
Average weight of a car:	3,100 lb/car	Shredder Auto Scrap	0.056070 \$/lb
Fraction removed:	8.0%		125.60 \$/ton
Hulk weight	1,273 kg/car	Non ferrous bundle	0.23 \$/lb
Number of cars processed:	5,497 car/mo	Transportation cost	(0.01) \$/lb
		Corrected non ferrous	0.22 \$/lb
Automobile shredder utilization:	70.0%		481.60 \$/ton
Shrinkage factor for automobiles:	26.1%	ASR (landfill cost)	12.50 \$/yd <sup>3</sup>
			0.01 \$/lb
Used transportation cost	0.010 \$/lb		22.40 \$/ton
Energy cost	0.268 \$/car	ASR density	1,250.00 lb/yd <sup>3</sup>
Variable maintenance cost	2.536 \$/car		
Fixed maintenance cost	1.900 \$/ton		
Insurance cost	2.470 \$/ton		
Capacity cost	1.583 \$/ton		
Utilization of shredder	95%		
<u>Operating Margin (\$/car)</u>		Material yield	22.94 \$/car
Hulk cost (\$/car)			(90.96) \$/car
Ferrous income		100.0%	113.69 \$/car
Non ferrous income		71.8% 99%	14.45 \$/car
Landfill cost	100.3%	2.40% 98%	(7.44) \$/car
Var. maintenance		100.3% 26.1%	(2.54) \$/car
Transportation			(4.00) \$/car
Energy cost			(0.27) \$/car
<u>Total fixed costs</u>		Allocation fraction to Automobile Shredding	\$ 90,660 \$/mo
Wages	137,600 \$/mo		\$ 42,140 \$ 16.49 \$/car
Employees	43 (instead of 43)	30.63%	per car 7.67
Hourly wage	20.00 \$/hr		
Hours per week	40 hr/week		
Weeks per month	4 week/mo		
Adm Salaries	58,157 \$/mo	30.63%	\$ 17,813
Employees	12		per car 3.24
Hourly wage	30.29 \$/hr		
Hours per week	40 hr/week		
Weeks per month	4 week/mo		
Fixed maintenance cost	14,000 \$/mo	70.00%	\$ 9,800
Unit cost	1.900 \$/ton		per car 1.78
Installed capacity (shredder only)	7,368 ton/mo		
Insurance cost	18,200 \$/mo	70.00%	\$ 12,740
Unit cost	2.470 \$/ton		per car 2.32
Installed capacity (shredder only)	7,368 ton/mo		
Capacity cost	11,667 \$/mo	70.00%	\$ 8,167
Unit cost	1.583 \$/ton		per car 1.49
Installed capacity (shredder only)	7,368 ton/mo		
	Operating Margin per ca	\$ 22.94	25% of buying price
	Fixed Costs per car	\$(16.49)	18% of buying price
	Profit per car	\$ 6.45	7% of buying price

Figure II.4.12

	Units	Equilibrium	Historical
t TO COMPLETE Sh CAPACITY	mo	36	36
LIFETIME OF Sh CAPACITY	mo	240	240
t TO CORRECT Ds CAPA GAP	mo	18	18
Sh CAPACITY UTILIZATION		0.95	0.95
Hulks weight	kg/mo	1,273.44	1210.99
Cars being processed	car/mo	1,000,000	1,000,000
Future shredding	ton/mo	1,273,443	1,210,990
Profit effect on Sh capacity		1.00	1.2
Indicated capacity	ton/mo	1,340,466.24	1,529,671.58
Shs aging rate	ton/(mo*mo)	5,585.28	6,373.63
Indicated capacity on order	ton/mo	201,069.94	229,450.74

Figure II.4.13

Capacity in use	7,000 (ton/mo)
Utilization	95%
Installed Capacity	7,368.42 (ton/mo)
<b>Unit Fixed cost</b>	<b>12.30 (\$/ton)</b>
Wages	42,140.00
Salaries	17,813.43
Maintenance	9,800.00
Insurance	12,740.00
Replacement cost	8,166.67
	<u>90,660.09</u>

Figure II.4.14

Average Weight of Hulks	1,273.44 (kg/car)		
Hulks old cars	1,363.85 (kg/car)		
Old cars rate	0.78 (fraction)		
Hulks of new cars	947.23 (kg/car)		
New cars rate	0.22 (fraction)		
Total car rate	1.00E+06 (car/mo)		
<b>Variable costs</b>			
Hulk cost		90,960,209 (\$/mo)	90.96 (\$/car)
Factor to correct hulk price	0.892857 (net/gross)		
Corrected Hulk price	71 (\$/ton)		
Hulks bought	1,000,000 (car/mo)		
Energy cost		268,182 (\$/month)	0.27 (\$/car)
Sh Unit cost	0.2106 (\$/ton)		
Ton shredded	1,273,443 (ton/mo)	ope cost 2,804,545	
Variable maintance cost		2,536,364 (\$/month)	2.54 (\$/car)
Maintance var unit cost	1.9917 (\$/ton)		
Ton shredded	1,273,443 (ton/mo)		
Landfill cost		7,589,120 (\$/month)	7.59 (\$/car)
Landfill Unit cost	22.40 (\$/ton)		
Sh landfilling rate	338,800,000 (kg/mo)		
Transportation		4,000,000 (\$/month)	4.00 (\$/car)
Transportation Unit cost	3.1411 (\$/ton)		
Ton shredded	1,273,443 (ton/mo)		
<b>Fixed cost</b>		16,492,922 (\$/month)	16.49 (\$/car)
Required capacity	1,273,443 (ton/mo)		
Utilization	95%		
Installed capacioty	1,340,466 (ton/mo)		
Unit cost of capacity	12.30 (\$/ton)		
<b>Total cost</b>		<b>121,846,797 (\$/month)</b>	<b>121.85 (\$/car)</b>
Revenue from ferrous material		113,694,668 (\$/month)	113.69 (\$/car)
Scrap price	125.60 (\$/ton)		
Total material processed	1,273,443 (ton/mo)		
Ferrous content	71.80%	914.36 kg/hulk	
Ferrous recovery fraction	99%		
Ferrous material sold	905,212 (ton/mo)		
Revenue from nonferrous materials		14,454,042 (\$/month)	14.45 (\$/car)
Nonferrous metals bundle price	481.60 (\$/ton)		
Total material processed	1,273,443 (ton/mo)		
Nonferrous content	2.40%	30.63 kg/hulk	
Nonferrous recovery fraction	98%		
Nonferrous material sold	30,013		
<b>Total revenue</b>		<b>128,149,664 (\$/month)</b>	<b>128.15 (\$/car)</b>
<b>Profit</b>		<b>6,302,858 (\$/month)</b>	<b>6.30 (\$/car)</b>
		5% (%sales)	
		37,817,146 \$/semester	

Figure II.4.15

## 10. Additional initial information

The stock *Cumulative margin of new cars' dismantling* starts at zero under both scenarios since it is an information variable. The initial prices for equilibrium and historical values are presented in figure II.4.16.

	Units	Equilibrium	Historical
Junk car price	\$/car	\$ 50.00	\$ 80.00
Hulk price (received by Ds)	\$/ton	\$ 71.43	\$ 89.29
Scrap price	\$/net ton	\$ 125.60	\$ 148.00

Figure II.4.16

## Chapter II.5

### Analysis From the Equilibrium

In this chapter, the system is analyzed using the equilibrium condition as a starting point. The first 4 sections contain analysis of the system when single inputs are changed. Two policy variables were studied separately: plastic usage and DFD. They are discussed in sections 1 and 4. Two exogenous variables are also studied: sales and GDP in sections 2 and 3.

The second half of the chapter (sections 5 through 8) includes the analysis of the system behavior when more than one input is changed simultaneously. Section 5 deals with the exogenous prices (*x-variables*). Section 6 analyzes policy variables within the context of partial simulation (gaming). Section 7 integrates varying conditions in GDP, exogenous prices, and policy decisions. The last section includes a Monte Carlo analysis varying the retirement fractions to test the robustness of the model to these inputs.

The Automobile Recycling Dynamic Model was built sector by sector. Each sector was tested extensively, changing inputs to ensure that the proposed formulation generates a behavior that is understandable, and properly represents what the industry does. In order to keep this work to a manageable size, the complete testing process is not included.



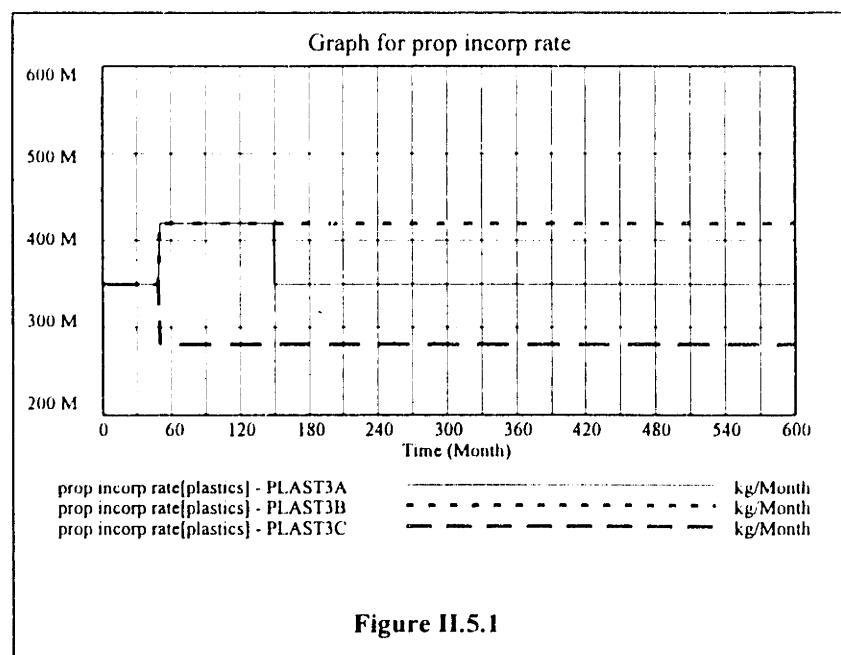
Once the sectors were tested individually, the assembly of the model was conducted and again the model output was compared to expectations. This process was followed in order to build a robust model and to generate insights simultaneously.

In this chapter, results from simple changes to the equilibrium conditions are discussed. In most cases, the equilibrium condition is the start of the simulation, and then, after a few months, a perturbation is introduced to the system. In the course of the following sections many preliminary results will be shared. Because perturbations to the system are presented in increasing order of difficulty, the reader will be able, at the end of the chapter, to make informed and inquisitive hypotheses about the possible behavior of the system to policy and to exogenous changes.

The Automobile Recycling Dynamic Model has more than 1,500 variables. To keep the work short, only the first analysis (section 1) will be explained in detail. In general, most of the discussion revolves around prices for scrap, hulk and junk cars and some environmental indicators such as ASR, and number of cars abandoned.

## 1. Changes in Plastic Usage

This section presents the most detailed analysis of the interactions in the model. A series of graphs and descriptions integrate the analysis. The focus is on studying the effect of changes in the plastic content of cars being sold. Initially, three simulations are presented. In all of them, the plastic content

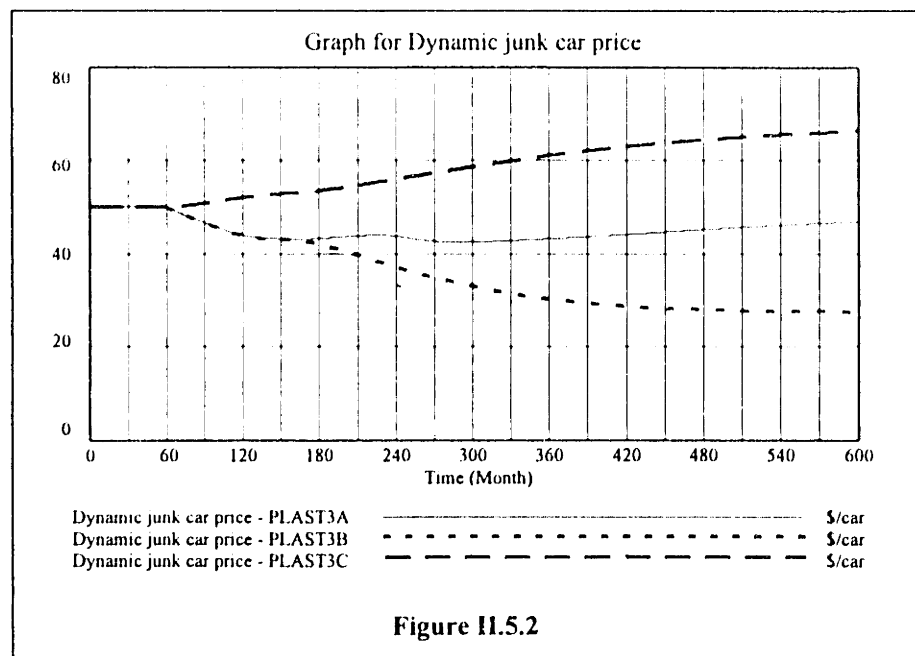


was changed while the total mass of the cars was kept constant, by varying the ferrous content.

- **CURRENT:** Is the reference equilibrium simulation. In the other simulations, the initial 50 months correspond to the equilibrium condition.
- **PLAST3A:** The plastic content is increased by 20% in month 50 and then reduced back to previous level in month 150. The plastic content in the equilibrium was 350 kg/car. This "step-up and step-down" simulation involves a change of 70 kg/car.
- **PLAST3B:** In this case the input is a "step-up" function. The plastic level is increased in 20%, at month 50, and kept at that level for the rest of the simulation.
- **PLAST3C:** This represents a "step-down" input. At month 50, the level of plastics is reduced by 20% and kept at that level for the rest of the simulation.

Figure II.5.2, showing the *Junk car price* for the 3 simulations (PLAST3X), illustrates that the effects on the "step-down" and "step-up" simulations are not symmetric. This is a result of the self-maximizing profit structure. Most of the discussion in this section is focused on the simulations PLAST3A ("step-up & step-down") and PLAST3B ("step-up"). At the end of the section a summary of PLAST3C is presented.

When the plastic content is increased suddenly and the total weight is kept constant, the composition adjustment is achieved by decreasing the ferrous content. Therefore, a sudden increase in plastic usage translates

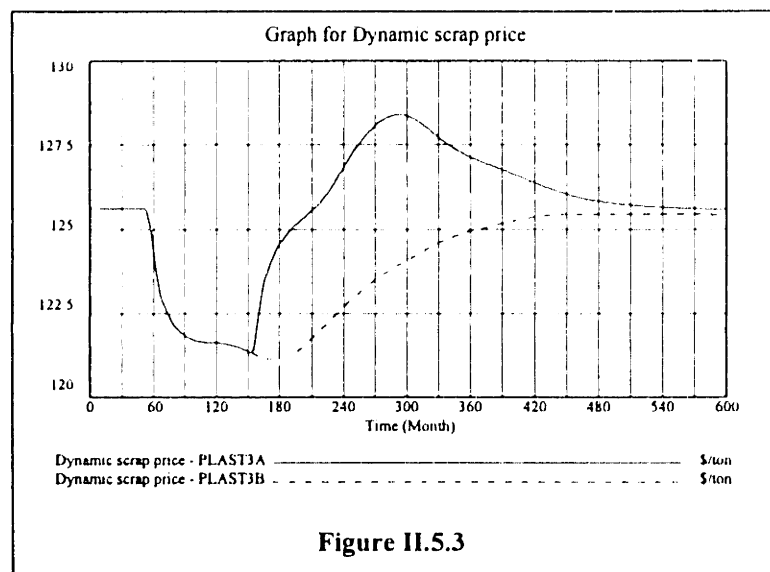


immediately in a sudden decrease in the demand for steel. Since the recycling system has proportionally more steel than what is required under this new condition (to achieve the desired scrap fraction), the perceived scrap fraction increases rapidly. One can expect the market to reduce the *scrap price*.

In the case of a sudden change back to the previous plastic usage (PLAST3A), the scrap price turns out to be too low to get enough scrap supply after month 150. This is rapidly corrected by returning to the previous price level. However, the scrap price keeps increasing beyond the equilibrium level. This is because the 100 months step function reduced the total ferrous material in the system. As a consequence, the steel industry would need to offer higher prices for the scrap to be able to stimulate enough supply after month 150. The relative value of this metal would have been increased. Figure II.5.3 illustrates this; the scrap price in the case of PLAST3A (“up & down”) shows a period, from month 180 to almost the end of the simulation where the scrap price is higher than the equilibrium level.

Figure II.5.3 also shows how, if the system is left unmolested after the initial perturbation, it would tend to go back to the equilibrium condition.

In the case of a sustained increase in plastic usage (PLAST3B), the *scrap price* would see only a slow recovery towards the previous level.



However, we expect the total amount of recycling to decrease, because an increase in plastic has a double negative effect: it reduces the sources of income for the recycling industry and increases the total costs (most of the plastic is landfilled). This work suggests that this value loss will eventually be completely transferred to the consumer, putting at risk the incoming flows of cars into recycling.

The price of hulks follows a trend similar to the *scrap price*. The major difference is that there is no overshoot in the case of a swing back to equilibrium levels (PLAST3A). As explained, the hulks' value is reduced as more plastic is incorporated in cars due to the double cost effect. There is a new equilibrium price when the increased level of plastic is sustained for a long time. The new long-run

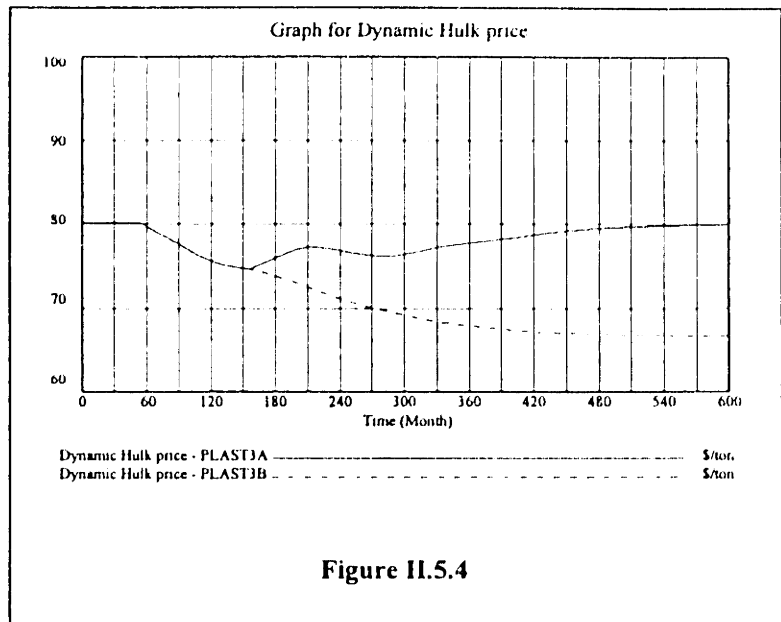


Figure II.5.4

equilibrium price is \$67.7/ton, a 17% reduction from the starting \$80/ton. Figure II.5.4 illustrates these changes.

The price of junk cars also follows a trend similar to the *scrap price*. An increase of 20% in plastic usage would translate into a drop of approximately 44.5% in price (from \$50 to \$27.6 per car). Figure II.5.5 presents these changes.

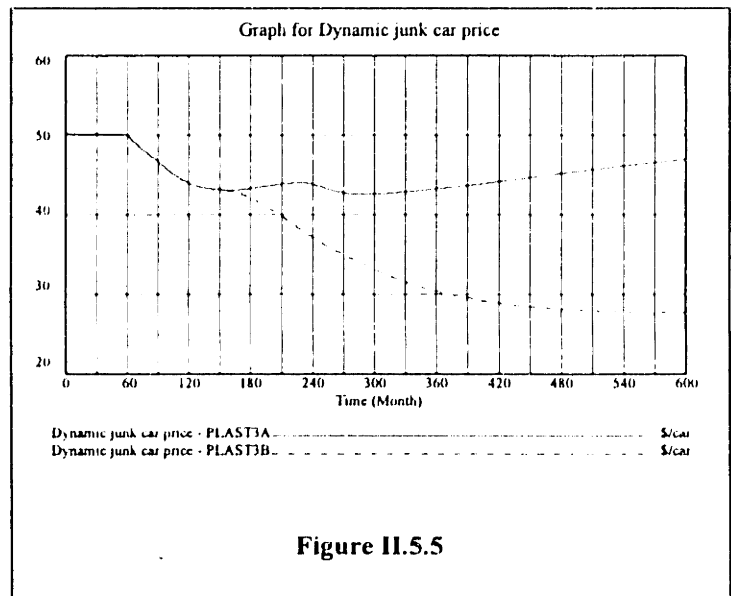


Figure II.5.5

As a result of the changes in junk car prices, the *supply fraction* changes. It is important to remember that the *supply fraction* quantifies the part of the stock of *deregistered cars* that will be brought to

the dismantlers per month, given the price of the junk cars. As the dismantling rate is reduced when the price of junk cars is dropping, cars accumulate in the "deregistered" stock. This car accumulation tends to increase the supply of cars. This is why, when the price of junk cars

increases in the simulation where the previous plastic usage is reestablished (PLAST3A), the supply of cars overshoots.

Suddenly, the price is such that it would almost trigger the same fraction of cars as under the initial equilibrium, but there are more cars in this stock. This overshoot in cars being processed by the industry is what generates later (in month 300, approximately) a pressure for the hulk price to go down.

A sustained increase in plastics usage would cause a sustained increase in the level of cars waiting to be brought to the recycling industry (*Old deregistered cars*).

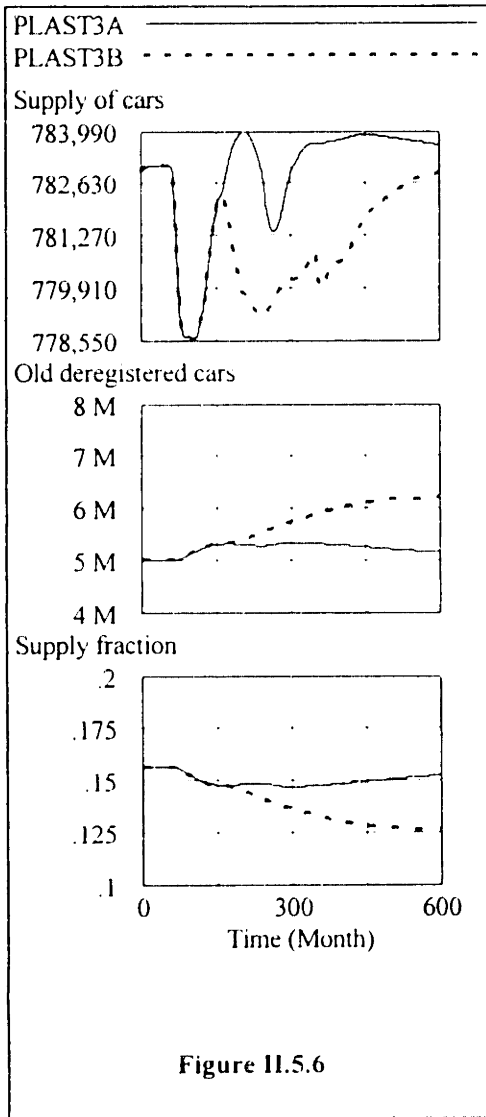


Figure II.5.6

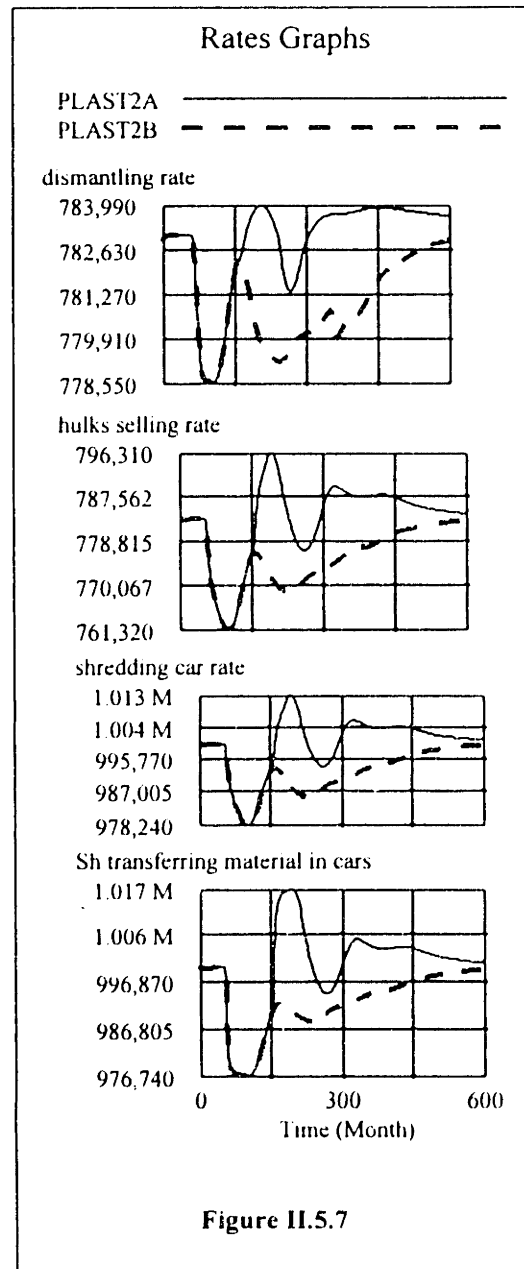


Figure II.5.7

As shown in figure II.5.7, the rate at which cars are brought in (supply of cars) is the primary influence in determining the rest of the flows in the system. One can see that the rates *dismantling*, *hulks selling*, *shredding*, and *Sh transferring materials* follow a similar path.

Figure II.5.8 illustrates an interesting behavior in the case when the plastic usage goes back to the previous level (PLAST3A). After month 150 the ferrous demand is corrected to its previous level and the scrap fraction rapidly goes back to its desired level. However, in month 280 we observe that the fraction goes down. The supply of scrap corresponds to the variable *selling prop rate shredded[Ferrous]*, which is based on *prop outflow from shredded material[Ferrous]*. One can see in figure II.5.9 that the average content of ferrous in the inventory of shredded hulks drops as a result of less ferrous material usage in the past. It recovers after the establishment of the previous usage levels. In addition, the shredding rate follows the pattern based on dismantling rates. The combined effect is that the scrap supply fraction goes down for a second time after having been in the proximity of the desired level before month 300. In other words, the first time the scrap fraction goes down because there is less demand for steel, the second time because there is less supply of scrap.

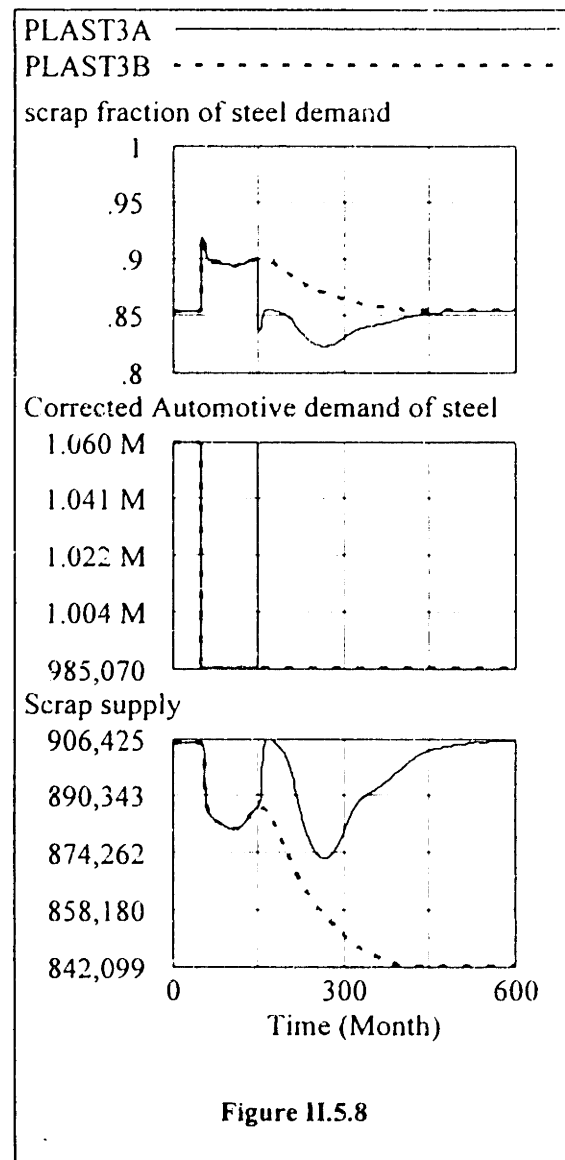


Figure II.5.8

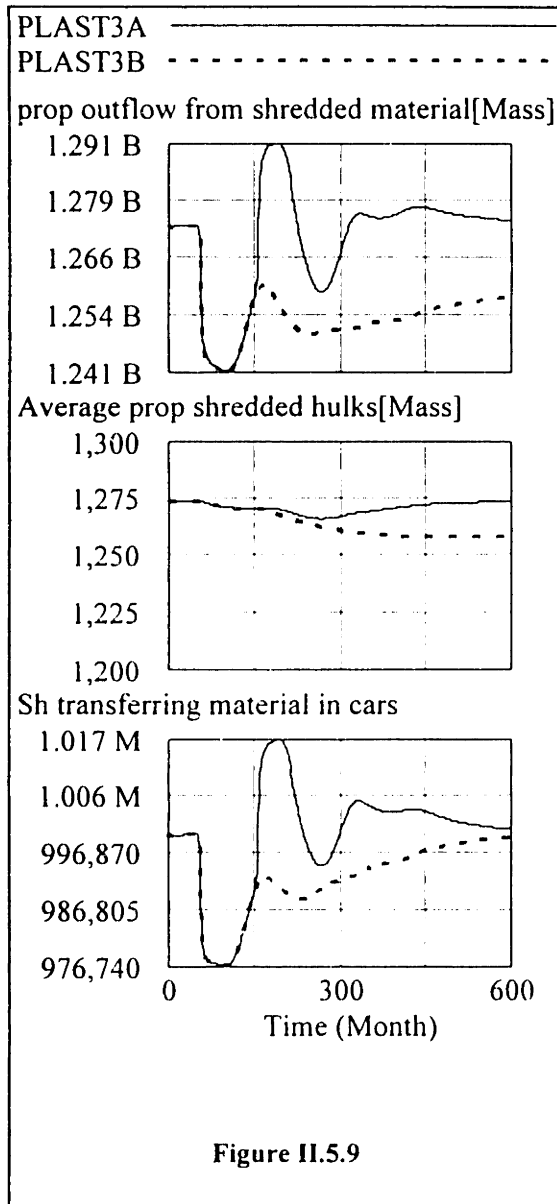


Figure II.5.9

the car structure to extract more valuable materials and, at least partially, offset the negative impact of less ferrous content. Thus, their revenues from hulks decrease, and the revenues from recycling increase slightly. Their labor costs go up because they dismantle cars more extensively. The fixed cost also increases because as more dismantling is done, more capacity is required and built.

As shown in figure II.5.10, one of the consequences of increasing the level of plastic usage, is that more mass would be recycled by the dismantlers. However, this increase in recycling is not a consequence of an increase in dismantlers' profit. Contrarily, as dismantlers see their revenues reduce because the hulk price goes down, they undertake more recycling. That is, they go into deeper levels of

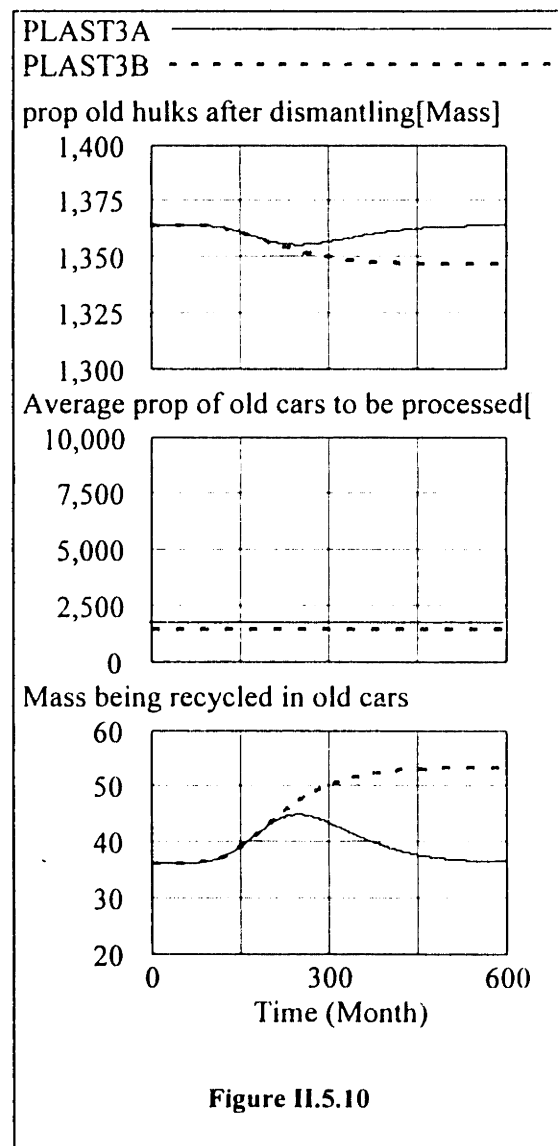
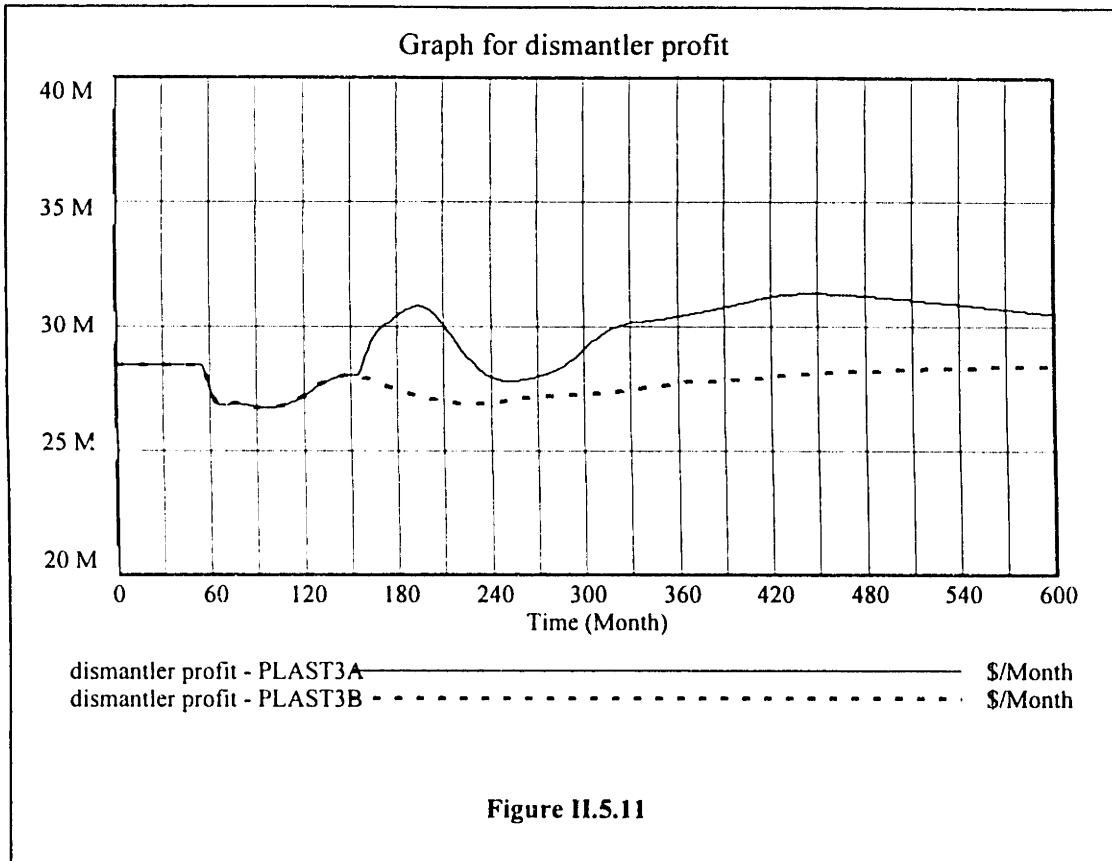


Figure II.5.10



At the same time, dismantlers try to offset part of these unfavorable events by reducing the price of the junk cars and consequently a part of their costs.

In the long run, dismantlers would transfer the additional costs to the owner of the junk car. This is the reason for achieving a long run profit equilibrium level similar to that which existed.

In the case of a temporary increase in plastics (PLAST3A) the overshoot and undershoot in profitability is caused by the combination of the increase in hulk price and the particular dismantling rate described above.

The cumulative dismantlers' profits in these scenarios are:

- Equilibrium: \$17.02 billion.
- PLAST3A: \$17.71 billion
- PLAST3B: \$16.60 billion



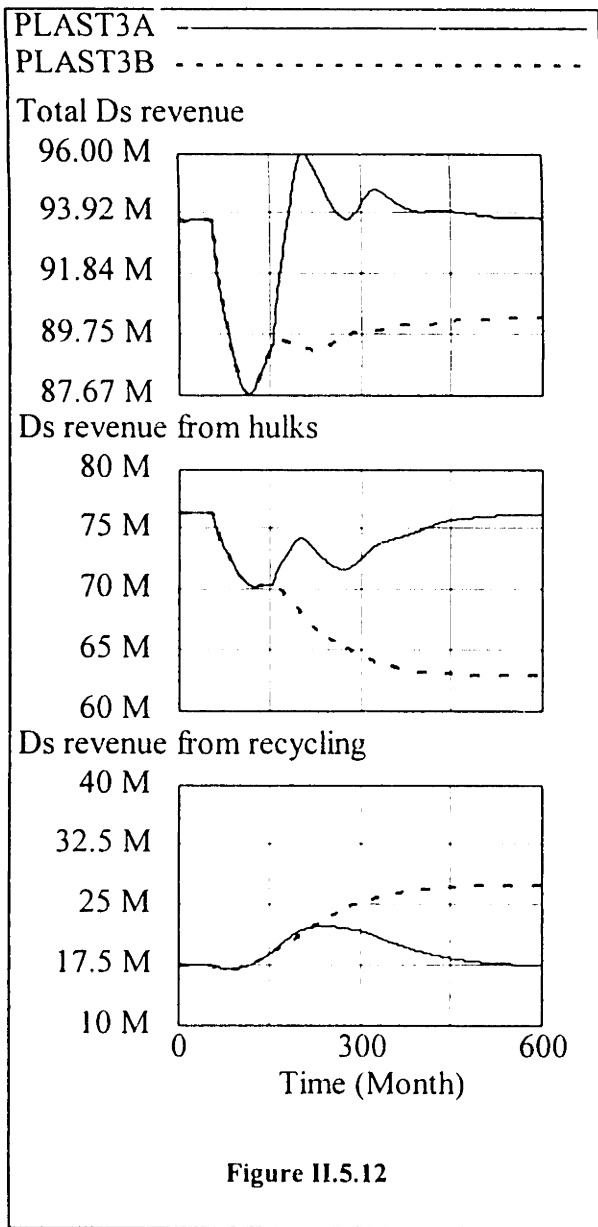


Figure II.5.12

At the equilibrium, the total dismantling cost is approximately \$65.5 million/month. Labor is approximately 15%, fixed cost is almost 23%, while the rest (61%) is the cost of acquiring the junk cars.

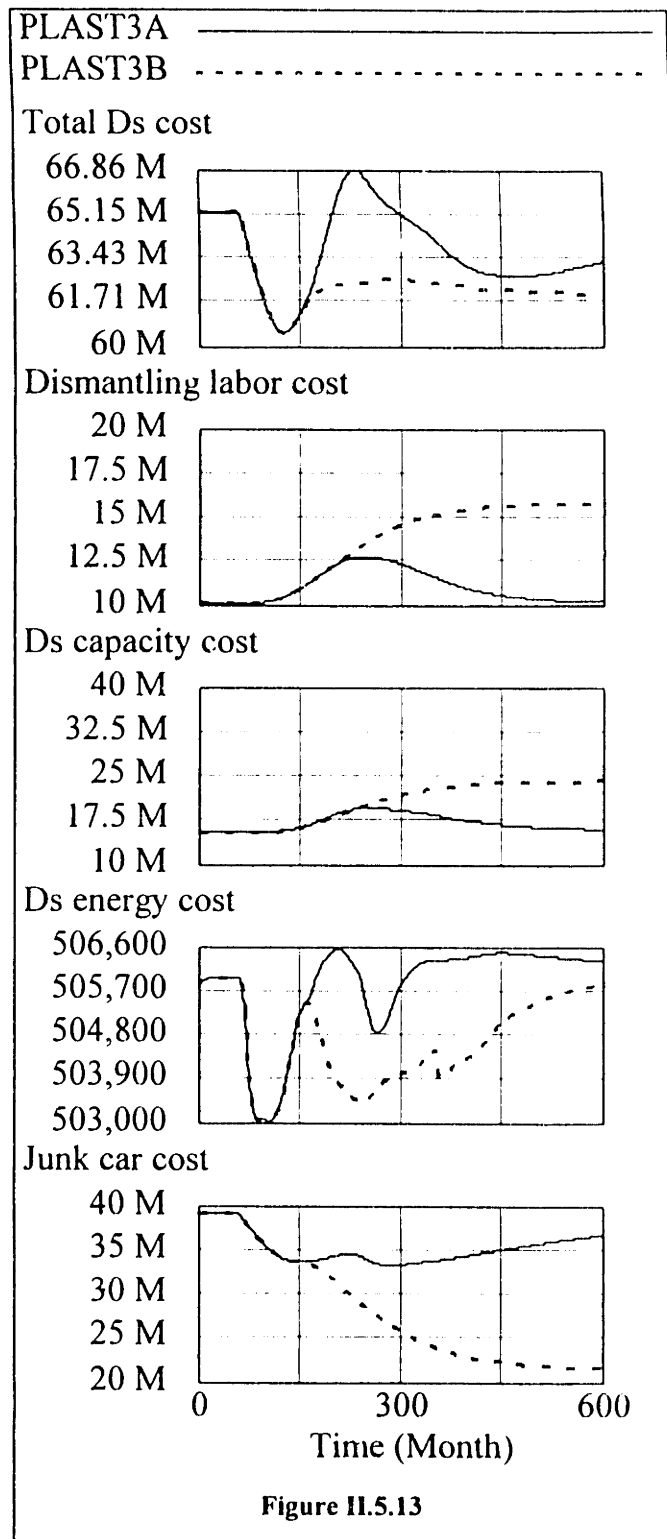
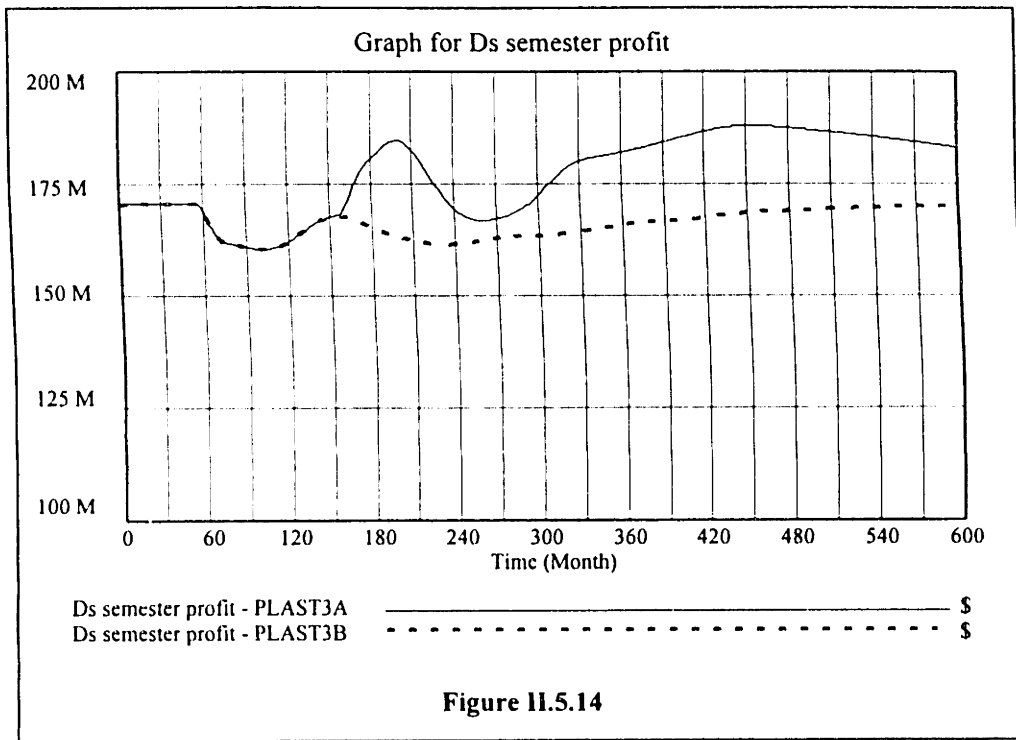
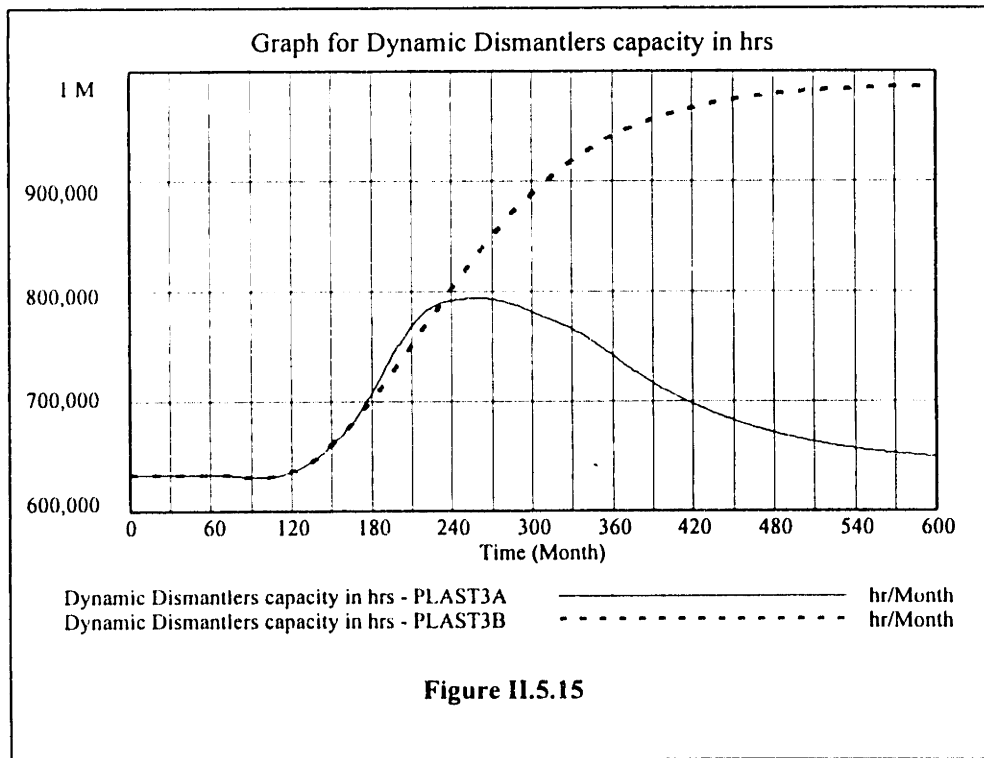


Figure II.5.13



As has been mentioned, dismantlers' capacity grows as a consequence of the increase in dismantling. Figure II.5.15 shows this capacity increase.



An increase in plastic usage has several effects on shredders' profit. On the revenue side, there is a fast drop in the scrap price. As a consequence, they try to hold their inventories for longer periods, and less material is sold. Figure II.5.16 shows this change in sales rate.

Associated with this, less income from nonferrous material would also be earned.

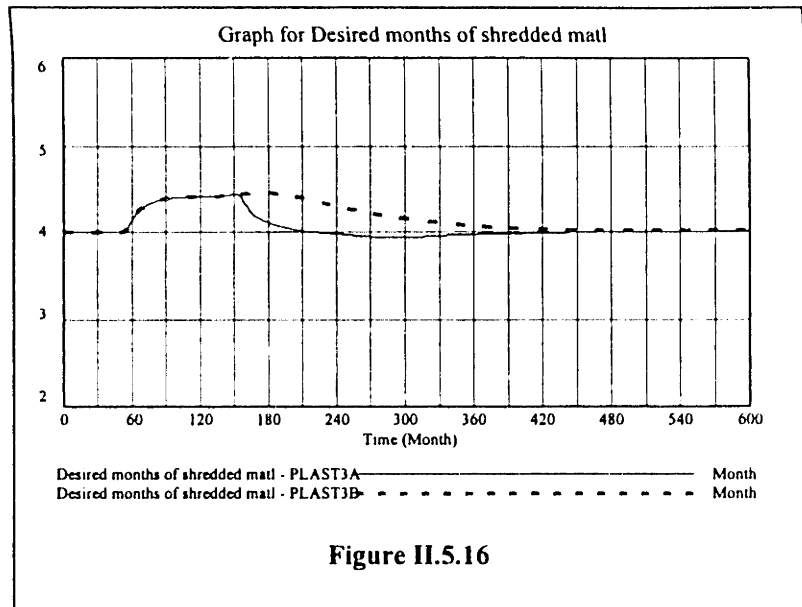


Figure II.5.16

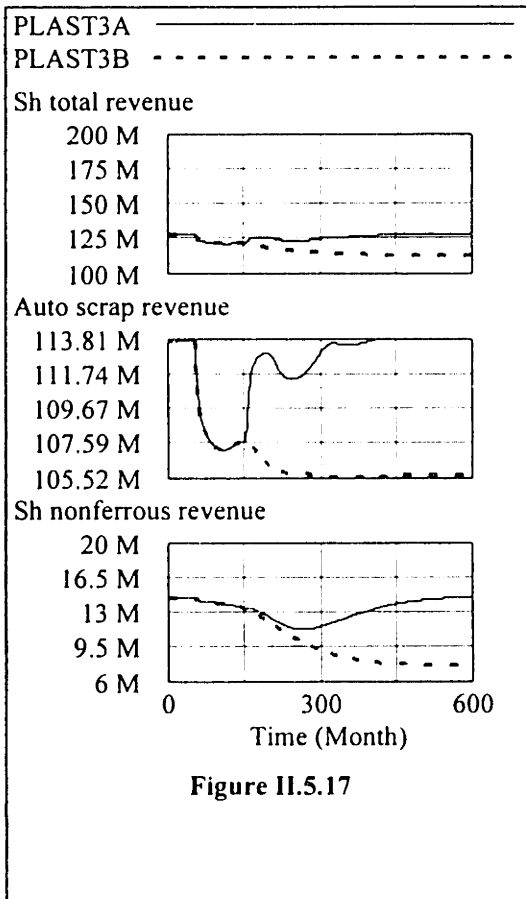


Figure II.5.17

On the cost side, the landfill costs increase, but the hulk acquisition cost decreases because they offer lower prices and because hulks weigh less since more dismantling has been conducted. The operation cost follows the same pattern as dismantling rates. The fixed cost is reduced, because when incoming flows (less number of hulks, lighter hulks) go down, capacity tends to contract.

The combined effect is that in the short-term, shredders see their profit hurt because the adjustment of *hulk price* does not happen instantaneously.

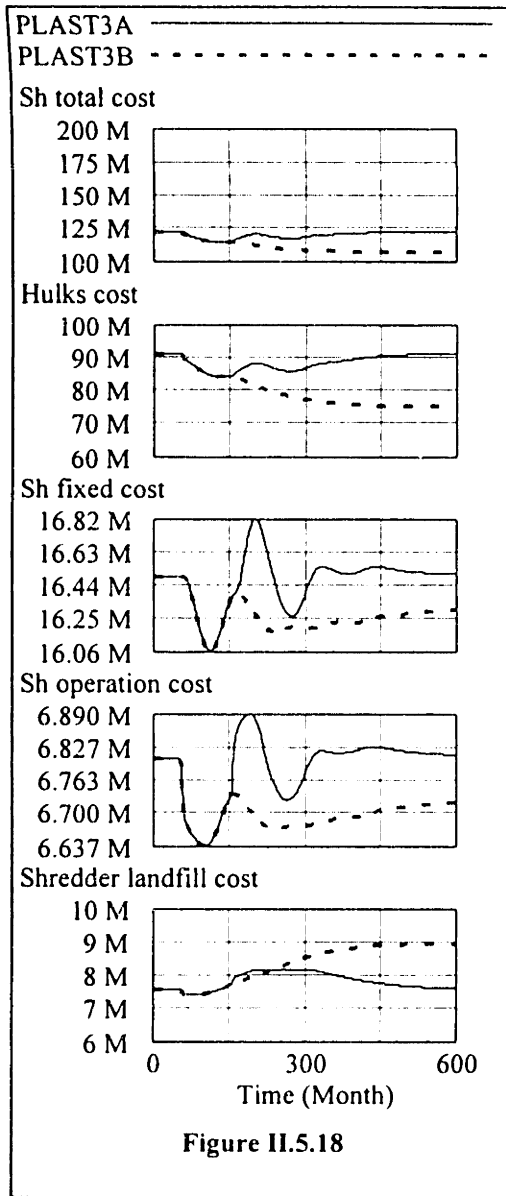


Figure II.5.18

However, as shown in figure II.5.19, shredders' profit adjusts over the long-run. The oscillation observed in this variable is a normal consequence of the processing rates oscillation.

Figure II.5.18 breaks shredders' costs out. At equilibrium, the total cost to the shredders is approximately \$120 million/month. The acquisition of the hulks represents 75%, the fixed cost is almost 13%, while the landfill and operation cost are both 6%. As a consequence, one can expect shredders to be relatively robust to economic fluctuations because they can reflect their profitability trends on a major portion of their costs (*hulks price*).

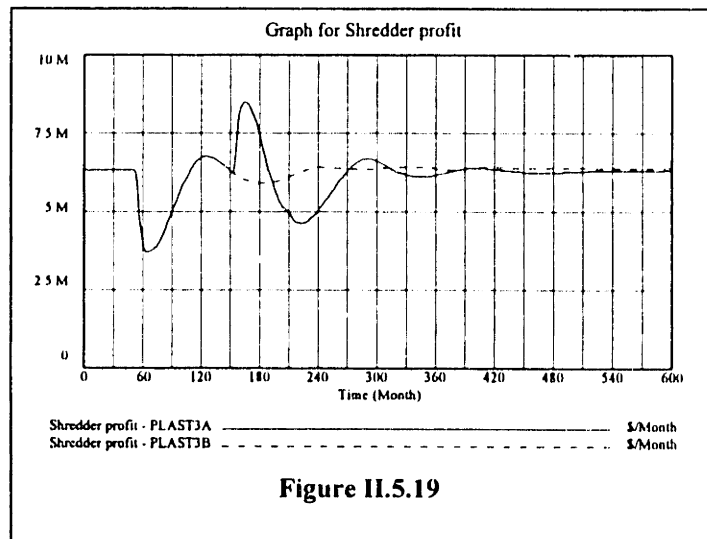
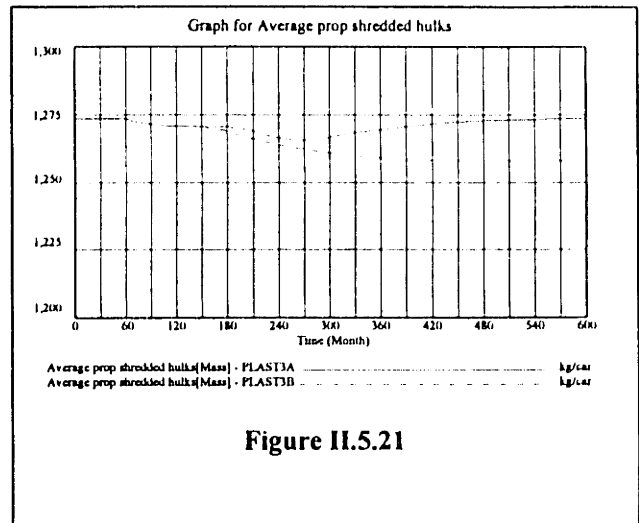
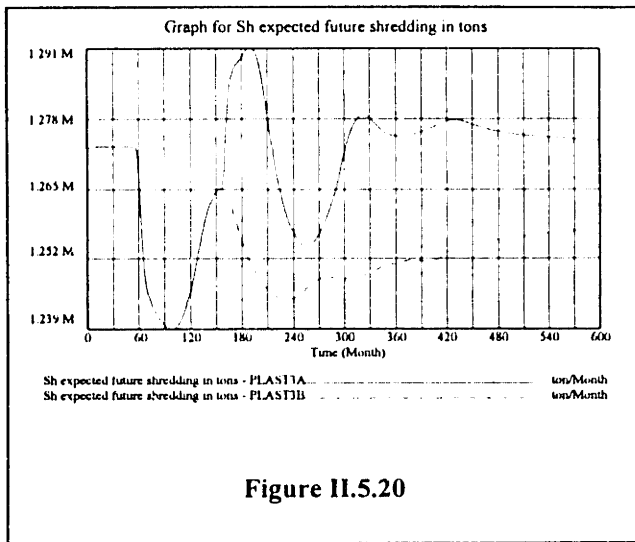


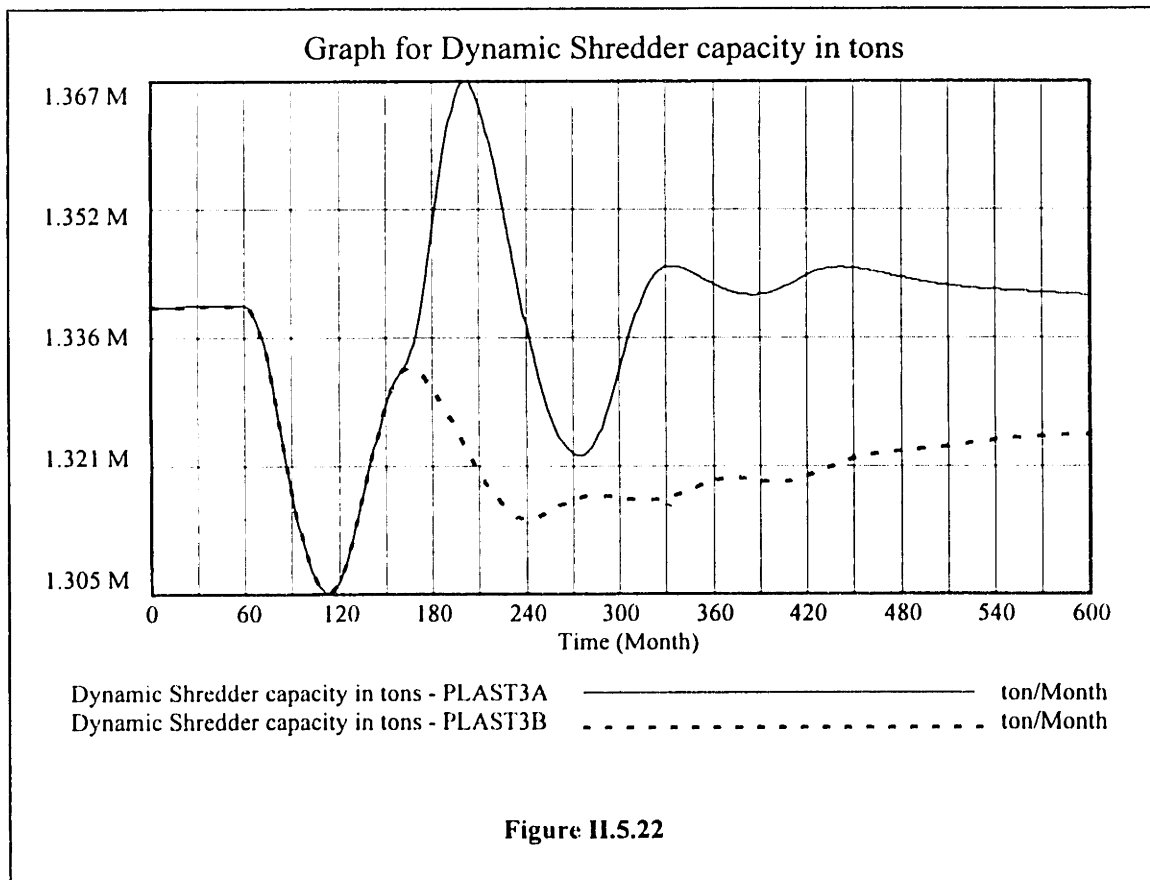
Figure II.5.19

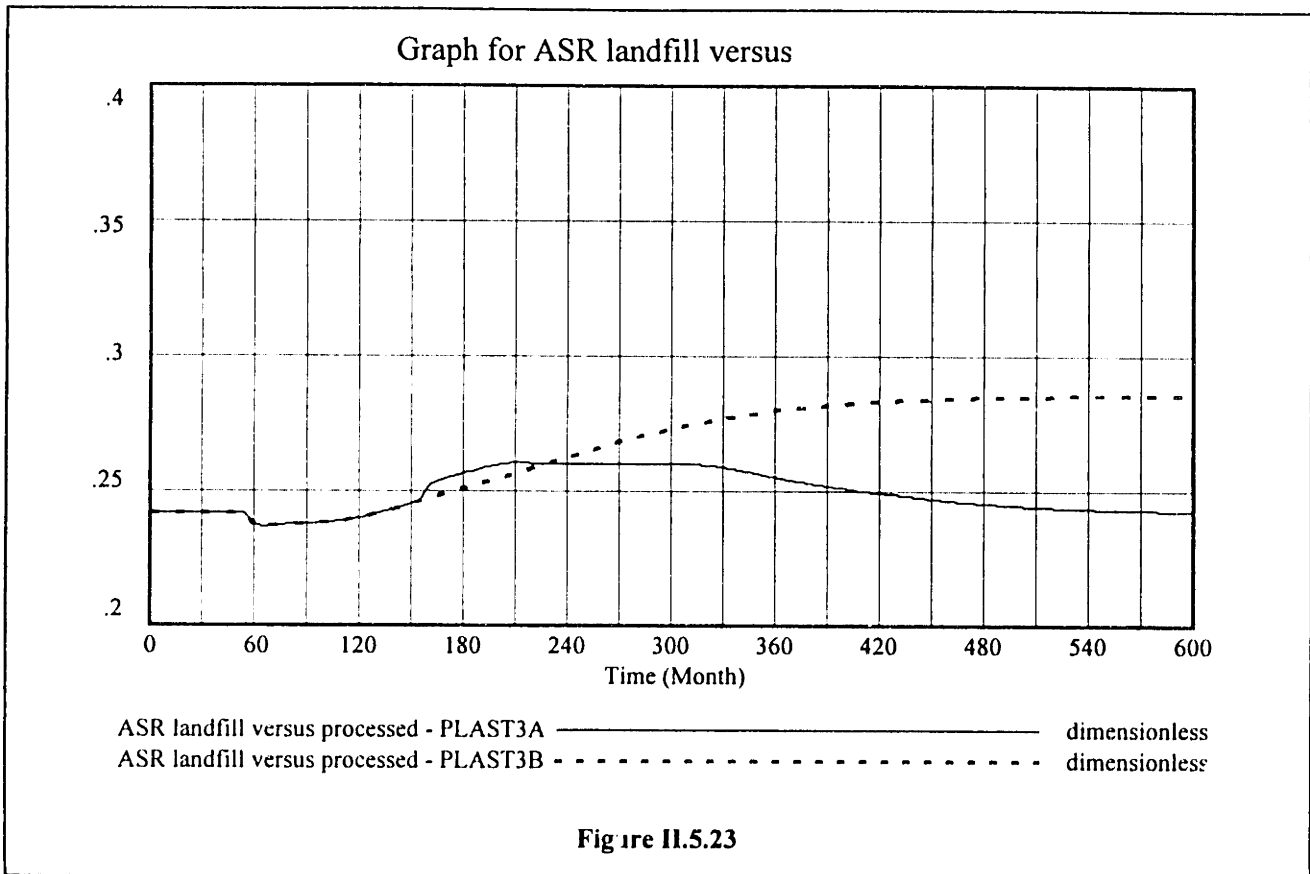
The cumulative shredders' profits for these scenarios are:

- Equilibrium: \$3.782 billion
- PLAST3A: \$3.672 billion
- PLAST3B: \$3.709 billion



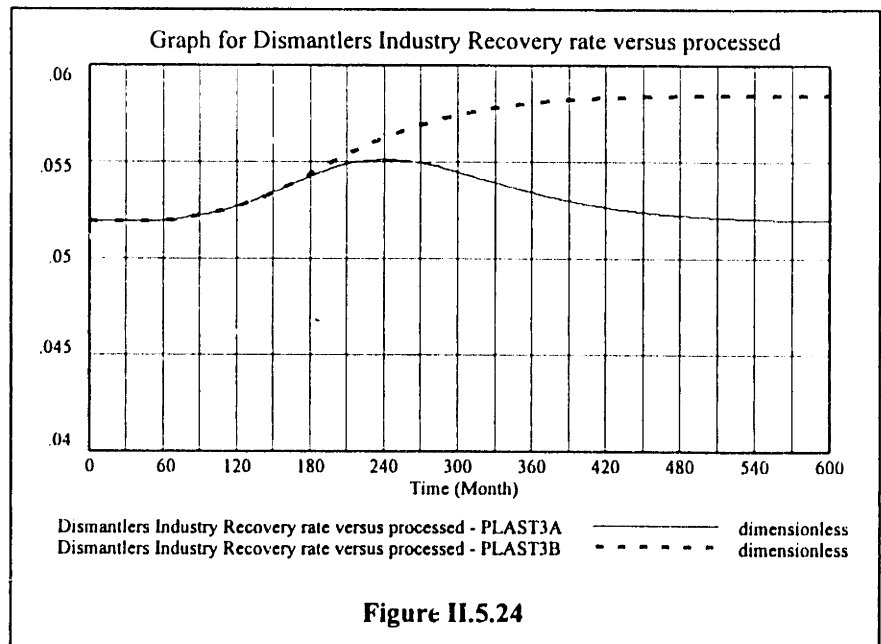
*Shredders' capacity* follows the pattern dictated by their expectations. Expectations in this case are based on the rates at which they receive hulks and the *average weight of hulks*. Figures II.5.20 - 22 present the behavior of these variables.





The increase of plastic used in cars translates into more material going to the landfill. The starting level of ASR is 24.16% -- the equilibrium level. When the plastic usage increase is sustained, ASR becomes 28.51%. This represents an increase of 18%, which is less than the 20% increase in plastic usage.

One could speculate that this discrepancy is due to the additional dismantling performed in cars. However, that is only one of the causes. The total contribution of dismantlers to recycling is still modest. *Dismantlers Industry recovery rate* (compared to the total mass they process) goes



from 5.2% to 5.8%.

The other reason for the 2% discrepancy is that, as prices go down, cars accumulate in the system. This increase in the stocks of cars involves an increase in the “inventories of plastic” in the system. Accordingly, the ASR generation is smaller than what it would have been if car accumulation did not occur in the system.

The maximum level of ASR generation in the scenario PLAST3A is 26% in month 233.

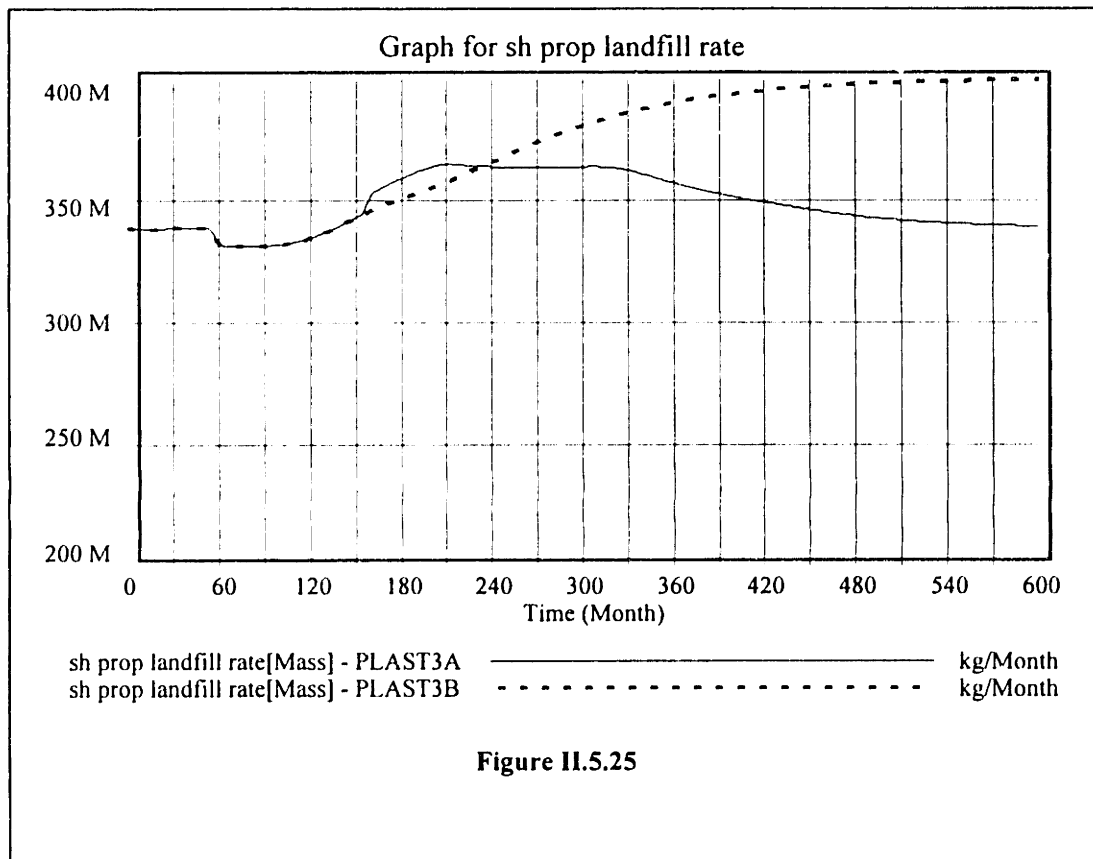


Figure II.5.25 illustrates how the system sends more material to the landfill. In PLAST3B, almost 400 million kg/month of fluff are sent to the landfill. This corresponds to 18% more than in the equilibrium run.

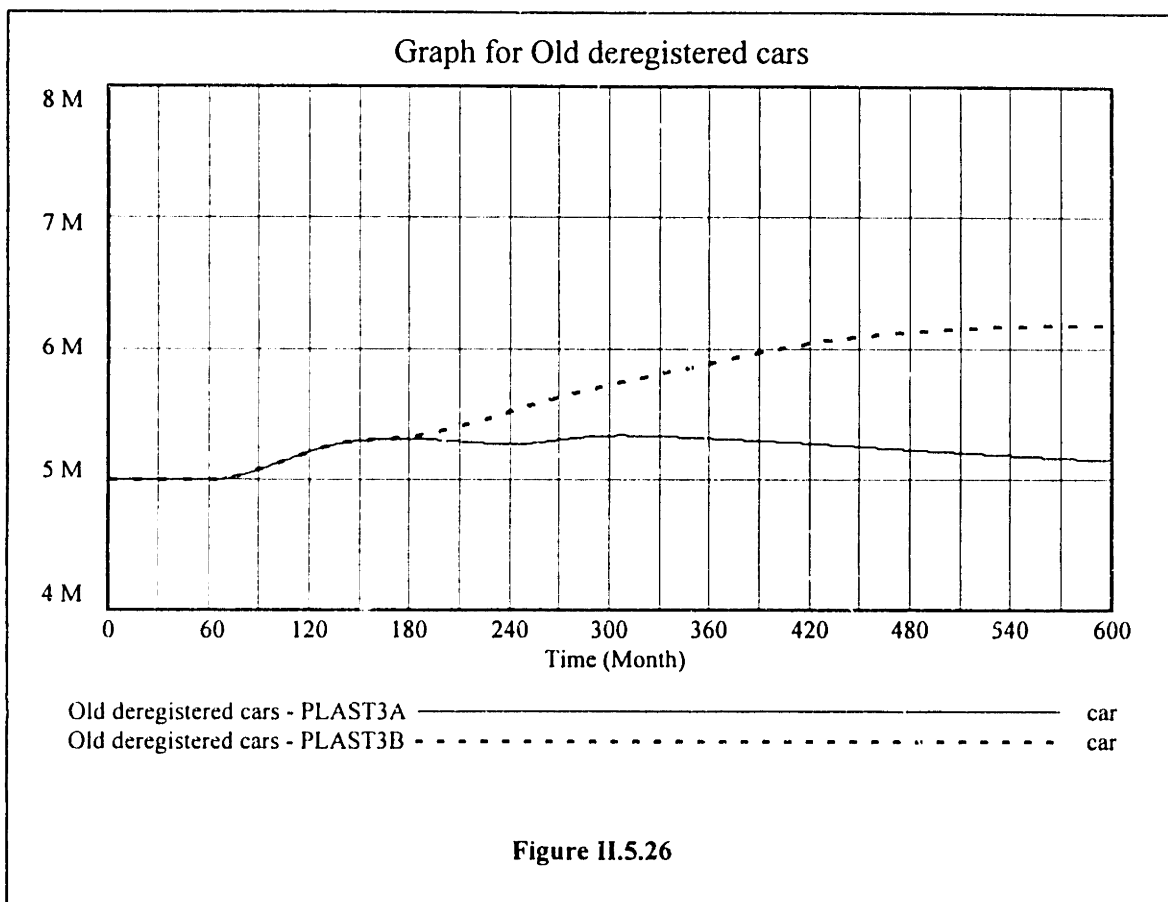


Figure II.5.26

As expected, the reduction in *junk car price* explained above results in an increase in the stock of *old deregistered cars*. Figure II.5.26 shows how this stock in PLAST3B increases from 5 to 6.2 million cars.

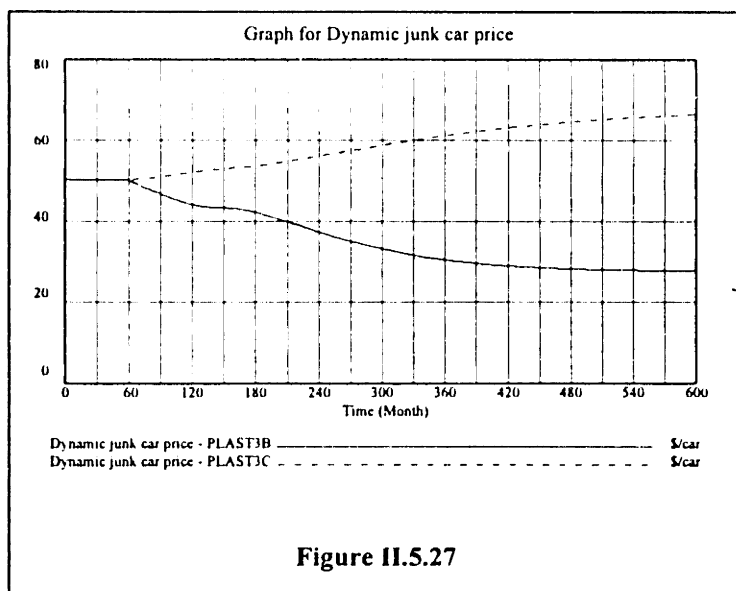


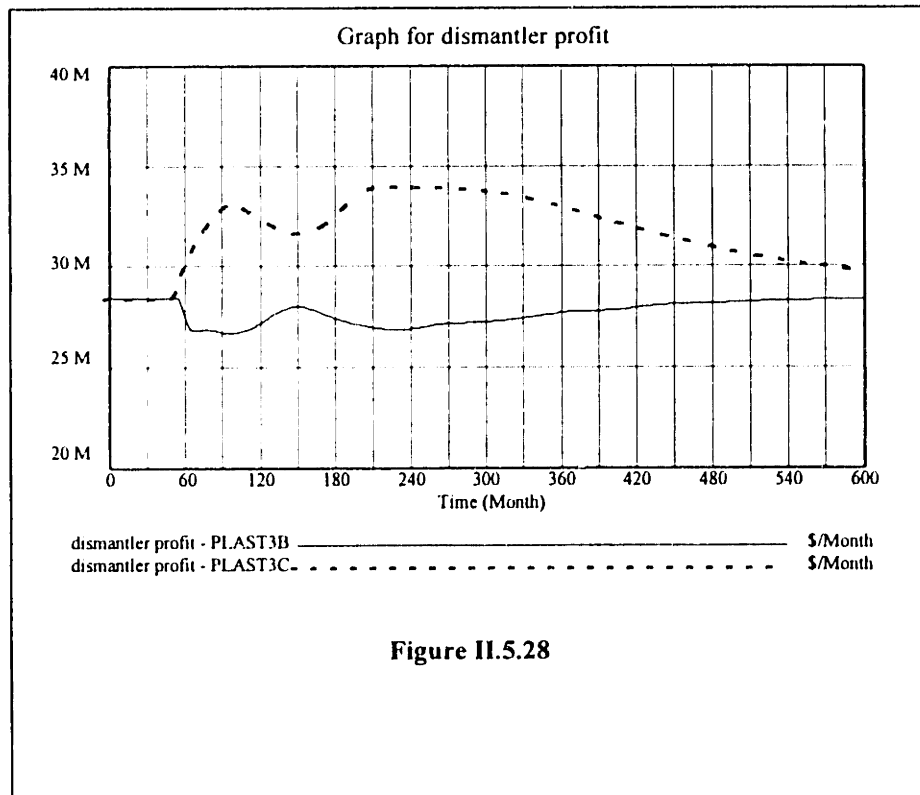
Figure II.5.27

Figure II.5.27 compares the *Junk car price* under the scenarios where the plastic content was increased and decreased by 20% (PLAST3B and PLAST3C). It illustrates how the behavior is not symmetrical. This is because dismantlers would not be willing to transfer completely the additional economic benefits they encounter.



Dismantlers try to maximize their profit, not to achieve a constant margin. Figure II.5.28 shows how *dismantlers' profit* varies within these simulations. One can see that in the favorable case, PLAST3C, they do proportionately better; their profit increases by more than \$4 million/month at the peak, while in the unfavorable case the drop is only \$3 million/month.

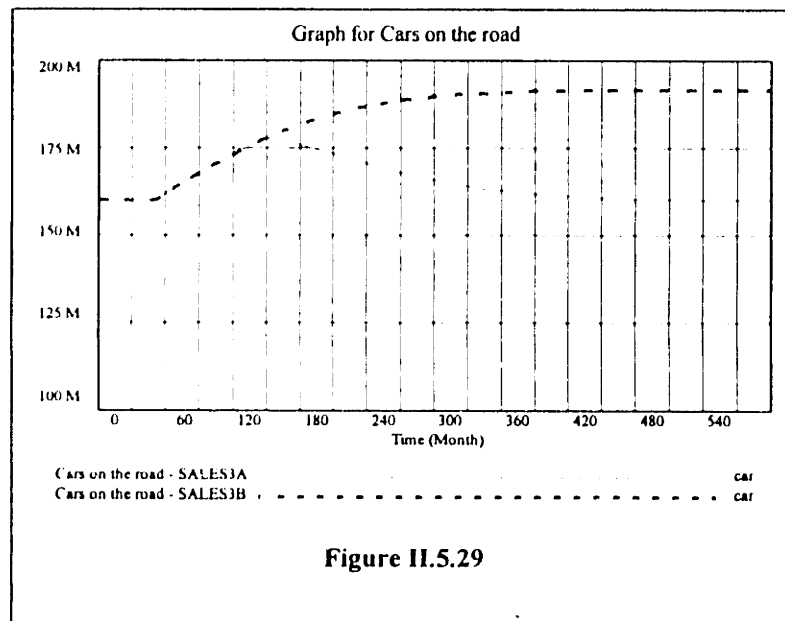
This profit maximizing strategy implies that dismantlers would be more reluctant to reflect savings than incremental costs on the *junk car price*. In PLAST3C, for example, the *cumulative dismantlers' profit* is \$19.07 billion, 12% above the equilibrium value.



## 2. Changes in Sales

In this section sales were suddenly increased in month 50 to 1.2 million cars per month, and reduced back to 1 million in month 150 in the case of scenario SALES3A. In scenario SALES3B sales were kept at 1.2 million after month 50. Again, the initial 50 months of both simulations correspond to the equilibrium described at the beginning of this chapter. It is important to notice that this increase of sales was produced by directly changing the *sales* variable. In the next section the dynamic calculation of sales, estimated via GDP, will be analyzed.

Figure II.5.29 shows that an increase in sales results in an increase in the fleet of cars on the road. In scenario SALES3A, where the previous level of sales is reestablished, the long-term equilibrium is the same as when the simulation started. In the other case, the equilibrium is reached at a higher level of cars being used.



The sudden increase in sales modifies the scrap fraction because suddenly there is more production of automobiles and the steel industry would need more scrap to sustain the desired *scrap fraction*. Between month 50 and 150, we can expect the whole set of prices to increase, because the ferrous content in the system is relatively more valuable. One can see in figure

II.5.30 that in the long-run the scrap fraction adjusts even in the scenario SALES 3B, where more cars are sold, because more cars would be deregistered with time.

When the sales level is recovered (SALES3A) the *perceived fraction* goes back quickly to the previous level. However, as time elapses the additional cars sold during the period of increased sales (month 50 to 150) get retired, and now the system has more scrap than what is required. The *scrap fraction* overshoots above the desired level.

Thus, we can expect prices to decrease and to de-stimulate the scrap production, in an oscillation manner. Figure II.5.30 illustrates this behavior.

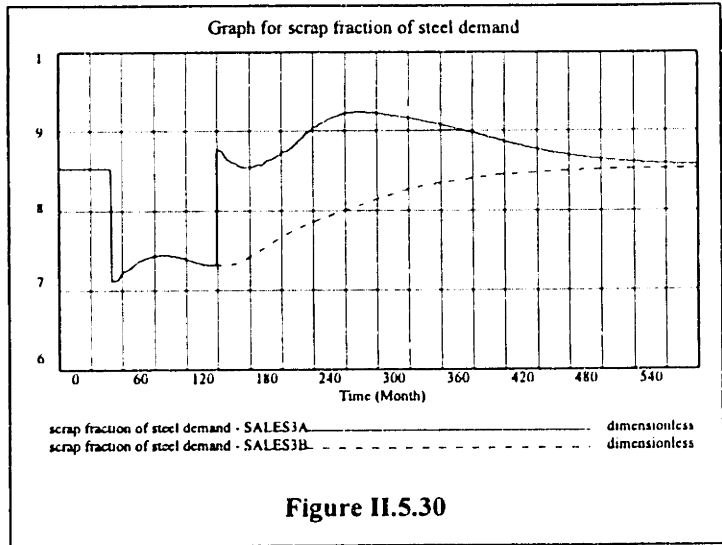


Figure II.5.30

Figures II.5.31 and 32 present the prices during these simulations. In scenario SALES3B there is a gradual recovery towards the previous equilibrium. In the other scenario the recovery is

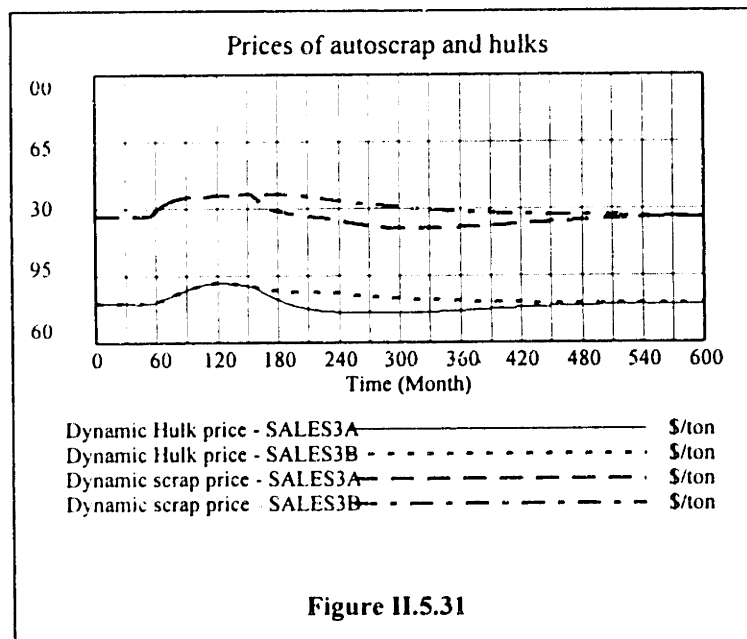


Figure II.5.31

accompanied by an undershoot in prices. Figure II.5.31 presents the *hulk price* and the *scrap price* in the same graph. There is clearly some parallelism between these two variables.

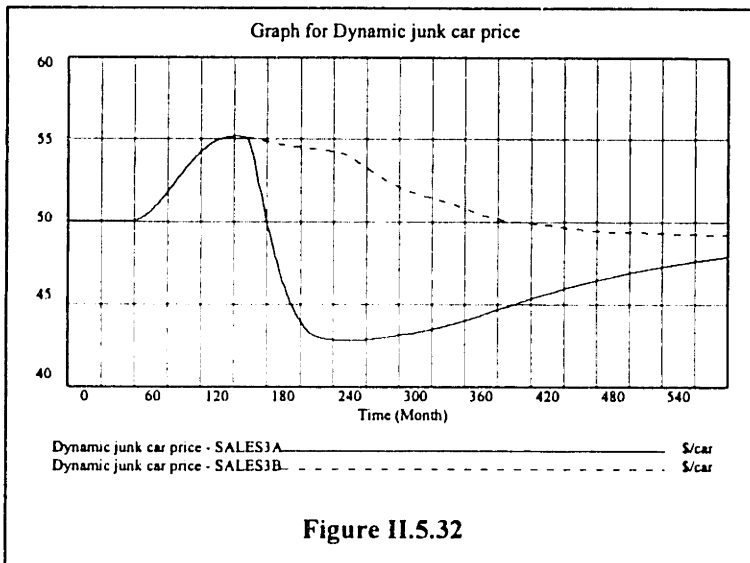


Figure II.5.32 presents the *junk car price* pattern. We can see again that the scenario of "step-up and step-down" (SALES3A) causes the system to undershoot with regard to the long-term equilibrium price; due to the adjustment delay associated with the pricing mechanism.

In the case of the *scrap* and the *hulk price*, both go back to the previous equilibrium level. The time horizon does not allow for the same to happen in the case of the junk cars.

As a consequence of the increase in sales, we can observe a corresponding increase in the amount of automobiles being left out of the recycling loop. Figure II.5.33 shows that a long-term increase in sales of 20% causes the stock of abandoned cars to increase 20% as well. In scenario SALES3A, where the previous level of sales is reestablished, equilibrium will be reached at the initial level.

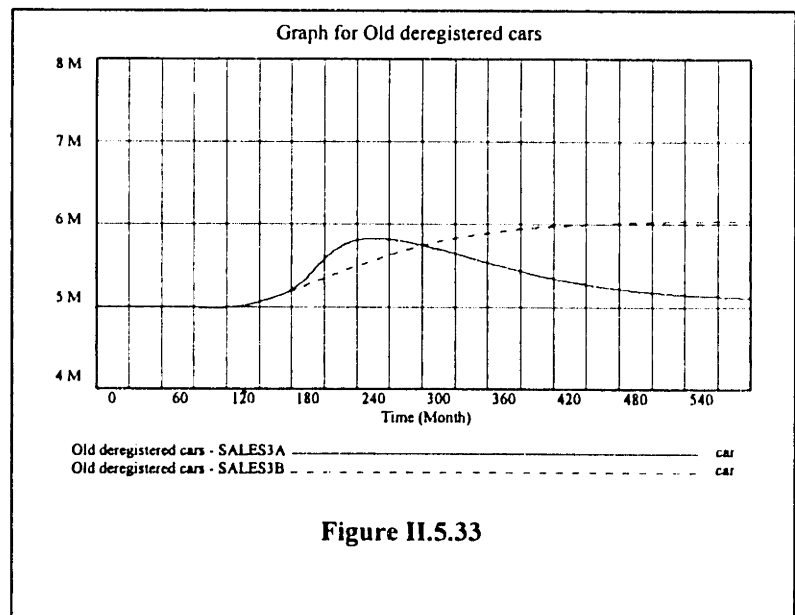
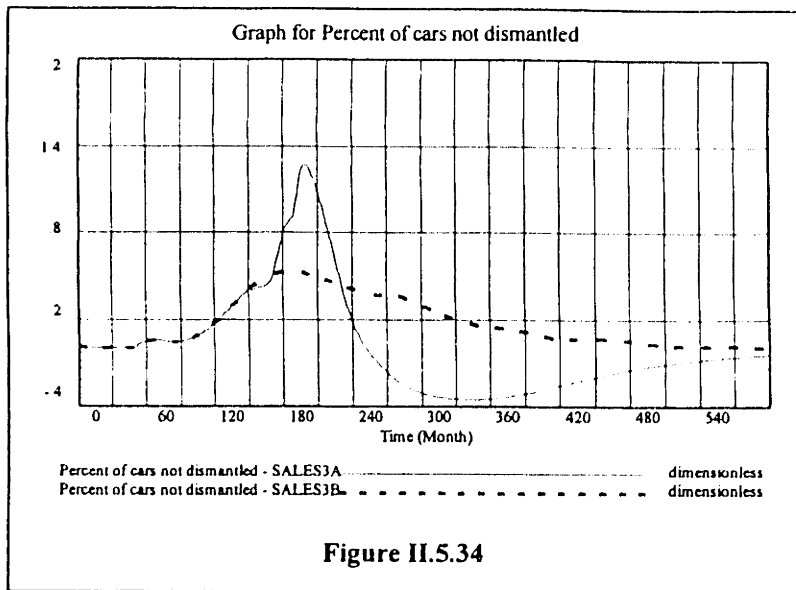
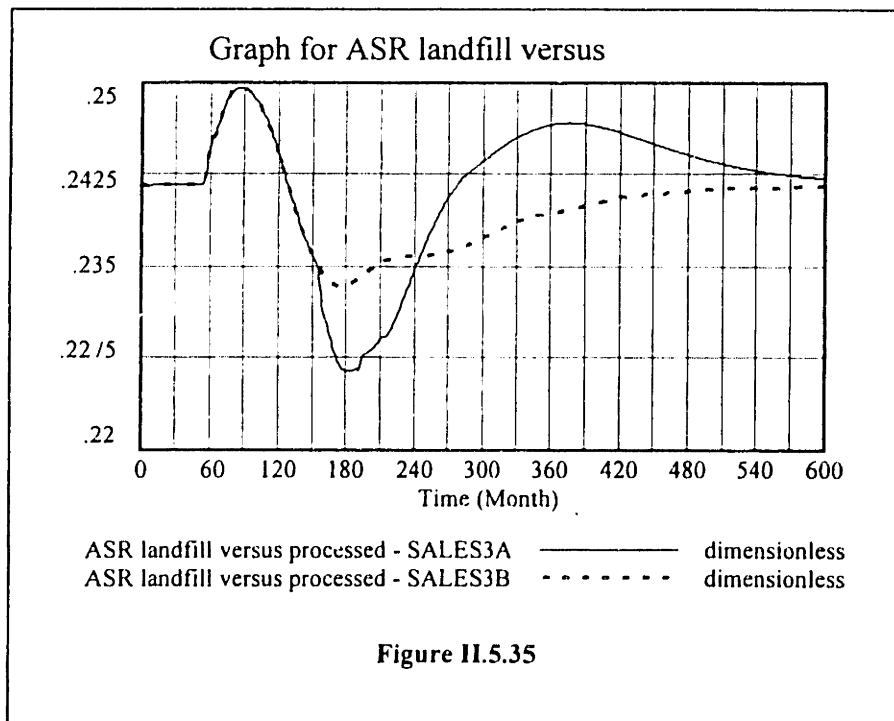


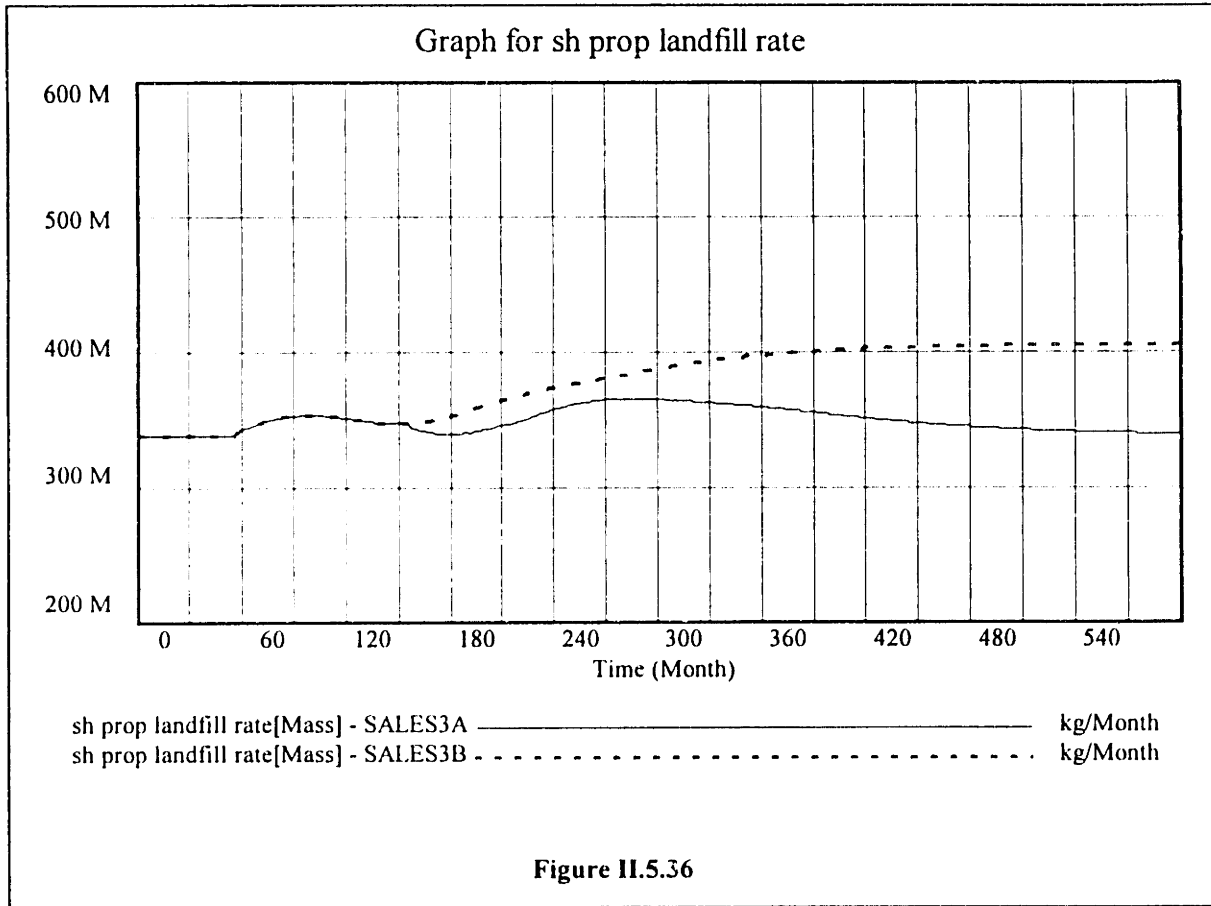
Figure II.5.34 and II.5.35 present more on the effects of sales on the environment. One can see that the effect on cars not being recycled is relatively modest. The scenario SALES3A cause the *percent of cars not being recycled* to swing in a range of almost 2%.



By the same token, the effect on ASR, as a percentage of the material processed does not change significantly. This is consistent with expectations because the nature of the automobile is the same in all aspects: composition, weight and level of DFD. Entities would basically process more cars, realize more profits and send more material to the landfill on a total mass count, as shown in figure II.5.36.

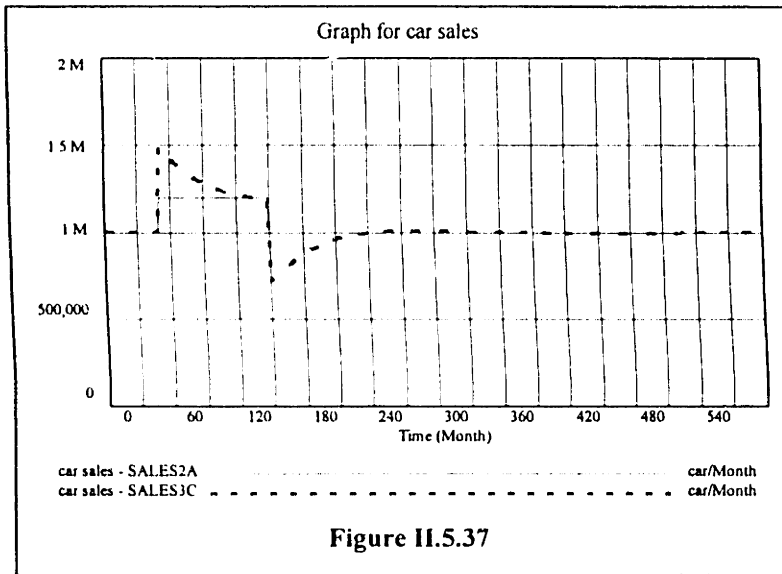






At the beginning of the simulations, the system was sending 338.2 million kilograms/month to the landfills. In scenario SALES3A this rate oscillates slightly and reaches the previous equilibrium level. When the increased level of sales are sustained, the system produces 405.6 million kilograms/month. This represents the expected increase of almost 20%.

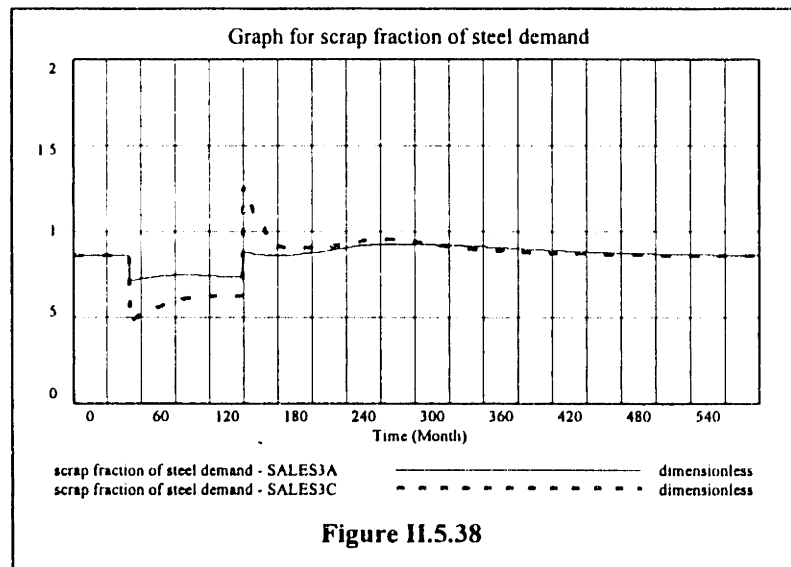
### 3. Changes in GDP



Scenario SALES3C in Figure II.5.37 shows the sales behavior when GDP is used as the exogenous variable and is subject to a 20% increase in month 50, and a 20% decrease in month 150. There are two peaks in the months when the changes are introduced. They are the result of the stock adjustment mechanism explained in chapter 3

where GDP defines an ideal number of cars on the road and sales are proportional to the gap between the ideal and the actual number of cars.

Figure II.5.38 illustrates how these peaks exaggerate the behavior observed in scenario SALES3A, when the sales were manipulated exogenously. Accordingly, we can expect the prices to behave in an amplified way, presenting two overshoots associated with the months of the drastic changes. The next two figures present these results and demonstrate that GDP changes cause the system to react in a more sensible way compared to when sales are changed directly.





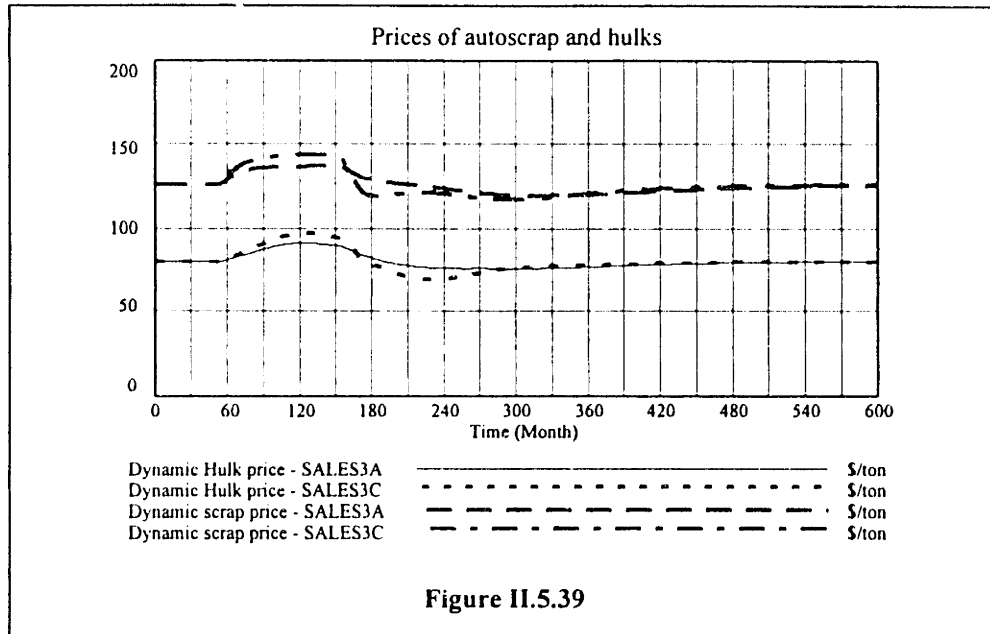


Figure II.5.39

Figure II.5.40 shows that the peaks in the price of junk cars are more severe in case SALES3C than in the case of scenario SALES3A. It also reflects that the dismantlers would benefit from the increase in sales. Their cumulative profit in scenario SALES3C is \$20.29 billion, almost 9% more than in SALES3A.

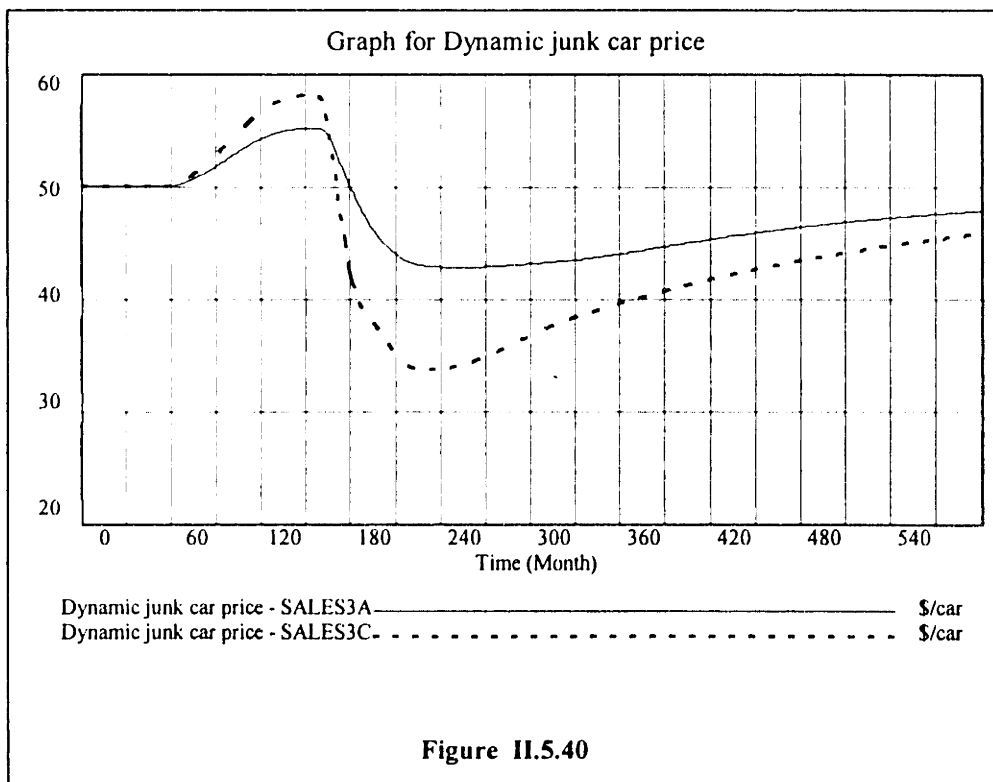
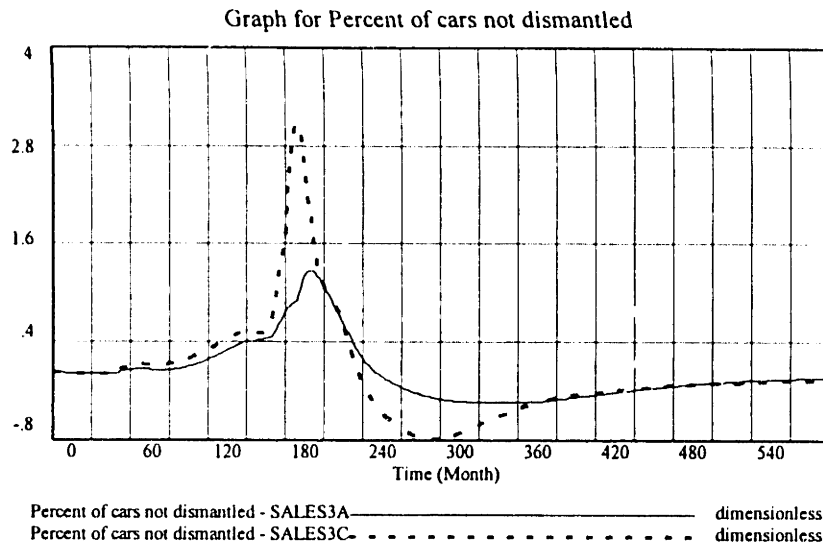


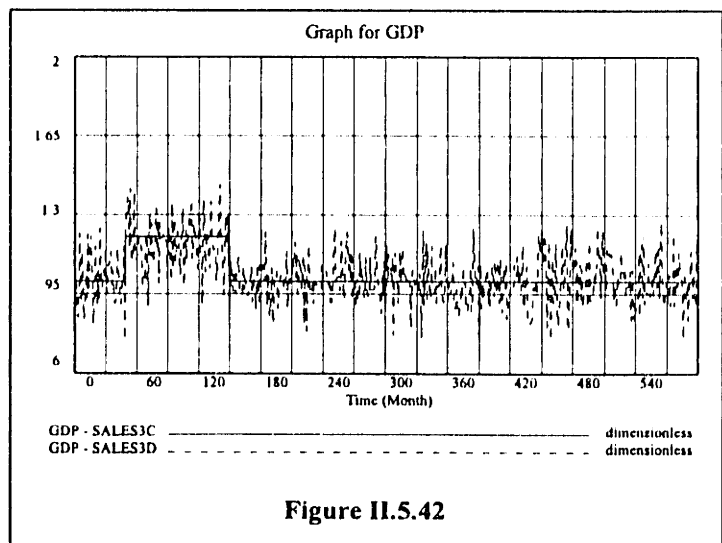
Figure II.5.40



**Figure II.5.41**

One of the most important differences between scenario SALES3A and SALES3C is observed in the oscillation in *Percent of cars not dismantled*, which, in the case of scenario SALES3C reaches 3%. Unfortunately, in the positive side it reaches only -0.8%. Figure II.5.41 shows this behavior.

Figure II.5.42 incorporates the effect of random noise on scenario SALES3C. *Vensim's random generator* is used to calculate a random number that fluctuates within the values of 0.8 to 1.2. This random number is then applied, multiplying it by the calculated GDP. This creates scenario SALES3D.



**Figure II.5.42**

Figure II.4.43 shows the effect of this on *junk car price*. It is interesting to note, how the inclusion of high frequency variation causes the system to show some oscillate characteristics.

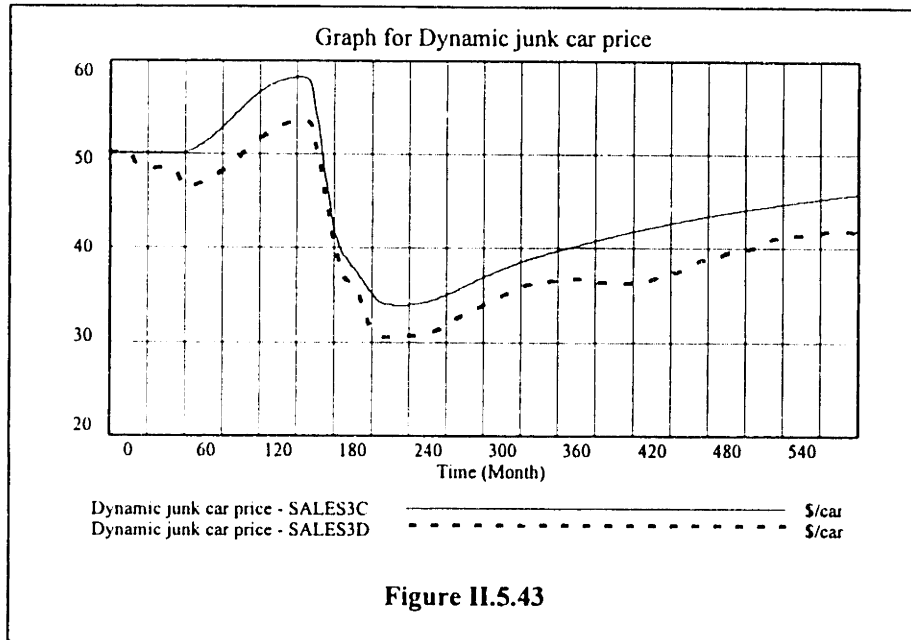


Figure II.5.43

Figure II.5.44, presenting the *hulk price* behavior, is more clear in terms of the oscillation.

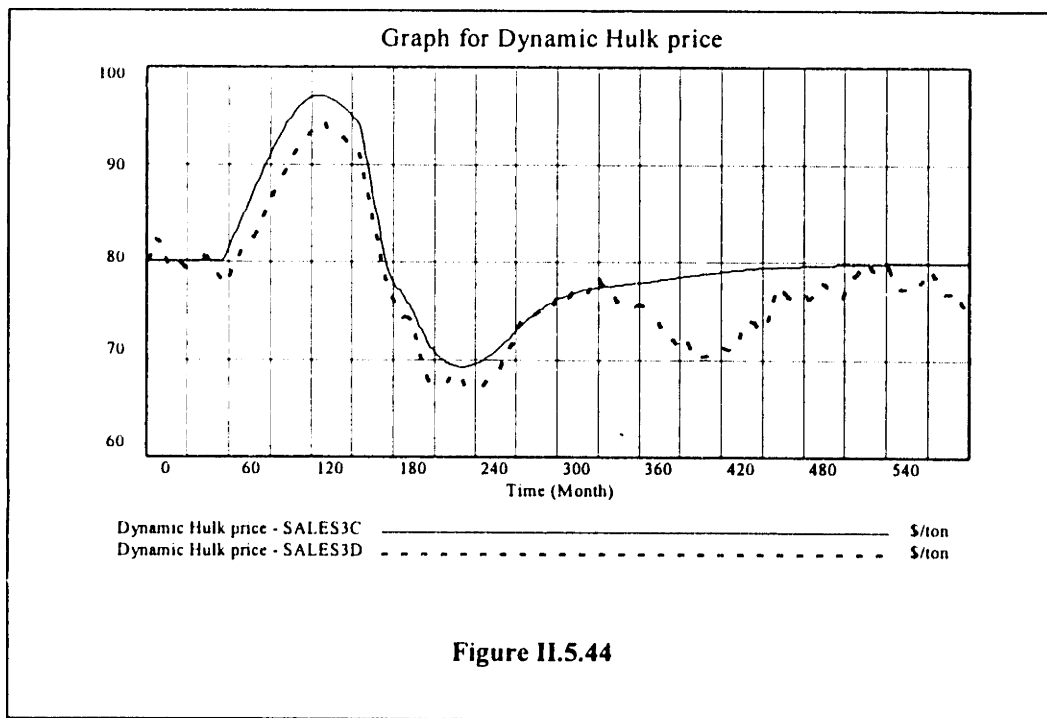
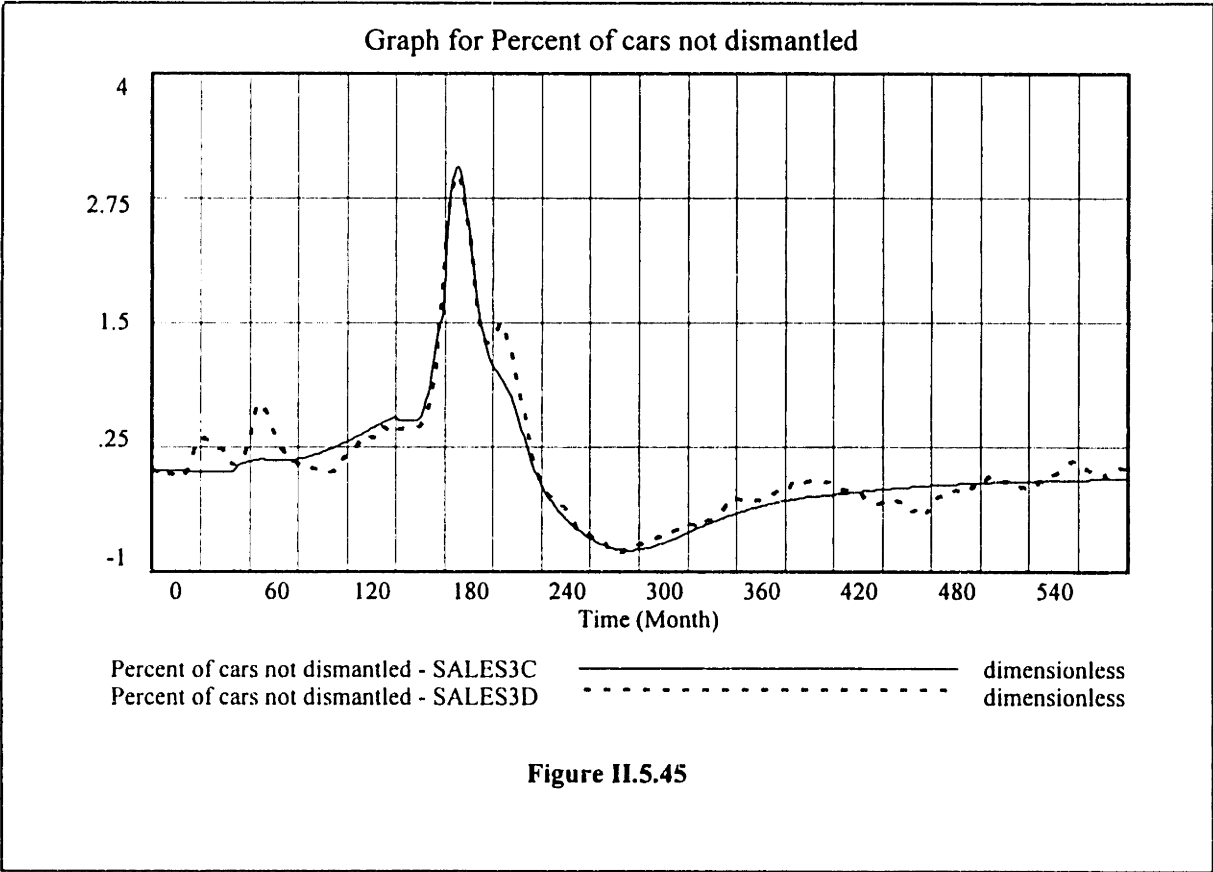
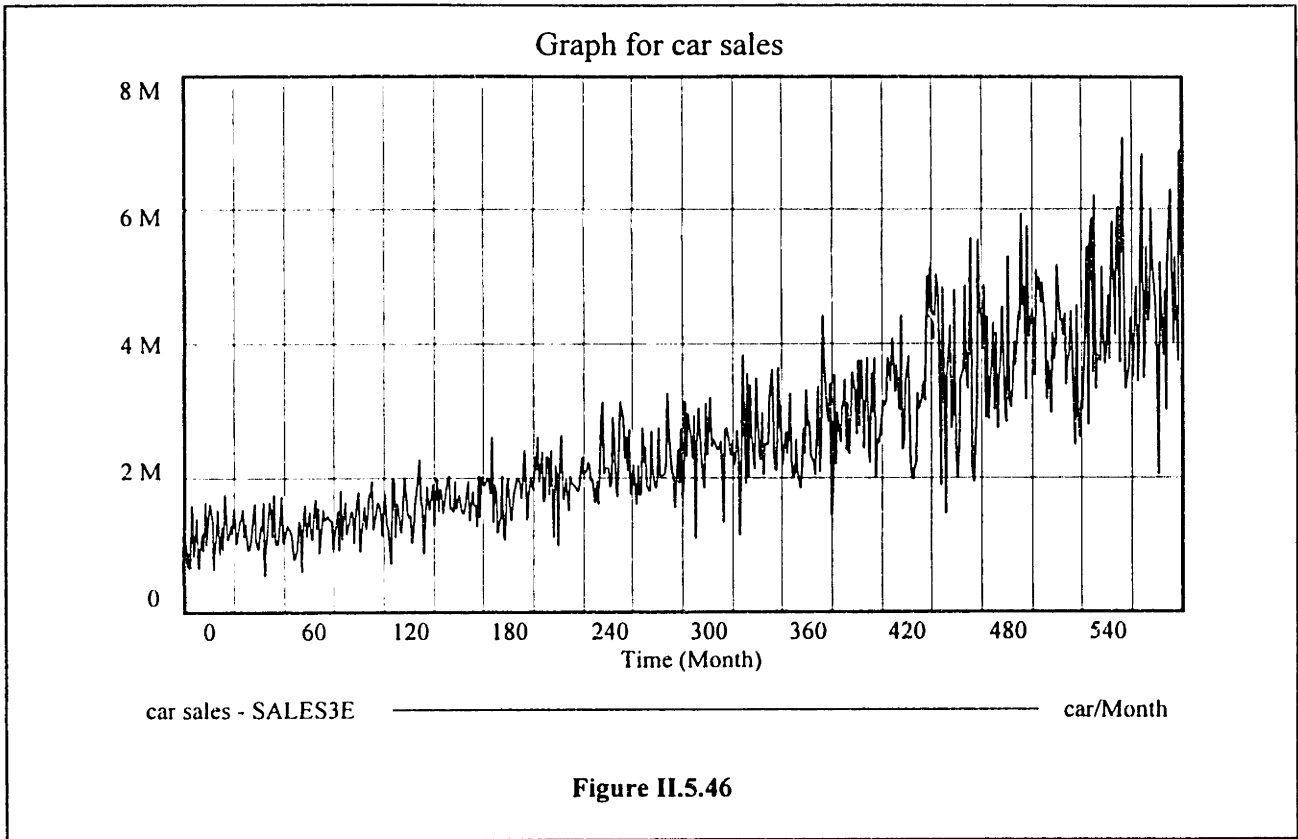


Figure II.5.44

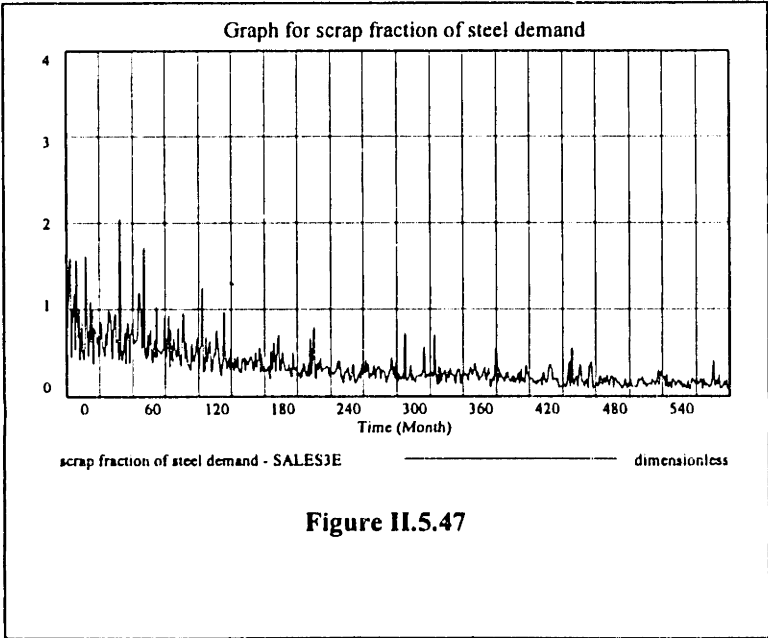
The most important consequence of this change in the environmental arena is presented in figure II.5.45, where the *Percent of cars not being processed* is shown. A minor oscillation mode with a dampening effect is observed in the behavior of the system.





One of the most interesting scenarios associated with changes in GDP is the one created when a continuously growing economy is simulated. In figure II.5.46 sales of automobiles are presented when a constant annual growth of 3% is assumed (scenario SALES3E). The random component is also included.

The reader can easily imagine that under these circumstances the scrap fraction would only decrease. As explained, the whole recycling system involves significant delays. Under equilibrium, it takes on average, 13 years for vehicles to be retired, and then almost three years before the ferrous materials to get back into the steel industry (6



months of cars abandoned, 18 months of dismantled hulks, 2 months of shredders' raw material inventory, and 4 months of shredded product). If prices went up inventories would go down (reduction of inventory coverage) and the delay could be shorter. However, this does not solve the problem; it would only "drain" the system further. The fundamental issue here is that the delays associated with using, disposing and recycling automobiles causes the scrap fraction to deteriorate continuously when the system is subject to a continuously growing economy.

Under these conditions we can expect prices to increase. Figure II.5.48 presents hulk and scrap prices. The formulation proposed establishes a limit to the effect of scrap fraction deviation on scrap price. In other words, the continuously decreasing scrap fraction can suggest a continuously increasing scrap price. However, since in reality there is a substitution possibility, it is assumed that there is maximum price that steel mills would be willing to pay for the scrap.

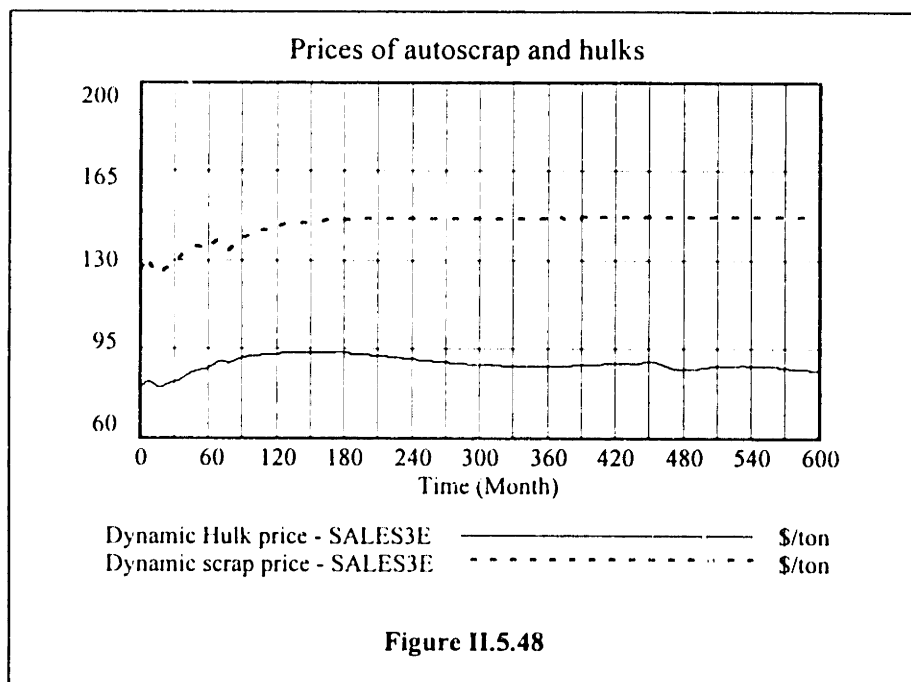


Figure II.5.48

Beyond this price, most of the steel would be produced from ore. When starting from equilibrium, the price of the scrap reaches almost 150 dollars/ton. Accordingly, hulk price increases as well.

Figure II.5.49 presents an interesting behavior of the price of junk cars. The initial part corresponds to the dynamic explained above; the delays associated with the physical flows create an increasing scarcity of scrap. This phenomenon pushes prices of scrap and hulks up. Increases in the *hulk price* cause dismantlers to sell their inventories faster, and as a result, the adequacy of the hulks inventory goes

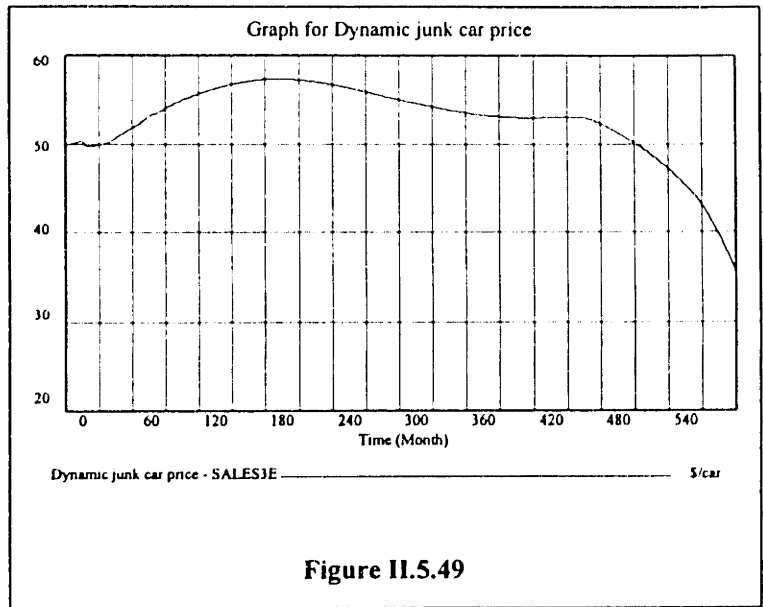


Figure II.5.49

down. Dismantlers are eager to get more cars and thus, they increase the *junk car price*. This explains the *junk car price* behavior until month 180.

However, the system accumulates cars at the abandoned stage in a continuous mode. Increases in this stock allow the dismantlers to offer a lower price for the junk cars and still get the amount they want. After month 180, dismantlers are able to reduce the *junk car price* significantly.

Figure II.5.50 illustrates the behavior of *old deregistered cars* in the system, and figure II.5.51 provides a more detailed description of this accumulation situation.

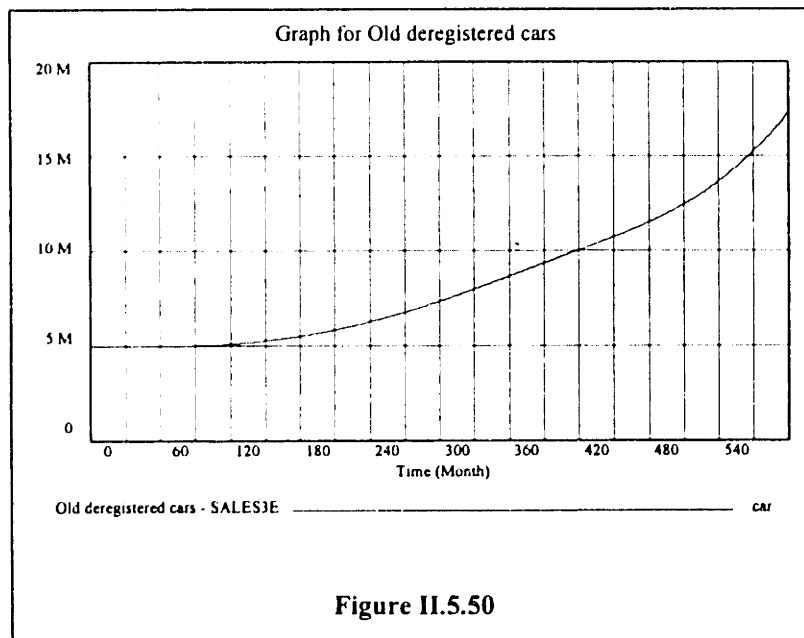
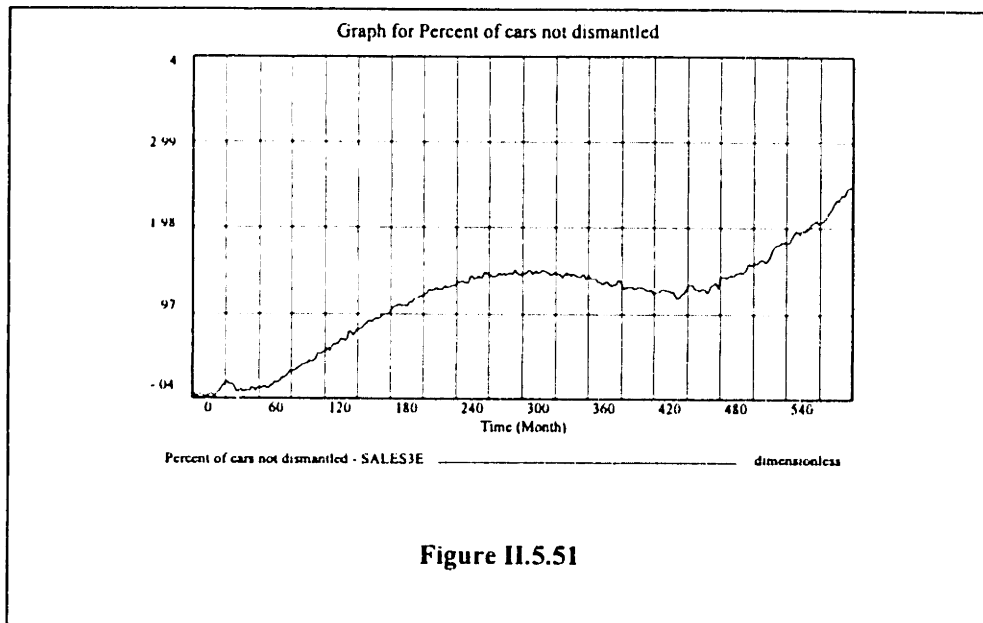
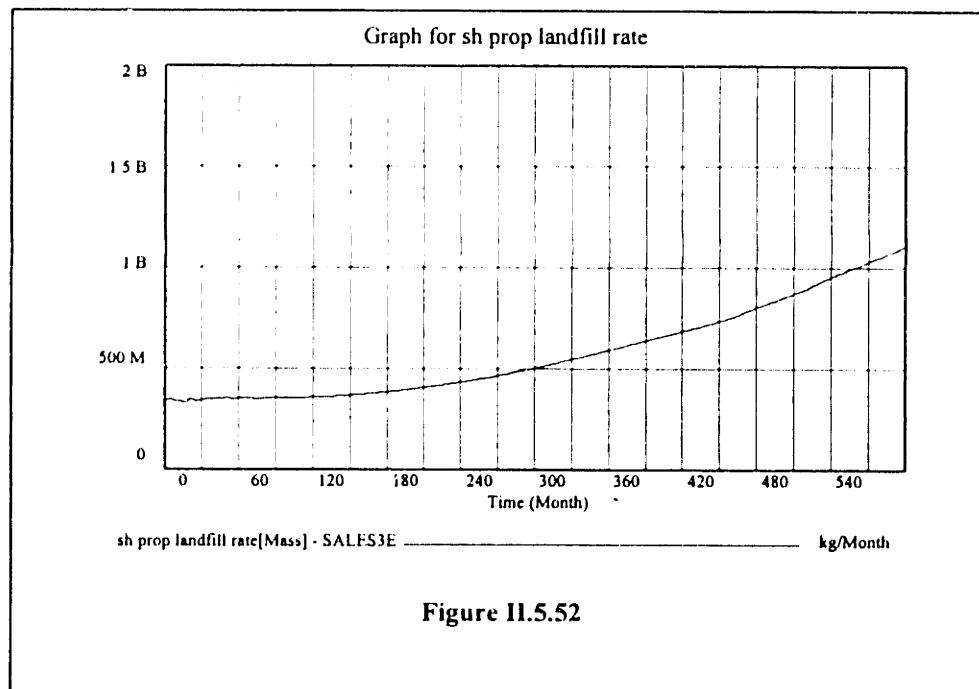


Figure II.5.50



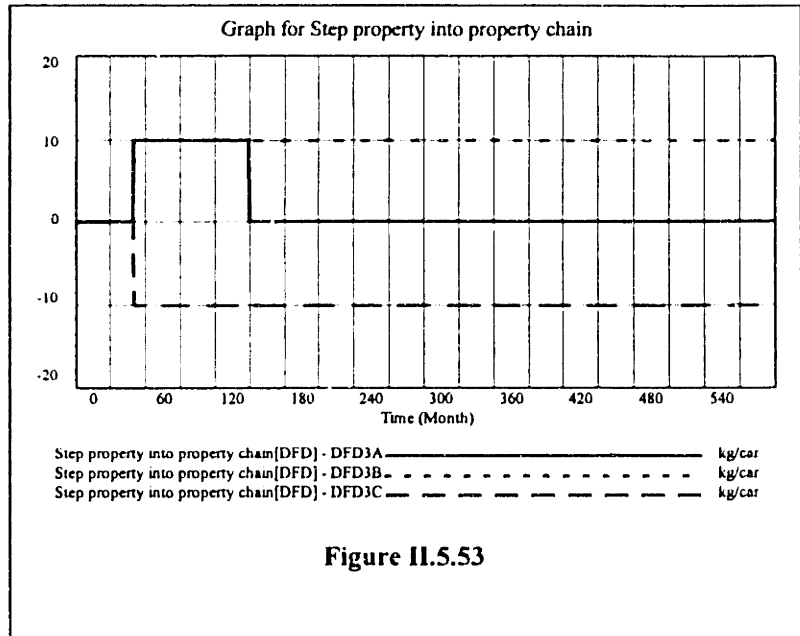
Although this does not influence the ASR in percentage terms, it obviously increases in absolute figures (tons). Figure II.5.52 shows how the rate at which the system sends ASR to the landfills also increases exponentially.





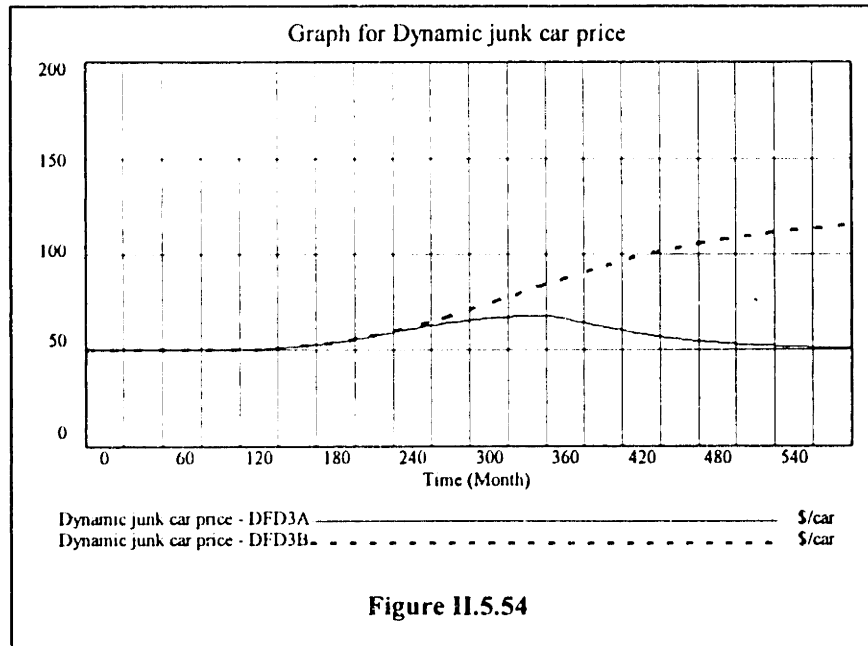
**4. Effect of Design for Disassembly (DFD)**

In scenarios DFD3A, DFD3B and DFD3C the level of design for disassembly at the point of sales has been changed. Again, the first 50 months correspond to the equilibrium condition, DFD3A correspond to the scenario “step-up & step-down”, DFD3B to “step-up” and DFD3C to “step-down”. The step in this case goes from 1 to 10. This tremendous increment was used only to amplify the effect of design for disassembly, although it is probably not an achievable



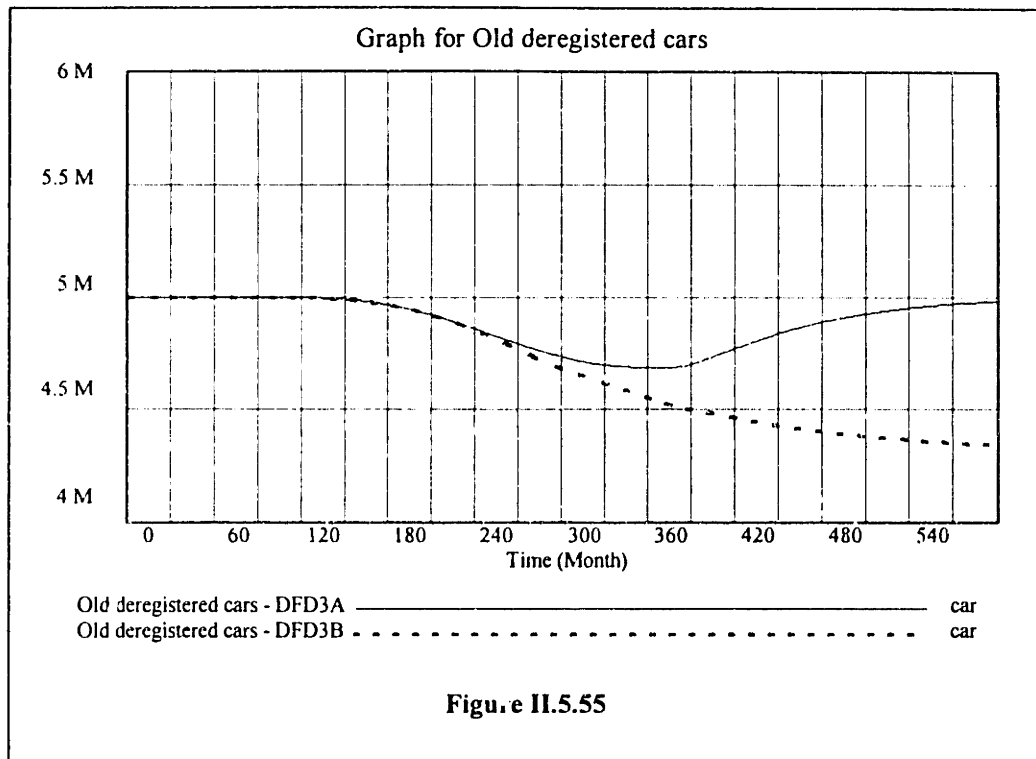
level. Figure II.5.53 shows the inputs used to create these runs.

Figure II.5.54 presents the effect on *junk car price* for the first two scenarios. Scrap price and hulks price see almost no changes. The rationale is simple; when cars have a better level of



DFD, dismantlers disassemble more of the car. Alternatively, for the same level of dismantling, they incur in lower costs. The cost savings have two components: less direct labor and less fixed cost, because they need less capacity to do the job.

This increment in



profitability results in higher prices to stimulate the flow of vehicles into the dismantlers' operations. Figure II.5.55 presents this effect on the stock of abandoned cars, which is modestly reduced.

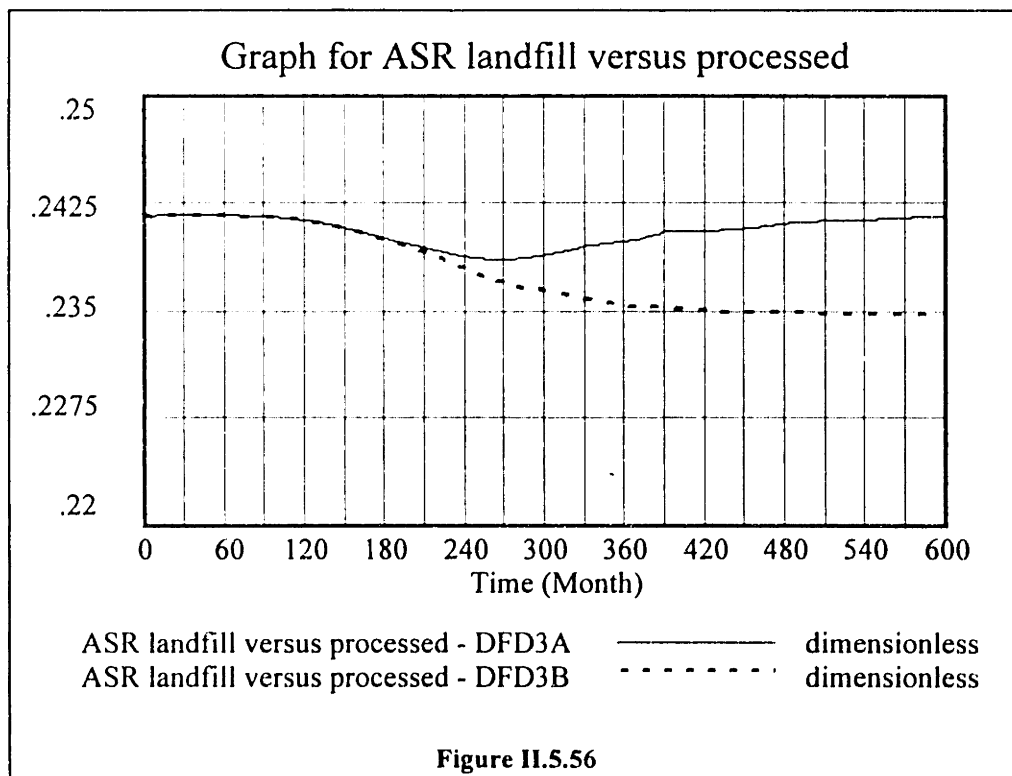


Figure II.5.56 shows the effect of DFD on the generation of ASR. Not surprisingly, the increase in DFD results in an effective reduction in ASR. This is because a significant portion of the additional dismantling results in recycled plastic. However, it is important to note that an increase of 10 times the level of DFD only produces a reduction in ASR from 24.16% (of the vehicle weight) to 23.5%.

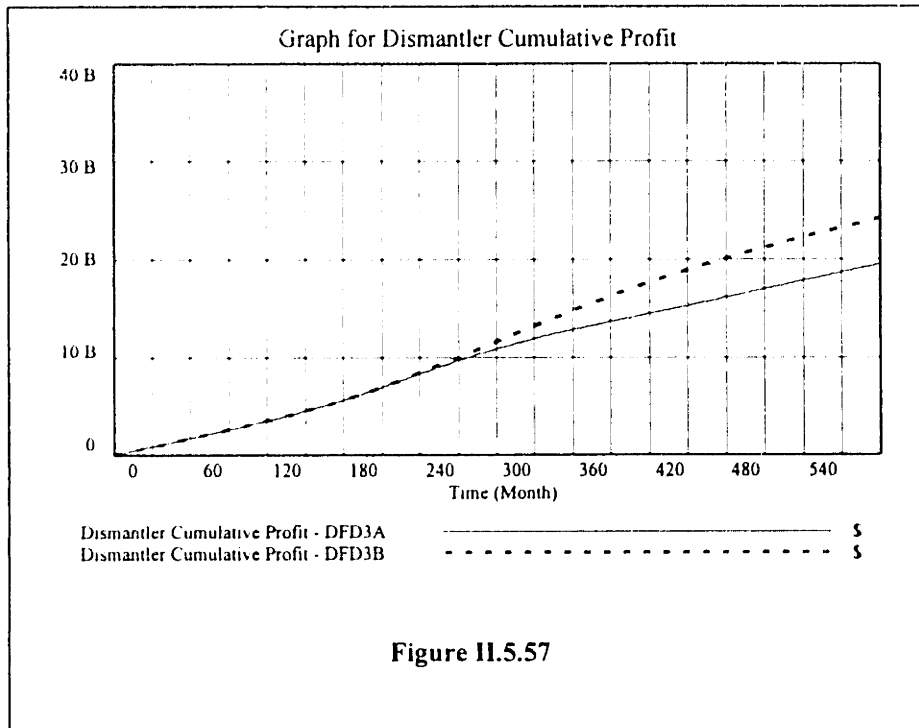


Figure II.5.57

On the other hand, figure II.5.57 presents the effect of DFD on dismantlers' cumulative profitability. One can observe a significant benefit; final cumulative profit goes from \$19.42 billion to \$24.16.

Figure II.5.58 shows the reduction in total mass going to the landfills when the DFD level is increased by a factor of ten. The effect is a reduction of less than 3%.

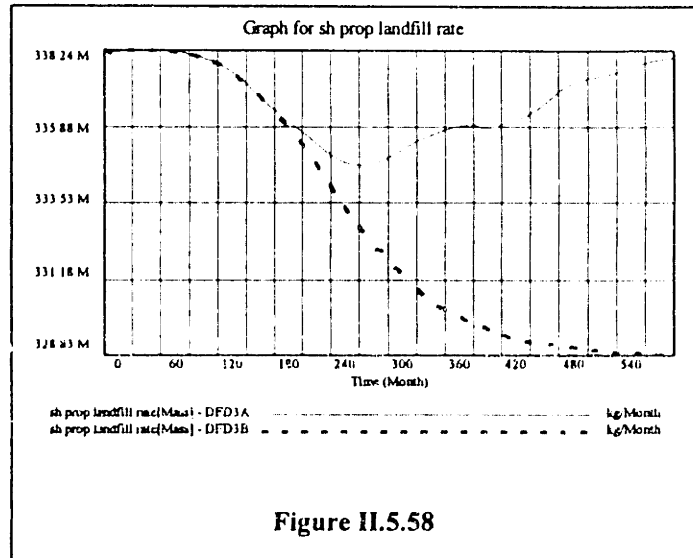


Figure II.5.58

Scenario DFD3C, where the level of design for disassembly is reduced (“step-down” scenario). Helps to illustrate why dismantlers are in the best position to benefit from design changes.

In this scenario, an extremely adverse situation is simulated. The drastic reduction in DFD is equivalent to a sharp increase in costs. Accordingly, dismantlers would reduce the *junk car* price as necessary. Figures II.5.59 and 60 show how dismantlers would be able to protect their profit to a certain extent by reducing the *junk car price* significantly.

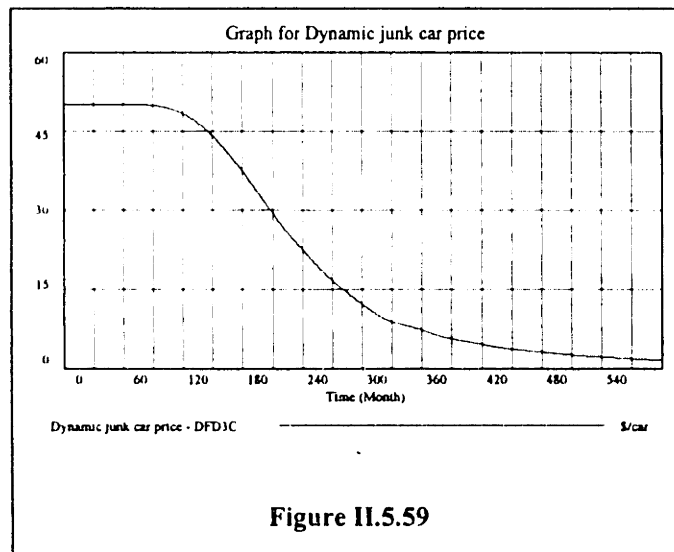


Figure II.5.59

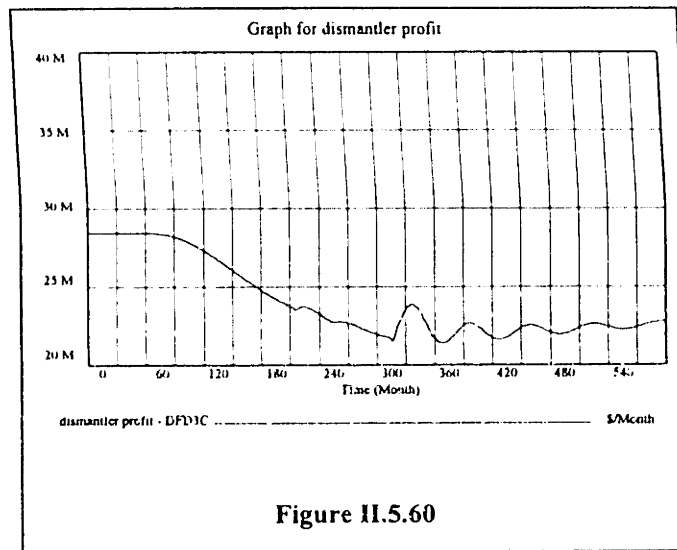


Figure II.5.60

As a result of the sharp decrease in the junk car price, the stock of abandoned cars increases dramatically, as presented in figure II.5.61. In fact, this accumulation is one of the reasons that allow dismantlers to decrease the junk car price so much. As explained, as more cars are abandoned, it would be easier for dismantlers to access vehicles for processing for a given price.

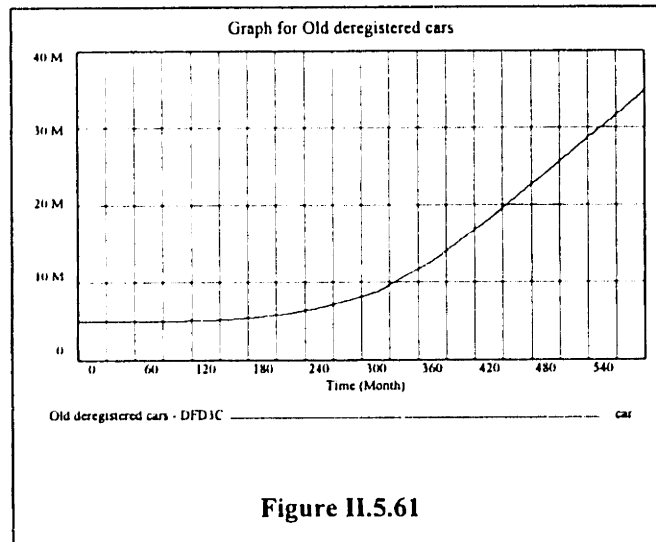
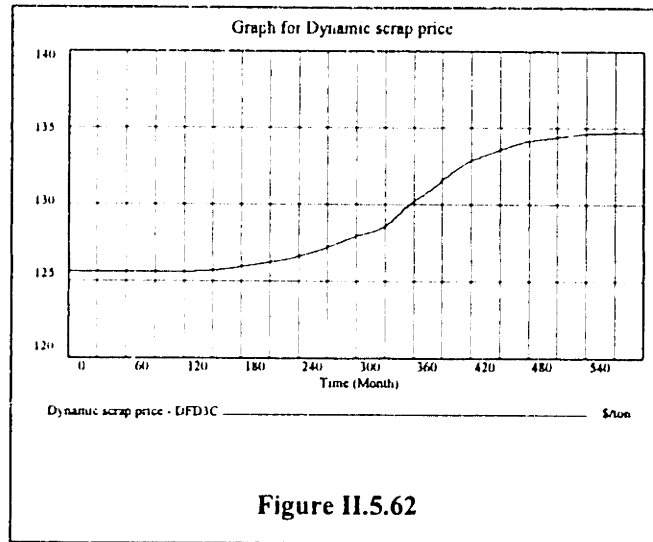


Figure II.5.61

During the period where dismantlers reduce their throughput, there is a relative shortage of scrap. Therefore the prices of hulks and scrap increase. Figure II.5.62 shows the behavior of the scrap price.

DFD3C is a very radical and unlikely, scenario. Disassembly costs increase beyond what can be reasonably expected. However, this scenario illustrates a major part of the industry dynamics. Disassembly cost is a dismantlers' issue. They do not control the type of design cars have, but once they get the vehicles, they "own" that design level. There is no mechanism for them to pass savings to consumers or to use them in incremental disassembly or recycling. On the other hand, the *junk car price* mechanism allows them to transfer additional disassembly costs.



It is easy to generalize that incremental benefits associated with prices of materials or reductions in labor costs would not be transferred to consumers or to the environment. Dismantlers would capitalize these benefits to achieve their own monetary objectives.

5. Simultaneous Changes in *x*-variables

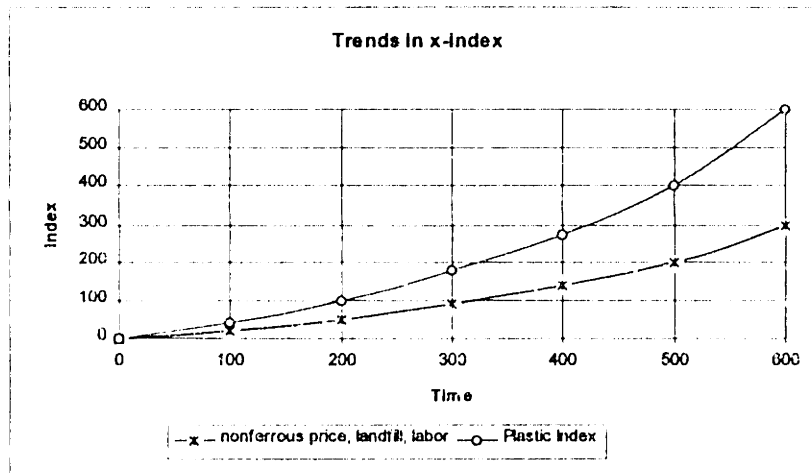
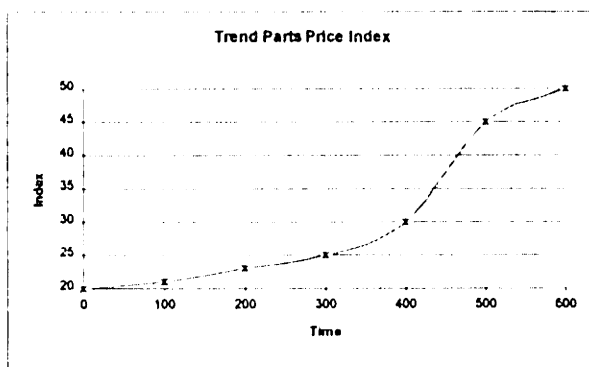


Figure II.5.63

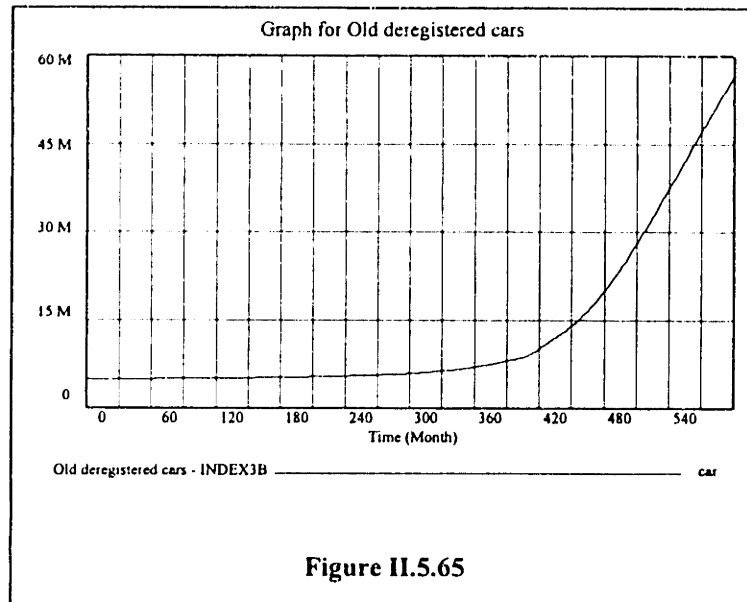
Scenario INDEX3B was created to test the robustness of the automobile recycling industry to changes in the disassembly drivers. In this scenario 5 out of the 8 *x*-variables were changed in a continuous manner. The level of Design for Disassembly, the Ferrous and the Plastic content were kept constant because they represent policy decisions, and the objective of this simulation is to test the system against exogenous changes. In all cases the drivers of disassembly were changed by changing the corresponding *index*-variable. The level of nonferrous price, and the level of landfill and labor costs were increased by 200% in the 50 years considered as figure II.5.63 illustrates. Plastic prices were increased by 600% under the optimistic assumption that the establishment of an active market for recycled plastics is likely to happen.



In the case of the *Parts price index* the increment is less radical because the market for parts is considered to be mature. The input used in this case is presented in figure II.5.64.

Figure II.5.64

As shown in figure II.5.65 these changes in prices and costs would be enough for the system to present serious problems. By month 360 the stock of cars deregistered starts increasing in a dramatic manner. Note that in this scenario the initial level corresponds to the equilibrium described in previous sections. Changes, however, are introduced starting from the first month of the simulation.



Although the ASR in percentage terms does not show major swings, the *percent of cars not dismantled* increases to more than 30%. One can expect these type of results from a decrease in the price of the junk cars as a result of a less profitable dismantling practice. Figures II.5.66 to 69 illustrate this situation.

Starting in month 370 the *scrap fraction* starts dropping rapidly as a consequence of the reduction in processing rates of dismantlers and shredders. The *autoscrap price* increase causes the *hulk price* to increase as well, however this corrective mechanism is not strong enough to prevent the accumulation of *deregistered cars* described above. In fact, the analysis of the system behavior after month 370 should be performed with a grain of salt. The stock of *abandoned cars* reaches 7 million in month 370 and afterwards grows rapidly. Government intervention is clearly a potential risk at that time.



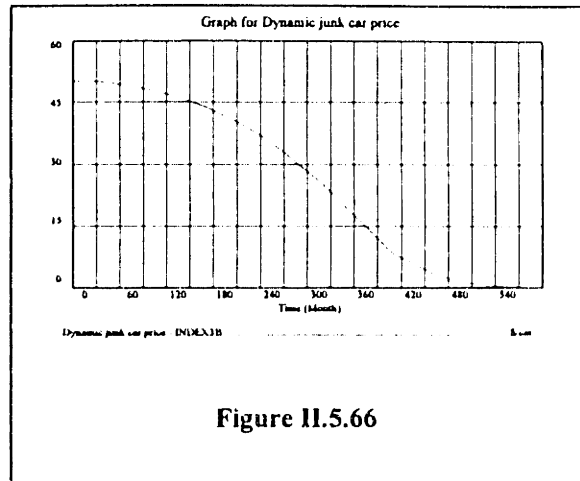


Figure II.5.66

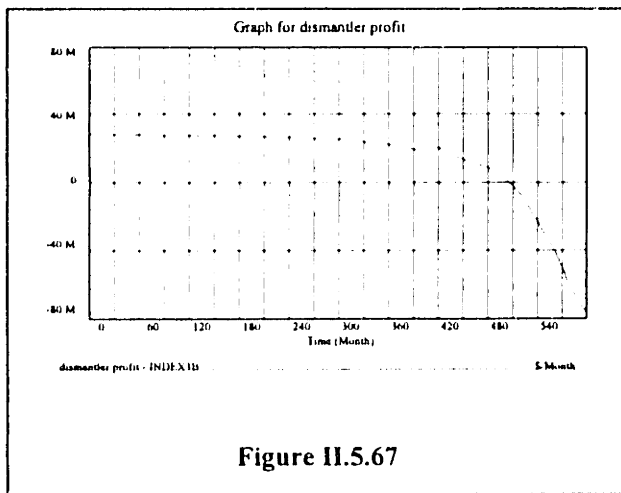


Figure II.5.67

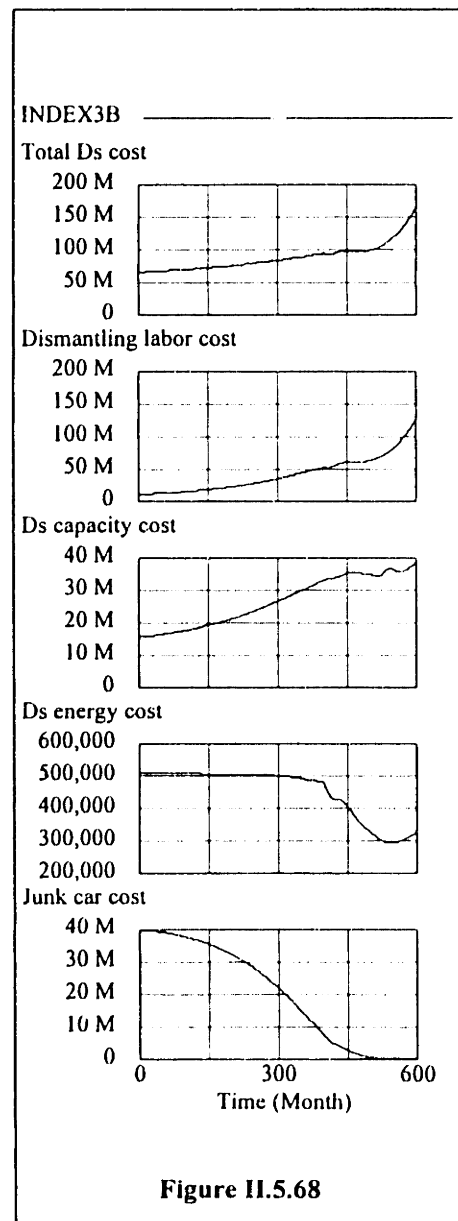
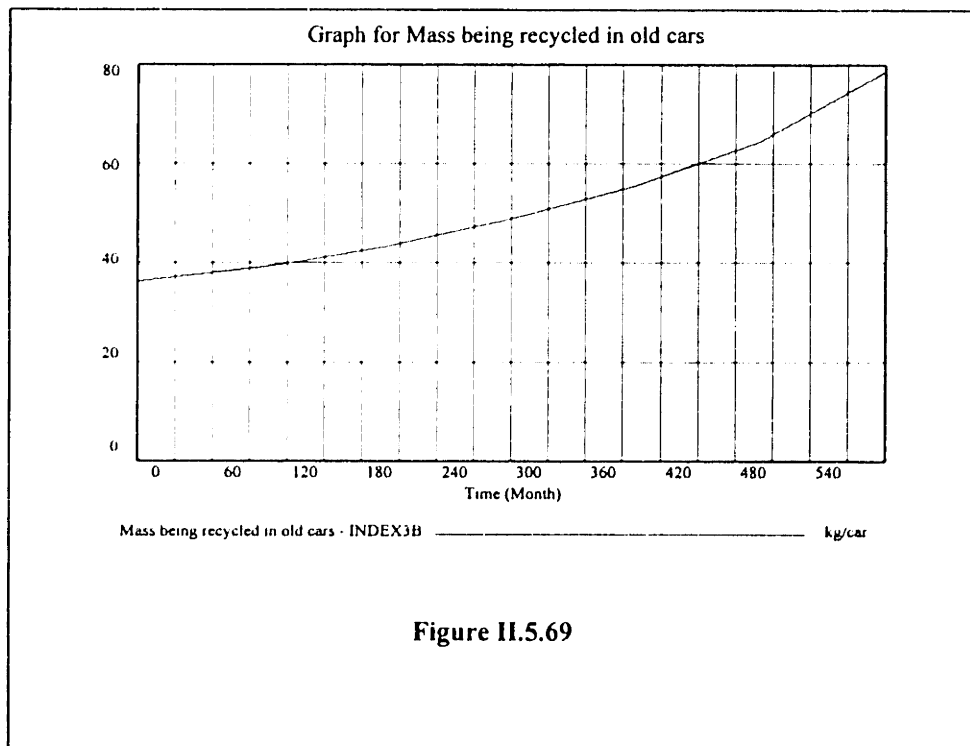


Figure II.5.68

It is interesting to note that even under these unfavorable conditions -- escalating dismantling and landfill costs -- dismantlers would disassemble more. Figure II.5.69 shows that even though the whole car is lighter, the amount of material dismantled has increased. The rationale is that, dismantlers, observing their profitability reducing, decide to go deeper into the car structure to recover valuable material. Unfortunately, the incremental dismantling is done in pursuit of the non-ferrous metals, while most of the additional plastic would remain in the hulk.



## 6. An Overview of Policy Decisions

In this section a scenario is created combining changes in policy decisions. Simulations TREND3A, TREND3B, and TREND3C are partial simulations that run from month 0 to 200, from month 200 to 400 and from month 400 to 600, respectively. Changes in policy variables are introduced, therefore in months 200 and 400 according to the following table.

CONSTANT TARGET PROPERTY	TREND3A (months 0-200)	TREND3B (months 200-400)	TREND3C (months 400-600)
[MASS] (kg/vehicle)	1,400	1,200	1,100
[FERROUS] (kg/vehicle)	980	610	510
[NON-FERROUS] (kg/vehicle)	70	140	190
[PLASTICS] (kg/vehicle)	350	450	500
[DFD]	1	2	3

To create this scenario the following changes have to be made:

- The *Switch to allow changes in property into chain* must be 1.
- The *Switch to allow changes in property into chain* must be 1.
- The *Switch to develop constant property cars* must be 1.
- The *Switch to use historical trends* must be 1.
- *Variable prop into development [X]* has to be modified taking out the “step” part.

It should read, for example in the case of the vehicle weight:

```
variable prop into development[Mass]= IF THEN ELSE(Switch to use
prop trend = 1, weight trend, CONSTANT TARGET PROP[Mass])
```

- Under the Dataset/Simulation window, the variable *FINAL TIME* has to be modified for each partial run, using the “constants” button.
- Under the same window, the *CONSTANT PROPERTY[X]* variables have to be modified according to the policy decisions.
- Each partial simulation should be based on the previous one and the “Resume” option should be selected.

Figure II.5.70 illustrates the average weight of cars being sold under these conditions.

As figure II.5.71 shows, these policies cause the junk car price to drop. Figure II.5.70 presents a similar behavior for the hulk and scrap prices. The underlying reason is that as less steel is used to produce cars, the relative value of the scrap decreases.

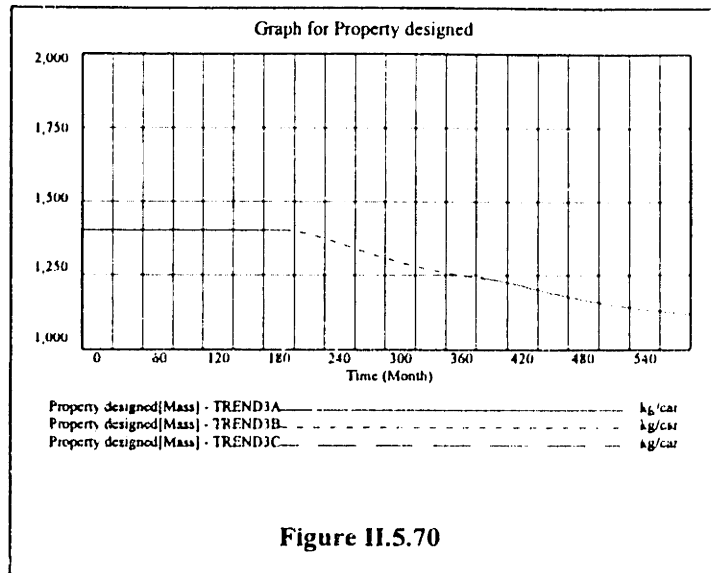


Figure II.5.70

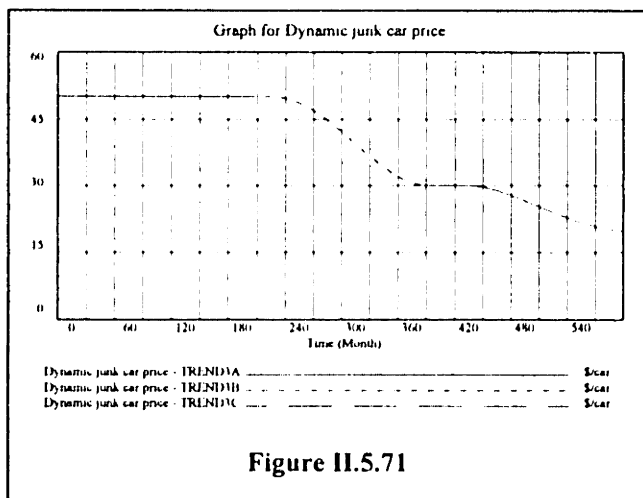


Figure II.5.71

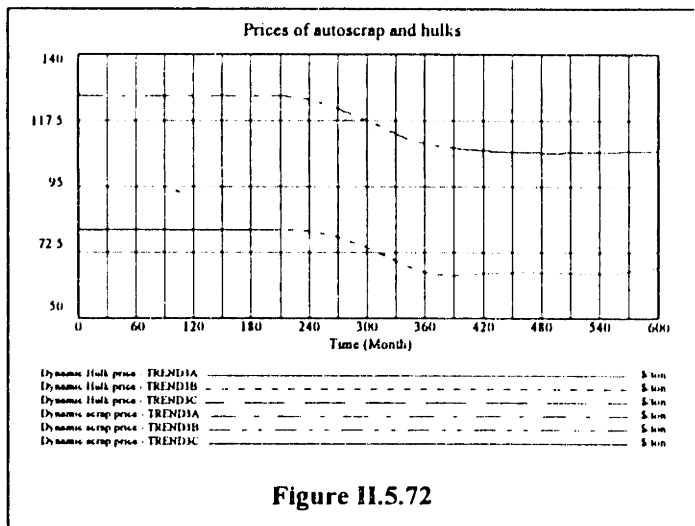


Figure II.5.72

One of the consequences of this drop in prices is that cars accumulate in the deregistered stock, as figure II.5.73 shows.

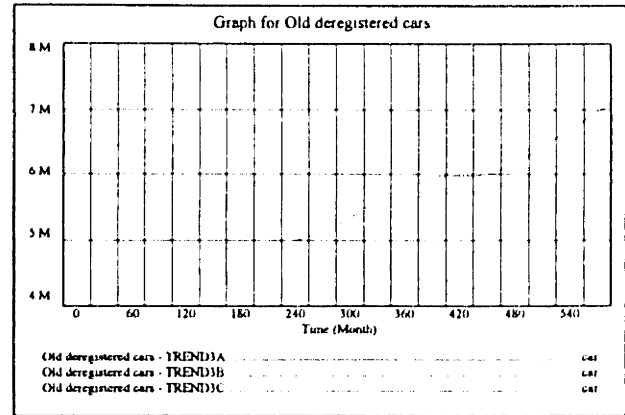


Figure II.5.73

In addition to the accumulation of vehicles waiting to be processed, there is a significant increase in the generation of ASR. Figure II.5.74 indicates that almost 34% of the car's mass would end up in the landfills under these conditions.

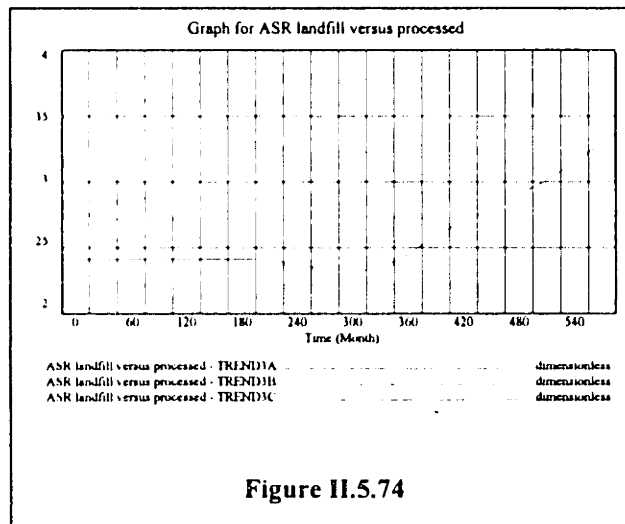


Figure II.5.74

**7. Integrating Changes in *x*-variables, Policy Decisions and GDP**

The simultaneous changes in drivers of dismantling (*x*-variables) explained in section II.5 are used when creating the scenario

ETREN3C. In addition, it is assumed that the economy grows at a constant 2.5% per annum. Finally, extrapolation of historical trends in policy decision is considered as shown in figures II.5.75 to 79.

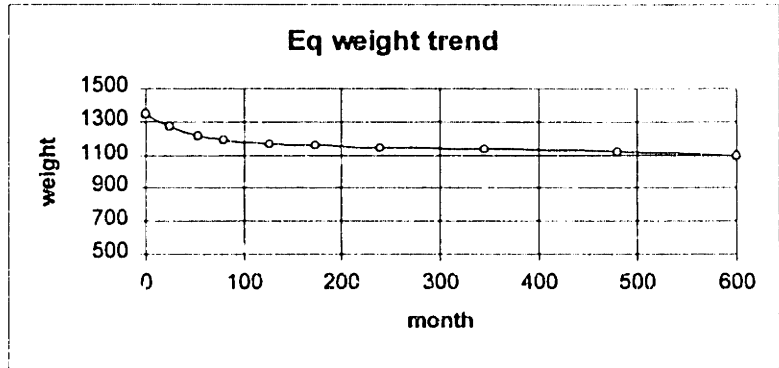


Figure II.5.75

In figure II.5.75 one can observe that

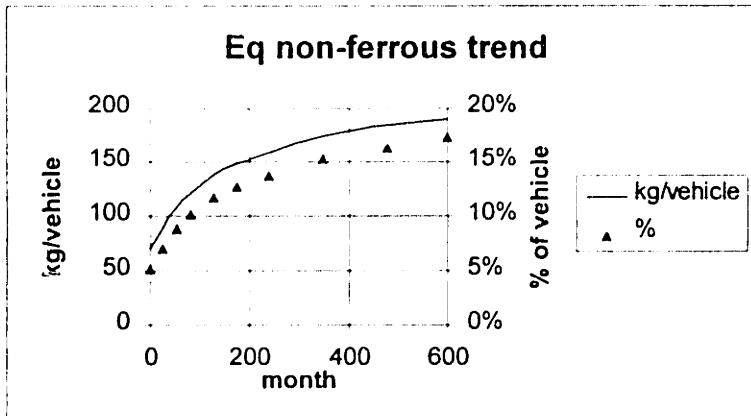


Figure II.5.76

the total weight of the vehicle is reduced from 1,400 kg/car to 1,100.

Figure II.5.76 shows that that the nonferrous content changes from 5% to almost 17%.

The plastic content goes from 25% to 35%, while the ferrous portion is

reduced from 70% to approximately 48%. The level of Design for Disassembly is increased from 1 to 3.3.

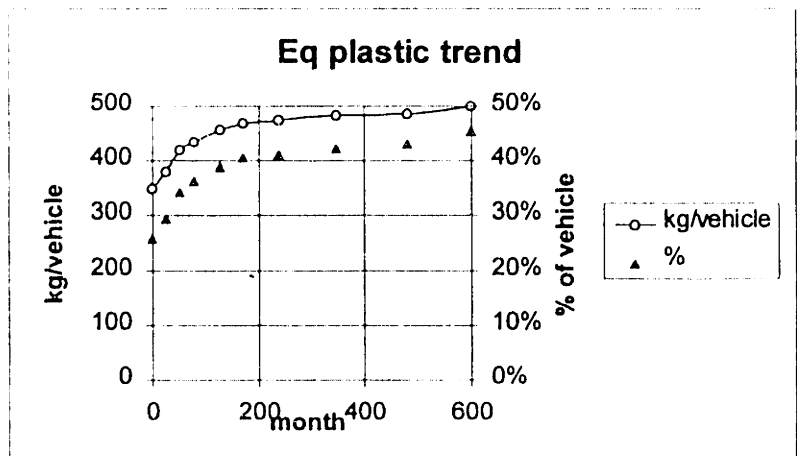


Figure II.5.77

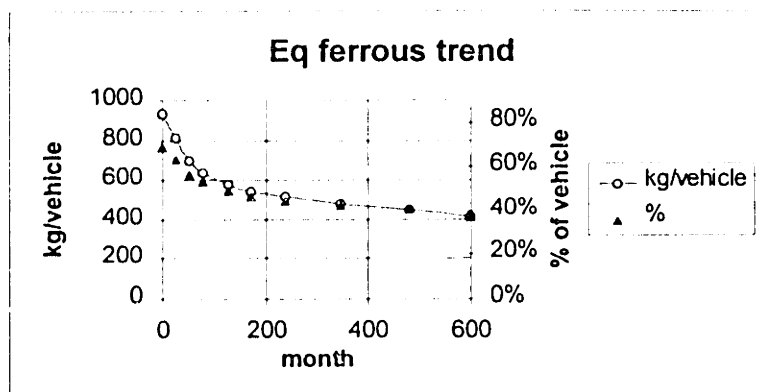


Figure I.5.78

As mentioned, in this scenario sales are triggered by changes in GDP, which is assumed to increase continuously at 2.5% per year. The scenario includes the 20% random component explained in section II.5.2.

This scenario is of interest because it integrates most of the changes discussed so far. Exogenous prices and costs (*x-variables*), growth in GDP (and therefore *sales*), and policy decisions are all considered in this run.

The inputs used in this scenario are the author's extrapolation of historical trends for illustration purposes. They do not represent, by any means, a forecast. Rather, they are possible and interesting conditions to test the system behavior.

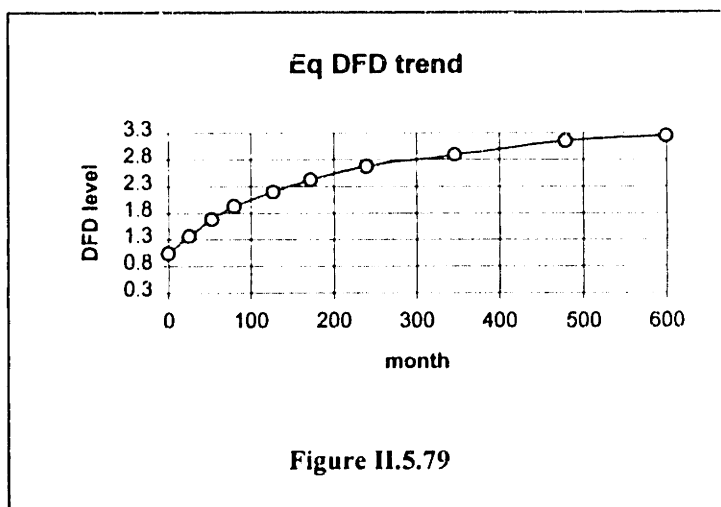


Figure II.5.79

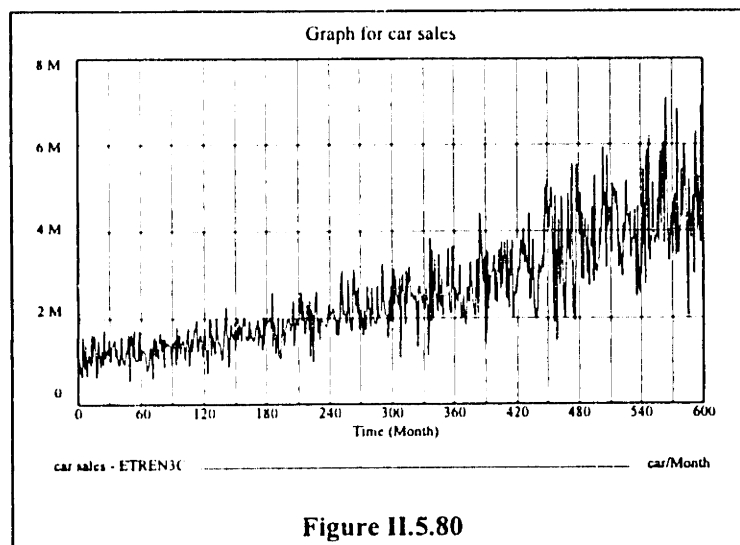
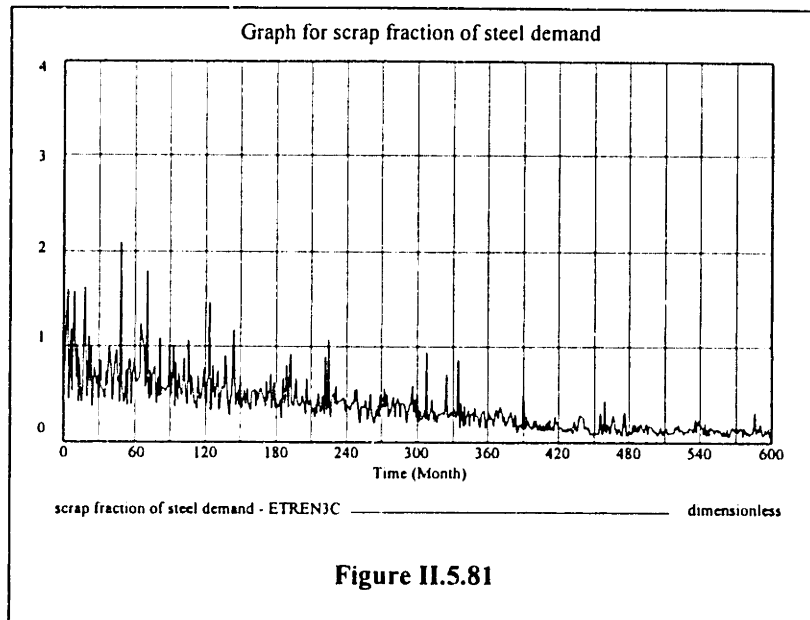


Figure II.5.80

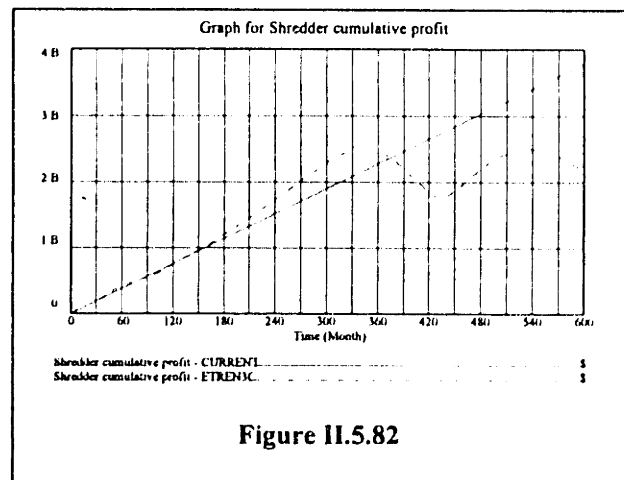
In section II.5.5 the use of these *x-variables* put the system under major pressure. In section II.5.6 similar policy decisions were, as well, enough to put the whole industry at risk. However, in section II.5.3, it was shown that an increasing sales rate results in increasing profit levels for both dismantlers and shredders. In this scenario the merging of these three

conditions are studied.

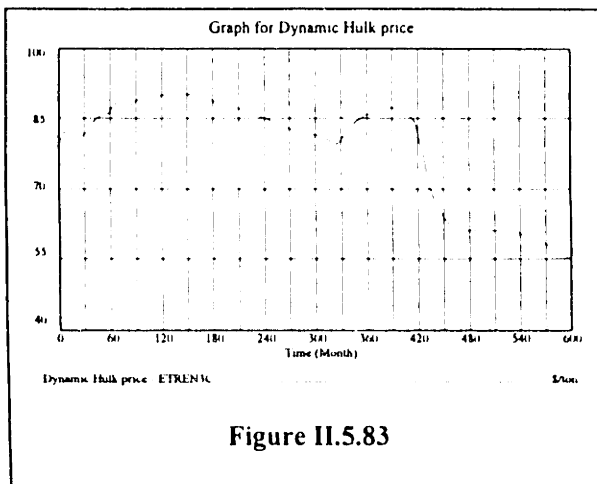


As presented in figure II.5.82, shredders' profitability is better than in the equilibrium run until month 180. During this initial period shredders are capable of sustaining a healthy operation based on several factors. They keep the *hulk price* from increasing drastically. They benefit from the incremental revenue associated with the additional non-ferrous material in the hulks. Shredders also capitalize a reduction in fixed costs because they can reduce the size of the operation, relatively speaking, given that hulks weigh less. Finally, the autocrap price reaches almost \$150/ton.

However, they are confronted with a rapidly increasing landfill cost, which goes from \$7.5 million per month at the start of the simulation, to more than \$83 million per month at the end.







The hulk price shows an upward behavior between months 330 and 390 driven by the effect of low utilization rates. The weight reduction causes shredders to have over-capacity and they try to encourage dismantlers to sell more hulks to utilize their capacity. This temporary increase in *hulks price* hurts the profitability during that period significantly.

Once the capacity adjustments have been done, the shredders' operation is not healthy and again they will try pass their incremental costs to dismantlers by reducing the hulk price further. The combination of these two variables (*shredders' profit* and *hulk price*) introduces an oscillatory mode into the system.

The story is somewhat different in the case of dismantlers. Their profitability collapses as a result of the reduction in *hulk price*, and the increase in costs. They have to undertake more recycling per car, but at a higher variable and fixed cost. The figure II.5.84 illustrates this situation.

As a result of poor economic performance, they have to reduce the price of the junk cars to zero with the corresponding accumulation of abandoned cars. In month 330, more than 10% of the cars being retired are not brought to the recycling industry. This represents an alarming accumulation rate because the retirement has increased to almost 1.7 million cars per month due to the increase in sales.

Note that any type of analysis after month 330 is difficult because the industry as a whole is about to collapse.

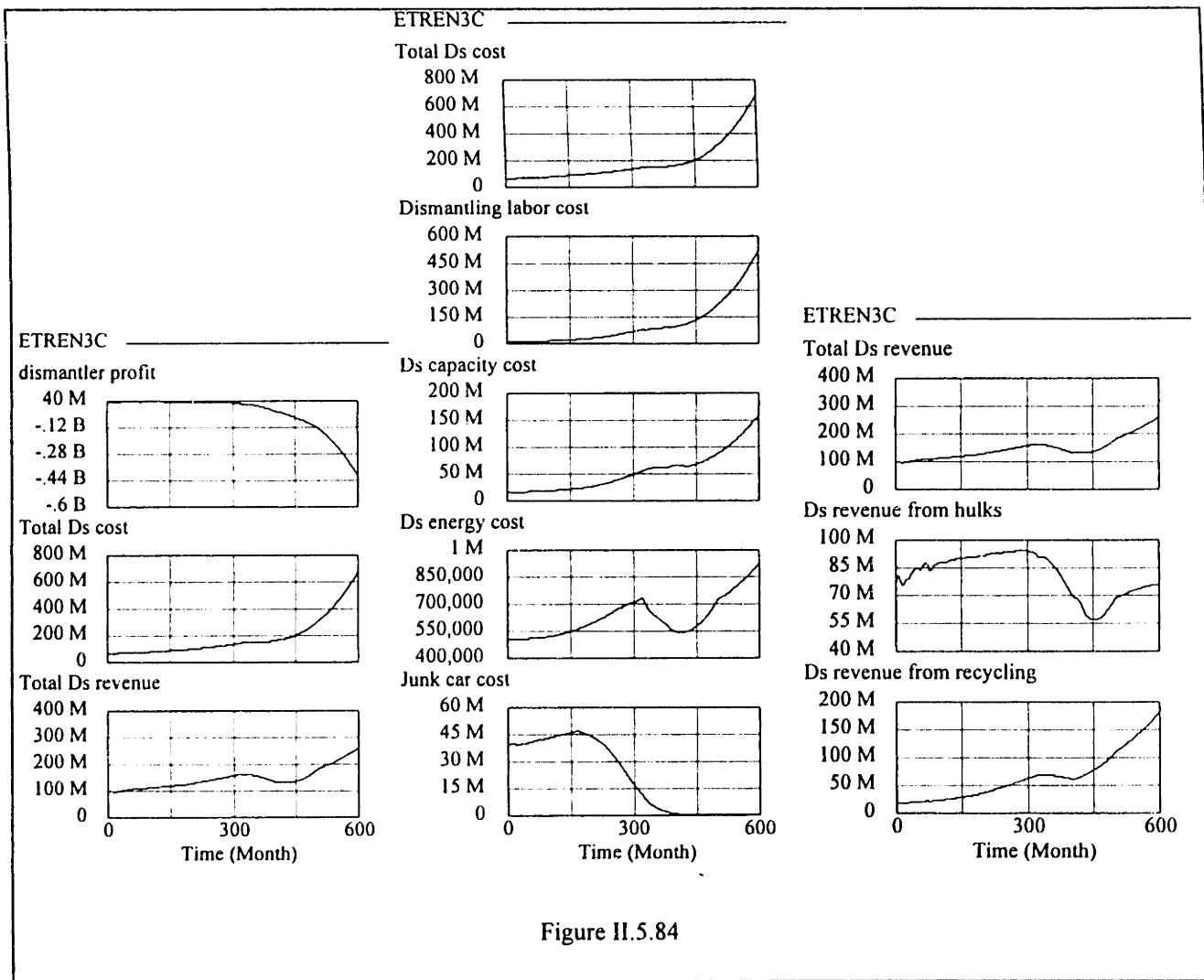


Figure II.5.84

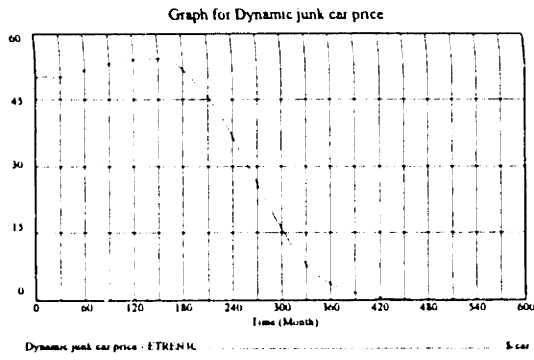


Figure II.5.85

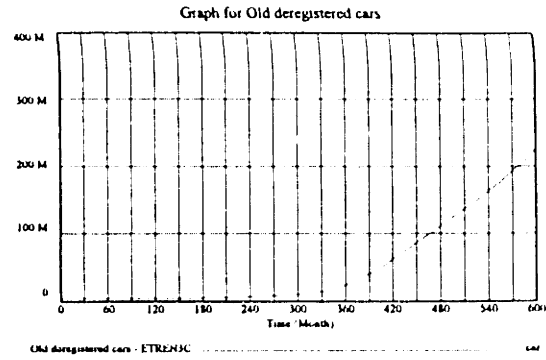


Figure II.5.86

Finally, the generation of ASR increases as a percent of the total car weight because the car has significantly more non-metal materials.

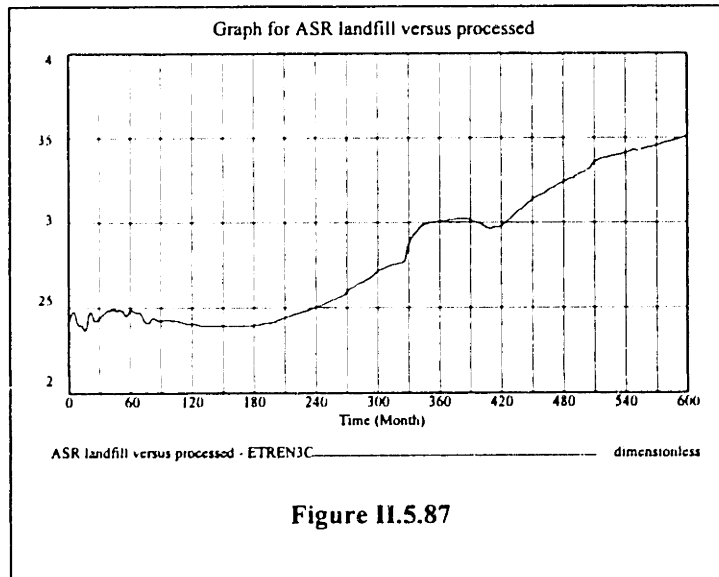


Figure II.5.87

Under these conditions it does not seem that the automobile recycling infrastructure would be able to continue operations under the current economic-driven structure.

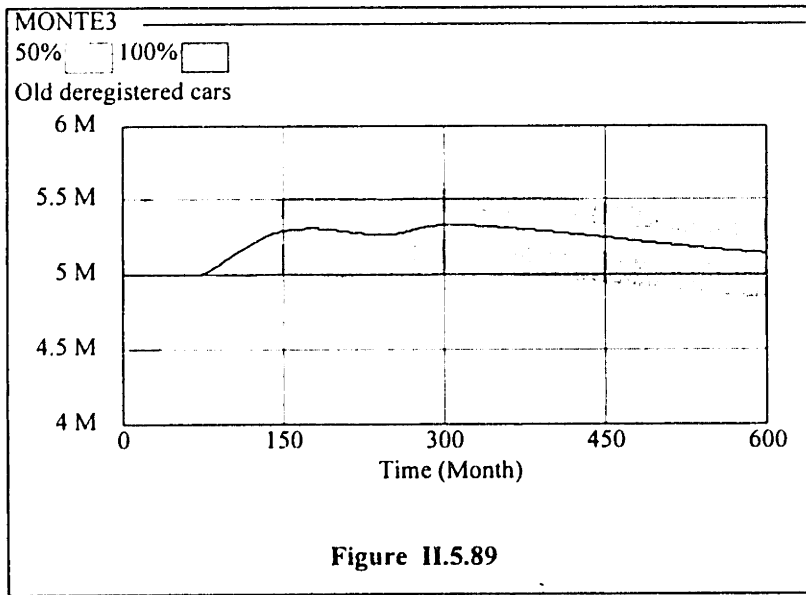
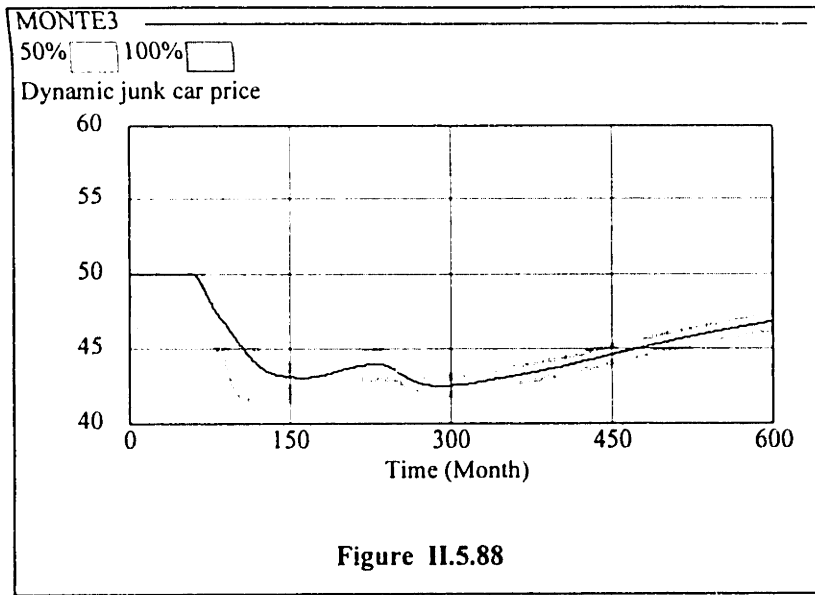
### 8. Monte Carlo Simulation on *retirement fractions*

In this section a Monte Carlo simulation is performed to study the effect of uncertainty in the *retirement fraction* variables. The following table presents the values used in the previous simulations and the distribution intervals used in the Monte Carlo simulation. Due to lack of better information, the *retirement fractions* were defined as having a uniform distribution centered in the values reported by Libertiny [Libertiny 1993]. The value ranges are defined within a variation from the base values of +20 and -20%. The following table presents the values used in this sensitivity study.

Age cohort	Retirement fraction based on Libertiny's estimates	Minimum used during the MC simulation	Maximum used during the MC simulation
0 to 3 years old	0.01500	0.0120	0.0180
3 to 6 years old	0.06497	0.0520	0.0780
6 to 9 years old	0.14976	0.1198	0.1797
9 to 12 years old	0.36489	0.2919	0.4379
12 to 15 years old	0.57960	0.4637	0.6955
15 to 18 years old	0.79810	0.6382	0.9574
18 to 21 years old	1.00000	1.0000	1.0000

The Monte Carlo simulation presented in the following figures is based on the basic scenario called MONTE3. This scenario corresponds to the scenario PLAST3A discussed in detail at the beginning of this chapter. A sudden increase in the content of plastic is introduced in month 50 followed by a re-establishment of the previous level of plastic usage in month 150.

Figures II.5.86 and 87 present the 50% and 100% confidence intervals for the variables *junk car price* and *old deregistered cars*. These graphs demonstrate that the model is structurally robust. Relatively large uncertainty on the retirement fractions does not seem to produce major deviations from the discussed behavior.



## Chapter II.6

### Analysis From Historical Conditions

In this chapter a brief overview of the structural behavior of the system is presented using the historical conditions described in chapter II.4. It is important to recognize that this scenario is not completely calibrated. For example, *sales* are generated assuming that the initial stage, although based on historical values, is one that corresponds to the equilibrium *number of cars on the road*. In other words, if *GDP* is not changed, the sales rate would remain constant.

The historical conditions here presented refer to the actual values of almost all of the stocks in the model. Stocks in the *Aging* sector and every cohort in the *Main* sector are initialized using values based on reported trends. The initial stock levels in the *Properties* sector are also based on the bibliographic research conducted [AAMA Facts and Figures 1994].

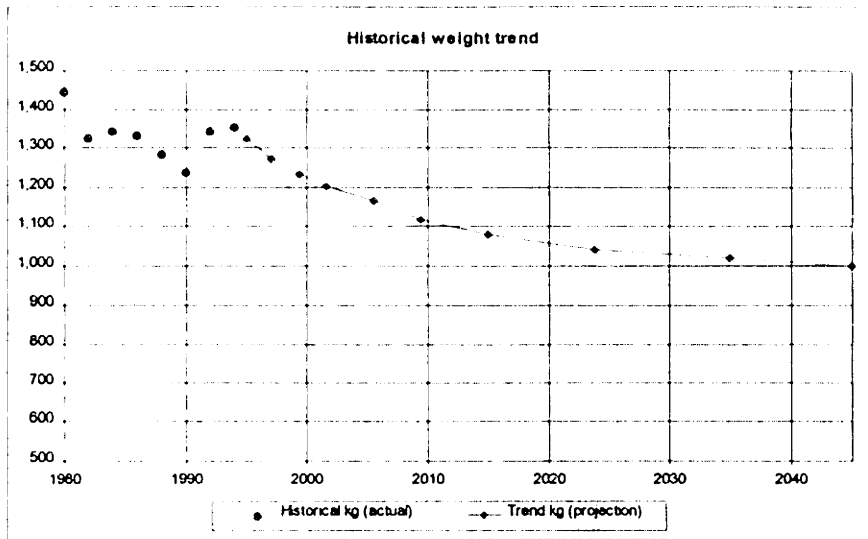


Figure II.6.1

Figures II.6.1 to 4 present the historical values of the policy variables and the trends used to create this simulation: HISTO3A. It is assumed that the vehicle weight will be reduced to 1,000 kilograms and that the plastic component will reach 37% of the total vehicle weight.

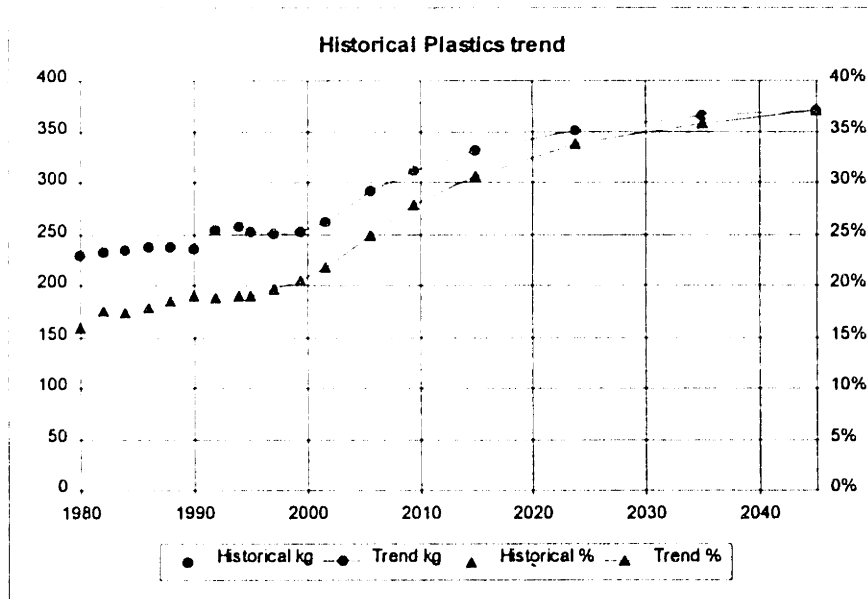


Figure II.6.2

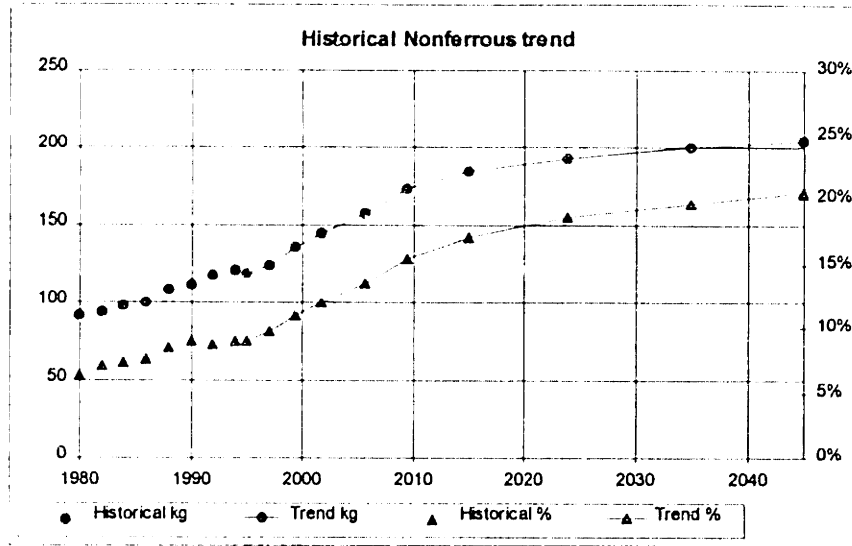


Figure II.6.3

The non-ferrous composition reaches 20% of the vehicle weight, while the ferrous fraction goes down from 70% to 43%.

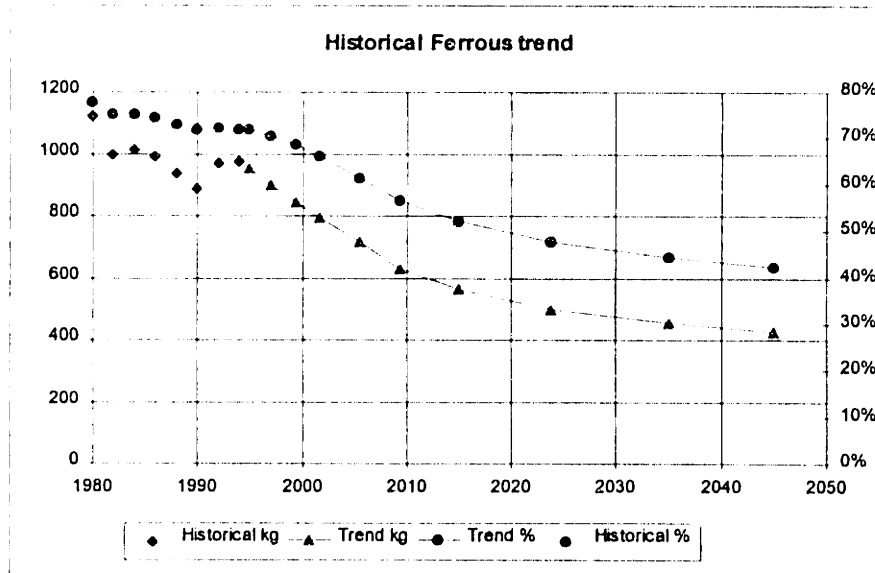
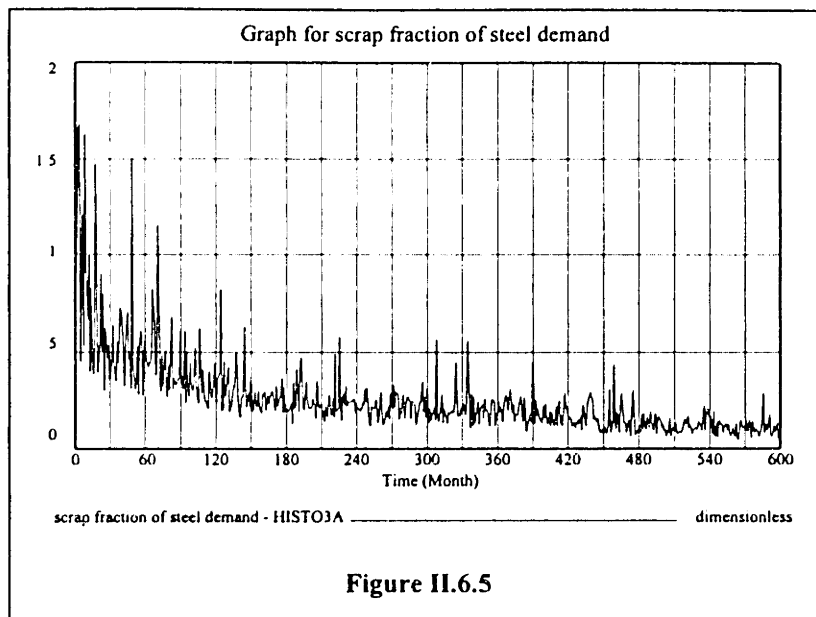


Figure II.6.4

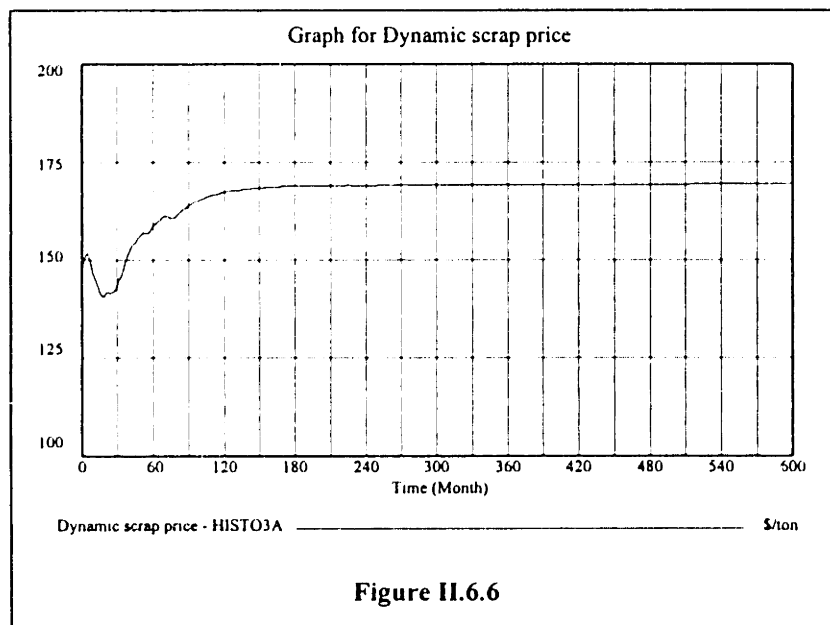


Following is the condition of the most relevant switches and variables to create this scenario.

- *Switch to turn to equilibrium level of stocks = 0*
- *Switch to develop constant property vehicles = 0*
- *Switch to use property trend = 1*
- *Switch to use historical property trend = 1*
- *Switch to change GDP = 1*
- *Use of the random escalator in variable GDP*
- *Switch to have long-term growth = 1*
- *Switch to have equilibrium levels in property stocks = 0*
- *Switch to dynamically calculate properties = 1*
- *Switch to allowing changes into prop chain = 1*
- *Switch to use dynamic sales = 1*



As discussed in the previous chapter, a continuously growing economy results in a continuous deterioration of the *scrap fraction*. Figure II.6.5 illustrates this pattern.



As a consequence, the *scrap price* increases to the level where complete substitution is likely to happen. The initial reduction in the scrap price might be a calibration error, or the result caused by the initial conditions which include historical records for the *scrap price*. They are the market values during the summer of 1995. In any case, the long-run *scrap price* is close to \$170 per ton.

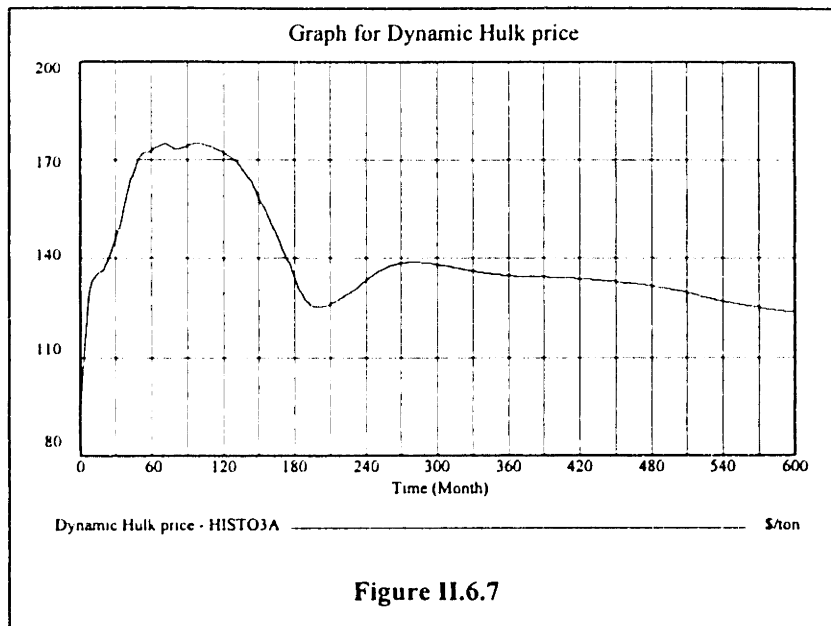


Figure II.6.7

The *hulk price* increases sharply until month 100 due to the effect of utilization rates on *hulk price*. It happens that there is extra-capacity in the system and shredders try to encourage incremental flows of hulks into their operations. Due to the time delays in capacity acquisition this effect swings back after month 120 and contributes to the reduction in *hulk price*. The gradual reduction of *hulk price* after month 300 is caused by the increase in operation costs.

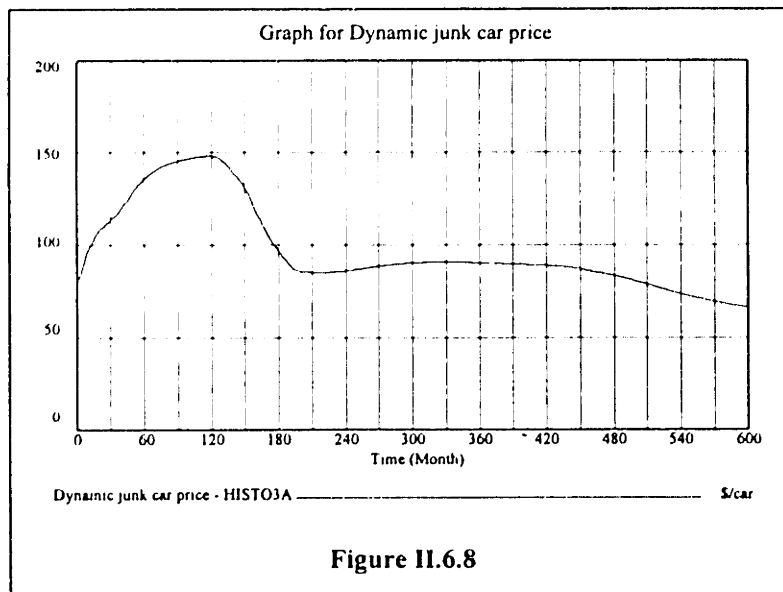
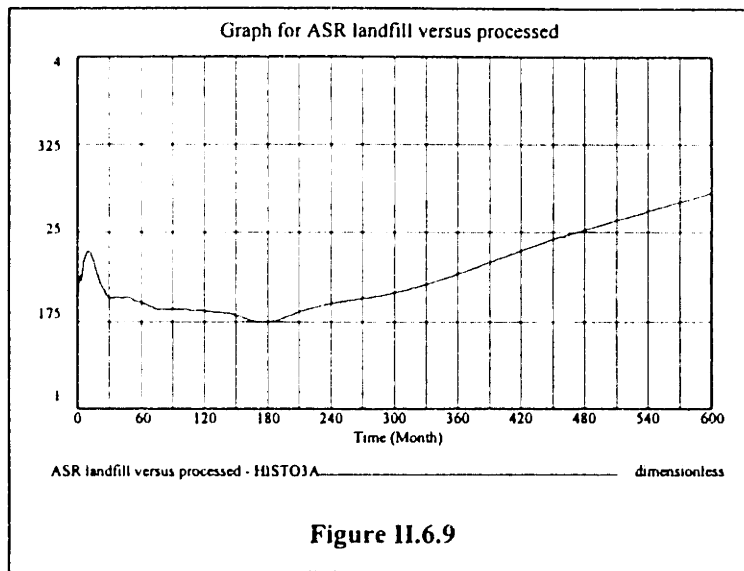


Figure II.6.8

There is a high level of parallelism between the *hulk price* and the *junk car price* in this scenario, as shown in figures II.6.7 and 8. The industry reflects its operational costs efficiently.



However, figure II.6.9 illustrates how the ASR generation as a percent of the total vehicle weight deteriorates after month 180. This figure makes an additional point. It suggests that the initial level of ASR might be below what is frequently considered the industry standard: 25%. This is not completely surprising because that number is generally estimated, using a one-to-one relationship, based on the vehicle plastic composition. It ignores the effect of dismantling.

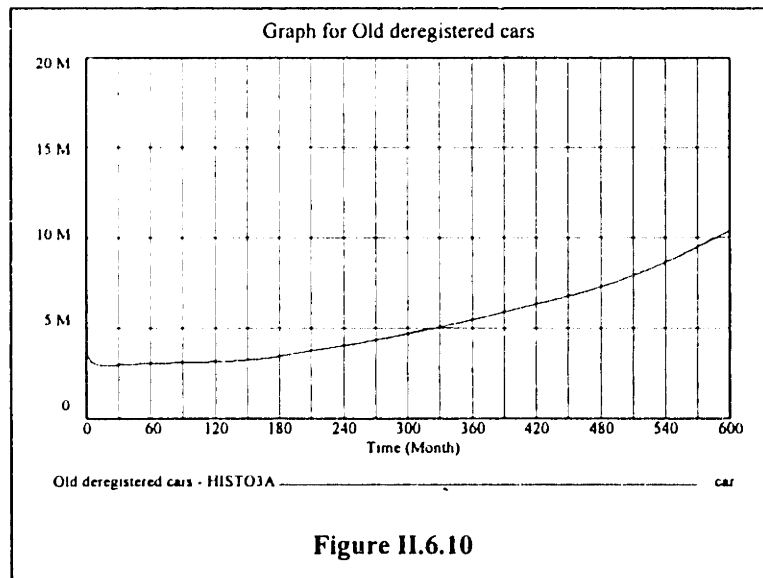


Figure II.6.10 shows that under these conditions the stock *old deregistered cars* increases continuously. In the short term, this growing trend is modest, but is accelerated as time elapses.

To illustrate the impact of exogenous prices in the system behavior, one final scenario is discussed: HISTO3B. This run is based on the previous one but incorporates the trends in exogenous prices discussed in chapter II.5. For that purpose the *Switch to use trend in indexes* is set equal to 1.

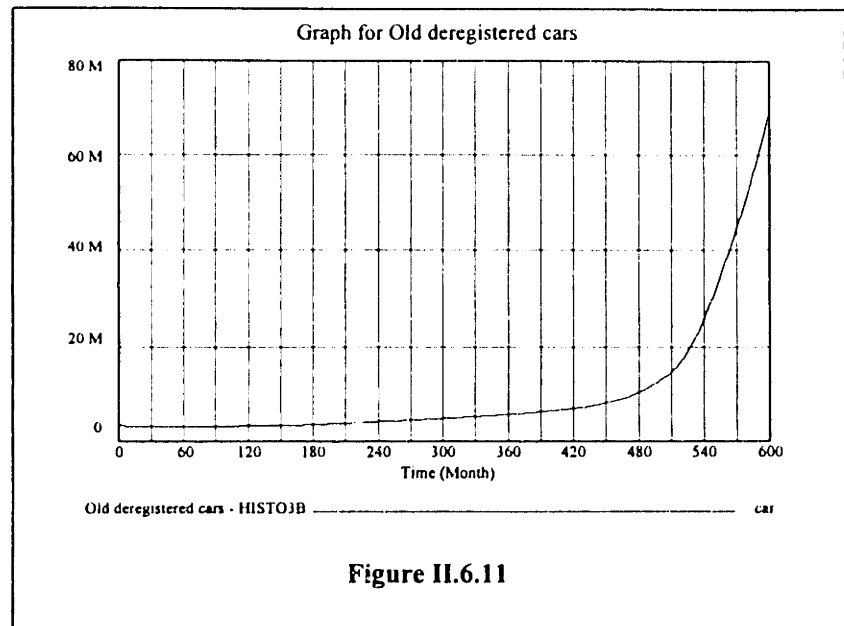


Figure II.6.11

Figure II.6.11 shows again that the industry will see major problems if the exogenous prices follow the suggested trends. The accumulation of abandoned cars gets out of control in the long-run. However, it points out something more interesting, this potential collapse would be very difficult to foresee if one does not look far into the future. Consider for example, figure II.6.12, which is the same as II.6.11 but takes into consideration half the time horizon. If one looks at this trend it would not be obvious that the risks for the whole automobile recycling industry are significant.

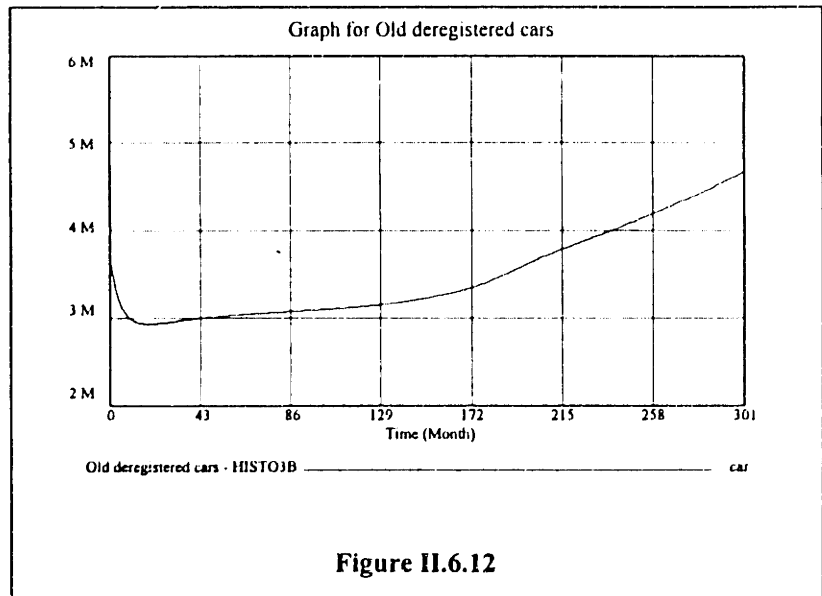


Figure II.6.12

## Part III

# Conclusions and Recommendations

This part includes a general discussion of the insights generated in this research; the disassembly analysis of “Car A” and the understanding of the Automobile Recycling Industry in North America. Learning from the disassembly analysis and sensitivity studies, and a reflection based on the Automobile Recycling Dynamic Model and the policy testing are included. Additional thoughts on possible areas for future research are shared, as well as the VRP reaction to the work is presented here.

### 1. The Disassembly Problem

The approach followed to analyze the disassembly issue proved to be an efficient one, capable of dealing with a large and complex product such as an automobile. The inclusion of the heuristic simplifications helped significantly by reducing the size of the problem. The genetic algorithm used by the DMA is able to solve the optimization challenge of an automobile dismantled into 550 parts in a very efficient way.

The disassembly analysis of “Car A” greatly increased the level of knowledge about the economics of disassembly for recovery of this vehicle. The process itself was difficult, but proved to be a viable way of learning.

The use of the Disassembly Model Analyzer on modified DML files constitutes an interesting process because it allows one to evaluate recyclability of automobile designs. That is, changes in composition, weight, removal times and precedence constraints, among other attributes can be specified on a theoretical basis by changing the information on a DML file of a similar automobile. The DMA permits one to evaluate the recyclability of these “conceptual vehicles”, using the information on these modified DML files even before the designs are complete. This is a valuable tool on its own, because it might provide for an effective methodology for designers’ evaluation of new concepts.

### Disassembly Practices

The DMA results from analysis of “Car A” were compared to the common dismantling practices conducted on this type of vehicle. It turns out that the optimum disassembly plan matches the current practice well. This indicates that the opportunity for improving the current dismantling practices is not significant. In other words, dismantlers do a good job in determining the profit-maximizing disassembly plan of this type of vehicle. It is important to remember that the knowledge and experience used to determine disassembly plans has been passed from experienced dismantlers to apprentices along various generations. In this sense, the economic survival of the fittest might have already taken place; those companies that were not capable of identifying close-to-optimum disassembly plans may have gone out of business.

Disassembly for Material Recovery

Based on the sensitivity analyses of prices and costs performed on “Car A” it seems that economics will permit only minimal recycling of non-metals. Reasonable design changes or market fluctuations will not have a great effect. The following table supports this conclusion by highlighting some results from the sensitivity analyses.

Sensitivity run	Percent ASR expected by the DMA profit-optimized disassembly plan	Improvement with respect to Percent ASR in the base case
Base case	26%	NA
Prices of plastics increased by 30%	24%	7.7%
Scrap price increased by 50%	24%	0.0%
Resale prices increased by 50%	24%	0.0%
Labor cost reduced by 50%	26%	0.0%
Landfill cost increased by 50%	26%	0.0%

This table presents an extremely discouraging set of results. It turns out that scrap price, resale price, labor cost and landfill cost do not have any impact in the level of dismantling within reasonable intervals. The influence of prices of recycled plastics is relatively modest as well.

The landfill effect is not surprising because under the current structure dismantlers can send any type of material with the hulks they sell to the shredders and get paid -- by the ton -- for these materials. In other words, dismantlers do not send anything to the landfills, instead they always get paid for their scrap products. An alternative pricing mechanism may help; if dismantlers were paid in a composition-specific way, they could implement a different approach on what to do with the plastic part of the vehicles.

The labor cost and the scrap price effects are somewhat more surprising. Changes in these two variables do have an effect in the profits dismantlers can realize, but do not change the optimum disassembly plan of “Car A”.



It can also be inferred that Design for Disassembly would not make a great improvement in environmental terms, since its major effect is that it reduces the overall labor expense. Thus, as in the case of labor sensitivity, DFD turns out to be an inefficient stimuli for recycling.

So far the potential for improvement does not seem promising:

- It has been argued that a the profit-maximizing disassembly plan of a typical "old car" (without sellable parts) does not include any significant dismantling for material recovery and that this situation corresponds to the current actual practice.
- As for the future, it was explained that reasonable changes in market prices and costs would produce, at best, very modest improvements in the amount of material being recovered at the dismantling stage.

Does this mean that there is no possibility of improvement? The optimistic scenario presented in the following table would suggest that there are some opportunities. This scenario was created by incorporating a significant level of DFD and the use of virgin material prices. Elimination of contamination, homogenous selection of materials for certain parts and reduction in the number of precedence constraints are some of the DFD elements included.

Sensitivity run	Percent ASR expected by the DMA profit-optimized disassembly plan	Improvement with respect to Percent ASR in the base case
Elimination of contaminated materials, identification of all materials and reduction in precedence constraints (increase in level of DFD) and use of virgin prices for the value of recycled materials (the optimistic case)	11%	57%

Based on this scenario, one could suggest that improvements in DFD in conjunction with radical increases of prices could result in better levels of disassembly for material recovery. The focus in searching for these conditions has to be integrating several factors simultaneously.

However, it seems like the relatively low values of recycled plastics may not allow for manual dismantling for material recovery. Perhaps solutions to vehicle recycling problems lie outside the disassembly area. In other words, the analyses seem to indicate that it will not be economical to dismantle automotive plastics and other non-metals for recycling in the foreseeable future. Destructive disassembly, partial recovery of material and other types of mechanical separation may have a better opportunity to improve this aspect of automobile recycling. These alternatives represent a major technological challenge.

### Areas for Future Research

The following represent a non-comprehensive list of areas that might generate interesting additional learning:

- Use of the DML and DMA in other types of vehicles.
- Further understanding of the DFD possibilities by running sensitivity analyses on this specific parameter.
- Calibration of the empirical equations using information from different vehicles.
- Research on alternative separations and classification procedures, such as destructive dismantling, partial recovery of materials and automated selection mechanism for non-metal materials

## 2. Automobile Recycling Industry Analysis

It has been mentioned that one of the most valuable aspects of a dynamic model is the research process itself. Interviews about operation practices and discussions about mental models with industry participants is extremely insightful. The modeling process brings additional learning because it forces model builders to identify the relevant information and to structure the decision processes in the system. These activities improved intuition for the people participating in the project.

At the heart of the dynamic model creation is the identification of the major feedback loops in the system under analysis. The introduction of Part II of this work, and chapter II.2 provide a detailed description of the feedback loops identified in the Automobile Recycling Industry in North America. Figure III.1 captures a significant portion of the dynamics in this industry. It provides the basis for the dynamic model and can be used by related entities in discussion to explore alternative paths to improve the system and identify future areas for research.

The ARDM was used to explore the system's behavior under different scenarios and policy alternatives. Chapter II.5 contains complete results of the tests conducted using the equilibrium condition as the starting point. Chapter II.6 shows how one can expect the actual system to behave considering the real level of most of the stocks in the system.

The dynamic model proved to be a valuable tool to understand the system structure. The combination of material accounting with the dynamic determination of transfer prices (junk car, hulk, and autoscrap prices), and as a consequence the dynamic determination of flows, resulted in a model that clearly identifies and quantifies the environmental effects associated with disposing of automobiles. For example, it is important to recognize that the ASR generation is not a good stand-alone indicator of the industry recycling efficiency. One can imagine a scenario where ASR generation is reduced, but the number of abandoned cars increases.

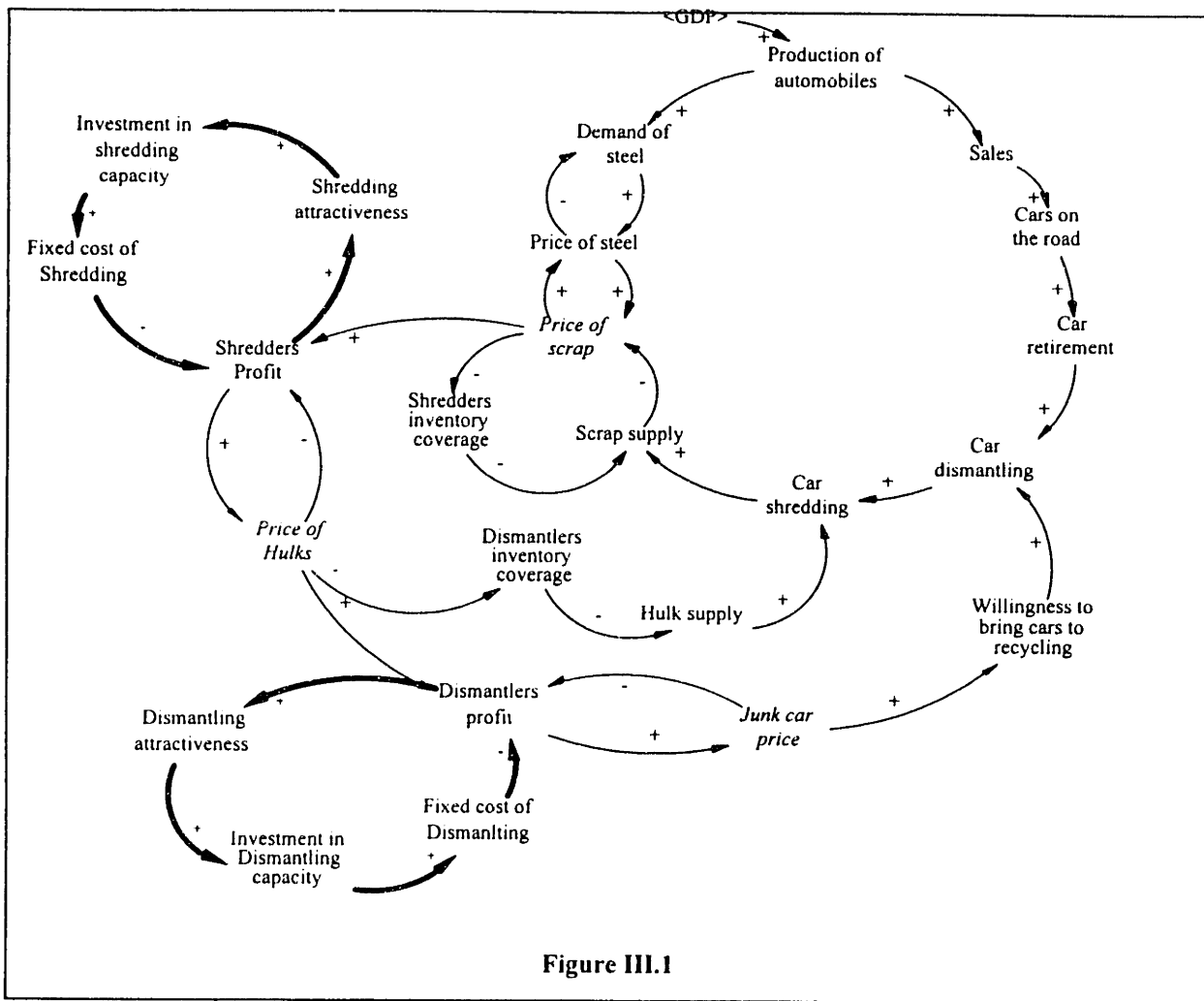


Figure III.1

The model can also be used to emphasize interactions among involved entities. This can be especially useful when the VRP collaborators discuss projects, because it provides one with a completely explicit platform on how the industry works. Each initiative can be understood as a potential modification of some identifiable parameter or as creating additional relationships. In this sense, the model could be used (and expanded) to understand the potential benefits of alternative projects and help the VRP in giving an adequate level of priority to projects.

The studies in chapter II.5 and II.6 do not represent a comprehensive study of the system. They were used to illustrate the use of the model and to generate initial insights. Following is a discussion of the initial results.

### Industry Robustness

The main conclusion on this area depends on what automobile manufacturers' policies are assumed. Extrapolating historical trends in policies involve further reducing total vehicle mass and increasing the content of non-metals, and non-ferrous metals, while reducing the ferrous portion of automobiles. Chapter II.6 and section II.5.7 showed that under these assumptions the industry will face major problems to survive.

Of course, this conclusion is not a prediction. The whole purpose of this work is to participate in understanding the system in such a way that related parties, and specifically automobile manufacturers, can act to reduce the environmental impact of disposing of automobiles. Thus, concluding that the Automobile Recycling Industry in North America has low possibilities to exist under its current structure in the future, should be interpreted as saying that the structure has to change for the industry to survive, as opposed to saying that the industry is facing an imminent and unavoidable collapse.

In other words, the purely economic-driven structure does not seem to be able to manage the simple extrapolation of historical trends in vehicle weight and composition. Nor does it seem capable of dealing with plausible increases in prices defined outside the system, such as labor and landfill costs, and non-ferrous metals and plastic prices.

There are two factors that lead to this conclusion. First, there is a structural deficiency in the system that does not take into consideration environmental objectives properly. Second, the automobile manufacturers' policies are of paramount importance in terms of the industry viability.

Structural Deficiency

A self-maximizing decision rule has the tendency of reflecting additional costs faster than incremental savings when defining input prices. As shown in scenario PLAST3X, this creates an asymmetry in the system response when defining transfer prices.

It can be seen that in scenario PLAST3B, where the plastic content was increased and sustained at the higher level throughout the simulation, a different price response takes place, than in the case of PLAST3C. In scenario PLAST3C the plastic component was decreased. The dismantler profit was reduced by 2.5% in the first case, while in PLAST3C an increase of almost 12% is observed. Figure II.2 summarizes these results.

Scenario	Description	Cum Ds profit (billions)	Cum Sh profit (billion)	Eq junk car price (\$/car)	Eq hulk price (\$/ton)	Eq scrap price (\$/ton)	Long-run ASR (%)	Cum mass landfilled (billion kg)	Mass dismantled per car (kg/car)	abandoned cars (million cars)
CURRENT	Equilibrium run	\$17.02	\$3.78	\$50.04	\$80.00	\$125.59	24.15%	202.93	36.20	4.997
PLAST3A	step-up & step down in plastic composition (20%) vs equilibrium	\$17.71 4.1%	\$3.67 -2.9%	\$46.84 -6.4%	\$79.87 -0.2%	\$125.57 0.0%	24.21% 0.2%	208.95 3.0%	36.32 0.3%	5.14 2.9%
PLAST3B	step-up in plastic composition vs equilibrium	\$16.60 -2.5%	\$3.71 -1.9%	\$27.64 -44.8%	\$66.76 -16.6%	\$125.40 -0.2%	28.51% 18.1%	222.81 9.8%	53.37 47.4%	6.187 23.8%
PLAST3C	step-down in plastic composition vs equilibrium	\$19.02 11.8%	\$3.69 -2.4%	\$66.31 32.5%	\$94.45 18.1%	\$125.75 0.1%	19.73% -18.3%	181.64 -10.5%	15.1 -58.3%	4.697 -6.0%

Figure III.2

In contrast, the effect on ASR generation is almost symmetrical: total cumulative mass sent to the landfills in PLAST3B increased by 10% while in the case of PLAST3C it decreased by 10.5%.

When comparing the DFD effect, the same type of results are observed. Increases in DFD (scenario DFD3B) creates 42% more profits to dismantlers in the equilibrium run. When DFD is reduced (scenario DFD3C) profits go down 15%.

Scenario	Description	Cum Ds profit (billions)	Cum Sh profit (billion)	Eq junk car price (\$/car)	Eq hulk price (\$/ton)	Eq scrap price (\$/ton)	Long-run ASR (%)	Cum. mass landfilled (billion kg)	Mass dismantled per car (kg/car)	abandoned cars (million cars)
CURRENT	Equilibrium run	\$17.02	\$3.78	\$50.04	\$80.00	\$125.59	24.15%	202.93	36.20	4.997
DFD3A	step-up & step down in DFD (10 points)	\$19.42	\$3.78	\$50.71	\$80.06	\$125.65	24.14%	200.00	36.21	4.98
	vs. equilibrium	14.1%	-0.1%	1.3%	0.1%	0.0%	0.0%	-1.4%	0.0%	-0.3%
DFD3B	step-up & step down in DFD (10 points)	\$24.16	\$3.79	\$115.10	\$79.84	\$125.55	24.48%	199.78	44.31	4.34
	vs. equilibrium	42.0%	0.1%	130.0%	-0.2%	0.0%	1.4%	-1.6%	22.4%	-13.1%
DFD3C	step-down in DFD (10 points)	\$14.46	\$3.23	\$1.58	\$89.82	\$134.69	21.55%	193.06	28.10	34.77
	vs. equilibrium	-15.0%	-14.6%	-96.8%	12.3%	7.2%	-10.8%	-4.9%	-22.4%	595.8%

Figure III.3

These results make one point clear: dismantlers “own” the junk cars when they acquire them. Accordingly, they perform on them what is optimum for their monetary objectives. The following argument is an example that illustrates the point:

Suppose that the adoption of certain automobile manufactures’ *policy x* is known to cause dismantlers additional disassembly costs. It might be tempting to think that an increase in DFD level would offset the incremental costs and result in the same level of dismantling for material recovery as before the adoption of *policy x*.

Nothing is further from the truth. There is no mechanism that relates one-to-one the level of dismantling to the level of DFD. In all cases, the material recovery level will be defined in terms of the disassembly plan that produces maximum profits. In other words, it is possible that the adoption of *policy x* accompanied by an increase in DFD results in lower level of disassembly, in lower junk car price, and in an improved dismantlers’ profit. Dismantlers can reflect the

incremental cost of *policy x* in the junk car price and capitalize a good portion of the benefits of DFD.

An increase of plastic usage results in a the total increase in the plastic in the system. As explained, each entity participating in automobile recycling tries to sustain its profitability. It participates in the economic determination of prices, and, under these scenarios, is capable of sustaining its operation and its profit. In scenario PLAST3B, cumulative profits for both shredders and dismantlers are fundamentally the same as in the equilibrium run.

However, it has been explained that plastic usage represents a pure cost to the system. Thus, one can ask “Who paid the incremental cost?” The answer is we all did.

A significant increase in material landfilled is generated. Figure III.3 shows that in the equilibrium run a total of 201 billion kilograms are sent to the landfill. In scenario PLAST3B this amount increases by 9.8%. Since in scenarios created, the increasing amounts of ASR do not result in increasing tipping fees, we all paid the price of the increase in plastic usage partially by accepting more ASR in our landfills.

There is a second component to the environmental cost. Although the variable *Percent of cars not dismantled* does not present major changes during these simulations (within 1%), the total number of cars abandoned does. Figure III.2 shows that an accumulation of deregistered cars takes place. Starting at 5 million and reaching 6.2 million, this stock increases by almost 24%. Thus, we also paid the price of an increased usage of plastics by accepting more cars to sit and wait to be processed.

The purely economically driven industry, as its own name suggests, has no environmental considerations. People recycle cars and recover materials from this process because they make money doing it. The pollution as an externality argument is, of course, behind this complex issue. At the end, the fluff sent to the landfill, or the number of cars abandoned are externalities. Everybody is worse-off if they increase, but no one is better-off preventing them.



What type of additions to the economic-driven structure can one think to improve both the economic viability of the industry and the environmental performance? This is precisely the most interesting area for expansion of this research. It may involve consideration of government intervention, and evaluation of alternative structures.

### **3. The Influence of the Automobile Manufacturers**

In scenario PLAST3B the amount of material dismantled is larger than in the equilibrium scenario by almost 47%. This is a counterintuitive result because in PLAST3B cars are sold with 20% more plastic.

The reason behind this phenomenon is interesting. As dismantlers perceive their profit reducing, they undertake more recycling, going into deeper levels of the cars' structure. They do this seeking to increase their recycling revenue. They try to offset, at least partially, the other negative conditions.

This result has to be taken with a grain of salt. It is tempting to jump to the conclusion that policies oriented towards reducing dismantlers' profit might be beneficial from the environmental perspective. Although some of these policies might indeed increase the level of dismantling, they would most probably cause the junk car price to go down with the corresponding increase in the number of cars abandoned.

### **DFD**

DFD is an activity that comes at some cost. Automobile manufacturers would need to balance the benefits (very modest) of improving the level Design for Disassembly against its cost. Clearly, the dismantlers benefit from this activity, because they are in the best position to capitalize from lower costs of disassembly.

As explained, self-motivated enterprises seeking to maximize profit would reduce the potential environmental improvement because they have control of the dismantling level.

One can argue that consumers benefit as well, since they would receive, after all, more money for their junk cars. Although this is true, we should examine carefully the intention of DFD.

Automobile manufacturers would presumably incorporate higher levels of DFD not to pass onto consumers an additional monetary benefit, but rather to increase the recycling of cars.

One can ask "Why should dismantlers benefit from an increase in DFD at a cost to the automobile manufacturers?", "What if they were asked to realize the *same* profit and recycle *more*?"

### Car Weight and Material Composition

The scenarios where the car weight and the material composition were changed indicate that these variables, within reasonable ranges, are enough to either ensure the industry survival, or the industry collapse. However, this is not new. Historical trends in car weight and material composition were precisely the sources of the most somber questions associated with the future of the industry before this work was undertaken.

Besides, car weight and material composition are defined based on many other --and likely more important -- performance characteristics. Fuel efficiency, driving performance and cost are among them.

What is new is that the model allows the VRDC and the automobile manufacturers to evaluate the possible effects of alternative policies. The ARDM may help them understand the tremendous delays in the system and might stimulate thinking in terms of managing, today, the possible future consequences of their decisions.

Scenarios Review

Figures III.4 to III.6 summarize the results on the scenarios created based on changes in exogenous variables.

Scenario	Description	Cum Ds profit (billions)	Cum Sh profit (billion)	Eq junk car price (\$/car)	Eq hulk price (\$/ton)	Eq scrap price (\$/ton)	Long-run ASR (%)	Cum. mass landfilled (billion kg)	Mass dismantled per car (kg/car)	abandoned cars (million cars)
CURRENT	Equilibrium run	\$17.02	\$3.78	\$50.04	\$80.00	\$125.59	24.15%	202.93	36.20	4.997
SALES3A	step-up & step down in sales (20%) vs. equilibrium	\$18.66 9.6%	\$3.78 -0.2%	\$47.87 -4.3%	\$79.80 -0.3%	\$125.13 -0.4%	24.22% 0.3%	209.59 3.3%	36.20 0.0%	5.101 2.1%
SALES3B	step-up in sales vs. equilibrium	\$19.63 15.3%	\$4.51 19.4%	\$49.22 -1.6%	\$79.90 -0.1%	\$125.67 0.1%	24.14% 0.0%	227.33 12.0%	36.20 0.0%	6.035 20.8%

Figure III.4

Scenario	Description	Cum Ds profit (billions)	Cum Sh profit (billion)	Eq junk car price (\$/car)	Eq hulk price (\$/ton)	Eq scrap price (\$/ton)	Long-run ASR (%)	Cum mass landfilled (billion kg)	Mass dismantled per car (kg/car)	abandoned cars (million cars)
CURRENT	Equilibrium run	\$17.02	\$3.78	\$50.04	\$80.00	\$125.59	24.15%	202.93	36.20	4.997
SALES3C	step-up & step down in GDP (20%) vs. equilibrium	\$29.29 72.1%	\$3.72 -1.7%	\$45.79 -8.5%	\$79.87 -0.2%	\$125.36 -0.2%	24.20% 0.2%	209.59 3.3%	36.20 0.0%	5.193 3.9%
SALES3D	step-up & step down in GDP (20%) with random component vs. equilibrium	\$20.40 19.9%	\$3.15 -16.6%	\$41.30 -17.5%	\$74.85 -6.4%	\$116.31 -7.4%	23.29% -3.6%	208.98 3.0%	36.20 0.0%	5.416 8.4%
SALES3E	GDP growing at 3% per annum vs. equilibrium	\$33.58 97.3%	\$13.98 269.6%	\$35.85 -28.4%	\$86.36 7.9%	\$146.96 17.0%	23.26% -3.7%	345.01 70.0%	36.20 0.0%	17.31 246.4%

Figure III.5

Scenario	Description	Cum Ds profit (billions)	Cum Sh profit (billion)	Eq junk car price (\$/car)	Eq hulk price (\$/ton)	Eq scrap price (\$/ton)	Long-run ASR (%)	Cum mass landfilled (billion kg)	Mass dismantled per car (kg/car)	abandoned cars (million cars)
CURRENT	Equilibrium run	\$17.02	\$3.78	\$50.04	\$80.00	\$125.59	24.15%	202.93	36.20	4.997
INDEX3B	use of historical trends in x-variables (exogenous prices) <i>vs equilibrium</i>	\$8.56 -49.7%	\$0.39 -89.7%	\$0.06 -99.9%	\$70.28 -12.2%	\$144.95 15.4%	14.93% -38.2%	184.46 -9.1%	78.55 117.0%	56.31 1026.9%
TREND3A, TREND3B, TREND3C	changes in policy variables (gaming mode) <i>vs equilibrium</i>	\$16.41 -3.6%	\$3.58 -5.3%	\$19.59 -60.9%	\$67.18 -16.0%	\$107.02 -14.8%	33.51% 38.8%	208.38 2.7%	57.46 58.7%	7.087 41.8%
ETREN3C	simultaneous changes in policy variables and x-variables, with GDP growing at 2.5% per annum <i>vs equilibrium</i>	(\$20.90) -222.8%	\$2.17 -42.6%	\$0.00 -100.0%	\$54.94 -31.3%	\$147.01 17.1%	23.79% -1.5%	306.57 51.1%	98.28 171.5%	225.17 4406.1%

Figure III.6

### Areas for Future Research

The following is a list of the alternative areas for future work:

- The ARDM can be expanded to include the possible effect of new technologies to process ASR, such as pyrolysis, for example.
- The ARDM can be expanded to include purely non economic incentives. This area is extremely interesting because it may allow for a coordinated, well orchestrated set of government mandates to improve the system performance. It may allow for searching for the optimum (least) expensive way of achieving certain environmental objectives.

- The ARDM can be used to create a “management flight-simulator” (game) with a friendly interface to allow decision makers and interested parties to learn about the dynamics of the system.
- The ARDM could be fine-tuned to closer resemble historical information and be used as a forecast tool.

## **6. VRP’s Reaction to Work**

The results of this study were presented to the VRDC on April 19, 1996. The initial reaction was extremely positive. The center considered that both the methodology and the actual results represent a major contribution to its objectives. They expressed interest in having the game built for them and to eventually work on expanding the model to cover several of the areas proposed above.

## Bibliographic References

1. AAMA, **Motor Vehicle Facts and Figures**, American Automobile Manufacturers Association, 1994.
2. **Annual Statistical Report**. American Iron and Steel Institute, 1993.
3. **Arthur D. Little, Inc.** "Recycling State-of-the-Art for Scrapped Automobiles", Final Report to the American Iron and Steel Institute, 1992.
4. **Automotive Engineering**, "American Plastics Council technology update", page 49-51, August 1995.
5. **Automotive News**, "Data Book", 1995.
6. **Curlee, T. R., Das, S., Rizy, C. G., Schexnayder, S. M.** "Automobile recycling in the United States: energy impacts and waste generation", Resources, Conservation, and Recycling, Vol. 14, pages 265-284, 1995.
7. **Curlee, T. R., Das, S., Rizy, C. G., Schexnayder, S. M.** "Recent Trends in Automobile Recycling: An Energy and Economic Assessment", Oak Ridge National Laboratory report for the US Department of Energy, 1994.
8. **Environmental Protection Agency (EPA), Office of Research and Development.** "Life-Cycle Design Guidance Manual: Environmental Requirements and the Product System", Washington, DC, 1993.
9. **Field, F. R., Ehrenfeld, J. R., Roos, D., Clark, J. P.** "Automotive Recycling Policy: Findings and Recommendations", Prepared for the Automotive Industry Board of Governors, World Economic Forum, Davos, Switzerland, 1994.
10. **Forrester, J.W.** "Policies, Decisions, and Information Sources for Modeling", Modeling for Learning Organizations. J. D. W. Morecroft and J. D. Sterman. System Dynamics Series. Productivity Press. Portland, Oregon. 1994.
11. **Girard, A., Boothroyd, G.** "Design for Disassembly", Department of Industrial and Manufacturing Engineering Green Report #90, University of Rhode Island, 1995.
12. **Iwai, T.** "Toyota's Activities for the Environment", International Journal of Environmentally Conscious Design and Manufacturing, Vol. 4, No. 1, 1995.
13. **Johnson, M. R., Wang, M.** "Planning product disassembly for material recovery opportunities", International Journal of Production Research, Vol. 33, No. 11, pages 3119-3142, 1995.

14. **Liberity, G., Z.** "A New Look at the Service Life Expectancy of Passenger Cars in the United States", SAE Technical Paper Series, 930840, International Congress nad Exposition, Detroit, MI, March, 1993.
15. **Machine Design**, "Recycling Automotive Seats", page 74, February 23, 1995.
16. **Morecroft, J., D., W., and Sterman, J., D.** Modeling for Learning Organizations, System Dynamics Series. Productivity Press. Portland, Oregon. 1994.
17. **Navin-Chandra, D., Bansal, R.** "The Recovery Problem: The Tradeoff Between Designing for Environmental Compatibility and Commercial Viability", International Journal of Environmentally Conscious Design and Manufacturing, Vol. 3, No. 2, 1995.
18. **Navin-Chandra, D.** "Tools for Demanufacturing Analysis and Design Planning", Proceedings of Auto Recycle '95, Dearborn, MI, 1995.
19. **Pindyck, R., S., and Rubinfeld, L.** "Stock adjustment effect", Microeconomics, Third Edition, Prentice-Hall Inc., New Jersey, 1994.
20. **Plastic Engineering**, page 21, December 1995.
21. **Richmond, B.** "Systems thinking: critical thinking skills of the 1990s", System Dynamics Review, vol. 9, no 2, summer 1993.
22. **R. L. Polks & Company Report.** "Passenger Cars Scrapage and Growth in the USA", 1995
23. **Robert R. Nathan Associates, Inc.** "Price-Volume Relationships for the supply of scrap iron and steel: a study of the price elasticity of demand", Metal Scrap Research and Education Foundation, January, 1979.
24. **Simon, M.** "Design for Dismantling", Professional Engineering, pages 20-22, November, 1991.
25. **Spicer, A., Wang, M.** "A Software Tool for Analysis of the Retirement Phase of a Product Currently Under Design", Proceedings of the Third International Congress on Environmentally Conscious Design and Manufacturing, Las Cruces, NM, 1995.
26. **Spicer, A., Wang, M.** "Optimal Disassembly Sequence Generation for Complex Products: An Artificial Intelligence Approach", Proceedings of the Third International Congress on Environmentally Conscious Design and Manufacturing, Las Cruces, NM, 1995.
27. **US Congress, Office of Technology Assessment.** "Green Products by Design: Choices for a Cleaner Environment", OTA-E-541, US Government Printing Office, Washington, DC, 1992.

**28. US Department of Commerce.** "Recent Trends in Automobile Recycling: An Energy and Economic Assesment", DE94-008562, United States Department of Energy, Oak Ridge, Tennessee, March 1994.

**29.** Wards Auto World, 1994 and 1995.



Car A. Timestudy Data. June, 1995. Stock Number F33605.  
Hierarchical Structure, Times, Masses, Material, Material Identification, Total Number of "befores" per part, Comments. Selected information

#	Name	Parts H.#	Time (secs)	Mass (kgs)	Material	Marked	#	Total # before	Cum time	Befores	Fasteners	Comments
1	DoorFrontRight	120	33	33.34	Mixed	--	1	0	33	Nothing	2-13, 3-EC	
2	DoorFrontRight Panel	225	95	2.96	Mixed	--	2	1	100	DoorFrontRight.MirrorPanel	4-Ph	
3	DoorFrontRight Panel Handle		51	0.40	SKOP	N	3	0	51	Nothing	4-Ph, 4Rivets	
4	DoorFrontRight Panel Light		73	0.02	SKOP	N	4	0	73	Nothing	6Rivets!!	
5	DoorFrontRight Panel SpeakerCover		56	0.01	SKOP	N	5	0	56	Nothing	6Rivets!!	Contaminated glue
6	DoorFrontRight Panel BottomCover		35	0.04	Textile contaminated	NR	6	0	35	Nothing	Glue	
7	DoorFrontRight Panel TopCover		51	0.34	Mixed	--	7	0	51	Nothing		
8	DoorFrontRight Panel TopCover TopPlastic		60	0.06	SKOP	N	8	0	60	Nothing	Stapled plus glued	
9	DoorFrontRight Panel TopCover CarpetCover		10	0.02	Textile	NR	9	1	70	DoorFrontRight.Panel.TopCover.TopPlastic	Stapled plus glued	
10	DoorFrontRight Panel TopCover Foam		250	0.02	SKOP	N	10	2	320	DoorFrontRight.Panel.TopCover.CarpetCover	Stapled plus glued	Contaminated glue
11	DoorFrontRight Panel TopCover Base		0	0.26	ABS contaminated	Y	11	3	320	DoorFrontRight.Panel.TopCover.Foam	Stapled plus glued	
12	DoorFrontRight Panel Base		0	1.96	ABS	Y	12	6	331	DoorFrontRight.Panel		
13	DoorFrontRight MirrorPanel		5	0.02	ABS	Y	13	0	5	Nothing	1-Ph	
14	DoorFrontRight Shoddy		14	0.12	Shoddy	NR	14	2	114	DoorFrontRight.Panel	3 Pushins	
15	DoorFrontRight Structure		0	31.70	Mixed	--	15	4	147	DoorFrontRight..DoorFrontRight.Shoddy		
16	DoorFrontRight Structure Base		0	30.34	Mixed	--	16	6	283	DoorFrontLeft.Structure.Mirror		
17	DoorFrontRight Structure Base Steel		24	21	Ferrous	NR	17	0		M		
18	DoorFrontRight Structure Base SKOS		3	79	SKOS	N	18	0		M		
19	DoorFrontRight Structure Base Glass		2	34	Glass	NR	19	0		M		
20	DoorFrontRight Structure Mirror	128	69	0.92	Mixed	--	20	1	74	DoorFrontRight.MirrorPanel	3-8mm	
21	DoorFrontRight Structure Mirror House		0	0.625	Mixed	--	21	4	109	DoorFrontRight.Structure.Mirror. DoorFrontRight.Structure.Mirror.Lens. DoorFrontRight.Structure.Mirror.Electrical		
22	DoorFrontRight Structure Mirror House		60	0.069	SKOP	N	22	5	169	DoorFrontRight.Structure.Mirror.House	5-Ph, 3-2way screws	
23	DoorFrontRight Structure Mirror House		0	0.351	SKOP	N	23	6	169	DoorFrontRight.Structure.Mirror.House.Plastic1		
24	DoorFrontRight Structure Mirror House		0	0.03	Ferrous	NR	24	6	169	DoorFrontRight.Structure.Mirror.House.Plastic1		
25	DoorFrontRight Structure Mirror House		0	0.175	Aluminum	N	25	6	169	DoorFrontRight.Structure.Mirror.House.Plastic1		
26	DoorFrontRight Structure Mirror Lens		20	0.14	SKOS	N	26	0	20	Nothing	Glass and plastic	
27	DoorFrontRight Structure Mirror Electrical		15	0.16	SKOS	N	27	1	35	DoorFrontRight.Structure.Mirror.Lens	3-Ph	
28	DoorFrontLeft Panel	120	100	34.88	Mixed	--	28	0	100	Nothing	2-13, 1-10	
29	DoorFrontLeft Panel Handle	225	95	3.04	Mixed	--	29	1	100	DoorFrontLeft.MirrorPanel	4-Ph	
30	DoorFrontLeft Panel MirrorEC		51	0.40	SKOP	N	30	0	51	Nothing	4-Ph, 4Rivets	
31	DoorFrontLeft Panel Light		72	0.04	SKOS	N	31	0	52	Nothing		
32	DoorFrontLeft Panel SpeakerCover		56	0.01	SKOP	N	32	0	73	Nothing	6Rivets!!	
33	DoorFrontLeft Panel BottomCover		35	0.04	Textile	NR	33	0	56	Nothing	6Rivets!!	Contaminated glue
34	DoorFrontLeft Panel TopCover		51	0.34	Mixed	--	34	0	35	Nothing	Glue	
35	DoorFrontLeft Panel TopCover		51	0.34	Mixed	--	35	0	51	Nothing		

#	Name	Parts H.#	Time (secs)	Mass (kg)	Material	Marked	#	Total # before	Cum time	Before	Fasteners	Comments
36	DoorFrontLeft.Panel.TopCover.TopPlastic		60	0.06	SKOP	N	36	0	60	Nothing	Stapled plus glued	
37	DoorFrontLeft.Panel.TopCover.CarpetCov		10	0.02	Textile	NR	37	1	70	DoorFrontLeft.Panel.TopCover.TopPlastic DoorFrontLeft.Panel.TopCover.CarpetCov	Stapled plus glued	
38	DoorFrontLeft.Panel.TopCover.Foam		250	0.02	SKOP	N	38	2	320	er	Stapled plus glued	Contaminated glue
39	DoorFrontLeft.Panel.TopCover.Base		0	0.26	ABS contaminated	Y	39	3	320	DoorFrontLeft.Panel.TopCover.Foam DoorFrontLeft.Panel. DoorFrontLeft.Panel.Handle. DoorFrontLeft.Panel.Light. DoorFrontLeft.Panel.SpeakerCover. DoorFrontLeft.Panel.TopCover	Stapled plus glued	
40	DoorFrontLeft.Panel.Base		0	1.96	ABS	Y	40	6	331	Nothing	1-Ph	
41	DoorFrontLeft.MirrorPanel		5	0.02	ABS	Y	41	0	5	Nothing	3 Pushins	
42	DoorFrontLeft.Shoddy		14	0.12	Shoddy	NR	42	2	114	DoorFrontLeft.Panel		
43	DoorFrontLeft.Structure		0	31.26	Mixed	---	43	4	214	DoorFrontLeft.DoorFrontLeft.Shoddy		
44	DoorFrontLeft.Structure.Mirror	128	69	0.92	Mixed	---	44	1	74	DoorFrontLeft.MirrorPanel DoorFrontLeft.Structure.Mirror. DoorFrontLeft.Structure.Mirror.Lens. DoorFrontLeft.Structure.Mirror.Electrical		Power Mirror
45	DoorFrontLeft.Structure.Mirror.House		0	0.625	Mixed	---	45	4	109	DoorFrontLeft.Structure.Mirror.House		
46	DoorFrontLeft.Structure.Mirror.House.Pl		60	0.069	SKOP	N	46	5	169	DoorFrontLeft.Structure.Mirror.House.Pl	5-Ph. 3-2way screws	
47	DoorFrontLeft.Structure.Mirror.House.Pl		0	0.351	SKOP	N	47	6	169	stc1		
48	DoorFrontLeft.Structure.Mirror.House.St		0	0.03	Ferrous	NR	48	6	169	stc1		
49	DoorFrontLeft.Structure.Mirror.House.Al		0	0.175	Aluminum	N	49	6	169	stc1		
50	DoorFrontLeft.Structure.Mirror.Lens		20	0.14	SKOS	N	50	0	20	Nothing	N	
51	DoorFrontLeft.Structure.Mirror.Electrical		15	0.16	SKOS	N	51	1	35	DoorFrontLeft.Structure.Mirror.Lens	3-Ph	
52	DoorFrontLeft.Structure.Base		0	30.78	Mixed	---	52	6	216	DoorFrontRight.Structure. DoorFrontRight.Structure.Mirror		
53	DoorFrontLeft.Structure.Base.Steel		24.57	Ferrous	NR	---	53	0	M			
54	DoorFrontLeft.Structure.Base.SKOS		3.65	SKOS	N	---	54	0	M			
55	DoorFrontLeft.Structure.Base.Glass		2.36	Glass	NR	---	55	0	M			
56	DoorRearRight	130	21	25.50	Mixed	---	56	0	21	Nothing	2-13. 1-EC	Arm Rest Damaged in removal
57	DoorRearRight.Panel		80	2.20	Mixed	---	57	0	80	Nothing	1-Ph. 2-5.5	
58	DoorRearRight.Panel.Ashtray	225	90	0.22	Mixed	---	58	0	90	Nothing	1-phi. 2 rivets	
59	DoorRearRight.Panel.Ashtray.Steel		0	0.11	Ferrous	NR	59	0	M			
60	DoorRearRight.Panel.Ashtray.SKOS		50	0.11	SKOS	N	60	0	M			
61	DoorRearRight.Panel.Light		40	0.01	SKOP	N	61	0	50	Nothing	6 Pl	
62	DoorRearRight.Panel.Handle		40	0.30	SKOP	N	62	0	40	Nothing		Contaminated glue
63	DoorRearRight.Panel.BottomCover		30	0.06	Textile	NR	63	0	30	Nothing	Glue	
64	DoorRearRight.Panel.TopCover		80	0.36	Mixed	---	64	0	80	Nothing	Sribets	
65	DoorRearRight.Panel.TopCover.TopPlastic		60	0.06	SKOP	N	65	0	60	Nothing	Stapled plus glued	
66	DoorRearRight.Panel.TopCover.CarpetCov		10	0.02	Textile	NR	66	1	70	DoorRearRight.Panel.TopCover.TopPlastic DoorRearRight.Panel.TopCover.CarpetCov	Stapled plus glued	
67	DoorRearRight.Panel.TopCover.Foam		250	0.02	SKOP	N	67	2	320	er	Stapled plus glued	Contaminated glue
68	DoorRearRight.Panel.TopCover.Base		0	0.26	ABS contaminated	Y	68	3	320	DoorRearRight.Panel.TopCover.Foam	Stapled plus glued	

#	Name	Parts H.#	Time (secs)	Mass (kg)	Material	Marked	#	Total # before	Cum time	Belongs	Fasteners	Comments
69	DoorRearRight Panel Base		0	1.14	ABS	Y	69	6	370	DoorRearRight Panel		
70	DoorRearRight Structure		0	23.28	Mixed	NR	70	2	101	DoorRearRight Panel Ashtray, DoorRearRight Panel Light, DoorRearRight Panel Handle, DoorRearRight Panel Bottom Cover, DoorRearRight Panel Top Cover		
71	DoorRearRight Structure Steel			18.58	Ferrous	NR	71	0		M		
72	DoorRearRight Structure SKOS			2.91	SKOS	N	72	0		M		
73	DoorRearRight Structure Glass			1.79	Glass	NR	73	0		M		
74	DoorRearLeft Panel	130	21	25.50	Mixed	---	74	0	21	Nothing		2-13, 1-EC
75	DoorRearLeft Panel Ashtray	225	40	2.22	Mixed	---	75	0	40	Nothing		1-Ph, 2-5-5
76	DoorRearLeft Panel Light		90	0.22	Mixed	---	76	0	90	Nothing		1-ph, 2 rivets
77	DoorRearLeft Panel Ashtray Steel			0.11	Ferrous	NR	77	0		M		
78	DoorRearLeft Panel Ashtray SKOS			0.11	SKOS	N	78	0		M		
79	DoorRearLeft Panel Light		50	0.01	SKOP	N	79	0	50	Nothing		6 PI
80	DoorRearLeft Panel Handle		40	0.30	SKOP	N	80	0	40	Nothing		
81	DoorRearLeft Panel Bottom Cover		30	0.06	Textile	NR	81	0	30	Nothing		Glue
82	DoorRearLeft Panel Top Cover		80	0.36	Mixed	---	82	0	80	Nothing		9 rivets
83	DoorRearLeft Panel Top Cover Top Plastic		60	0.06	SKOP	N	83	0	60	Nothing		Stapled plus glued
84	DoorRearLeft Panel Top Cover Carpet Cover		10	0.02	Textile	NR	84	1	70	DoorRearLeft Panel Top Cover, Top Plastic		Stapled plus glued
85	DoorRearLeft Panel Top Cover Foam		250	0.02	SKOP	N	85	2	320	DoorRearLeft Panel Top Cover, Carpet Cover		Stapled plus glued
86	DoorRearLeft Panel Top Cover Base		0	0.26	ABS contaminated	Y	86	3	320	DoorRearLeft Panel Top Cover, Foam		Stapled plus glued
87	DoorRearLeft Panel Base		0	1.14	ABS	Y	87	6	330	DoorRearLeft Panel		
88	DoorRearLeft Structure		0	23.28	Mixed	---	88	2	61	DoorRearLeft Panel, DoorRearLeft Panel Ashtray, DoorRearLeft Panel Light, DoorRearLeft Panel Handle, DoorRearLeft Panel Bottom Cover, DoorRearLeft Panel Top Cover		
89	DoorRearLeft Structure Steel			18.58	Ferrous	NR	89	0		M		
90	DoorRearLeft Structure SKOS			2.91	SKOS	N	90	0		M		
91	DoorRearLeft Structure Glass			1.79	Glass	NR	91	0		M		
92	SeatFrontRight	202	91	21.72	Mixed	---	92	0	91	Nothing		3-13, 1-18
93	SeatFrontRight HeadRest	206	4	0.88	Mixed	---	93	0	4	Nothing		
94	SeatFrontRight HeadRest Cover		50	0.14	Textile contaminated	NR	94	0	50	Nothing		Contaminated foam+glue
95	SeatFrontRight HeadRest Base		0	0.76	Mixed	---	95	2	54	SeatFrontRight HeadRest Cover, SeatFrontRight HeadRest		
96	SeatFrontRight HeadRest Base Foam		4	0.62	PUR	N	96	3	58	SeatFrontRight HeadRest Base		
97	SeatFrontRight HeadRest Base Steel		20	0.22	SKOP	NR	97	4	58	SeatFrontRight HeadRest Base, Foam		
98	SeatFrontRight Lateral Cover		85	0.68	PUR	N	98	1	111	SeatFrontRight		
99	SeatFrontRight Back Foam		2	0.80	Textile contaminated	NR	99	0	85	Nothing		Without taking cover
100	SeatFrontRight Back Cover		2	0.04	SKOP	N	100	1	87	SeatFrontRight Back Foam		Contaminated foam+glue
101	SeatFrontRight ArmRest Covers		240	0.70	Mixed	---	101	0	2	Nothing		
102	SeatFrontRight ArmRest		1	0.08	SKOP	N	102	1	242	SeatFrontRight ArmRest Covers		
103	SeatFrontRight ArmRest Big Cover		23	0.16	Textile contaminated	NR	103	2	243	SeatFrontRight ArmRest		Contaminated foam+glue
104	SeatFrontRight ArmRest Cover		0	0.56	Mixed	---	104	2	265	SeatFrontRight ArmRest		
105	SeatFrontRight ArmRest Base		115	0.16	PUR	N	105	3	265	SeatFrontRight ArmRest, Cover		
106	SeatFrontRight ArmRest Base Foam		0	0.40	Ferrous	NR	106	4	380	SeatFrontRight ArmRest, Base		
107	SeatFrontRight ArmRest Base Steel		0	0.40	Ferrous	NR	107	5	380	SeatFrontRight ArmRest, Base, Foam		

#	Name	Part H.#	Time (secs)	Mass (kg)	Material	Marked	Total # before	Cum time	Before	Fasteners	Comments
108	SealFrontRight BottomCover		100	0.58	Textile contaminated	NR	108	191	SealFrontRight		Contaminated foam+glue
109	SealFrontRight BottomFoam		82	0.88	PUR	N	109	173	SealFrontRight		Note Without taking the cover
110	SealFrontRight BottomBase		0	16.36	Mixed	—	110	627	SealFrontRight, BottomFoam, SealFrontRight BottomCover, SealFrontRight ArmRestBigCover, SealFrontRight Back Cover, SealFrontRight LateralCover, SealFrontRight HeadRest, SealFrontRight, SealFrontMiddle		
111	SealFrontRight BottomBase Steel			16.20	Ferrous	NR	111	0	M		
112	SealFrontRight BottomBase SKOS			0.16	SKOS	N	112	0	M		
113	SealFrontRight SealbelFrontMiddle		0	0.22	Mixed	—	113	333	SealFrontRight ArmRest, SealFrontRight		
114	SealFrontRight SealbelFrontMiddle Latch		5	0.09	Ferrous	NR	114	0	5 Nothing		
115	SealFrontRight SealbelFrontMiddle Brake		0	0.05	Ferrous	NR	115	4	333 SealFrontRight SealbelFrontMiddle		
116	SealFrontRight SealbelFrontMiddle Strap		5	0.08	Polyester	N	116	1	10 SealFrontRight SealbelFrontMiddle Latch		
117	SealFrontLeft	202	785	27.24	Mixed	—	117	0	785 Nothing		Power motor - not functional
118	SealFrontLeft SealbelFrontMiddleLower	210	0	0.18	Mixed	—	118	3	940 SealFrontLeft ArmRest, SealFrontLeft		
119	SealFrontLeft SealbelFrontMiddleLower Buckle		8	0.08	SKOS	N	119	0	8 Nothing		
120	SealFrontLeft SealbelFrontMiddleLower Bracket		0	0.06	Ferrous	NR	120	4	SealFrontLeft SealbelFrontLower Buckle, SealFrontLeft ArmRest, SealFrontLeft		
121	SealFrontLeft SealbelFrontMiddleLower Strap		0	0.04	Polyester	N	121	1	8 SealFrontLeft SealbelFrontLower Buckle		
122	SealFrontLeft HeadRest	206	10	0.88	Mixed	—	122	0	10 Nothing		
123	SealFrontLeft HeadRest Cover		50	0.14	Textile contaminated	NR	123	0	50 Nothing		Contaminated foam+glue
124	SealFrontLeft HeadRest Base		0	0.76	Mixed	—	124	2	60 SealFrontLeft HeadRest Cover, SealFrontLeft HeadRest		
125	SealFrontLeft HeadRest Base Foam		4	0.62	PUR	N	125	3	64 SealFrontLeft HeadRest Base		
126	SealFrontLeft HeadRest Base Steel		0	0.12	Ferrous	NR	126	4	64 SealFrontLeft HeadRest Base Foam		
127	SealFrontLeft LateralCover		20	0.14	SKOP	N	127	1	805 SealFrontLeft	3-Ph	
128	SealFrontLeft BackFoam		85	0.68	PUR	N	128	0	85 Nothing		Contaminated foam+glue
129	SealFrontLeft BackCover		2	0.80	Textile contaminated	NR	129	1	87 SealFrontLeft BackFoam		
130	SealFrontLeft ArmRestCovers		10	0.04	SKOP	N	130	0	10 Nothing		
131	SealFrontLeft ArmRest		145	0.72	Mixed	—	131	1	155 SealFrontLeft ArmRestCovers	1-LongScrew?	
132	SealFrontLeft ArmRestBigCover		1	0.08	SKOP	N	132	2	156 SealFrontLeft ArmRest		
133	SealFrontLeft ArmRest Cover		45	0.16	Textile contaminated	NR	133	2	200 SealFrontLeft ArmRest		Contaminated foam+glue
134	SealFrontLeft ArmRest Base		0	0.56	Mixed	—	134	3	200 SealFrontLeft ArmRest Cover		
135	SealFrontLeft ArmRest Base Foam		115	0.16	PUR	N	135	4	315 SealFrontLeft ArmRest Base		
136	SealFrontLeft ArmRest Base Steel		0	0.40	Ferrous	NR	136	5	315 SealFrontLeft ArmRest Base Foam		

#	Name	Parts H.#	Time (secs)	Mass (kg)	Material	Marked	#	Total # before	Cum time	Before	Fasteners	Comments
137	SeatFrontLeft BottomCover		100	0.42	Textile contaminated	NR	137	2	905	SeatFrontLeft LateralCover		Contaminated foam+glue
138	SeatFrontLeft BottomFoam		82	0.90	PUR	N	138	3	987	SeatFrontLeft BottomCover SeatFrontLeft BottomFoam, SeatFrontLeft ArmRestBogCover, SeatFrontLeft ArmRestCovers, SeatFrontLeft BackCover, SeatFrontLeft BackFoam, SeatFrontLeft HeadRest, SeatFrontLeft SeatbeltFrontMiddleLower		In the case of the bottom foam, we have chosen to use the dismantling method which is prejudicial towards foam
139	SeatFrontLeft BottomBase		0	22.04	Mixed	—	139	1	1240			
140	SeatFrontLeft BottomBase Steel			20.94	Ferrous	NR	140	0	M			
141	SeatFrontLeft BottomBase SKOS			1.10	SKOS	N	141	0	M			
142	RearviewMirror		10	0.30	SKOS	N	142	0	10	Nothing		
143	SeatRearBottom	215	43	6.64	Mixed	—	143	0	43	Nothing	2-Clips	Contaminated foam+glue
144	SeatRearBottom Cover		30	1.00	Textile contaminated	NR	144	0	30	Nothing		
145	SeatRearBottom Base		0	5.68	Mixed	—	145	2	73	SeatRearBottom Cover, SeatRearBottom		
146	SeatRearBottom Base Foam		1524	2.52	PUR	N	146	3	1597	SeatRearBottom Base		
147	SeatRearBottom Base Steel		0	3.06	Mixed	—	147	4	1597	SeatRearBottom Base Foam		
148	SeatRearBottom Base Steel SKOP			2.91	Ferrous	NR	148	0	M			
149	SeatRearBottom Base Steel SKOP			0.15	SKOP	N	149	0	M			
150	SeatRearBack	215	16	7.20	Mixed	—	150	1	59	SeatRearBottom	2-10	
151	SeatRearBack Base		0	6.02	Mixed	—	151	3	93	SeatRearBack, SeatRearBack Cover SeatRearBack Base		
152	SeatRearBack Base Steel		0	3.28	Mixed	—	152	5	518	SeatRearBack Base Foam		
153	SeatRearBack Base Steel			0.03	Ferrous	NR	153	0	M			
154	SeatRearBack Base Steel SKOP			3.25	SKOP	N	154	0	M			
155	SeatRearBack Base Foam		425	2.70	Mixed	—	155	0	425	Nothing		
156	SeatRearBack Base Foam		0	2.48	PUR	N	156	2	545	SeatRearBack Base Foam, SeatRearBack Base Foam, SKOS		
157	SeatRearBack Base Foam SKOS		120	0.22	SKOS	N	157	1	545	SeatRearBack Base Foam		
158	SeatRearBack Cover		34	1.14	Textile contaminated	NR	158	0	34	Nothing		Contaminated foam+glue is it recyclable with the clips on it?
159	APillarTrimLeft		3	0.20	Mixed	—	159	0	3	Nothing	3-Clips	
160	APillarTrimLeft Clips		20	0.01	Ferrous	NR	160	1	23	APillarTrimLeft		
161	APillarTrimLeft ABS			0.19	ABS	Y	161	2	23	APillarTrimLeft Clips		
162	APillarTrimRight		5	0.20	Mixed	—	162	0	5	Nothing	3-Clips	
163	APillarTrimRight Clips		20	0.01	Ferrous	NR	163	1	25	APillarTrimRight		
164	APillarTrimRight ABS			0.19	ABS	Y	164	2	25	APillarTrimRight Clips		
165	SurvivorRight		9	0.52	SKOS	N	165	0	9	Nothing	3-Ph	
166	SurvivorLeft		9	0.80	SKOS	N	166	0	9	Nothing	3-Ph	
167	GrabHandleFrontRight		9	0.10	SKOS	N	167	0	9	Nothing	2-Ph	
168	GrabHandleRearRight		9	0.10	SKOS	N	168	0	9	Nothing	2-Ph	
169	GrabHandleRearLeft		9	0.10	SKOS	N	169	0	9	Nothing	2-Ph	
170	Clothes-hangerRight		5	0.01	SKOP	N	170	0	5	Nothing	1-Ph	
171	Clothes-hangerLeft		5	0.01	SKOP	N	171	0	5	Nothing	1-Ph	

#	Name	Parts H.#	Time (secs)	Mass (kg)	Material	Marked	#	Total # before	Cum time	Before	Fasteners	Comments
172	DomelightCover		3	0.04	SKOP	N	172	0	3	Nothing		
173	DomelightAssembly		10	0.16	SKOS	N	173	1	13	Domelight Cover	1-Ph	
174	CPillarRight		7	0.40	PP	Y	174	0	7	Nothing		HCPP
175	CPillarLeft		7	0.40	PP	Y	175	0	7	Nothing		HCPP
176	SeatbeltFrontRightCover		7	0.01	SKOP	N	176	0	7	Nothing		
177	BPillarUpperRight		13	0.10	PP	Y	177	1	20	SeatbeltFrontRightCover		
178	SeatbeltFrontLeftCover		2	0.01	SKOP	N	178	0	2	Nothing		
179	BPillarUpperLeft		10	0.10	PP	Y	179	1	12	SeatbeltFrontLeftCover		
180	Headliner	224	8	2.00	SKOS	N	180	1	130	BPillarUpperLeft, BPillarUpperRight, SunvisorRight, SunvisorLeft, APillarTrimLeft, APillarTrimRight, GrabHandleFrontRight, GrabHandleRearRight, GrabHandleRearLeft, ClothesHangerRight, ClothesHangerLeft, CPillarRight, CPillarLeft	5-Ph, 500T	
181	BPillarLowerRight		65	0.72	TPO	Y	181	2	85	BPillarUpperRight	5-Ph, 500T	
182	BPillarLowerLeft		43	0.70	TPO	Y	182	2	55	BPillarUpperLeft	5-Ph, 500T	
183	SeatbeltFrontRight	210	12	1.40	Mixed	—	183	3	97	BPillarLowerRight	1-Ph, 500T	
184	SeatbeltFrontRightSteelcase		0	0.86	Mixed	—	184	7	174	SeatbeltFrontRight, Strap		
185	SeatbeltFrontRightSteelcaseSteel			0.82	Ferrous	NR	185	0		M		
186	SeatbeltFrontRightSteelcaseSKOP			0.04	SKOP	N	186	0		M		
187	SeatbeltFrontRightStrap		20	0.16	Polyester	N	187	6	174	SeatbeltFrontRight, Lead		
188	SeatbeltFrontRightOthers		12	0.10	Mixed	—	188	4	109	SeatbeltFrontRight		
189	SeatbeltFrontRightOthersSteel			0.09	Ferrous	NR	189	0		M		
190	SeatbeltFrontRightOthersSKOP			0.01	SKOP	N	190	0		M		
191	SeatbeltFrontRightLead		45	0.02	Lead	N	191	5	154	SeatbeltFrontRight Others		
192	SeatbeltFrontLeft	210	20	1.40	Mixed	—	192	3	75	BPillarLowerLeft	1-Ph, 500T	
193	SeatbeltFrontLeftSteelcase		0	0.86	Mixed	—	193	7	132	SeatbeltFrontLeft, Strap		
194	SeatbeltFrontLeftSteelcaseSteel			0.82	Ferrous	NR	194	0		M		
195	SeatbeltFrontLeftSteelcaseSKOP			0.04	SKOP	N	195	0		M		
196	SeatbeltFrontLeftStrap		20	0.16	Polyester	N	196	6	132	SeatbeltFrontLeft, Lead		
197	SeatbeltFrontLeftOthers		12	0.24	Mixed	—	197	4	87	SeatbeltFrontLeft		
198	SeatbeltFrontLeftOthersSteel			0.22	Ferrous	NR	198	0		M		
199	SeatbeltFrontLeftOthersSKOP			0.02	SKOP	N	199	0		M		
200	SeatbeltFrontLeftLead		25	0.02	Lead	N	200	5	112	SeatbeltFrontLeft Others		
201	BPillarShoddyRight		2	0.08	Mixed	NR	201	4	99	SeatbeltFrontRight	2Snaps	
202	BPillarShoddyRightShoddy		23	0.03	Shoddy	NR	202	5	122	BPillarShoddyRight		
203	BPillarShoddyRightSKOP		0	0.05	SKOP	N	203	6	122	BPillarShoddyRight, Shoddy		Steel staples and shoddy as contamination
204	BPillarShoddyLeft		2	0.10	Mixed	—	204	4	77	SeatbeltFrontLeft	2Snaps	
205	BPillarShoddyLeftShoddy		23	0.04	Shoddy	NR	205	5	100	BPillarShoddyLeft		Steel staples and shoddy as contamination
206	BPillarShoddyLeftSKOP		0	0.06	SKOP	N	206	6	100	BPillarShoddyLeft, Shoddy		Steel staples and shoddy as contamination
207	QuarternRight		15	0.18	Mixed	—	207	5	159	SeatRearBottom, SeatRearBack, BPillarLowerRight	1-Ph, 1-500T	
208	QuarternRightShoddy		3	0.08	Shoddy	NR	208	6	162	QuarternRight		
209	QuarternRightPP		0	0.10	PP	Y	209	7	162	QuarternRight, Shoddy		
210	QuarternLeft		16	0.18	Mixed	—	210	5	130	SeatRearBottom, SeatRearBack, BPillarLowerLeft	1-Ph, 1-500T	
211	QuarternLeftShoddy		3	0.08	Shoddy	NR	211	6	133	QuarternLeft		
212	QuarternLeftPP		0	0.10	PP	Y	212	7	133	QuarternLeft, Shoddy		
213	KickPanelRight		17	0.06	PP	Y	213	4	107	APillarTrimRight, BPillarLowerRight	1-Ph	

#	Name	Parts H.#	Time (secs)	Mass (kg)	Material	Marked	#	Total # before	Cum time	Refuses	Fasteners	Comments
214	KickPanelLeft		9	0.06	PP	Y	214	4	67	APillarTrimLeft, BPillarLowerLeft	1-Ph	
215	ThirdBrakeLight		60	0.34	Mixed		215	0	60	Nothing	2-Ph	Difficult to reach screw
216	ThirdBrakeLight Lens		2	0.01	SKOP	N	216	1	62	ThirdBrakeLight		Contaminated chrome paint
217	ThirdBrakeLight Reflector		5	0.04	PC contaminated	Y	217	2	67	ThirdBrakeLight Lens		
218	ThirdBrakeLight Case		0	0.26	Mixed		218	3	67	ThirdBrakeLight Reflector		
219	ThirdBrakeLight Case Steel		15	0.06	Ferrous	NR	219	4	82	ThirdBrakeLight Case		
220	ThirdBrakeLight Case Plastic		0	0.20	SKOP	N	220	5	82	ThirdBrakeLight Case Steel		
221	SpeakerCovers(?)		3	0.22	Ferrous	NR	221	0	3	Nothing		With paint
222	ParcelTray	221	23	1.58	SKOS	N	222	4	145	ThirdBrakeLight, SeatRearBack, SpeakerCover (2)		
223	SpeakerRearLeft	644	27	0.70	Mixed		223	5	172	ParcelTray		3-5.5mm 1-EC
224	SpeakerRearLeft Steel			0.67	Ferrous	NR	224	0	M			
225	SpeakerRearLeft SKOP			0.04	SKOP	N	225	0	M			
226	SpeakerRearRight	644	36	0.70	Mixed		226	5	181	ParcelTray		3-5.5 1-EC
227	SpeakerRearRight Steel			0.67	Ferrous	NR	227	0	M			
228	SpeakerRearRight SKOP			0.04	SKOP	N	228	0	M			
229	ParcelTrayShoddy		31	0.68	Shoddy	NR	229	7	238	SpeakerRearLeft, SpeakerRearRight		
230	BackSeatShoddy		10	2.18	Shoddy	NR	230	2	69	SeatRearBack		
231	SeatbeltRearRight	210	47	0.96	Mixed		231	5	192	ParcelTray		1-500T, 1-40
232	SeatbeltRearRight Steelcase		0	0.62	Mixed		232	1	234	SeatbeltRearRight, Strap, Steelcase		
233	SeatbeltRearRight Steelcase Steel			0.59	Ferrous	NR	233	0	M			
234	SeatbeltRearRight Steelcase SKOP			0.03	SKOP	N	234	0	M			
235	SeatbeltRearRight Strap		5	0.14	Polyester	N	235	8	226	SeatbeltRearRight Lead		
236	SeatbeltRearRight PlasticCase		8	0.02	SKOP	N	236	0	8	Nothing		
237	SeatbeltRearRight Others		4	0.10	Mixed		237	6	196	SeatbeltRearRight		
238	SeatbeltRearRight Others Steel			0.09	Ferrous	NR	238	0	M			
239	SeatbeltRearRight Others SKOP			0.01	SKOP	N	239	0	M			
240	SeatbeltRearRight Lead		25	0.02	Lead	N	240	7	221	SeatbeltRearRight Others		
241	SeatbeltRearLeft	210	47	0.96	Mixed		241	5	192	ParcelTray		1-500T, 1-40
242	SeatbeltRearLeft Steelcase		0	0.62	Mixed		242	1	234	SeatbeltRearLeft, Strap, Steelcase		
243	SeatbeltRearLeft Steelcase Steel			0.59	Ferrous	NR	243	0	M			
244	SeatbeltRearLeft Steelcase SKOP			0.03	SKOP	N	244	0	M			
245	SeatbeltRearLeft Strap		5	0.14	Polyester	N	245	8	226	SeatbeltRearLeft Lead		
246	SeatbeltRearLeft PlasticCase		8	0.02	SKOP	N	246	0	8	Nothing		
247	SeatbeltRearLeft Others		4	0.10	Mixed		247	6	196	SeatbeltRearLeft		
248	SeatbeltRearLeft Others Steel			0.09	Ferrous	NR	248	0	M			
249	SeatbeltRearLeft Others SKOP			0.01	SKOP	N	249	0	M			
250	SeatbeltRearLeft Lead		25	0.02	Lead	N	250	7	221	SeatbeltRearLeft Others		
251	SeatbeltRearRightLower	210	12	0.36	Mixed		251	1	55	SeatRearBottom		1-18mm
252	SeatbeltRearRightLower Others		15	0.10	Mixed		252	0	15	Nothing		
253	SeatbeltRearRightLower Others Steel			0.09	Ferrous	NR	253	0	M			
254	SeatbeltRearRightLower Others SKOP			0.01	SKOP	N	254	0	M			
255	SeatbeltRearRightLower Strap		15	0.08	Polyester	N	255	1	30	SeatbeltRearRightLower Others		
256	SeatbeltRearRightLower Buckle		0	0.08	SKOS	N	256	3	32	SeatbeltRearRightLower PlasticCase		
257	SeatbeltRearRightLower Latch		0	0.10	Ferrous	NR	257	3	32	SeatbeltRearRightLower PlasticCase		
258	SeatbeltRearRightLower PlasticCase		2	0.02	SKOP	N	258	2	32	SeatbeltRearRightLower Strap		
259	SeatbeltRearLeftLower	210	8	0.26	Mixed		259	1	51	SeatRearBottom		1-18mm
260	SeatbeltRearLeftLower Strap		0	0.04	Polyester	N	260	5	96	SeatbeltRearLeftLower Buckles		
261	SeatbeltRearLeftLower PlasticCase		15	0.02	SKOP	N	261	0	15	Nothing		
262	SeatbeltRearLeftLower Steel		10	0.10	Ferrous	NR	262	1	25	SeatbeltRearLeftLower PlasticCase		

#	Name	Parts H.#	Time (secs)	Mass (kg)	Material	Marked	#	Total # before	Cum time	Before	Fasteners	Comments	
263	SeatbeltRearLeftLower Buckles		20	0.14	SKOS	N	263	2	45	SeatbeltRearLeftLower Steel			
264	LowerIP		60	1.12	Mixed	--	264	0	60	Nothing	4-277		
265	LowerIP Steel		0	1.09	Ferrous	NR	265	2	65	LowerIP.SKOP. LowerIP			
266	LowerIP SKOP		5	0.03	SKOP	N	266	0	5	Nothing			
267	LowerIPReinforcement		8	0.18	Ferrous	NR	267	1	68	LowerIP	2-8mm		
268	LowerIPReinforcement2		44	1.22	Ferrous	NR	268	2	112	LowerIPReinforcement	4-13mm		
269	SpeakerRearRight Steel			0.67	Ferrous	NR	269	269		M			
270	SpeakerRearRight SKOP			0.04	SKOP	N	270	270		M			
271	SteeringColumnSupport		120	2.26	Mixed	--	271	8	1354	InstrumentPanel	5-10mm		
272	SteeringColumnSupport Electrical		20	0.28	SKOS	N	272	9	1374	SteeringColumnSupport			
273	SteeringColumnSupport Case		0	1.80	Aluminum	N	273	1	1379	SteeringColumnSupport Electrical.			
274	SteeringColumnSupport Bracket		5	0.14	Ferrous	NR	274	9	1359	SteeringColumnSupport Bracket			
275	SteeringColumnTurnSignal		25	0.22	SKOS	N	275	4	262	SteeringColumnSupport			
276	SteeringColumnLowerPanel		125	0.08	SKOP	N	276	3	237	SteeringColumnLowerPanel			
										LowerIPReinforcement2			
277	SteeringColumnAssembly		140	10.06	Mixed	--	277	5	402	SteeringColumnTurnSignal	4-13mm, 2-20T, 5- Column can't be removed all in one piece		
278	SteeringColumnAssembly AirBag		60	1.70	Mixed	--	278	0	60	Nothing	Clips		
279	SteeringColumnAssembly AirBag Steel			1.19	Ferrous	NR	279	0		M			
280	SteeringColumnAssembly AirBag SKOS			0.51	SKOS	N	280	0		M			
281	SteeringColumnAssembly Base		0	8.36	Mixed	--	281	7	462	SteeringColumnAssembly AirBag.			
282	SteeringColumnAssembly Base Steel			7.52	Ferrous	NR	282	0		M			
283	SteeringColumnAssembly Base SKOP			0.84	SKOP	N	283	0		M			
284	TrunkCloseOut		7	0.84	Mixed	--	284	0	7	Nothing			
285	TrunkCloseOut Shoddy		0	0.26	Shoddy	NR	285	2	57	TrunkCloseOut. TrunkCloseOut.SKOS			
286	TrunkCloseOut SKOS		50	0.58	SKOS	N	286	1	57	TrunkCloseOut		Big piece of plastic with staples	
287	TrunkScuffPlateRear		2	0.12	PP	Y	287	0	2	Nothing			
288	TrunkSpareTireCover		2	1.80	Mixed	--	288	0	2	Nothing			
289	TrunkSpareTireCover Carpet		45	0.19	Textile	NR	289	1	47	TrunkSpareTireCover	Glue		
290	TrunkSpareTireCover Cardboard		0	1.61	SKOS	N	290	2	47	TrunkSpareTireCover Carpet	Cardboard with sponge		
291	SpareTire		3	11.30	Mixed	--	291	2	27	Jack			
292	SpareTire Rim		126	6.55	Ferrous	NR	292	3	153	SpareTire			
293	SpareTire Rubber		0	4.73	Rubber	NR	293	4	153	SpareTire Rim			
294	Jack		22	2.44	Ferrous	NR	294	1	24	SpareTire Rim			
295	TrunkLiner		33	3.56	Mixed	--	295	4	62	TrunkSpareTireCover	Butterfly		
296	TrunkLiner Shoddy		245	0.24	Shoddy	NR	296	5	307	SpareTire. TrunkScuffPlateRear			
297	TrunkLiner Carpet		0	3.32	Carpet	NR	297	6	307	TrunkLiner			
298	WeatherStripping		66	6.78	Elastomer	N	298	0	66	TrunkLiner Shoddy			
299	TailLightCoverRight		91	0.54	SKOP	N	299	0	91	Nothing	3 wing nuts	Black part is ABS. painted with chrome	
300	TailLightCoverRight Red		100	0.16	SKOP	N	300	1	191	TailLightCoverRight			
301	TailLightCoverRight Black		0	0.38	ABS contaminated	Y	301	2	191	TailLightCoverRight.Red			
302	TailLightCoverLeft		166	91	0.52	SKOP	N	302	0	91	Nothing	3 wing nuts	Black part is ABS. painted with chrome
303	TailLightCoverLeft Red		100	0.16	SKOP	N	303	1	191	TailLightCoverLeft			
304	TailLightCoverLeft Black		0	0.38	ABS contaminated	Y	304	2	191	TailLightCoverLeft.Red			



#	Name	Parts H.#	Time (secs)	Mass (kg)	Material	Marked	#	Total # before	Cum time	Before	Fasteners	Comments
305	TailLightCoverCenter	166	59	1.28	SKOS	N	305	0	55	Nothing	12-10mm	Includes License Plate Holder Has large metal pieces that must be removed by the plastic shredder
306	FasciaRearUpper	1907	61	1.73	PLUR	N	306	0	61	Nothing	10-11mm	
307	FasciaRearLower	1907	117	8.56	Zenoid	N	307	0	117	Nothing	6-10mm	
308	EnergyAbsorberRearLeft	108	25	2.46	Ferrous	NR	308	1	142	FasciaRearLower	2-13mm	
309	EnergyAbsorberRearRight	108	35	2.46	Ferrous	NR	309	1	152	FasciaRearLower	2-13mm	
310	DeckLid	170	110	13.26	Mixed	—	310	0	110	Nothing	4-8mm, 1-EC	Center light was part of this, but hasn't been included in the weight yet
311	DeckLid Steel			13.13	Ferrous	NR	311	0	M			
312	DeckLid SKOS			0.13	SKOS	N	312	0	M			
313	WingHarnessCloseOut		7	0.30	SKOP	N	313	0	7	Nothing		2 WipersCombined
314	WiperAssemblies	626	14	0.92	Mixed	—	314	0	14	Nothing		
315	WiperAssemblies Steel		100	0.66	Ferrous	NR	315	1	114	WiperAssemblies		
316	WiperAssemblies Blade		0	0.06	Mixed	—	316	2	114	WiperAssemblies.Steel		
317	WiperAssemblies Blade Elastomer		0	0.04	SKOR	N	317	3	114	WiperAssemblies.Blade		Elastomer
318	WiperAssemblies.Blade SKOM		0	0.02	SKOM	N	318	3	114	WiperAssemblies.Blade		Usually one piece (2 pieces this time) Some foam+glue contamination \$20-\$25 if it works, \$1-\$0.75 if it doesn't
319	CowlVent	123	73	0.54	ABS	Y	319	1	87	WiperAssemblies	10-Ph	
320	Battery	600	48	20.00	Core product	NR	320	0	48	Nothing		
321	AirCleanerAssembly	319	21	1.70	Mixed	—	321	1	69	Battery	4-8mm	
322	AirCleanerAssembly Hose		10	0.40	Mixed	—	322	2	79	AirCleanerAssembly		
323	AirCleanerAssembly Hose Clamp		2	0.06	SKOM	N	323	3	81	AirCleanerAssembly.Hose		
324	AirCleanerAssembly Hose SKOR		0	0.34	SKOR	N	324	4	81	AirCleanerAssembly.Hose.Clamp		Rubber
325	AirCleanerAssembly Top		60	0.40	PP	Y	325	3	139	AirCleanerAssembly.Hose	4-9mm	
326	AirCleanerAssembly Bottom		0	0.66	PP	Y	326	4	139	AirCleanerAssembly.Top		
327	AirCleanerAssembly Filter		0	0.18	SKOS	N	327	4	139	AirCleanerAssembly.Top		
328	WasherCoolantBottleAssembly	627	18	0.90	Mixed	—	328	0	19	Nothing	1-8mm	
329	WasherCoolantBottleAssembly Bottles		0	0.82	PP	Y	329	2	38	WasherCoolantBottleAssembly.Rubber		
330	WasherCoolantBottleAssembly Rubber		20	0.08	SKOR	N	330	1	38	WasherCoolantBottleAssembly		
331	HeatBoxAssemblyBase		45	2.24	PET	Y	331	0	45	Nothing	1-7mm, 1-8mm, 5-11mm, 1-ODC, 1-Vac	
332	HeatBoxAssembly	673	780	8.64	Mixed	—	332	8	2014	InstrumentPanel		
333	HeatBoxAssembly EC		37	0.24	SKOS	N	333	9	2051	HeatBoxAssembly	3-5-16	
334	HeatBoxAssembly LateralCover		49	0.05	PP	Y	334	1	2100	HeatBoxAssembly.EC	4-5-16	
335	HeatBoxAssembly Elastomer		5	0.05	SKOR	N	335	1	2105	HeatBoxAssembly.LateralCover		Elastomer
336	HeatBoxAssembly Filter1		5	0.81	Aluminum	N	336	1	2110	HeatBoxAssembly.Elastomer		
337	HeatBoxAssembly SpringHeater		25	0.04	SKOS	N	337	9	2039	HeatBoxAssembly	2-5-16	
338	HeatBoxAssembly Panel1		10	0.23	Mixed	—	338	9	2024	HeatBoxAssembly	2 Clips	

#	Name	Parts H #	Time (secs)	Mass (kg)	Material	Marked	Total # before	Cum time	Before	Fasteners	Comments
339	HeatBoxAssembly_Panell1 Sponge		10	0.02	SKOP	N	339	1	2034 HeatBoxAssembly_Panell1		
340	HeatBoxAssembly_Panell1 PP		0	0.21	PP	Y	340	1	2034 HeatBoxAssembly_Panell1_Sponge	6-5/16	Contaminated with glue and sponge
341	HeatBoxAssembly_Duct1		60	0.77	Mixed		341	1	2084 HeatBoxAssembly_Panell1	2-5/16, 1-Clip	Mostly Al
342	HeatBoxAssembly_Duct1 Pump		10	0.10	Mixed		342	9	2024 HeatBoxAssembly		
343	HeatBoxAssembly_Duct1 Pump_Aluminum			0.08	Aluminum	N	343	0	M		
344	HeatBoxAssembly_Duct1 Pump_SKOP			0.02	SKOP	N	344	0	M		
345	HeatBoxAssembly_Duct1 Structure		0	0.67	Mixed		345	1	2084 HeatBoxAssembly_Duct1_Pump		
346	HeatBoxAssembly_Duct1 Structure_Steel		10	0.04	Ferrous	NR	346	1	2104 HeatBoxAssembly_Duct1		Mostly PP
347	HeatBoxAssembly_Duct1 Structure_PP		0	0.56	PP	Y	347	1	2104 HeatBoxAssembly_Duct1_Structure		
348	HeatBoxAssembly_Duct1 Structure_SKOS		30	0.07	SKOS	N	348	1	2134 HeatBoxAssembly_Duct1_Structure_SKOS		
349	HeatBoxAssembly_Elastomer2		5	0.13	SKOR	N	349	9	2019 HeatBoxAssembly		Elastomer
350	HeatBoxAssembly_Fan		30	0.12	PP	Y	350	1	2114 HeatBoxAssembly_Duct1	1-Clip	
351	HeatBoxAssembly_Motor		60	1.60	Mixed		351	1	2174 HeatBoxAssembly_Fan	5-5/16	
352	HeatBoxAssembly_Motor_Steel			1.20	Ferrous	NR	352	0	M		
353	HeatBoxAssembly_Motor_Copper			0.24	Copper	NP	353	0	M		
354	HeatBoxAssembly_Motor_SKOS			0.16	SKOS	N	354	0	M		
355	HeatBoxAssembly_Duct2		45	0.50	Mixed		355	1	2069 HeatBoxAssembly_Panell1	2-5/16, 2-3/16	
356	HeatBoxAssembly_Duct2_SKOS		10	0.03	SKOS	N	356	1	2079 HeatBoxAssembly_Duct2		
357	HeatBoxAssembly_Duct2_PP		0	0.47	PP	Y	357	1	2079 HeatBoxAssembly_Duct2_SKOS		
358	HeatBoxAssembly_Eox		0	3.85	Mixed		358	2	2345 HeatBoxAssembly_Duct2		
359	HeatBoxAssembly_Box_SKOP		0	0.09	SKOP	N	359	2	2945 HeatBoxAssembly_Motor		
360	HeatBoxAssembly_Box_Filter2		600	1.81	Aluminum	N	360	2	2945 HeatBoxAssembly_Elastomer2		
361	HeatBoxAssembly_Box_PP		0	1.95	PP	Y	361	2	2945 HeatBoxAssembly_SpringHeater		
362	GasPedalAssembly		41	0.52	Mixed		362	0	2945 HeatBoxAssembly_Filter1	Glue, 8-5/16, 3Clips	
363	GasPedalAssembly_Steel		45	0.48	Ferrous	NR	363	1	2945 HeatBoxAssembly_Box_Filter2	2-13mm, 1clip	
364	GasPedalAssembly_SKOP		0	0.04	SKOP	N	364	2	86 GasPedalAssembly	4-13mm, 1-10mm, 1 clip	
365	BreakPedalAssembly		77	2.23	Mixed		365	6	1311 InstrumentPanel	1-8mm	
366	BreakPedalAssembly_Bracket		5	0.26	Ferrous	NR	366	9	1316 BreakPedalAssembly		
367	BreakPedalAssembly_Rubber		10	0.07	SKOR	N	367	1	1326 BreakPedalAssembly_Bracket		
368	BreakPedalAssembly_Base		0	1.90	Ferrous	NR	368	1	1326 BreakPedalAssembly_Rubber		
369	SteeringColumnSupport2		12	0.62	SKOS	N	369	8	1246 InstrumentPanel	3-11mm	
370	TrunkReleaseCase		10	0.04	ABS	N	370	0	10 Nothing	1-Ph, 1 pushin	
371	Carpet	222	40	15.88	Mixed		371	1	1078 APillarTrimLeft, APillarTrimRight, BPillarLowerLeft, BPillarLowerRight, CPillarLeft, CPillarRight, SeatFrontRight, SeatFrontLeft		Wet
372	Carpet_Shoddy		73	6.38	Shoddy	NR	372	1	1151 Carpet		
373	Carpet_Carpet		0	9.50	Carpet	NR	373	1	1151 Carpet_Shoddy		
374	RearHeaterDuct		7	0.78	PP	Y	374	1	1085 Carpet	2-7mm	
375	ECU	5907	47	1.08	Mixed		375	1	94 InstrumentPanel_GloveBox	2-11mm	
376	ECU_Steel			0.11	Ferrous	NR	376	0	M		
377	ECU_Aluminum			0.22	Aluminum	N	377	0	M		
378	ECU_SKOS			0.76	SKOS	N	378	0	M		
379	EmergencyBrake		35	1.62	Ferrous	NR	379	3	147 LowerPReinforcement2	3-10mm, 1 steel cut	
380	FrontInsulator		76	6.34	Mixed		380	1	EmergencyBreak, Instrument_Panell		
381	FrontInsulator_Shoddy		120	0.98	Shoddy	NR	381	1	1463 GasPedalAssembly, BreakPedalAssembly		
382	FrontInsulator_SKOS		0	5.36	SKOS	N	382	1	1583 FrontInsulator_SKOS		

#	Name	Parts H #	Time (secs)	Mass (kg)	Material	Marked #	Total # before	Cum time	Before	Fasteners	Comments
383	BatteryCase	607	20	0.76	SKOP	N	383	1	Battery	3-10mm	Easier after Drivetrain
384	BrakeBooster	540	100	4.14	Mixed	--	384	0	Nothing	2-12mm, 2-14mm	Contaminated with a good deal of Steel
385	BrakeBooster Steel		2.28	Ferrous	NR	385	0	M			
386	BrakeBooster Aluminum		1.24	Aluminum	N	386	0	M			
387	BrakeBooster SKOP		0.62	SKOP	N	387	0	M			Sponge with glue
388	FirewallInsulation		9	0.44	SKOS	N	388	2	1859 DriveTrain, BrakeBooster	3-Ph	
389	CoolingFanShroudAssembly	672	17	3.66	Mixed	--	389	0	Nothing	2-11mm	
390	CoolingFanShroudAssembly Steel		1.47	Ferrous	NR	390	0	M			
391	CoolingFanShroudAssembly SKOS		2.21	Ferrous	NR	391	0	M			
392	CoolingFanModule	655?	6	0.72	Mixed	--	392	0	Nothing	2-11mm	
393	CoolingFanModule Steel		0.50	Ferrous	NR	393	0	M			
394	CoolingFanModule SKOS		0.22	SKOS	N	394	0	M			
395	AirBagSensor	653/65	7	0.34	Mixed	--	395	0	Nothing	4-8mm	
396	AirBagSensor Steel		0.27	Ferrous	NR	396	0	M			
397	AirBagSensor SKOS		0.07	SKOS	N	397	0	M			
398	CruiseServo	623/6	11	1.08	Mixed	--	398	0	Nothing	2-13mm	
399	CruiseServo Steel		0.22	Ferrous	NR	399	0	M			
400	CruiseServo SKOS		0.86	SKOS	N	400	0	M			
401	EngineHarness	648	60	3.16	Mixed	--	401	3	AirBagSensor, CoolingFanModule, DriveTrain	1-8mm	
402	EngineHarness Steel		0.63	Ferrous	NR	402	0	M			
403	EngineHarness Copper		0.47	Copper	NR	403	0	M			
404	EngineHarness SKOS		2.05	SKOS	N	404	0	M			
405	ACManifoldAssembly		15	3.90	Mixed	--	405	1	1765 DriveTrain	3-8mm	
406	ACManifoldAssembly Steel		3.32	Ferrous	NR	406	0	M			
407	ACManifoldAssembly SKOS		0.59	SKOS	N	407	0	M			
408	AirBagSensor2	653/65	45	0.26	Mixed	--	408	0	Nothing	2-8mm	
409	AirBagSensor2 Steel		0.21	Ferrous	NR	409	0	M			
410	AirBagSensor2 SKOS		0.05	SKOS	N	410	0	M			
411	AssortedJunk		340	3.30	SKOS	N	411	1	2090 DriveTrain		
412	AirDam		15	0.34	Elastomer	N	412	0	Nothing	3-Ph	
413	WheelHouseLinerFrontRight		45	1.22	Mixed	--	413	0	Nothing	4-Pushin	
414	WheelHouseLinerFrontRight SKOS		3	1.13	SKOS	N	414	1	48 WheelHouseLinerFrontRight		
415	WheelHouseLinerFrontRight PP		0	0.09	PP	Y	415	2	48 WheelHouseLinerFrontRight SKOS		Contaminated material with (4 big) staples, (4) clips
416	WheelHouseLinerFrontLeft		45	1.10	Mixed	--	416	0	Nothing	4-Pushin	
417	WheelHouseLinerFrontLeft SKOS		3	1.13	SKOS	N	417	1	48 WheelHouseLinerFrontLeft		
418	WheelHouseLinerFrontLeft PP		0	0.09	PP	Y	418	2	48 WheelHouseLinerFrontLeft SKOS		Contaminated material with (4 big) staples, (4) clips
419	CharcoalCanister		8	0.82	SKOS	N	419	0	Nothing	1-8mm	
420	VacuumTank		7	0.74	SKOP	N	420	1	52 WheelHouseLinerFrontLeft	1-8mm	Contaminated with Elastomer
421	HomAssembly	613	2	0.60	Mixed	--	421	0	Nothing	1-13mm	
422	HomAssembly Steel		0.48	Ferrous	NR	422	0	M			
423	HomAssembly SKOP		0.12	SKOP	N	423	0	M			

#	Name	Parts H.#	Time (secs)	Mass (kg)	Material	Marked	#	Total # before	Cum time	Before	Fasteners	Comments
424	RockerMoldingRight	189	75	1.44	Elastomer	Y	424	0	75	Nothing	7-Pushin, 1-nvel	EPDM
425	RockerMoldingLeft	189	42	1.40	Elastomer	Y	425	0	42	Nothing	7-Pushin	EPDM
426	WheelRearRight	560	15	16.28	Mixed	—	426	0	15	Nothing	5-lognuts	PC-ABS
427	WheelRearRightCover	570	1	0.18	PC	Y	427	0	1	Nothing		
428	WheelRearRight Rim	126	7.18	Aluminum	N	428	1	141	WheelRearRight			
429	WheelRearRight Rubber	585	1	8.84	SKOR	N	429	2	142	WheelRearRight Rim		
430	WheelRearLeft	560	15	16.38	Mixed	—	430	0	15	Nothing	5-lognuts	PC-ABS
431	WheelRearLeft Cover	570	1	0.20	PC	Y	431	0	1	Nothing		
432	WheelRearLeft Rim	126	7.18	Aluminum	N	432	1	141	WheelRearLeft			
433	WheelRearLeft Rubber	585	1	8.84	SKOR	N	433	2	142	WheelRearLeft Rim		
434	WireHarnessCover	115	0.48	PP	Y	434	1	1193	Carpet		16-Pushin	
435	TrunkRelease	58	0.42	Mixed	NR	435	1	1261	TrunkReleaseCase	WireHarnessCover	2-Pushin, 2-Clips	
436	TrunkRelease Steel		0.38	Ferrous	NR	436	0		M			
437	TrunkRelease SKOP		0.04	SKOP	N	437	0		M			
438	WireHarness	650	180	3.94	Mixed	—	438	1	1373	WireHarnessCover		
439	WireHarness.Steel		0.79	Ferrous	NR	439	0		M			
440	WireHarness.Copper		0.59	Copper	NR	440	0		M			
441	WireHarness.SKOP		2.56	SKOP	N	441	0		M			
442	WindshieldWiperMotor	620	30	1.98	Mixed	—	442	2	117	CowVent	3-8mm, 1-clip	
443	WindshieldWiperMotor.Steel		1.49	Ferrous	NR	443	0		M			
444	WindshieldWiperMotor.Magnesium		0.20	Magnesium	N	444	0		M			
445	WindshieldWiperMotor.Copper		0.30	Copper	NR	445	0		M			Mostly Glass. two people required for 4-40
446	WindShieldFront	270	426	11.76	Mixed	—	446	0	426	Nothing		
447	RearFrame		0	279.0	Ferrous	NR	447	1	10482	DoorFrontLeft, DoorRearRight, DoorFrontRight, DoorRearLeft, DoorRearLeft, Headliner, B.PillarShoddyRight, B.PillarShoddyLeft, QuartertrimRight, Quartertrim,Left, KickPanelRight, KickPanelLeft, ParcelTrayShoddy, BackSeatShoddy, SeatbeltRearRight RearviewMirror, Headliner, KickPanelRight, KickPanelLeft, SteeringColumnAssembly, WeatherStripping, WiringHarnessCloseOut AirCleanerAssembly, WasherCoolantBottleAssembly, HeatBoxAssemblyBase HeatBoxAssembly, Carpet SteeringColumnSupportZ CoolingFanModule, CoolingFanShroudAssembly		
448	FrontClip	100	720	174.5	Mixed	—	448	6	7502	FrontClip, RadiatorHeatExchanger, Fittings	4-10mm, 3-8mm	
449	FrontClip, RadiatorHeatExchanger	675	164	4.76	Mixed	—	449	2	187	CoolingFanShroudAssembly		
450	FrontClip, RadiatorHeatExchanger.Hoses		30	0.28	Ferrous	NR	450	3	217	FrontClip, RadiatorHeatExchanger		
451	FrontClip, RadiatorHeatExchanger.Fittings		10	0.06	Ferrous	NR	451	4	227	FrontClip, RadiatorHeatExchanger.Hoses		
452	FrontClip, RadiatorHeatExchanger.Elastomer		10	0.09	Elastomer	N	452	5	237	FrontClip, RadiatorHeatExchanger.Fittings		
453	FrontClip, RadiatorHeatExchanger.LeftEnd		60	0.38	PP	Y	453	6	297	FrontClip, RadiatorHeatExchanger.Elastomer		PAGE
454	FrontClip, RadiatorHeatExchanger.Nuts		30	0.05	Ferrous	NR	454	3	217	FrontClip, RadiatorHeatExchanger		
455	FrontClip, RadiatorHeatExchanger.RightEnd		60	0.56	Mixed	—	455	4	277	FrontClip, RadiatorHeatExchanger.Nuts		
456	FrontClip, RadiatorHeatExchanger.RightEnd.Ca		10	0.49	Ferrous	NR	456	0	10	Nothing		
457	FrontClip, RadiatorHeatExchanger.RightEnd.PA		0	0.08	Ferrous	NR	457	1	10	id.Cap		PAGE
458	FrontClip, RadiatorHeatExchanger.CoolantTube		0	0.52	Copper	NR	458	5	277	id		Brass
459	FrontClip, RadiatorHeatExchanger.FmsChit		0	2.56	Aluminum	N	459	9	597	Nothing		

#	Name	Parts H.#	Time (secs)	Mass (kg)	Material	Marked	#	Total # before	Cum. time	Beliefs	Fasteners	Comments
460	FrontClip ACCCondensor	679	78	2.12	Mixed	--	460	3	265	.FrontClip.RadiatorHeatExchanger	3-8mm, 2-QDC, 2-Clips	
461	FrontClip ACCCondensor Aluminum			1.80	Aluminum	N	461	0		M		
462	FrontClip ACCCondensor Steel			0.32	Ferrous	NR	462	0		M		
463	FrontClip MarkerLightFrontLeft	168	80	0.34	SKOP	N	463	0	80	Nothing	1-Ph, 2-11mm, 2-EC	
464	FrontClip MarkerLightFrontRight	168	40	0.34	SKOP	N	464	0	40	Nothing	1-Ph, 2-11mm, 2-EC	
465	FrontClip LightFrontAssembly	114	197	4.26	Mixed	--	465	2	532	FrontClip.FasciaFrontLower, FrontClip.FasciaFrontUpper	13-8mm	Add Center light
466	FrontClip LightFrontAssembly HeadLightLeft		60	0.86	SKOP	N	466	0	60	Nothing	3-P	
467	FrontClip LightFrontAssembly HeadLightLeft SI		0	0.02	Ferrous	NR	467	2	90	left.Plastic1		
468	FrontClip LightFrontAssembly HeadLightLeft PI		30	0.36	SKOP	N	468	1	90	FrontClip.LightFrontAssembly.HeadLightLeft		Contaminated with chrome, steel, and other plastic (pi)
469	FrontClip LightFrontAssembly HeadLightLeft PI		0	0.47	SKOP	N	469	2	90	FrontClip.LightFrontAssembly.HeadLightLeft		
470	FrontClip LightFrontAssembly HeadLightRight		60	0.86	SKOP	N	470	0	60	Nothing	3-P	
471	FrontClip LightFrontAssembly HeadLightRight S		0	0.02	Ferrous	NR	471	2	90	FrontClip.LightFrontAssembly.HeadLightRight		
472	FrontClip LightFrontAssembly HeadLightRight P		30	0.36	SKOP	N	472	1	90	FrontClip.LightFrontAssembly.HeadLightRight		
473	FrontClip LightFrontAssembly HeadLightRight P		0	0.47	SKOP	N	473	2	90	FrontClip.LightFrontAssembly.HeadLightRight		Same composition than head lights
474	FrontClip LightFrontAssembly Center		43	1.06	SKOP	N	474	0	43	Nothing	4-8mm	
475	FrontClip LightFrontAssembly Frame		0	2.45	PET	Y	475	6	695	FrontClip.LightFrontAssembly.HeadLightLeft, FrontClip.LightFrontAssembly.Center, FrontClip.LightFrontAssembly		
476	FrontClip FasciaFrontLower	1057	115	9.68	Zenoid	N	476	0	115	Nothing	6-10mm	Contaminated with Steel W0504
477	FrontClip FasciaFrontUpper	1057	220	1.20	PUR contaminated	N	477	1	335	FrontClip.FasciaFrontLower	4-11mm, 2-Pi	
478	FrontClip EnergyAbsorberFrontRight	108	43	2.50	Ferrous	NR	478	1	158	FrontClip.FasciaFrontLower	3-10mm	
479	FrontClip EnergyAbsorberFrontLeft	108	44	2.50	Ferrous	NR	479	1	159	FrontClip.FasciaFrontLower	3-10mm	
480	FrontClip RadiatorShroud		16	0.28	TPO	Y	480	0	16	Nothing	4-8mm	TPO-EP
481	FrontClip Hood	117	100	21.92	Mixed	--	481	0	100	Nothing	4-8mm, 1-EC, 2-clips	
482	FrontClip Hood Insulation		18	0.64	SKOP	N	482	0	18	Nothing	7-Pi	
483	FrontClip Hood Cover		0	21.28	Ferrous	NR	483	2	118	Hood.Insulation, Hood		

#	Name	Parts H.#	Time (secs)	Mass (kg)	Material	Marked	#	Total # before	Cum time	Before	Fasteners	Comments
484	FrontClip Frame		0	124.63	Ferrous	NR	484	8	8599	.FrontClip. .FrontClip.RadiatorHeatExchanger. .FrontClip.ACCondensor. .FrontClip.MarkerLightFrontLeft. .FrontClip.MarkerLightFrontRight. .FrontClip.LightFrontAssembly. .FrontClip.FasciaFrontUpper. .FrontClip.EnergyAbsorberFrontRight	2-10mm, 8-13mm, 5-8mm, 10-EC, 1-Clamp, 1-11mm, 1-Clip, 1-VacLine, 1-7mm, 2-QDC, 2-15mm, 4-18mm, 2-7/16 4-10mm, 1-1-15mm, 1-10mm elect connector	
485	DriveTrain	300&400	1750	457.85	Mixed	—	485	0	1750	Nothing		
486	DriveTrain.ACCompressor	681	30	6.36	Mixed	—	486	1	1780	.DriveTrain		
487	DriveTrain.ACCompressor.Steel			3.82	Ferrous	NR	487	0		M		
488	DriveTrain.ACCompressor.SKOM			2.54	Zinc	N	488	0		M		Al/Zinc
489	DriveTrain.Alternator	601	57	6.58	Mixed	—	489	0	57	Nothing	1-15mm, 1-10mm	
490	DriveTrain.Alternator.Copper			2.80	Copper	NR	490	0		M		
491	DriveTrain.Alternator.Magnesium			1.00	Magnesium	N	491	0		M		
492	DriveTrain.Alternator.Steel			2.78	Ferrous	NR	492	0		M		
493	DriveTrain.PowerSteering	550	143	6.34	Mixed	—	493	0	143	Nothing	3-13mm, 1-10mm, 1-18mm	
494	DriveTrain.PowerSteering.Steel			3.01	Ferrous	NR	494	0		M		
495	DriveTrain.PowerSteering.Aluminum			3.01	Zinc	N	495	0		M		Al/Zinc
496	DriveTrain.PowerSteering.SKOP			0.32	SKOP	N	496	0		M		
497	DriveTrain.Starter	604	95	3.50	Mixed	—	497	1	1845	.DriveTrain	3-13mm, 1-15mm, 1-18mm	
498	DriveTrain.Starter.Steel			2.10	Ferrous	NR	498	0		M		
499	DriveTrain.Starter.Magnesium			0.53	Magnesium	N	499	0		M		
500	DriveTrain.Starter.Copper			0.88	Copper	NR	500	0		M		
501	DriveTrain.Engine	300	1519	200.00	Mixed	—	501	1	3289	.DriveTrain		A lot of manual work partially due that some nuts were not removed when hanging (from the bottom)
502	DriveTrain.Engine.Steel			150.00	Ferrous	NR	502	0		M		
503	DriveTrain.Engine.SKOM			30.00	SKOM	N	503	0		M		
504	DriveTrain.Engine.SKOS			20.00	SKOS	N	504	0		M		
505	DriveTrain.Transmission	400	240	94.55	Mixed	—	505	2	3529	.DriveTrain.Engine		
506	DriveTrain.Transmission.Steel			47.28	Ferrous	NR	506	0		M		
507	DriveTrain.Transmission.SKOM			47.28	SKOM	N	507	0		M		
508	DriveTrain.WheelRight	560	15	16.28	Mixed	—	508	0	15	Nothing		
509	DriveTrain.WheelRight.Cover	570	5	0.20	PC-ABS	Y	509	0	5	Nothing		
510	DriveTrain.WheelRight.Rim	126	7.18	Aluminum	N	510	1	141	.DriveTrain.WheelRight			
511	DriveTrain.WheelRight.Rubber	585	1	8.84	SKOR	N	511	2	142	.DriveTrain.WheelRight.Rim		
512	DriveTrain.WheelLeft	560	15	16.28	Mixed	—	512	0	15	Nothing		
513	DriveTrain.WheelLeft.Cover	570	5	0.20	PC-ABS	Y	513	0	5	Nothing		
514	DriveTrain.WheelLeft.Rim	126	7.18	Aluminum	N	514	1	141	.DriveTrain.WheelLeft			
515	DriveTrain.WheelLeft.Rubber	585	1	8.84	SKOR	N	515	2	142	.DriveTrain.WheelLeft.Rim		

#	Name	Parts H.#	Time (secs)	Mass (kg)	Material	Marked	#	Total # before	Cum time	Before	Fasteners	Comments
516	Drive Train Cradle Suspension Assy		1	107.96	Ferrous	NR	516	5	3540	Drive Train Wheel Right. Drive Train Wheel Left. Drive Train Transmission		
517	Instrument Panel	250	825	35.96	Mixed		517	7	1234	Lower IP. Steering Column. Wiring Harness Close Out	11-8mm, 16-EC, 1-10mm, 1-awc, 1-cable 8-20T, 1-7mm	PE*
518	Instrument Panel Duct Work	60	0.52	PE		N	518	8	1294	Instrument Panel		
519	Instrument Panel Evap Duct	46	1.14	Mixed			519	9	1340	Instrument Panel Duct Work		
520	Instrument Panel Duct Work 2	45	0.44	PE		N	520	1	1385	Instrument Panel Evap Duct		PE*
521	Instrument Panel Hoses	15	0.25	SKOP		N	521	1	1400	Instrument Panel Duct Work 2		
522	Instrument Panel Wire Harness	649	874	5.62	Mixed		522	1	2274	Instrument Panel Hoses	5-20T, 9-PI	Unusually Difficult. Most of time was for EC's. Review time to less intense worker (Dave)
523	Instrument Panel Wire Harness Steel			1.12	Ferrous	NR	523	0				
524	Instrument Panel Wire Harness Copper			0.84	Copper	NR	524	0				
525	Instrument Panel Wire Harness SKOP			3.65	SKOP	N	525	0				
526	Instrument Panel Dash Pain	10	0.20	SKOS		N	526	1	1395	Instrument Panel Duct Work 2		
527	Instrument Panel Dimmer	120	0.26	Mixed			527	1	1505	Instrument Panel Duct Work 2		
528	Instrument Panel Dimmer Steel			0.12	Ferrous	NR	528	0				
529	Instrument Panel Dimmer SKOP			0.14	SKOP	N	529	0				Longer than typical time
530	Instrument Panel Radio	628	232	1.48	Mixed		530	0	232	Nothing		
531	Instrument Panel Radio SKOM			1.18	Ferrous	NR	531	0				
532	Instrument Panel Radio SKOP			0.30	SKOP	N	532	0				
533	Instrument Panel Tray Assembly		177	0.50	PP0 contaminated	Y	533	1	409	Instrument Panel Radio	2-Clips	PP0* Some steel (two clips & springs) and fabric. Some PE Marked. Elec Components
534	Instrument Panel Cluster Bezel	254	97	1.32	SKOS	N	534	0	97	Nothing		
535	Instrument Panel Cluster	255	15	1.54	SKOS	N	535	1	112	Instrument Panel Cluster Bezel	4-20T	
536	Instrument Panel Heater Control		20	0.26	SKOS	N	536	1	117	Instrument Panel Cluster Bezel	4-20T	
537	Instrument Panel Glove Box		47	2.52	Mixed		537	0	47	Nothing		
538	Instrument Panel Glove Box Front		60	0.56	Mixed		538	1	107	Instrument Panel Glove Box	9-Ph	
539	Instrument Panel Glove Box Front PPO		10	0.51	PPO	Y	539	2	117	Instrument Panel Glove Box Front	2-Ph	
540	Instrument Panel Glove Box Front SKOP		0	0.05	SKOP	N	540	3	117	Instrument Panel Glove Box Front PPO		Some foam
541	Instrument Panel Glove Box Steel		0	1.37	Ferrous	NR	541	2	107	Instrument Panel Glove Box Front		
542	Instrument Panel Glove Box SKOP		0	0.59	SKOP	N	542	2	107	Instrument Panel Glove Box Front		
543	Instrument Panel Ashtray		103	1.04	Mixed		543	1	2786	Instrument Panel Tray Assembly. Instrument Panel Wire Harness	2-20T, 2-10mm	
544	Instrument Panel Ashtray Steel			0.99	Ferrous	NR	544	0				
545	Instrument Panel Ashtray SKOP			0.05	SKOP	N	545	0				
546	Instrument Panel Center Bezel		2	0.18	ABS	N	546	1	2788	Instrument Panel Ash Tray		ABS*
547	Instrument Panel Clock	256	9	0.10	SKOS	N	547	1	2283	Instrument Panel Wire Harness	2-15T	
548	Instrument Panel Air Bag Passenger	253	107	4.86	Mixed		548	1	2391	Instrument Panel Air Bag Cover.	4-20T, 3-8mm	
549	Instrument Panel Air Bag Passenger Steel			3.89	Ferrous	NR	549	0				
550	Instrument Panel Air Bag Passenger SKOS			0.97	SKOS	N	550	0				

#	Name	Parts H.#	Time (secs)	Mass (kg)	Material	Marked	#	Total # before	Cum time	Before	Fasteners	Comments
551	.InstrumentPanel AirBagCover		10	0.20	PC	Y	551	0	10	Nothing	4-PI	PC* 7 Steel clips and some rubber contamination
552	.InstrumentPanel Frame		76	5.94	Ferrous	NR	552	2	3299	.InstrumentPanel, .InstrumentPanel.Clock, .InstrumentPanel.DashBrain, .InstrumentPanel.Dimmer, .InstrumentPanel.CenterBezel, .InstrumentPanel.Cluster, .InstrumentPanel.HeaterControl, .InstrumentPanel.GloveBox, .InstrumentPanel.AirBagPassenger		Some wires attached PP Foam, PVC Skin, Dylark Substrate
553	.InstrumentPanel Skin		0	6.50	SKOP	N	553	2	3299	.InstrumentPanel.Frame		



Appendix II  
Data from the Design of Experiments. Car A. "New Car" (resale values)

Experiment Number	1	2	3	4	5	6	7	8	9	10	11	12
Parts Resold	43	43	43	43	42	43	44	44	43	43	44	44
Resale Price	\$820.60	\$1,641.70	\$820.60	\$1,641.70	\$815.60	\$820.60	\$1,647.30	\$1,647.30	\$818.40	\$818.40	\$823.40	\$1,647.30
Resold Mass (kg)	856.19	856.19	856.19	856.19	844.43	859.19	857.79	857.79	846.03	846.03	857.79	857.79
Resold Ferrous (kg)	698.42	698.42	396.31	593.03	336.83	338.07	497.5	497.50	699.63	699.63	594.23	594.23
Resold Nonferrous (kg)	42.1	42.1	339.73	42.1	298.28	289.08	244.46	244.46	42.34	42.34	42.34	42.34
Resold Non-metal (kg)	115.67	115.67	120.15	221.06	209.32	232.04	115.83	115.83	104.06	104.06	221.22	221.22
Dismantler Recycling Income	\$0.00	\$0.00	\$0.10	\$0.10	\$0.10	\$0.00	\$0.77	\$0.13	\$0.51	\$0.40	\$0.51	\$0.93
Dismantler Recycling (kg)	0	0	1.62	1.62	1.62	0	2.15	1.34	1.34	2.15	1.34	2.15
Dismantler Recycling Ferrous (kg)	0	0	1.62	1.62	1.62	0	0	0	0	0	0	0
Dismantler Recycling Nonferrous (kg)	0	0	0	0	0	0	0.81	0	0	0.81	0	0.81
Dismantler Recycling Non-metal (kg)	0	0	0	0	0	0	1.34	1.34	1.34	1.34	1.34	1.34
Dismantler Income from Shredder	\$31.35	\$31.35	\$31.25	\$31.25	\$31.95	\$30.85	\$31.13	\$31.17	\$31.88	\$31.83	\$31.17	\$31.13
Shredded Mass (kg)	522.54	522.54	520.92	520.92	532.68	514.15	518.76	519.57	531.33	530.52	519.57	518.76
Shredder Recycled Material (kg)	369.308	369.308	367.68	356.56	357.18	354.62	367.06	367.87	367.87	356.55	356.74	355.93
Shredder Landfilled Material (kg)	153.232	153.232	153.24	164.36	175.5	159.53	151.7	151.7	163.46	173.97	162.83	162.83
Dismantling Time (s)	7731	7731	7731	7731	7305	9343	7349	7344	6918	6923	7344	6349
Dismantler Cost	\$68.72	\$128.85	\$128.85	\$128.85	\$121.75	\$83.05	\$151.70	\$65.28	\$115.30	\$115.38	\$65.28	\$65.32
Dismantler Profit	\$783.23	\$1,544.20	\$723.10	\$1,544.20	\$725.90	\$768.40	\$1,527.50	\$1,613.32	\$735.49	\$735.25	\$789.80	\$1,614.04

Appendix II  
Results from the Design of Experiments. Car A. "Old Car" (no-resale values)

Experiment Number	1	2	3	4	5	6	7	8	9	10	11	12
Parts Resold	0	0	0	0	0	0	0	0	0	0	0	0
Resale Price	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00
Resold Mass (kg)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Resold Ferrous (kg)	0	0	0	0	0	0	0	0	0	0	0	0
Resold Nonferrous (kg)	0	0	0	0	0	0	0	0	0	0	0	0
Resold Non-metal (kg)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dismantler Recycling Income	\$0.00	\$0.00	\$53.16	\$0.00	\$42.71	\$0.00	\$12.34	\$46.95	\$0.79	\$8.77	\$0.26	\$3.36
Dismantler Recycling (kg)	0	0	61,248	0	45.03	0	34.41	48.48	0.81	27.56	0.81	3.86
Dismantler Recycling Ferrous (kg)	0	0	7,798	0	1.4	0	0	0	0	0	0	0
Dismantler Recycling Nonferrous (kg)	0	0	53.45	0	43.63	0	23.89	46.01	0.81	26.47	0.81	3.39
Dismantler Recycling Non-metal (kg)	0	0	0	0	0	10.52	0.47	0.47	0	1.09	0	0.47
Dismantler Income from Shredder	\$82.61	\$82.61	\$79.00	\$82.61	\$79.90	\$82.61	\$80.54	\$79.69	\$82.55	\$80.95	\$82.55	\$82.37
Shredded Mass (kg)	1376.87	1376.87	1316.09	1376.87	1332.92	1376.87	1342.27	1328.19	1375.86	1349.11	1375.86	1372.81
Shredder Recycled Material (kg)	1077.24	1077.24	1042.98	960.712	943.27	988.302	1080.34	1056.22	1076.43	961.83	959.9	957.32
Shredder Landfilled Material (kg)	299.63	299.63	273.11	416.158	389.65	388.568	261.93	271.97	299.43	387.28	415.96	415.49
Dismantling Time (s)	0	0	2366	0	1750	0	249	618	5	199	5	75
Dismantler Cost	\$0.00	\$0.00	\$21.03	\$0.00	\$15.56	\$0.00	\$4.15	\$10.30	\$0.04	\$1.77	\$0.04	\$1.25
Dismantler Profit	\$82.61	\$82.61	\$111.13	\$82.61	\$107.05	\$82.61	\$88.73	\$116.34	\$83.30	\$87.95	\$82.77	\$84.48
Landfill Rate	0.218	0.218	0.198	0.302	0.283	0.282	0.190	0.198	0.218	0.281	0.302	0.302

## Appendix III. Complete Documentation of the Automobile Recycling Dynamic Model (ARDM)

### .ages

- (001) Average age of car 0 to 3 = Purchase date-Average model of car 0 to 3  
Units: year  
Subtracting the Average model in the corresponding cohort from the Purchase date (calendar year during the simulation) one can calculate the Average age of the vehicles in that cohort.
- (002) Average age of car 12 to 15 = Purchase date-Average model of car 12 to 15  
Units: year  
Subtracting the Average model in the corresponding cohort from the Purchase date (calendar year during the simulation) one can calculate the Average age of the vehicles in that cohort.
- (003) Average age of car 15 to 18 = Purchase date-Average model of car 15 to 18  
Units: year  
Subtracting the Average model in the corresponding cohort from the Purchase date (calendar year during the simulation) one can calculate the Average age of the vehicles in that cohort.
- (004) Average age of car 18 to 21 = Purchase date-Average model of car 18 to 21  
Units: year  
Subtracting the Average model in the corresponding cohort from the Purchase date (calendar year during the simulation) one can calculate the Average age of the vehicles in that cohort.
- (005) Average age of car 3 to 6 = Purchase date- Average model of car 3 to 6  
Units: year  
Subtracting the Average model in the corresponding cohort from the Purchase date (calendar year during the simulation) one can calculate the Average age of the vehicles in that cohort.
- (006) Average age of car 6 to 9 = Purchase date- Average model of car 6 to 9  
Units: year  
Subtracting the Average model in the corresponding cohort from the Purchase date (calendar year during the simulation) one can calculate the Average age of the vehicles in that cohort.
- (007) Average age of car 9 to 12 = Purchase date- Average model of car 9 to 12  
Units: year  
Subtracting the Average model in the corresponding cohort from the Purchase date (calendar year during the simulation) one can calculate the Average age of the vehicles in that cohort.
- (008) Average age of new cars when retired = (Average age of car 0 to 3\*retiring 1 + Average age of car 3 to 6\*retiring 2+ Average age of car 6 to 9\*retiring 3) / New cars being retired  
Units: year  
Is the weighted average age of cars in the first 3 age-cohorts

- (009) Average age of old cars when retired = (Average age of car 9 to 12\*retiring 4 + Average age of car 12 to 15 \* retiring 5 + Average age of car 15 to 18\*retiring 6+Average age of car 18 to 21\*(retiring 7 +aging 7)) / Old cars being retired  
Units: year  
The Average age of the cars being retired is the weighted average of the ages of cars being retired from every cohort. The weight is given by the number of cars retiring at each flow. "Old cars" refers to the last 4 age-cohorts.
- (010) Ini model 1 = Ini 0 to 3\*MODEL1  
Units: car\*year  
Is the initial level of the corresponding stock. Used to generate equilibrium conditions. Is calculated based on the initial level of the Cars cohort (Ini x to y) and the constant MODEL(i), which represents the model of cars already in this cohort.
- (011) Ini model 2 = Ini 3 to 6\*MODEL2  
Units: car\*year  
Is the initial level of the corresponding stock. Used to generate equilibrium conditions. Is calculated based on the initial level of the Cars cohort (Ini x to y) and the constant MODEL(i), which represents the model of cars already in this cohort.
- (012) Ini model 3 =Ini 6 to 9\*MODEL3  
Units: car\*year  
Is the initial level of the corresponding stock. Used to generate equilibrium conditions. Is calculated based on the initial level of the Cars cohort (Ini x to y) and the constant MODEL(i), which represents the model of cars already in this cohort.
- (013) Ini model 4 = Ini 9 to 12\*MODEL4  
Units: car\*year  
Is the initial level of the corresponding stock. Used to generate equilibrium conditions. Is calculated based on the initial level of the Cars cohort (Ini x to y) and the constant MODEL(i), which represents the model of cars already in this cohort.
- (014) Ini model 5 = Ini 12 to 15\*MODEL5  
Units: car\*year  
Is the initial level of the corresponding stock. Used to generate equilibrium conditions. Is calculated based on the initial level of the Cars cohort (Ini x to y) and the constant MODEL(i), which represents the model of cars already in this cohort.
- (015) Ini model 6 =Ini 15 to 18\*MODEL6  
Units: car\*year  
Is the initial level of the corresponding stock. Used to generate equilibrium conditions. Is calculated based on the initial level of the Cars cohort (Ini x to y) and the constant MODEL(i), which represents the model of cars already in this cohort.
- (016) Ini model 7 =Ini 18 to 21\*MODEL7  
Units: car\*year  
Is the initial level of the corresponding stock. Used to generate equilibrium conditions. Is calculated based on the initial level of

Appendix III. Complete Documentation of the Automobile Recycling Dynamic Model

the Cars cohort (Ini x to y) and the constant MODEL(i), which represents the model of cars already in this cohort.

(017) INITIAL MODEL = 1995

Units: year

This is the initial calendar year of the simulation.

(018) Model in cars 0 to 3 = INTEG(model into chain-model trans1-model ret1

,Ini model 1)

Units: car\*year

This stock accumulates models. Is associated to a specific age cohort. Is increased by the inflow into the chain (Models into chain) and decreased by the retiring and transfer to the next cohort. Its initial value is determined by the variable Ini model(i).

(019) Model in cars 12 to 15 = INTEG(model trans4-model trans5-model ret5,Ini model 5)

Units: car\*year

This stock accumulates models. Is associated to a specific age cohort. Is increased by the inflow into the chain (Models into chain) and decreased by the retiring and transfer to the next cohort. Its initial value is determined by the variable Ini model(i).

(020) Model in cars 15 to 18 = INTEG(model trans5-model trans6-model ret6,Ini model 6)

Units: car\*year

This stock accumulates models. Is associated to a specific age cohort. Is increased by the inflow into the chain (Models into chain) and decreased by the retiring and transfer to the next cohort. Its initial value is determined by the variable Ini model(i).

(021) Model in cars 18 to 21 = INTEG(model trans6-model trans7-model ret7,Ini model 7)

Units: car\*year

This stock accumulates models. Is associated to a specific age cohort. Is increased by the inflow into the chain (Models into chain) and decreased by the retiring and transfer to the next cohort. Its initial value is determined by the variable Ini model(i).

(022) Model in cars 3 to 6 = INTEG(model trans1-model trans2-model ret2,Ini model 2)

Units: car\*year

This stock accumulates models. Is associated to a specific age cohort. Is increased by the inflow into the chain (Models into chain) and decreased by the retiring and transfer to the next cohort. Its initial value is determined by the variable Ini model(i).

(023) Model in cars 6 to 9 = INTEG(model trans2-model trans3-model ret3,Ini model 3)

Units: car\*year

This stock accumulates models. Is associated to a specific age cohort. Is increased by the inflow into the chain (Models into chain) and decreased by the retiring and transfer to the next cohort. Its initial value is determined by the variable Ini model(i).

(024) Model in cars 9 to 12 = INTEG(model trans3-model trans4-model ret4,Ini model 4)

Units: car\*year

This stock accumulates models. Is associated to a specific age cohort. Is increased by the inflow into the chain (Models into

chain) and decreased by the retiring and transfer to the next cohort. Its initial value is determined by the variable Ini model(i).

(025) model ret1 = Average model of car 0 to 3\*retiring 1  
Units: car\*year/Month

This is the rate at which models from this cohort get retired. It is a parallel flow based on retiring(i) and the Average Model in this cohort.

(026) model ret2 = Average model of car 3 to 6\*retiring 2  
Units: car\*year/Month

This is the rate at which models from this cohort get retired. It is a parallel flow based on retiring(i) and the Average Model in this cohort.

(027) model ret3 = retiring 3\*Average model of car 6 to 9  
Units: car\*year/Month

This is the rate at which models from this cohort get retired. It is a parallel flow based on retiring(i) and the Average Model in this cohort.

(028) model ret4 = retiring 4\*Average model of car 9 to 12  
Units: car\*year/Month

This is the rate at which models from this cohort get retired. It is a parallel flow based on retiring(i) and the Average Model in this cohort.

(029) model ret5 = retiring 5\*Average model of car 12 to 15  
Units: car\*year/Month

This is the rate at which models from this cohort get retired. It is a parallel flow based on retiring(i) and the Average Model in this cohort.

(030) model ret6 = retiring 6\*Average model of car 15 to 18  
Units: car\*year/Month

This is the rate at which models from this cohort get retired. It is a parallel flow based on retiring(i) and the Average Model in this cohort.

(031) model ret7 = retiring 7\*Average model of car 18 to 21  
Units: car\*year/Month

This is the rate at which models from this cohort get retired. It is a parallel flow based on retiring(i) and the Average Model in this cohort.

(032) model trans1 = Average model of car 0 to 3\*aging 1  
Units: car\*year/Month

This is the rate at which models get transferred from one cohort to the next. It is a parallel flow based on the aging(i) flow and the Average Model in the corresponding cohort.

(033) model trans2 = Average model of car 3 to 6\*aging 2  
Units: car\*year/Month

This is the rate at which models get transferred from one cohort to the next. It is a parallel flow based on the aging(i) flow and the Average Model in the corresponding cohort.

(034) model trans3 = Average model of car 6 to 9\*aging 3  
Units: car\*year/Month

This is the rate at which models get transferred from one cohort to the next. It is a parallel flow based on the aging(i) flow and the Average Model in the corresponding cohort.

(035) model trans4 = aging 4 \* Average model of car 9 to 12  
Units: car\*year/Month  
This is the rate at which models get transferred from one cohort to the next. It is a parallel flow based on the aging(i) flow and the Average Model in the corresponding cohort

(036) model trans5 = aging 5 \* Average model of car 12 to 15  
Units: car\*year/Month  
This is the rate at which models get transferred from one cohort to the next. It is a parallel flow based on the aging(i) flow and the Average Model in the corresponding cohort

(037) model trans6 = aging 6 \* Average model of car 15 to 18  
Units: car\*year/Month  
This is the rate at which models get transferred from one cohort to the next. It is a parallel flow based on the aging(i) flow and the Average Model in the corresponding cohort

(038) model trans7 = aging 7 \* Average model of car 18 to 21  
Units: car\*year/Month  
This is the rate at which models get transferred from one cohort to the next. It is a parallel flow based on the aging(i) flow and the Average Model in the corresponding cohort

(048) Purchase date = IF THEN ELSE(Switch to static model year=1, INITIAL\_MODEL, INITIAL\_MODEL + Time/YEAR)  
Units: year  
Calculates the model of cars being sold during the simulation. It is based on the Initial Model and Time. Considers a switch to "produce" always the same model (testing purposes)

(049) Switch to static model year = 0  
Units: dimensionless  
Creates a constant Purchase date (1995) For testing purposes

(050) YEAR = 12  
Units: Month/year  
Number of months per year. Used to convert units

### .aging

(051) aging 1 = Out of 0 to 3 \* (1-RET FRAC1)  
Units: car/Month  
Is the rate at which cars get old, and are transferred to the next age cohort

(052) aging 2 = Out of 3 to 6 \* (1-RET FRAC2)  
Units: car/Month  
Is the rate at which cars get old, and are transferred to the next age cohort

(053) aging 3 = Out of 6 to 9 \* (1-RET FRAC3)  
Units: car/Month  
Is the rate at which cars get old, and are transferred to the next age cohort

(054) aging 4 = Out of 9 to 12 \* (1-RET FRAC4)  
Units: car/Month  
Is the rate at which cars get old, and are transferred to the next age cohort

(055) aging 5 = Out of 12 to 15 \* (1-RET FRAC5)

Units: car/Month  
Is the rate at which cars get old, and are transferred to the next age cohort.

(056) aging 6 = Out of 15 to 18 \* (1-RET FRAC6)  
Units: car/Month  
Is the rate at which cars get old, and are transferred to the next age cohort.

(057) aging 7 = Out of 18 to 21 \* (1-RET FRAC7)  
Units: car/Month  
Is the rate at which cars get old, and are transferred to the next age cohort.

(058) Calculated number of cars = Ini cars on the road \* GDP  
Units: car  
This is the long-term equilibrium number of cars on the road. Depends on GDP and the initial level of cars.

(059) car sales = Sales  
Units: car/Month  
Is the rate of cars being incorporated into the fleet in use

(060) Cars from 0 to 3 years = INTEG(+car sales-aging 1-retiring 1, Ini 0 to 3)  
Units: car  
Is the number of cars in that cohort of age. Considers aging, sales and retirement flows.

(061) Cars from 12 to 15 years = INTEG(aging 4-retiring 5-aging 5, Ini 12 to 15)  
Units: car  
Is the number of cars in that cohort of age. Considers aging, sales and retirement flows.

(062) Cars from 15 to 18 years = INTEG(aging 5-aging 6-retiring 6, Ini 15 to 18)  
Units: car  
Is the number of cars in that cohort of age. Considers aging, sales and retirement flows.

(063) Cars from 18 to 21 years = INTEG(aging 6-retiring 7-aging 7, Ini 18 to 21)  
Units: car  
Is the number of cars in that cohort of age. Considers aging, sales and retirement flows.

(064) Cars from 3 to 6 years = INTEG(aging 1-aging 2-retiring 2, Ini 3 to 6)  
Units: car  
Is the number of cars in that cohort of age. Considers aging, sales and retirement flows.

(065) Cars from 6 to 9 years = INTEG(aging 2-aging 3-retiring 3, Ini 6 to 9)  
Units: car  
Is the number of cars in that cohort of age. Considers aging, sales and retirement flows.

(066) Cars from 9 to 12 years = INTEG(aging 3-aging 4-retiring 4, Ini 9 to 12)  
Units: car  
Is the number of cars in that cohort of age. Considers aging, sales and retirement flows.

Appendix III. Complete Documentation of the Automobile Recycling Dynamic Model

(067) Cars on the road = Cars from 0 to 3 years + Cars from 3 to 6 years + Cars from 6 to 9 years + Cars from 9 to 12 years + Cars from 12 to 15 years + Cars from 15 to 18 years + Cars from 18 to 21 years Units: car Is the total size of the fleet on the road	Units: car Equilibrium number of cars in the corresponding age-cohort
(068) changing GDP = IF THEN ELSE(Switch to have a GDP longterm growth=1, CONSTANT GDP*Compound growth, CONSTANT GDP+step GDP) Units: dimensionless Produces a GDP that changes in time. It can be exponentially growing or have a step form	(081) EQ 6 TO 9 = 3.3156e+007 Units: car Equilibrium number of cars in the corresponding age-cohort
(069) compound factor = Time/Month Units: dimensionless Corresponds to the value of the variable time, but dimensionless	(082) EQ 9 TO 12 = 2.81907e+007 Units: car Equilibrium number of cars in the corresponding age-cohort.
(070) Compound growth = (1+Monthly growth of GDP)^compound factor Units: dimensionless Evaluates an exponential growing factor	(083) FLAT SALES = 1e+006 Units: car/Month Is a constant input to test the model
(071) CONSTANT GDP = 1 Units: dimensionless Base initial GDP	(084) Fleet gap = Calculated number of cars - Cars on the road Units: car Is the difference between the actual number of cars and the long-term equilibrium level.
(072) CONTINUOUS ANNUAL GROWTH = 0.03 Units: dimensionless Is the expected annual growth of the economy	(085) GDP = IF THEN ELSE(Switch to change GDP=1, changing GDP, CONSTANT GDP) Units: dimensionless GDP can be held constant or change during the simulation.
(073) dismantling of new cars = DELAY3(New cars being retired, t TO DISMANTLE NEW CARS) Units: car/Month The rate at which new cars are dismantled is not dynamic. It is the retirement flow delayed.	(086) HIS 0 TO 3 = 2.11753e+007 Units: car This is the actual level of vehicles in this cohort (at the end of 1994)
(074) dismantling rate = IF THEN ELSE(Switch to turn dismantling rate constant = 1, Old cars being retired, MIN(Dismantler capacity in cars, Supply of cars)) Units: car/Month Dismantling rate is the minimum of capacity and supply of junk cars	(087) HIS 12 TO 15 = 1.19214e+007 Units: car This is the actual level of vehicles in this cohort (at the end of 1994)
(075) Dynamic sales = (Fleet gap/TIME TO CORRECT FLEET GAP) + Old cars being retired + New cars being retired Units: car/Month Sales are determined by immediate replacement and the adjustment required for GDP changes.	(088) HIS 15 TO 18 = 4.63557e+006 Units: car This is the actual level of vehicles in this cohort (at the end of 1994)
(076) EQ 0 to 3 = 3.6e+007 Units: car Equilibrium number of cars in the corresponding age-cohort	(089) HIS 18 TO 21 = 59432 Units: car This is the actual level of vehicles in this cohort (at the end of 1994)
(077) EQ 12 TO 15 = 1.79042e+007 Units: car Equilibrium number of cars in the corresponding age-cohort	(090) HIS 3 TO 6 = 2.73009e+007 Units: car This is the actual level of vehicles in this cohort (at the end of 1994)
(078) EQ 15 TO 18 = 7.52692e+006 Units: car Equilibrium number of cars in the corresponding age-cohort	(091) HIS 6 TO 9 = 2.78344e+007 Units: car This is the actual level of vehicles in this cohort (at the end of 1994).
(079) EQ 18 TO 21 = 1.52186e+006 Units: car Equilibrium number of cars in the corresponding age-cohort	(092) HIS 9 TO 12 = 1.81185e+007 Units: car This is the actual level of vehicles in this cohort (at the end of 1994)
(080) EQ 3 TO 6 = 3.546e+007	(093) Ini 0 to 3 = IF THEN ELSE(Switch to equilibrium stocks=1, EQ 0 to 3, HIS 0 TO 3) Units: car The initial level of the stock of cars depends on the switch to turn to equilibrium condition.

## Appendix III. Complete Documentation of the Automobile Recycling Dynamic Model

- (094) Ini 12 to 15 = IF THEN ELSE(Switch to equilibrium stocks=1,EQ 12 TO 15,HIS 12 TO 15)  
Units: car  
The initial level of the stock of cars depends on the switch to turn to equilibrium condition
- (095) Ini 15 to 18 = IF THEN ELSE(Switch to equilibrium stocks=1,EQ 15 TO 18,HIS 15 TO 18)  
Units: car  
The initial level of the stock of cars depends on the switch to turn to equilibrium condition
- (096) Ini 18 to 21 = IF THEN ELSE(Switch to equilibrium stocks=1,EQ 18 TO 21,HIS 18 TO 21)  
Units: car  
The initial level of the stock of cars depends on the switch to turn to equilibrium condition
- (097) Ini 3 to 6 = IF THEN ELSE(Switch to equilibrium stocks=1,EQ 3 TO 6,HIS 3 TO 6)  
Units: car  
The initial level of the stock of cars depends on the switch to turn to equilibrium condition
- (098) Ini 6 to 9 = IF THEN ELSE(Switch to equilibrium stocks=1,EQ 6 TO 9,HIS 6 TO 9)  
Units: car  
The initial level of the stock of cars depends on the switch to turn to equilibrium condition
- (099) Ini 9 to 12 = IF THEN ELSE(Switch to equilibrium stocks=1,EQ 9 TO 12,HIS 9 TO 12)  
Units: car  
The initial level of the stock of cars depends on the switch to turn to equilibrium condition
- (100) Ini cars on the road = IF THEN ELSE(Switch to equilibrium stocks=1, INI EQ CARS ON THE ROAD,INI HIS CARS ON THE ROAD)  
Units: car  
The initial number of cars can be the equilibrium one or the actual
- (101) Ini new deregistered cars = MONTHS UNWANTED CARS\*sales to calculate initial stocks \* (1-Ini old car fraction)  
Units: car  
The initial level of this stock is calculated based on the estimated number of months in cars waiting to be processed, the fraction of old cars and the sales rate
- (102) Ini old deregistered cars = MONTHS UNWANTED CARS\*sales to calculate initial stocks \* Ini old car fraction  
Units: car  
The initial level of this stock is calculated based on the estimated number of months in cars waiting to be processed, the fraction of old cars and the sales rate
- (103) Month = 1  
Units: Month  
Conversion factor
- (104) Monthly growth of GDP = CONTINUOUS ANNUAL GROWTH/12  
Units: dimensionless  
Monthly growth is the annual growth divided by 12 (simplification)
- (105) New cars being retired = retiring 1+retiring 2+retiring 3  
Units: car/Month  
Is the sum of the first three retirement flows
- (106) New deregistered cars = INTEG(retiring 1+retiring 2+retiring 3-dismantling of new cars, Ini new deregistered cars)  
Units: car  
The stock of new cars deregistered increases by 3 retirement rates and decreases with dismantling rate
- (107) Old deregistered cars = INTEG(retiring 4+retiring 5+retiring 6+retiring 7 +aging 7 -dismantling rate,Ini old deregistered cars)  
Units: car  
This is a stock where cars that got retired accumulate before they get to the hands of dismantlers. Is a critical environmental performance indicator.
- (108) Out of 0 to 3 = Cars from 0 to 3 years/t TO AGE  
Units: car/Month  
The total outflow from this cohort is calculated based on an aging process; the stock level divided by the time to age (36 months). A fraction of this flow will get retired and the rest will be transferred to the next age cohort.
- (109) Out of 12 to 15 = Cars from 12 to 15 years/t TO AGE  
Units: car/Month  
The total outflow from this cohort is calculated based on an aging process; the stock level divided by the time to age (36 months). A fraction of this flow will get retired and the rest will be transferred to the next age cohort.
- (110) Out of 15 to 18 = Cars from 15 to 18 years/t TO AGE  
Units: car/Month  
The total outflow from this cohort is calculated based on an aging process; the stock level divided by the time to age (36 months). A fraction of this flow will get retired and the rest will be transferred to the next age cohort.
- (111) Out of 18 to 21 = Cars from 18 to 21 years/t TO AGE  
Units: car/Month  
The total outflow from this cohort is calculated based on an aging process; the stock level divided by the time to age (36 months). A fraction of this flow will get retired and the rest will be transferred to the next age cohort.
- (112) Out of 3 to 6 = Cars from 3 to 6 years/t TO AGE  
Units: car/Month  
The total outflow from this cohort is calculated based on an aging process; the stock level divided by the time to age (36 months). A fraction of this flow will get retired and the rest will be transferred to the next age cohort.
- (113) Out of 6 to 9 = Cars from 6 to 9 years/t TO AGE  
Units: car/Month  
The total outflow from this cohort is calculated based on an aging process; the stock level divided by the time to age (36 months). A fraction of this flow will get retired and the rest will be transferred to the next age cohort.
- (114) Out of 9 to 12 = Cars from 9 to 12 years/t TO AGE  
Units: car/Month  
The total outflow from this cohort is calculated based on an aging process; the stock level divided by the time to age (36 months). A fraction of this flow will get retired and the rest will be transferred to the next age cohort.

months). A fraction of this flow will get retired and the rest will be transferred to the next age cohort.

(115) random escalator = random generator/10+unit

Units: dimensionless

Creates a random number around the value of 1.

(116) RET FRAC1 = 0.015

Units: dimensionless

This is the researched fraction of the outflow that gets retired from this cohort. It represents the percentage of cars that, having aged to the limit of the corresponding age cohort, do not get into the next age cohort, but rather get disposed.

(117) RET FRAC2 = 0.064975

Units: dimensionless

This is the researched fraction of the outflow that gets retired from this cohort. It represents the percentage of cars that, having aged to the limit of the corresponding age cohort, do not get into the next age cohort, but rather get disposed.

(118) RET FRAC3 = 0.149756

Units: dimensionless

This is the researched fraction of the outflow that gets retired from this cohort. It represents the percentage of cars that, having aged to the limit of the corresponding age cohort, do not get into the next age cohort, but rather get disposed.

(119) RET FRAC4 = 0.364888

Units: dimensionless

This is the researched fraction of the outflow that gets retired from this cohort. It represents the percentage of cars that, having aged to the limit of the corresponding age cohort, do not get into the next age cohort, but rather get disposed.

(120) RET FRAC5 = 0.579601

This is the researched fraction of the outflow that gets retired from this cohort. It represents the percentage of cars that, having aged to the limit of the corresponding age cohort, do not get into the next age cohort, but rather get disposed.

(121) RET FRAC6 = 0.797811

Units: dimensionless

This is the researched fraction of the outflow that gets retired from this cohort. It represents the percentage of cars that, having aged to the limit of the corresponding age cohort, do not get into the next age cohort, but rather get disposed.

(122) RET FRAC7 = 1

Units: dimensionless

This is the researched fraction of the outflow that gets retired from this cohort. It represents the percentage of cars that, having aged to the limit of the corresponding age cohort, do not get into the next age cohort, but rather get disposed.

(123) retiring 1 = Out of 0 to 3\*RET FRAC1

Units: car/Month

The flow of cars being retired from this age-cohort depends on the outflow from the cohort and the retirement fraction.

(124) retiring 2 = Out of 3 to 6\*RET FRAC2

Units: car/Month

The flow of cars being retired from this age-cohort depends on the outflow from the cohort and the retirement fraction.

(125) retiring 3 = Out of 6 to 9\*RET FRAC3

Units: car/Month

The flow of cars being retired from this age-cohort depends on the outflow from the cohort and the retirement fraction.

(126) retiring 4 = Out of 9 to 12\*RET FRAC4

Units: car/Month

The flow of cars being retired from this age-cohort depends on the outflow from the cohort and the retirement fraction.

(127) retiring 5 = Out of 12 to 15\*RET FRAC5

Units: car/Month

The flow of cars being retired from this age-cohort depends on the outflow from the cohort and the retirement fraction.

(128) retiring 6 = Out of 15 to 18\*RET FRAC6

Units: car/Month

The flow of cars being retired from this age-cohort depends on the outflow from the cohort and the retirement fraction.

(129) retiring 7 = Out of 18 to 21\*RET FRAC7

Units: car/Month

The flow of cars being retired from this age-cohort depends on the outflow from the cohort and the retirement fraction.

(130) Sales = IF THEN ELSE(Switch to use dynamic sales=1,Dynamic sales, FLAT SALES+step sales)

Units: car/Month

Defines the sales that go into the aging pipeline. It can be a function of GDP (dynamic) or truly exogenous.

(131) step GDP = step(0.2,50)+step(-0.2,150)

Units: dimensionless

Defines a step function for GDP.

(132) step sales = IF THEN ELSE(Switch to step sales=1, step(200000,50)+step(-200000,150),0)

Units: car/Month

Creates the step function of sales.

(133) Switch to change GDP = 0

Units: dimensionless

Allows for changes in GDP when equal to 1.

(134) Switch to have a GDP longterm growth = 0

Units: dimensionless

Allows for a continuously growing GDP when equal to 1.

(135) Switch to step sales = 0

Units: dimensionless

Creates an step input into the aging pipeline when equal to 1

(136) Switch to use dynamic sales = 1

Units: dimensionless

Allows for determination of sales based on GDP when equal to 1.

(137) t TO AGE = 36

Units: Month

Is the average time cars stay in each age-cohort.

(138) TIME TO CORRECT FLEET GAP = 66

Units: Month

Is the stock adjustment delay used to relate GDP to sales

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(139) Average model of car 0 to 3 = Model in cars 0 to 3/Cars from 0 to 3 years

Units: year

It is the average model in the cohort. Divides the level of the stocks Model by the level of the stock of Cars.

(140) Average model of car 12 to 15 = Model in cars 12 to 15/Cars from 12 to 15 years

Units: year

It is the average model in the cohort. Divides the level of the stocks Model by the level of the stock of Cars.

(141) Average model of car 15 to 18 = Model in cars 15 to 18/Cars from 15 to 18 years

Units: year

It is the average model in the cohort. Divides the level of the stocks Model by the level of the stock of Cars.

(142) Average model of car 18 to 21 = Model in cars 18 to 21/Cars from 18 to 21 years

Units: year

It is the average model in the cohort. Divides the level of the stocks Model by the level of the stock of Cars.

(143) Average model of car 3 to 6 = Model in cars 3 to 6/Cars from 3 to 6 years

Units: year

It is the average model in the cohort. Divides the level of the stocks Model by the level of the stock of Cars.

(144) Average model of car 6 to 9 = Model in cars 6 to 9/Cars from 6 to 9 years

Units: year

It is the average model in the cohort. Divides the level of the stocks Model by the level of the stock of Cars.

(145) Average model of car 9 to 12 = Model in cars 9 to 12/Cars from 9 to 12 years

Units: year

It is the average model in the cohort. Divides the level of the stocks Model by the level of the stock of Cars.

(146) Average prop in platforms under development[property] =

Prop in platform under development[property]/Platform in development

Units: kg/vehicle

The average weight, composition and level of Design for Disassembly at the development stage is calculated by dividing the stock of each property (in the parallel flow) by the number of platforms in the development stage.

(147) Average prop of platforms being sold[property] =

Prop in platform in market

[property]

/Platforms in market

Units: kg/vehicle

The average weight, composition and level of Design for Disassembly in the market is calculated by dividing the stock of each property (in the parallel flow) by the number of platforms being offered to the market

(148) BASE NEW PLATFORMS RATE = 0.47619

Units: vehicle/Month

This is the estimated rate at which new platforms are conceptualized. Defined based on equilibrium conditions.

(149) CONSTANT PROPERTY[Mass] = 1400

CONSTANT PROPERTY[Ferrous] = 980

CONSTANT PROPERTY[Nonferrous] = 70

CONSTANT PROPERTY[plastics] = 350

CONSTANT PROPERTY[DFD] = 1

Units: kg/car

Is the equilibrium value of the property. Corresponds to the constant policy decisions.

(150) CONSTANT TARGET PROP[Mass] = CONSTANT PROPERTY[Mass]\*vehicle

CONSTANT TARGET PROP[Ferrous] = CONSTANT

PROPERTY[Ferrous]\*vehicle

CONSTANT TARGET PROP [Nonferrous]= CONSTANT

PROPERTY[Nonferrous]\*vehicle

CONSTANT TARGET PROP[plastics] = CONSTANT

PROPERTY[plastics]\*vehicle

CONSTANT TARGET PROP[DFD] = CONSTANT

PROPERTY[DFD]\*vehicle

Units: kg/vehicle

This is the constant property level, expressed in "vehicle" units

(151) DEVELOPMENT TIME = 48

Units: Month

The design leadtime is 48 months.

(152) DFD trend = IF THEN ELSE(Switch to use historical trends=1, his DFD trend,eq DFD trend)

Units: kg/vehicle

Is the DFD policy decision.

(153) DISCONTINUE TIME = 84

Units: Month

It is estimated that a platform is discontinued after being in the market for 7 years.

(154) eq DFD trend

Units: kg/vehicle

Is a set of changing policy values for DFD when simulation starts at equilibrium.

(155) eq ferrous metals trend

Units: kg/vehicle

Is a set of changing policy values for DFD when simulation starts at equilibrium.

(156) eq nonferrous metals trend

Units: kg/vehicle

Is a set of changing policy values for DFD when simulation starts at equilibrium.

(157) eq plastic trend

Units: kg/vehicle

Is a set of changing policy values for DFD when simulation starts at equilibrium.

(158) eq weight trend

Units: kg/vehicle

Is a set of changing policy values for DFD when simulation starts at equilibrium.

(159) ferrous metals trend = IF THEN ELSE(Switch to use historical trends=1, his ferrous metals trend,eq ferrous metals trend)

Units: kg/vehicle

When the simulation is to use policies changing over time, the trend used depends on what the starting conditions are: equilibrium or historical.

(160) his DFD trend

Units: kg/vehicle

Is a set of changing policy values for DFD when simulation starts at historical conditions.

(161) his ferrous metals trend

Units: kg/vehicle

Is a set of changing policy values for DFD when simulation starts at historical conditions.

(162) his nonferrous metals trend

Units: kg/vehicle

Is a set of changing policy values for DFD when simulation starts at historical conditions.

(163) his plastics trend

Units: kg/vehicle

Is a set of changing policy values for DFD when simulation starts at historical conditions.

(164) his weight trend

Units: kg/vehicle

Is a set of changing policy values for DFD when simulation starts at historical conditions.

(165) INI PLATFORMS IN MARKET = 40

Units: vehicle

Number of platforms being sold when the simulation starts.

(166) INI PLATFORMS UNDER DEVELOPMENT = 22.8571

Units: vehicle

Initial level of the stock.

(167) Ini prop in market [property] = IF THEN ELSE(Switch to equilibrium levels in properties=1, INI PLATFORMS IN MARKET\*CONSTANT TARGET PROP[property], INI PLATFORMS IN MARKET\*His prop level in market[property])

Units: kg

The initial level of the stock of properties being offered in the platforms in the market is a function of the initial target property and the number of initial platforms being offered. Sensitive to what the initial conditions are: equilibrium or historical.

(168) Ini prop under development[property]=IF THEN ELSE(Switch to turn to equilibrium levels in properties = 1, CONSTANT TARGET PROP[property]\*INI PLATFORMS UNDER DEVELOPMENT,His prop level in design[property] \* INI PLATFORMS UNDER DEVELOPMENT)

Units: kg

The initial level of properties in the development stock is a function of the initial number of platforms at that stage and the initial property level. Sensitive to what the initial conditions are: equilibrium or historical.

(169) new platform dev rate = BASE NEW PLATFORMS RATE

Units: vehicle/Month

Is the rate at which new platforms are "conceptualized" and the design teams begin working of them.

(170) new platform introduction rate = Platform in development/DEVELOPMENT TIME

Units: vehicle/Month

It is the rate at which new vehicles are designed and introduced to the market.

(171) nonferrous metals trend = IF THEN ELSE(Switch to use historical trends =1, his nonferrous metals trend,cq nonferrous metals trend)

Units: kg/vehicle

Is the variable policy decision on nonferrous materials. Sensitive to the initial conditions: equilibrium or historical.

(172) Old cars being retired = IF THEN ELSE(Switch to step retirement of old cars =1, retiring 4+retiring 5+retiring 6+retiring 7+aging 7+step old cars retiring, retiring 4+retiring 5+retiring 6+retiring 7+aging 7)

Units: car/Month

Is the total flow of cars being retired. The switch to step this variable is used to test the forecast structures.

(173) Perceived average prop[property] = SMOOTH(Average prop of platforms being sold[property]/vehicle, TIME TO PERCEIVED AVERAGE PROP[property])

Units: kg/car

This is the weight, composition, and level of DFD that the automakers would perceive.

(174) plastic trend = IF THEN ELSE(Switch to use historical trends=1,his plastics trend, eq plastic trend)

Units: kg/vehicle

Is the variable policy decision on plastics materials. Sensitive to the initial conditions: equilibrium or historical.

(175) platform discontinuation rate = Platforms in market/DISCONTINUE TIME

Units: vehicle/Month

Is the rate at which vehicles are discontinued and are no longer offered to the consumer.

(176) Platform in development = INTEG(new platform dev rate-new platform introduction rate ,INI PLATFORMS UNDER DEVELOPMENT)

Units: vehicle

The number of platforms being designed is a function of the rate at which new initiatives are incorporated and of the design completion rate (introduction of new platform rate).

(177) Platforms in market = INTEG(new platform introduction rate-platform discontinuation rate ,INI PLATFORMS IN MARKET)

Units: vehicle

Is the number of different platforms offered (sold) at any point in time. The number is increased as new platforms are designed and reduced as platforms get discontinued.

(178) prop discontinuation rate [property]= platform discontinuation rate \* Average prop of platforms being sold[property]

Units: kg/Month

The rate at which properties are discontinued depend on the platform discontinuation rate. It is assumed that the platforms are discontinued with the average property in the market cohort.

(179) Prop in platform in market[*property*] = INTEG(prop introduction rate[*property*] - prop discontinuation rate[*property*], Ini prop in market[*property*])  
Units: kg  
Corresponds to the stock of properties of platforms being offered to the market.

(180) Prop in platform under development[*property*] = INTEG(prop into development rate [*property*] - prop introduction rate[*property*], Ini prop under development[*property*])  
Units: kg  
This stock calculates the amount of each property associated to the platforms being developed.

(181) prop into development rate[*property*] = Target platform prop into dev[*property*] \* new platform dev rate  
Units: kg/Month  
This is the start of the parallel structure that tracks the property levels along the chain of platform development and platform in the market. This is the inflow of properties into the chain, it is a function of the target property (policy)\_and the new development rate

(182) prop introduction rate[*property*] = Average prop in platforms under development[*property*] \* new platform introduction rate  
Units: kg/Month  
This is the rate at which properties are transferred from the development stage into the market. The cars being developed are created with the average property in the development stage.

(183) Property designed[Mass] = Average prop of platforms being sold[Mass]/vehicle  
Property designed[Ferrous] = Average prop of platforms being sold[Ferrous]/vehicle  
Property designed[Nonferrous] = Average prop of platforms being sold[Nonferrous]/vehicle  
Property designed[plastics] = Average prop of platforms being sold[plastics]/vehicle  
Property designed[DFD] = Average prop of platforms being sold[DFD]/vehicle  
Units: kg/car  
It is the property level at which cars are sold. Corresponds to the Average property in the platforms being designed.

(184) step platform prop into dev[Mass] = step(280,100)+step(-280,200)  
step platform prop into dev[Ferrous] = (prop into development rate[Mass]-prop into development rate[Nonferrous]-prop into development rate[plastics])/new platform dev rate  
step platform prop into dev[Nonferrous] = step(14,100)+step(-14,200)  
step platform prop into dev[plastics] = step(196,100)+step(-196,200)  
step platform prop into dev[DFD] = step(2,100)  
Units: kg/vehicle

(185) Switch to develop constant property cars[Mass] = 1  
Switch to develop constant property cars[Ferrous] = 1  
Switch to develop constant property cars[Nonferrous] = 1  
Switch to develop constant property cars[plastics] = 1  
Switch to develop constant property cars [DFD]= 1  
Units: dimensionless

(186) Switch to equilibrium stocks = 1  
Units: dimensionless

This switch controls the initial level of several stocks in the model. It is used to test the model. Assigns the levels that correspond to an equilibrium condition.

(187) Switch to use historical trends = 0  
Units: dimensionless

(188) Switch to use prop trend = 1  
Units: dimensionless

(189) Target platform prop into dev[*property*] = IF THEN ELSE (Switch to develop constant property cars[*property*]=1, CONSTANT TARGET PROP[*property*], variable prop into development[*property*])  
Units: kg/vehicle  
This is the level of property that will go into the design chain.

(190) TIME TO PERCEIVED AVERAGE PROP[*property*] = 12  
Units: Month  
The Automakers would have a delay of 12 months to perceive the actual value of the average property being sold in the vehicles.

(191) variable prop into development[Mass]= IF THEN ELSE(Switch to use prop trend=1, weight trend, CONSTANT TARGET PROP[Mass]+step platform prop into dev[Mass])  
variable prop into development[Ferrous] = IF THEN ELSE(Switch to use prop trend = 1, ferrous metals trend, step platform prop into dev[Ferrous])  
variable prop into development[Nonferrous] = IF THEN ELSE(Switch to use prop trend=1, nonferrous metals trend, CONSTANT TARGET PROP[Nonferrous]+step platform prop into dev[Nonferrous])  
variable prop into development[plastics] = IF THEN ELSE (Switch to use prop trend = 1, plastic trend, CONSTANT TARGET PROP[plastics]+step platform prop into dev[plastics])  
variable prop into development[DFD] = IF THEN ELSE(Switch to use prop trend=1, DFD trend, CONSTANT TARGET PROP[DFD]+step platform prop into dev[DFD])  
Units: kg/vehicle  
This is the property level to be used in the development chain when running the simulation complete and using a certain policy trend.

(192) vehicle = 1  
Units: car/vehicle  
Conversion factor.

(193) weight trend = IF THEN ELSE(Switch to use historical trends=1, his weight trend, eq weight trend)  
Units: kg/vehicle

## .Control

### Simulation Control Parameters

(194) Cars being processed = dismantling of new cars+dismantling rate  
Units: car/Month

(195) ds profit per car = dismantler profit/dismantling rate  
Units: \$/car  
Evaluates the actual profit per car dismantlers get.

(196)  $D_s$  share of cumulative profit = IF THEN  
ELSE(Time=0,0.8448, Dismantler Cumulative Profit/total  
cumulative profit)  
Units: dimensionless  
Compares dismantlers' profit to the total profit made by the  
industry.

(197)  $d_s$  share of profit = IF THEN ELSE(Time=0,0.8444,  
dismantler profit/total monthly profit)  
Units: dimensionless  
Evaluates the fraction of the industry monthly profit  
corresponding to dismantlers.

(198)  $d_s$  share of profit per car = IF THEN  
ELSE(Time=0,0.8739, $d_s$  profit per car / total profit per car)  
Units: dimensionless  
Evaluates the fraction of the industry profit per car  
corresponding to the dismantlers.

(199) FINAL TIME = 600  
Units: Month  
The final time for the simulation.

(200) INITIAL TIME = 0  
Units: Month  
The initial time for the simulation.

(201) old to new car ratio =  $d_s$  profit per car/margin per  
new car  
Units: dimensionless  
Is a supplementary variable to observe potential differences in  
the effects of policies and scenarios on dismantling of old cars  
versus dismantling of new cars (using per car units)

(202) old to new profit ratio = dismantler profit/monthly  
margin from new cars  
Units: dimensionless  
Is a supplementary variable to observe potential differences in  
the effects of policies and scenarios on dismantling of old cars  
versus dismantling of new cars (using dollar/month units)

(203) SAVEPER =  
TIME STEP  
Units: Month  
The frequency with which output is stored

(204)  $sh$  profit per car = Shredder profit/shredding car rate  
Units: \$/car  
Is the profit per car shredders get.

(205)  $Sh$  share of cumulative profit = IF THEN  
ELSE(Time=0,0.1551, Shredder cumulative profit/total  
cumulative profit)  
Units: dimensionless  
Is the shredders' cumulative profit relative to the whole industry.

(206)  $sh$  share of profit = IF THEN ELSE(Time=0,0.1555,  
Shredder profit/total monthly profit)  
Units: dimensionless  
Is the shredders' profit per month relative to the industry's  
monthly profit.

(207)  $sh$  share of profit per car = IF THEN  
ELSE(Time=0,0.126, $sh$  profit per car / total profit per car)  
Units: dimensionless  
Is the shredders' profit per car relative to the industry's profit per  
car.

(208) TIME STEP = 1  
Units: Month  
The time step for the simulation.

(209) total cumulative profit = Dismantler Cumulative  
Profit+Shredder cumulative profit  
Units: \$  
The industry's cumulative profit is the sum of the profit of  
dismantlers and shredders.

(210) total monthly profit = dismantler profit+Shredder  
profit  
Units: \$/Month  
The industry monthly profit is the sum of the monthly profit of  
dismantlers plus shredders'.

(211) total profit per car =  $d_s$  profit per car+ $sh$  profit per car  
Units: \$/car  
The total profit per car made by the industry is the sum of the  
profit made by dismantlers plus the profit made by shredders.

## .dscal

(212) BASE NONFERROUS IN PARTS = 0.0763  
Units: dimensionless  
Is the equilibrium value, used for testing purposes.

(213) BASE PLASTIC IN PARTS = 0.2274  
Units: dimensionless  
Is the equilibrium value, used for testing purposes.

(214) BASE WEIGHT OF NEW CARS = 1400  
Units: kg/car  
Is the equilibrium value, used for testing purposes.

(215) error in fractions recycled in new cars =  
(nonferrous recycled in new cars+plastics recycled in new cars)  
-fraction of mass recycled in new cars  
Units: dimensionless  
An error maybe generated if the sum of the two fractions  
(nonferrous and plastics) become larger than the total fraction.

(216) error in fractions recycled in old cars =  
(nonferrous recycled in old cars+plastics recycled in old cars)  
-fraction of mass recycled in old cars  
Units: dimensionless  
An error maybe generated if the sum of the two fractions  
(nonferrous and plastics) become larger than the total fraction.

(217) FRACTION DISMANTLED IN PARTS = 0.621  
Units: dimensionless  
The experiments run on the DMA showed almost no change in  
the fraction of mass being dismantled as parts (at any reasonable  
range of prices of parts). This is the constant fraction found.

(218) fraction of ferrous in parts =1-fraction of nonferrous  
in parts-fraction of plastics in parts  
Units: dimensionless  
The ferrous fraction of the parts balances the total composition.

(219) fraction of mass recycled in new cars =  
MAX(0, $mr_0+mr_1$ \*DFD level in new cars  $n_1$  +  $mr_2$ \*nonferrous  
level in new cars  $n_2+mr_3$ \*plastic level in new cars  $n_3$  +

$mr4 * \text{Nonferrous price level 4} + mr5 * \text{Plastic price level 5} + mr6 * \text{Landfill cost level 6} + mr7 * \text{Labor cost level 7}$   
 Units: dimensionless  
 Equation obtained from the experiments run with the DMA.  
 Takes the level of seven variables and defines the amount of material, as a fraction of the total vehicle mass, that will be recycled from new cars, when the car has no parts to be removed (this equation is the same than for old cars because there is no value of parts). Cannot be negative.

(220)  $\text{fraction of mass recycled in old cars} = \text{MAX}(0, mr0 + mr1 * \text{DFD level in old cars } o1 + mr2 * \text{nonferrous level in old cars } o2 + mr3 * \text{plastic level in old car } o3 + mr4 * \text{Nonferrous price level 4} + mr5 * \text{Plastic price level 5} + mr6 * \text{Landfill cost level 6} + mr7 * \text{Labor cost level 7})$   
 Units: dimensionless  
 Equation obtained from the experiments run with the DMA.  
 Takes the level of seven variables and defines the amount of material, as a fraction of the total vehicle mass, that will be recycled from old cars. Cannot be negative.

(221)  $\text{fraction of nonferrous in parts} = \text{IF THEN ELSE}(\text{Switch to turn to constant parts dismantling} = 1, \text{BASE NONFERROUS IN PARTS, nonferrous parts composition graph}(\text{Nonferrous fraction in new cars being processed}))$   
 Units: dimensionless  
 The fraction of the parts made of nonferrous materials is a function of the vehicle composition.

(222)  $\text{fraction of plastics in parts} = \text{IF THEN ELSE}(\text{Switch to turn to constant parts dismantling} = 1, \text{BASE PLASTIC IN PARTS, plastic parts composition graph}(\text{Plastic fraction in new cars being processed}))$   
 Units: dimensionless  
 The fraction of the parts made of non-metal materials is a function of the vehicle composition.

(223)  $\text{FREQUENCY OF COMPLETE PARTS} = 0.5$   
 Units: dimensionless  
 This number is the estimated fraction of new cars that would have all their parts in good conditions and for which there would be a market for (assumes that cars are either in this condition or completely damaged). Completely damaged cars would be processed for material recovery only.

(224)  $\text{Kg ferrous recycled from old cars} = \text{MAX}(\text{Mass being recycled in old cars} - \text{Kg of nonferrous recycled from old cars} - \text{Kg plastics recycled from old cars}, 0)$   
 Units: kg/car  
 The ferrous material to be recycled balances the total material and the plastics and nonferrous recycling. Cannot be negative.

(225)  $\text{kg of ferrous in parts} = \text{fraction of ferrous in parts} * \text{Parts reused in kg per car}$  Units: kg/car  
 The amount of ferrous material in parts is the fraction times the total amount of mass in parts.

(226)  $\text{Kg of ferrous recycled new cars} = \text{MAX}(\text{Mass being recycled in new cars} - \text{Kg of nonferrous recycled new cars} - \text{Kg of plastics recycled new cars}, 0)$   
 Units: kg/car  
 The ferrous material to be recycled balances the total material and the plastics and ferrous recycling.

(227)  $\text{kg of ferrous reused or recycled in new cars} = \text{FREQUENCY OF COMPLETE PARTS} * \text{kg of ferrous in parts}$

$+ (1 - \text{FREQUENCY OF COMPLETE PARTS}) * \text{Kg of ferrous recycled new cars}$   
 Units: kg/car  
 The amount of ferrous material recovered from the new cars is the weighted sum of the material recycled plus the material in parts.

(228)  $\text{kg of nonferrous in parts} = \text{fraction of nonferrous in parts} * \text{Parts reused in kg per car}$   
 Units: kg/car  
 The amount of nonferrous material in parts is the non-ferrous fraction times the total amount of mass in parts.

(229)  $\text{Kg of nonferrous recycled from old cars} = \text{IF THEN ELSE}(\text{Switch to turn constant material recycling} = 1, 8.4, \text{MIN}(\text{Average prop of old cars to be processed}[\text{Nonferrous}], \text{Average prop of old cars to be processed}[\text{Mass}] * \text{nonf recycled from oc corrected}))$   
 Units: kg/car  
 The amount of material to be recycled per car is the fraction of the material corrected times the weight of the vehicle. Can be set constant for testing purposes.

(230)  $\text{Kg of nonferrous recycled new cars} = \text{IF THEN ELSE}(\text{Switch to turn constant material recycling} = 1, 8.4, \text{MIN}(\text{Average prop of new cars to be processed}[\text{Nonferrous}], \text{Average prop of new cars to be processed}[\text{Mass}] * \text{nonf recycled from nc corrected}))$   
 Units: kg/car  
 The amount of material to be recycled per car is the fraction of the material corrected times the weight of the vehicle. Can be set constant for testing purposes.

(231)  $\text{kg of nonferrous reused or recycled in new cars} = \text{MIN}((\text{FREQUENCY OF COMPLETE PARTS} * \text{kg of nonferrous in parts} + (1 - \text{FREQUENCY OF COMPLETE PARTS}) * \text{Kg of nonferrous recycled new cars}), \text{Average prop of new cars to be processed}[\text{Nonferrous}])$   
 Units: kg/car  
 The amount of nonferrous material recovered from the new cars is the weighted sum of the material recycled plus the material in parts.

(232)  $\text{kg of plastics in parts} = \text{fraction of plastics in parts} * \text{Parts reused in kg per car}$   
 Units: kg/car  
 The amount of plastic material in parts is the fraction times the total amount of mass in parts.

(233)  $\text{Kg of plastics recycled new cars} = \text{IF THEN ELSE}(\text{Switch to turn constant material recycling} = 1, 0, \text{MIN}(\text{Average prop of new cars to be processed}[\text{plastics}], \text{Average prop of new cars to be processed}[\text{Mass}] * \text{plas recycled from nc corrected}))$   
 Units: kg/car  
 The amount of material to be recycled per car is the fraction of the material corrected times the weight of the vehicle. Can be set constant for testing purposes.

(234)  $\text{kg of plastics reused or recycled in new cars} = \text{MIN}((\text{FREQUENCY OF COMPLETE PARTS} * \text{kg of plastics in parts} + (1 - \text{FREQUENCY OF COMPLETE PARTS}) * \text{Kg of plastics recycled new cars}), \text{Average prop of new cars to be processed}[\text{plastics}])$   
 Units: kg/car

The amount of plastics material recovered from the new cars is the weighted sum of the material recycled plus the material in parts.

(235) Kg plastics recycled from old cars = IF THEN ELSE (Switch to turn constant material recycling=1,0, MIN(Average prop of old cars to be processed[plastics], Average prop of old cars to be processed[Mass]\*plas recycled from oc corrected ))

Units: kg/car

The amount of material to be recycled per car is the fraction of the material corrected times the weight of the vehicle. Can be set constant for testing purposes.

(236) Mass being recycled in new cars = IF THEN ELSE( Switch to turn constant material recycling = 1, 8.4, MIN(Average prop of new cars to be processed[Mass], Average prop of new cars to be processed[Mass]\*fraction of mass recycled in new cars ))

Units: kg/car

The total mass being recycled is the total fraction times the vehicle weight. Can be set constant for testing purposes.

(237) Mass being recycled in old cars = IF THEN ELSE (Switch to turn constant material recycling = 1, 8.4, MIN(Average prop of old cars to be processed[Mass], Average prop of old cars to be processed[Mass]\*fraction of mass recycled in old cars))

Units: kg/car

The total mass being recycled is the total fraction times the vehicle weight. Can be set constant for testing purposes.

(238)  $mr0 = 0.0134505$

Units: dimensionless

Coefficient from the DOE.

(239)  $mr1 = 0.00058$

Units: dimensionless

Coefficient from the DOE

(240)  $mr2 = -0.0041$

Units: dimensionless

Coefficient from the DOE

(241)  $mr3 = 0.01279$

Units: dimensionless

Coefficient from the DOE.

(242)  $mr4 = -0.00167$

Units: dimensionless

Coefficient from the DOE.

(243)  $mr5 = 0.00585$

Units: dimensionless

Coefficient from the DOE

(244)  $mr6 = -0.00193$

Units: dimensionless

Coefficient from the DOE

(245)  $mr7 = -0.00295$

Units: dimensionless

Coefficient from the DOE

(246)  $nfm0 = 0.0121343$

Units: dimensionless

Coefficient from the DOE.

(247)  $nfm1 = 0.00038$

Units: dimensionless

Coefficient from the DOE.

(248)  $nfm2 = -0.00314$

Units: dimensionless

Coefficient from the DOE.

(249)  $nfm3 = 0.01153$

Units: dimensionless

Coefficient from the DOE.

(250)  $nfm4 = -0.00258$

Units: dimensionless

Coefficient from the DOE.

(251)  $nfm5 = 0.00594$

Units: dimensionless

Coefficient from the DOE.

(252)  $nfm6 = -0.00084$

Units: dimensionless

Coefficient from the DOE.

(253)  $nfm7 = -0.00302$

Units: dimensionless

Coefficient from the DOE.

(254) nonf recycled from nc corrected = IF THEN ELSE(error in fractions recycled in new cars >0, nonferrous recycled in new cars,(IF THEN ELSE( nonferrous recycled in new cars<=plastics recycled in new cars, nonferrous recycled in new cars,nonferrous recycled in new cars -error in fractions recycled in new cars)))

Units: dimensionless

Causes to reduce the nonferrous fraction by the error if the nonferrous fraction is the larger fraction between plastics and nonferrous.

(255) nonf recycled from oc corrected = IF THEN ELSE(error in fractions recycled in old cars >0, nonferrous recycled in old cars, (IF THEN ELSE(nonferrous recycled in old cars<=plastics recycled in old cars, nonferrous recycled in old cars,nonferrous recycled in old cars -error in fractions recycled in old cars)))

Units: dimensionless

Causes to reduce the nonferrous fraction by the error if the nonferrous fraction is the larger fraction between plastics and nonferrous.

(256) nonferrous parts composition graph ((0,0), (0.02,0.03), (0.034,0.052), (0.095,0.145), (0.222,0.345), (0.255,0.397), (0.333,0.518),(0.5,0.714),(0.631,0.835), (0.778,0.908), (1,1))

Units: dimensionless

Empirical graph to relate the composition of parts to the composition of the whole vehicle. Drawn from the DMI. files created at the DMA experimentation stage. Used for the nonferrous material.

(257) nonferrous recycled in new cars = MAX (0,nfm0+nfm1\*DFD level in new cars n1 + nfm2\*nonferrous level in new cars n2+nfm3\*plastic level in new cars n3 + nfm4\*Nonferrous price level 4+nfm5\*Plastic price level 5 + nfm6\*Landfill cost level 6+nfm7\*Labor cost level 7)

Units: dimensionless

Equation obtained from the experiments run with the DMA. Takes the level of seven variables and defines the amount of nonferrous material, as a fraction of the total vehicle mass, that will be recycled from new cars, when the car has no parts to be removed (this equation is the same than for old cars because there is no value of parts). Cannot be negative.

(258) nonferrous recycled in old cars = MAX  
 $(0, nfm0 + nfm1 * DFD \text{ level in old cars } o1 + nfm2 * \text{nonferrous level in old cars } o2 + nfm3 * \text{plastic level in old car } o3 + nfm4 * \text{Nonferrous price level } 4 + nfm5 * \text{Plastic price level } 5 + nfm6 * \text{Landfill cost level } 6 + nfm7 * \text{Labor cost level } 7)$   
 Units: dimensionless

Equation obtained from the experiments run with the DMA. Takes the level of seven variables and defines the amount of nonferrous material, as a fraction of the total vehicle mass, that will be recycled from new cars. Cannot be negative.

(259) Parts reused in kg per car = IF THEN ELSE(Switch to turn to constant parts dismantling = 1, BASE WEIGHT OF NEW CARS \* FRACTION DISMANTLED IN PARTS, Average prop of new cars to be processed [Mass] \* FRACTION DISMANTLED IN PARTS )  
 Units: kg/car  
 The mass removed in parts is the fraction obtained from the DMA runs times the mass of the new cars.

(260) plas recycled from nc corrected = IF THEN ELSE(error in fractions recycled in new cars > 0, plastics recycled in new cars, (IF THEN ELSE(plastics recycled in new cars < nonferrous recycled in new cars, plastics recycled in new cars, plastics recycled in new cars - error in fractions recycled in new cars)))  
 Units: dimensionless  
 Causes to reduce the plastic fraction by the error if the plastic fraction is the larger fraction between plastics and nonferrous

(261) plas recycled from oc corrected = IF THEN ELSE(error in fractions recycled in old cars > 0, plastics recycled in old cars, (IF THEN ELSE(plastics recycled in old cars < nonferrous recycled in old cars, plastics recycled in old cars, plastics recycled in old cars - error in fractions recycled in old cars)))  
 Units: dimensionless  
 Causes to reduce the plastic fraction by the error if the plastic fraction is the larger fraction between plastics and nonferrous

(262) plastic parts composition graph  
 $((0,0), (0.05, 0.025), (0.1, 0.055), (0.15, 0.1), (0.194, 0.148), (0.212, 0.171), (0.278, 0.269), (0.333, 0.351), (0.5, 0.568), (0.667, 0.759), (0.75, 0.83), (1, 1))$   
 Units: dimensionless  
 Empirical graph to relate the composition of parts to the composition of the whole vehicle. Drawn from the DML files created at the DMA experimentation stage. Used for the non-metal material

(263) plastics recycled in new cars = MAX  
 $(0, pmr0 + pmr1 * DFD \text{ level in new cars } n1 + pmr2 * \text{nonferrous level in new cars } n2 + pmr3 * \text{plastic level in new cars } n3 + pmr4 * \text{Nonferrous price level } 4 + pmr5 * \text{Plastic price level } 5 + pmr6 * \text{Landfill cost level } 6 + pmr7 * \text{Labor cost level } 7)$   
 Units: dimensionless  
 Equation obtained from the experiments run with the DMA. Takes the level of seven variables and defines the amount of non-metal material, as a fraction of the total vehicle mass, that will be recycled from new cars, when the car has no parts to be

removed (this equation is the same than for old cars because there is no value of parts). Cannot be negative.

(264) plastics recycled in old cars = MAX  
 $(0, pmr0 + pmr1 * DFD \text{ level in old cars } o1 + pmr2 * \text{nonferrous level in old cars } o2 + pmr3 * \text{plastic level in old car } o3 + pmr4 * \text{Nonferrous price level } 4 + pmr5 * \text{Plastic price level } 5 + pmr6 * \text{Landfill cost level } 6 + pmr7 * \text{Labor cost level } 7)$   
 Units: dimensionless

Equation obtained from the experiments run with the DMA. Takes the level of seven variables and defines the amount of non-metal material, as a fraction of the total vehicle mass, that will be recycled from old cars. Cannot be negative.

(265)  $pmr0 = 0.0007598$   
 Units: dimensionless  
 Coefficient from the DOE.

(266)  $pmr1 = 0.00076$   
 Units: dimensionless  
 Coefficient from the DOE.

(267)  $pmr2 = -5.7e-005$   
 Units: dimensionless  
 Coefficient from the DOE.

(268)  $pmr3 = 0.0007$   
 Units: dimensionless  
 Coefficient from the DOE.

(269)  $pmr4 = 0.00051$   
 Units: dimensionless  
 Coefficient from the DOE.

(270)  $pmr5 = -0.00065$   
 Units: dimensionless  
 Coefficient from the DOE.

(271)  $pmr6 = -0.0007$   
 Units: dimensionless  
 Coefficient from the DOE.

(272)  $pmr7 = 0.00063$   
 Units: dimensionless  
 Coefficient from the DOE.

(273) Switch to turn constant material recycling = 0  
 Units: dimensionless  
 Sets a constant dismantling practice if equal to 1

(274) Total kg dismantled in new cars = kg of ferrous reused or recycled in new cars + kg of nonferrous reused or recycled in new cars + kg of plastics reused or recycled in new cars  
 Units: kg/car  
 The total amount of materials removed from new cars is the sum of the three materials removed.

## .dscapa

(275) Actual Ds capacity utilization = dismantling rate / Dismantler capacity in cars  
 Units: dimensionless  
 Is the fraction of Ds capacity being utilized at any point in time

(276) Deviation in Ds utilization rate =

## Appendix III. Complete Documentation of the Automobile Recycling Dynamic Model

(Ds DESIRED CAPA UTILIZATION-Actual Ds capacity utilization)/Ds DESIRED CAPA UTILIZATION

Units: dimensionless

Evaluates the percent deviation in utilization rate for dismantlers.

(277) Dismantler capacity in cars =IF THEN ELSE(Switch to turn dismantling capacity constant =1, 1e+007,Dynamic Dismantlers capacity in hrs/Labor into dismantling)

Units: car/Month

Represents the number of cars that dismantlers can process given the current dismantling practice.

(278) Ds aging rate =

Dynamic Dismantlers capacity in hrs/LIFETIME OF Ds CAPA  
Units: hr/(Month\*Month)

Ds capacity gets old and is discarded at this rate; function of the level of the stock and with a (3th order) delay considering the time to age. This is the second element considered to order Ds capacity.

(279) Ds capa completion rate =

Ds Capacity in Order/t TO COMPLETE Ds CAPACITY  
Units: (hr/Month)/Month

Is the rate at which the ordered capacity gets installed and becomes functional. It is calculated with a 3rd order delay, considering the time to complete.

(280) Ds Capacity in Order = INTEG(+Ds capacity order rate-Ds capa completion rate,Ini Ds capacity on order)

Units: hr/Month

Capacity ordered. It will become actual capacity at the Completion rate.

(281) Ds capacity in order gap = Ds indicated capa in order-Ds Capacity in Order

Units: hr/Month

The difference between the indicated and the actual capacity in order is calculated here.

(282) Ds capacity indicated increment =

Expected dismantling capacity gap/t CORRECT Ds CAPA GAP  
Units: hr/(Month\*Month)

Dismantlers desire to close the gap between Indicated and actual capacity in the time "t to CORRECT GAP". This is the first of three elements considered to order capacity

(283) Ds capacity order rate =

MAX(Indicated Ds capacity change,0)

Units: hr/(Month\*Month)

Is the order at which capacity gets ordered. It can not be negative.

(284) Ds correction for capacity in order =

Ds capacity in order gap/t TO CORRECT Ds CAPA IN ORDER GAP

Units: hr/(Month\*Month)

Dismantlers desire to close the gap in capacity in "time to correct capa in order" This is the third element taken into consideration to order capacity

(285) Ds DESIRED CAPA UTILIZATION = 0.8

Units: dimensionless

Estimated desired utilization rate for dismantlers.

(286) Ds expected dismantling = Ds expected future

retiring old cars\*Ds expected future labor into cars

Units: hr/Month

The expected dismantling is the multiplication of the expected supply of cars (future retiring) by the expected future labor into cars.

(287) Ds indicated capa in order = Ds aging rate\*t TO COMPLETE Ds CAPACITY

Units: hr/Month

The Ds aging capa rate and the time to complete the capacity on order define the adequate level of capacity in order.

(288) Ds indicated capacity =

(Ds expected dismantling/Ds DESIRED CAPA UTILIZATION)\*Effect of profit in Ds ideal capacity\*Effect of utilization rate in Ds capacity

Units: hr/Month

The Dismantlers indicated capacity, increased by the Desired utilization factor and fine-tuned by the effect of profit in desired capacity.

(289) Dynamic Dismantlers capacity in hrs = INTEG(Ds capa completion rate-Ds aging rate,Ini Ds capacity)

Units: hr/Month

Is the actual Ds capacity. Is increased by the completion rate and decreased, as it gets old, by the capa aging rate.

(290) Effect of profit in Ds desired capacity graph ((-2,0.5),(-1,0.5),(0,0.7),(0.25,0.8),(0.48,0.9),(1,1),(1.1,1.08),(1.5,1.2),(10,1.2))

Units: dimensionless

Relationship between dismantling profits and desired capacity (efficient markets theory).

(291) Effect of profit in Ds ideal capacity =Effect of profit in Ds desired capacity graph(Relative Ds future profit)

Units: dimensionless

Evaluates the "attractiveness" of dismantling. Increases in profits would stimulate the installation of more dismantling capacity.

(292) Effect of utilization rate in Ds capacity = Effect of utilization rate on capacity graph(Deviation in Ds utilization rate)

Units: dimensionless

If the utilization rate of dismantlers is below the desired level, dismantlers would tend to reduce the orders for additional capacity.

(293) Effect of utilization rate on capacity graph ((-1,1.22),(-0.5,1.21),(-0.2,1.2),(-0.1,1.15),(-0.05,1.1),(0,1),(0.05,0.9),(0.1,0.85),(0.2,0.8),(0.5,0.79),(1,0.78))

Units: dimensionless

Relationship between dismantlers' capacity and utilization rates.

(294) Expected dismantling capacity gap = Ds indicated capacity-Dynamic Dismantlers capacity in hrs

Units: hr/Month

The Indicated capacity and the actual capacity define the gap

(295) Indicated Ds capacity change = Ds capacity indicated increment+Ds aging rate+Ds correction for capacity in order

Units: hr/(Month\*Month)

The total capacity to be ordered is the sum of the three elements: aging part, capacity in order gap, and indicated capacity gap.

(296) LIFETIME OF Ds CAPA = 180

Units: Month

It is estimated that a dismantling facility lasts 15 years.



(297) Relative Ds future profit = Expected future Ds profit per semester/Base Ds semester profit  
Units: dimensionless  
Defines what is the relative level of profit, comparing actual profit to a Standard (Base Ds semester profit)

(298) t CORRECT Ds CAPA GAP = 12  
Units: Month  
It is the time dismantlers would like to take to correct the capacity gap, considering future work, profits, and actual capacity.

(299) t TO COMPLETE Ds CAPACITY = 24  
Units: Month  
This is the time it takes to complete a Dismantlers' facility.

(300) t TO CORRECT Ds CAPA IN ORDER GAP = 6  
Units: Month  
Is the time Dismantlers would like to take to correct the gap in capacity in order

### .dsfore

(301) AVERAGE t FOR DISMANTLING FORECAST = 12  
Units: Month  
Number of past months the Dismantlers consider to make their forecast.

(302) conv2 = 1  
Units: sec/kg  
Conversion factor.

(303) DISMANTLERS HORIZON = 12  
Units: Month  
Time the Dismantlers consider into the future to make their forecast.

(304) Dismantlers perceived retiring = SMOOTH(Supply of cars observed by dismantlers,t TO PERCEIVE RETIRING)  
Units: car/Month  
Dismantlers perceive retiring with a delay of 3 months (t TO PERCEIVE RETIRING)

(305) dismantling per car in secs = dismantling time precalculation  
\*fraction of mass recycled in old cars\*conv2  
Units: sec/kg  
The dismantling done in cars is a function of the precalculation and the fraction of the mass being dismantled.

(306) dismantling time precalculation = (lo0+lo1\*DFD level in old cars o1+lo2\*nonferrous level in old cars o2+lo3\*plastic level in old car o3+lo4\*Nonferrous price level 4+lo5\*Plastic price level 5+lo6\*Landfill cost level 6+lo7\*Labor cost level 7)\*2  
Units: dimensionless  
Is part of the equation from the DMA runs that considers the levels of the seven variables to define a normalized amount of time spent in dismantling. This calculation has to be multiplied by the fraction of mass dismantled and by the mass of the car to give the seconds spent per car

(307) Ds expected future labor into cars = FORECAST(Labor into dismantling,AVERAGE t FOR DISMANTLING FORECAST,DISMANTLERS HORIZON)  
Units: hr/car  
The amount of time spent per car is the basis to forecast how much time the dismantlers will be spending in the future in dismantling cars.

(308) Ds expected future retiring old cars = FORECAST(Dismantlers perceived retiring,AVERAGE t FOR DISMANTLING FORECAST,DISMANTLERS HORIZON)  
Units: car/Month  
The Dismantlers make a forecast of retiring based on the retiring they perceive taking into consideration 6 months into the past and 6 months into the future.

(309) Ds t TO PERCEIVE RETIRING = 9  
Units: Month  
It is assumed that dismantlers take on average 9 months to perceive changes in retirement patterns.

(310) Expected future Ds profit per semester = FORECAST(Perceived Ds profit per semester,AVERAGE t FOR DISMANTLING FORECAST,DISMANTLERS HORIZON)  
Units: \$  
Dismantlers would project their future profit taking into consideration the previous and the next 6 months.

(311) hour = 3600  
Units: sec/hr  
Conversion factor.

(312) lo0 = 11.373  
Units: dimensionless  
Coefficient form the DOE.

(313) lo1 = -1.543  
Units: dimensionless  
Coefficient form the DOE

(314) lo2 = 0.575  
Units: dimensionless  
Coefficient form the DOE

(315) lo3 = 6.077  
Units: dimensionless  
Coefficient form the DOE

(316) lo4 = -1.671  
Units: dimensionless  
Coefficient form the DOE

(317) lo5 = 7.934  
Units: dimensionless  
Coefficient form the DOE

(318) lo6 = -0.713  
Units: dimensionless  
Coefficient form the DOE

(319) lo7 = -4.804  
Units: dimensionless  
Coefficient form the DOE

(320) Perceived Ds profit per semester = SMOOTH(Ds semester profit,t TO PERCEIVE Ds FINANCIAL INFO)

Units: \$

Dismantlers perceive their semester profit with a time delay.

(321)  $\text{step old cars retiring} = \text{step}(147218,100) + \text{step}(-147218,200)$

Units: car/Month

Produces a step function in cars being retired to test the forecast structure.

(322)  $\text{Supply of cars observed by dismantlers} = \text{DELAY3}(\text{Old cars being retired}, \text{Ds } t \text{ TO PERCEIVE RETIRING})$

Units: car/Month

This is how dismantlers perceive the retiring pattern.

(323)  $t \text{ TO PERCEIVE Ds FINANCIAL INFO} = 3$

Units: Month

The time it takes the dismantlers to perceive changes in the semester profit.

(324)  $t \text{ TO PERCEIVE RETIRING} = 3$

Units: Month

It is assumed that the Dismantling Industry analyzes the retiring of old cars 4 times per year.

(325)  $\text{variable labor into dismantling} = \text{Average prop of old cars to be processed}[\text{Mass}] * \text{dismantling per car in secs/hour}$

Units: hr/car

Is the amount of time spent per car in profit maximizing activities. Uses the time per kg of mass vehicle, the mass of cars being processed and it is expressed in hours.

### .dsprofit

(326)  $\text{BASE Ds CAR PROFIT} = 36.214$

Units: \$/car

Represents the initial standard profit per car dismantlers would like to protect.

(327)  $\text{Base Ds monthly profit} = \text{BASE Ds CAR PROFIT} * \text{sales to calculate initial stocks} * \text{Ini old car fraction}$

Units: \$/Month

Represents the initial standard profit per month dismantlers would like to protect

(328)  $\text{Base Ds semester profit} = \text{SEMESTER} * \text{Base Ds monthly profit}$

Units: \$

Represents the initial standard profit per semester dismantlers would like to protect

(329)  $\text{BASE UNIT DISMANTLING LABOR COST} = 20$

Units: \$/hr

The marginal cost of dismantling labor

(330)  $\text{conv4} = 1$

Units: \$/kg

Conversion factor

(331)  $\text{Corrected hulk price} = \text{Hulk price per ton} * \text{Gross to net ton factor}$

Units: \$/ton

Hulk price in net tons have to be corrected by the standard practice (difference between standard and gross)

(332)  $\text{Dismantler Cumulative Profit} = \text{INTEG}(\text{dismantler profit}, 0)$

Units: \$

The dismantlers' profit is accumulated in the simulation for reporting purposes.

(333)  $\text{dismantler profit} = \text{Total Ds revenue} - \text{Total Ds cost}$

Units: \$/Month

IS the monthly profit in the dismantling industry (dismantling of "old cars" only).

(334)  $\text{dismantler profit per hulk transferred} = \text{dismantler profit/hulks selling rate}$

Units: \$/car

A 'per vehicle' profit is calculated here for the dismantlers.

(335)  $\text{Dismantling labor cost} = \text{Dismantling labor cost per car} * \text{dismantling rate}$

Units: \$/Month

Dismantlers' cost in labor.

(336)  $\text{Dismantling labor cost per car} = \text{Labor into dismantling} * \text{Unit labor cost}$

Units: \$/car

Labor cost spent per car.

(337)  $\text{Ds capacity cost} = \text{Ds capacity for profit} * \text{Ds INI UNIT CAPACITY COST}$

Units: \$/Month

Represents the fixed cost of capacity.

(338)  $\text{Ds capacity for profit} = \text{IF THEN ELSE}(\text{Switch to disconnect ds capacity and profit} = 1, \text{INI Ds EQ CAPA}, \text{Dynamic Dismantlers capacity in hrs})$

Units: hr/Month

Allows to disconnect this sector from the dynamic determination of capacity.

(339)  $\text{Ds energy cost} = \text{dismantling rate} * \text{Ds UNIT ENERGY COST}$

Units: \$/Month

Monthly dismantlers' energy cost.

(340)  $\text{Ds INI UNIT CAPACITY COST} = 24.4438$

Units: \$/hr

Calculated capacity cost based on interviews and direct research. Presented in terms of dollars/unit of capacity.

(341)  $\text{Ds revenue from hulks} = \text{Ds revenue from hulks per car} * \text{hulks selling rate}$

Units: \$/Month

Revenue generated by selling hulks to shredders per month

(342)  $\text{Ds revenue from hulks per car} = \text{Average weight of old hulks transferred} * \text{Corrected hulk price}$

Units: \$/car

Revenue generated by selling hulks to shredders per hulk

(343)  $\text{Ds revenue from recycling} = \text{Ds revenue from recycling per car} * \text{hulks selling rate}$

Units: \$/Month

Revenue generated by selling recovered material.

(344)  $\text{Ds revenue from recycling per car} = \text{Average prop of old cars to be processed}$

[Mass]

**\*Precalc Ds revenue from recycling\*conv4**  
 Units: \$/car  
 Is the income per car Dismantlers generate by material recycling.

(345) Ds semester profit = INTEG(inc rate Ds semester profit-out rate Ds semester profit ,Base Ds semester profit)  
 Units: \$  
 The average semester profit for the dismantlers is evaluated to smooth out monthly noise.

(346) Ds UNIT ENERGY COST = 0.6461  
 Units: \$/car  
 Is the estimated cost of compacting the cars

(347) Gross to net ton factor = 0.892857  
 Units: dimensionless  
 Is the ratio of one "gross ton" to a "net ton" (2000/2240)

(348) inc rate Ds semester profit = dismantler profit  
 Units: \$/Month  
 The monthly profit is used and the rate at which the stock of semester profit increases

(349) Junk car cost =IF THEN ELSE(Switch to disconnect Ds profit from Junk car price=1,INI EQ JUNK CAR PRICE\* dismantling rate,Dynamic junk car price\* dismantling rate)  
 Units: \$/Month  
 Monthly dismantlers' cost of buying junk cars Allows to disconnect this variable from the dynamic determination of junk car price

(350) Labor into dismantling = variable labor into dismantling+STANDARD TIME TO PROCESS A CAR  
 Units: hr/car  
 The total amount of time spent in dismantling is the sum of the time to move cars into and from the dismantling station, the time spent removing parts required to sell the hulks, and the profit optimizing dismantling

(351) out rate Ds semester profit = Ds semester profit/SEMESTER  
 Units: \$/Month  
 The average semester profit is reduced considering this rate, everything in the stock will be go out every 6 months

(352) Precalc Ds revenue from recycling = ro0+ro1\*DFD level in old cars o1+ro2\*nonferrous level in old cars o2+ro3\*plastic level in old car o3+ro4\*Nonferrous price level 4+ro5\*Plastic price level 5+ro6\*Landfill cost level 6+ro7\*Labor cost level 7  
 Units: dimensionless  
 Equation from the DMA runs that estimates the income Dismantlers would receive for the material recycling done in old cars, needs to be multiplied by the vehicle weight to produce dollars per car

(353) Relative Ds margin per car sold = SMOOTH(dismantler profit per hulk transferred/BASE Ds CAR PROFIT, t TO PERCEIVE Ds FINANCIAL INFO)  
 Units: dimensionless  
 Evaluates the perceived profitability per hulk sold as a fraction of the desired level

(354) ro0 = 0.0102

Units: dimensionless  
 Coefficient from the DOE.

(355) ro1 = 0.00397  
 Units: dimensionless  
 Coefficient from the DOE.

(356) ro2 = -0.00352  
 Units: dimensionless  
 Coefficient from the DOE.

(357) ro3 = 0.00966  
 Units: dimensionless  
 Coefficient from the DOE.

(358) ro4 = -0.00213  
 Units: dimensionless  
 Coefficient from the DOE.

(359) ro5 = 0.0076  
 Units: dimensionless  
 Coefficient from the DOE.

(360) ro6 = 0.00079  
 Units: dimensionless  
 Coefficient from the DOE.

(361) ro7 = -0.00261  
 Units: dimensionless  
 Coefficient from the DOE.

(362) SEMESTER = 6  
 Units: Month  
 Conversion factor.

(363) STANDARD TIME TO PROCESS A CAR = 0.249  
 Units: hr/car  
 Is the time Dismantlers spend in moving around and taking out the required parts of each car they process.

(364) Switch to disconnect ds capacity and profit = 0  
 Units: dimensionless  
 Disconnects the capacity and the profits sectors for dismantlers when equal to 1

(365) Switch to disconnect Ds profit from Junk car price = 0  
 Units: dimensionless  
 Disconnects the dismantlers' profit sector and the junk car price sector when equal to 1.

(366) Switch to turn dismantling capacity constant = 0  
 Units: dimensionless  
 Switch that creates a constant and in excess capacity for the Dismantlers (1.5million cars month). Testing purposes.

(367) Total Ds cost = Dismantling labor cost+Ds capacity cost+Ds energy cost+Junk car cost  
 Units: \$/Month  
 The total cost for the dismantlers is the sum of dismantling, capacity, energy, and junk car costs.

(368) Total Ds revenue = Ds revenue from recycling+Ds revenue from hulks  
 Units: \$/Month  
 Dismantlers receive revenue from hulks and from recovered material

(369) Unit labor cost = (Labor c index/100 + 1) \* BASE  
UNIT DISMANTLING LABOR COST  
Units: \$/hr  
Labor cost can be changed using the index variable

### .dsrate

(370) BASE Ds STORAGE CAPACITY = 2.8191e+007  
Units: car  
Estimated total storage capacity for dismantlers

(371) BASE HULK PRICE = 80  
Units: \$/ton  
Initial price of hulks

(372) CONSTANT HULK PRICE = 80  
Units: \$/ton  
Initial price of hulks

(373) Desired Ds hulk transferring = MAX(dismantling  
rate+Desired selling rate to correct Disma hulks,Hulks selling  
based on storage limitations)  
Units: car/Month  
The selling of hulks is defined considering the dismantling rate,  
the level of desired inventory and the limitations of storage.

(374) Desired months of Dismantled Hulks = Relative  
months of Dismantled Hulks desired \* BASE MONTHS Ds  
HULKS DESIRED  
Units: Month  
Desired inventory coverage for dismantlers

(375) Desired selling rate to correct Disma hulks =  
Dismantled hulks gap/  
t TO CORRECT Ds INVENTORY  
Units: car/Month  
Is the incremental rate of selling hulk desired to correct the  
inventory gap.

(376) Dismantled hulks gap = Dismantled hulks-Ideal  
Dismantled Hulks  
Units: car  
Difference between the desired number of hulks and the actual  
level of this dismantlers' inventory.

(377) Ds storage usage = Dismantled hulks/BASE Ds  
STORAGE CAPACITY  
Units: dimensionless  
Fraction of the storage space used.

(378) Hulk price per ton = IF THEN ELSE(Switch to  
change hulk price=1,Variable hulk price,CONSTANT HULK  
PRICE)  
Units: \$/ton  
Structure used to test individual sectors using different values of  
hulk price.

(379) Hulks selling based on storage limitations = Ds  
storage usage \* dismantling rate  
Units: car/Month  
If the storage limit is reached, the selling of hulks would be  
determined by this rate.

(380) Ideal Dismantled Hulks = Desired months of  
Dismantled Hulks \* Ds expected future retiring old cars

Units: car

The dismantlers inventory coverage (desired months of  
dismantled hulks) is converted in number of cars considering the  
expected future retiring

(381) Junk car price and desired Dismantled hulks graph ((-  
1.25,11 111),(0.4 444), 0.125,3.722),(0.275,3.111),  
0.5,2),(0.75,1.333), (1.1),(1.25,0.778), 1.5,0.667),  
1.75,0.611),(1.875,0.556),(2,0.5),(2.25,0.444),(3.75,0.333))  
Units: dimensionless  
Relationship between junk car price and dismantlers' inventory  
coverage.

(382) Possible hulk transferring = MAX(Dismantled  
hulks/Month,0)  
Units: car/Month  
Limit on transferring of hulks based on availability.

(383) Relative hulk price = Hulk price per ton/BASE  
HULK PRICE  
Units: dimensionless  
Hulks price is compared to the base price.

(384) Relative months of Dismantled Hulks desired = Junk  
car price and desired Dismantled hulks graph  
(  
Relative hulk price)  
Units: dimensionless  
The relative hulk price is the input to evaluate the relative  
number of months desired or dismantlers' inventory

(385) step hulk price = step(16,100)+step(-16,200)  
Units: \$/ton  
Creates a step change in hulk price. Used for testing purposes.

(386) t TO CORRECT Ds INVENTORY = 12  
Units: Month  
Desired time to correct dismantlers' inventory.

(387) Variable hulk price = IF THEN ELSE(Switch to  
dynamically calculate hulk price=1,Dynamic Hulk  
price,CONSTANT HULK PRICE +step hulk price)  
Units: \$/ton  
Allows to change values for the hulk price. Testing purposes.

### .hulkp

(388) BASED Sh MARGIN PER CAR = 22.81  
Units: \$/car  
This the base margin per car estimated from the research. It was  
calculated at 80\$/ton Hulk price and \$125.6/ton scrap price.

(389) combined effect on price = Effect of Sh inventory in  
hulk price \* Effect of Sh utilization rate on hulk price  
Units: dimensionless  
The effects associated to managing the shredders' inventory and  
the utilization rate inventory are combined in one variable.

(390) Dynamic Hulk price = INTEG(hulk price change  
rate,Ini hulk price)  
Units: \$/ton  
This is the market Hulk price. It is reduced and increased based  
on the monthly price change rate.

(391) Effect of Sh inventory in hulk price =  
IF THEN ELSE(Actual Sh capacity utilization >= 1, 1,

Effect of adequacy of inventory in price graph(Sh relative inventory))  
Units: dimensionless  
The effect on the target price of Hulks based on the adequacy of level of inventory is evaluated here.

(392) Effect of Sh utilization rate on hulk price = Effect of utilization rates on prices graph(Deviation in Sh utilization rate)  
Units: dimensionless  
The fractional deviation in utilization rate on the shredders' facilities is considered here to calculate an effect on hulk price. This structure stabilizes prices (takes out the oscillation characteristic prices).

(393) hulk price change rate = Hulk price gap/  
t for hulk price change  
Units: \$(/ton\*Month)  
The change of Hulk price is calculated considering the price gap and the Desired time to correct price.

(394) Hulk price gap = Target Hulk price-Dynamic Hulk price  
Units: \$/ton  
The Hulk price gap is calculated: the target minus the actual price.

(395) Hulk price per car to protect margin = Sh expected income per car-Sh expected cost without hulks-BASED SH MARGIN PER CAR  
Units: \$/car  
The amount of money the Shredders would like to spend per hulk is a function of their expectations in terms of income and cost.

(396) Hulk price per ton to protect margin = Hulk price per car to protect margin/Sh expected future ton hulk weight  
Units: \$/ton  
The price, in weight terms, of the hulks is calculated based on the Shredders' expectation on the future Hulk weight.

(397) Mass ton Sh rm inventory = Prop in Sh raw material inv[Mass]/Ton  
Units: ton  
This is the total amount of material (in tons) waiting to be shredded.

(398) Sh DESIRED t TO CORRECT HULK PRICE = 6  
Units: Month  
This is the time the Shredders would like to take to correct the Hulk price (make it equal to the target Hulks price)

(399) Sh expected cost without hulks = Sh expected cost per car-Sh expected cost of hulks per car  
Units: \$/car  
This is the expected cost per car without considering the hulk cost.

(400) Sh inventory for pricing = Sh expected future shredding in tons\*(Desired months of shredded matl+MONTHS FOR SHREDDERS RM INVENTORY)  
Units: ton  
The total inventory of shredders is considering to evaluate the effect of inventory in hulk price.

(401) Sh relative inventory = (Mass ton shredded+Mass ton Sh rm inventory)/Sh inventory for pricing  
Units: dimensionless

Represents the fraction of the ideal level of inventory that the Shredders have.

(402) t for hulk price change = Sh DESIRED t TO CORRECT HULK PRICE/SLOWER GAINS

Units: Month  
The desired change in hulk price might be corrected by the variable "slower gains" to test sensitivity and to calibrate the model.

(403) Target Hulk price = (Hulk price per ton to protect margin/Gross to net ton factor)\*combined effect on price  
Units: \$/ton  
The target Hulk price tries to protect the Desired margin and takes into consideration the adequacy of the level of inventory.

### .inival

(404) BASE DISMANTLING DONE IN HULKS  
EQ[Mass] = 126.526  
BASE DISMANTLING DONE IN HULKS EQ[Ferrous] = 65.622  
BASE DISMANTLING DONE IN HULKS EQ[Nonferrous] = 39.374  
BASE DISMANTLING DONE IN HULKS EQ [plastics]= 21.53  
Units: kg/car  
Is the equilibrium level of dismantling per car considering the distribution of old and new cars, the Fraction of new cars with all parts in good condition, and the amount of dismantling in each of these cases.

(405) BASE DISMANTLING DONE IN HULKS  
HIS[Mass] = 115.01  
BASE DISMANTLING DONE IN HULKS HIS[Ferrous] = 76.24  
BASE DISMANTLING DONE IN HULKS HIS[Nonferrous] = 17.55  
BASE DISMANTLING DONE IN HULKS HIS[plastics] = 21.21  
Units: kg/car  
Is the historical level of dismantling per car considering the distribution of old and new cars, the Fraction of new cars with all parts in good condition, and the amount of dismantling in each of these cases.

(406) BASE DISMANTLING DONE IN OLD CARS  
HIS[Mass] = 6.361  
BASE DISMANTLING DONE IN OLD CARS HIS[Ferrous] = 0  
BASE DISMANTLING DONE IN OLD CARS HIS [Nonferrous] = 6.36  
BASE DISMANTLING DONE IN OLD CARS HIS[plastics] = 0.001  
BASE DISMANTLING DONE IN OLD CARS HIS[DFD] = 0  
Units: kg/car  
Initial level of dismantling considering historical conditions. Evaluated empirically from the experimental work at the VRDC and the use of the DMA. Fine-tuned by research on actual practices.

(407) BASE DISMANTLING OF OLD CARS EQ [Mass]= 3c 149  
BASE DISMANTLING OF OLD CARS EQ [Ferrous]= 0

## Appendix III. Complete Documentation of the Automobile Recycling Dynamic Model

BASE DISMANTLING OF OLD CARS EQ[Nonferrous] = 6.11  
 BASE DISMANTLING OF OLD CARS EQ[plastics] = 0.0873035

BASE DISMANTLING OF OLD CARS EQ[DFD] = 0

Units: kg/car

Initial level of dismantling considering equilibrium conditions. Evaluated empirically from the experimental work at the VRDC and the use of the DMA. Fine-tuned by research on actual practices.

(408) Eq property 1[property] = CONSTANT  
 PROPERTY[property]\*EQ 0 to 3

Units: kg

Is the equilibrium value of the initial level of the mass cohort(i). Calculated based on the Equilibrium level of the stock of cars (EQ x to y) and a constant weight of automobiles.

(409) Eq property 2[property] = CONSTANT  
 PROPERTY[property]\*EQ 3 TO 6

Units: kg

Is the equilibrium value of the initial level of the mass cohort(i). Calculated based on the Equilibrium level of the stock of cars (EQ x to y) and a constant weight of automobiles.

(410) Eq property 3[property] = CONSTANT  
 PROPERTY[property]\*EQ 6 TO 9

Units: kg

Is the equilibrium value of the initial level of the mass cohort(i). Calculated based on the Equilibrium level of the stock of cars (EQ x to y) and a constant weight of automobiles.

(411) Eq property 4[property] = CONSTANT  
 PROPERTY[property]\*EQ 9 TO 12

Units: kg

Is the equilibrium value of the initial level of the mass cohort(i). Calculated based on the Equilibrium level of the stock of cars (EQ x to y) and a constant weight of automobiles.

(412) Eq property 5[property] = CONSTANT  
 PROPERTY[property]\*EQ 12 TO 15

Units: kg

Is the equilibrium value of the initial level of the mass cohort(i). Calculated based on the Equilibrium level of the stock of cars (EQ x to y) and a constant weight of automobiles.

(413) Eq property 6[property] = CONSTANT  
 PROPERTY[property]\*EQ 15 TO 18

Units: kg

Is the equilibrium value of the initial level of the mass cohort(i). Calculated based on the Equilibrium level of the stock of cars (EQ x to y) and a constant weight of automobiles.

(414) Eq property 7[property] = CONSTANT  
 PROPERTY[property]\*EQ 18 TO 21

Units: kg

Is the equilibrium value of the initial level of the mass cohort(i). Calculated based on the Equilibrium level of the stock of cars (EQ x to y) and a constant weight of automobiles.

(415) half = 2

Units: dimensionless

Conversion factor.

(416) HIS AVERAGE PROP 1[Mass] = 1352.5

HIS AVERAGE PROP 1[Ferrous] = 974.1

HIS AVERAGE PROP 1[Nonferrous] = 121.1

HIS AVERAGE PROP 1[plastics] = 257.3

HIS AVERAGE PROP 1[DFD] = 1

Units: kg/car

Is the historical average level of property in the first age-cohort.

(417) HIS AVERAGE PROP 2[Mass] = 1238.2

HIS AVERAGE PROP 2[Ferrous] = 890.2

HIS AVERAGE PROP 2[Nonferrous] = 111.8

HIS AVERAGE PROP 2[plastics] = 236.2

HIS AVERAGE PROP 2[DFD] = 1

Units: kg/car

Is the historical average level of property in the second age-cohort.

(418) HIS AVERAGE PROP 3[Mass] = 1285.6

HIS AVERAGE PROP 3[Ferrous] = 938.5

HIS AVERAGE PROP 3[Nonferrous] = 109.1

HIS AVERAGE PROP 3[plastics] = 238

HIS AVERAGE PROP 3[DFD] = 1

Units: kg/car

Is the historical average level of property in the third age-cohort.

(419) HIS AVERAGE PROP 4[Mass] = 1343.7

HIS AVERAGE PROP 4[Ferrous] = 1011.8

HIS AVERAGE PROP 4[Nonferrous] = 98.2

HIS AVERAGE PROP 4[plastics] = 233.7

HIS AVERAGE PROP 4[DFD] = 0.5

Units: kg/car

Is the historical average level of property in the fourth age-cohort.

(420) HIS AVERAGE PROP 5[Mass] = 1325.8

HIS AVERAGE PROP 5[Ferrous] = 1000

HIS AVERAGE PROP 5[Nonferrous] = 93.7

HIS AVERAGE PROP 5[plastics] = 232.1

HIS AVERAGE PROP 5[DFD] = 0.5

Units: kg/car

Is the historical average level of property in the fifth age-cohort.

(421) HIS AVERAGE PROP 6[Mass] = 1445.1

HIS AVERAGE PROP 6[Ferrous] = 1124.1

HIS AVERAGE PROP 6[Nonferrous] = 91.7

HIS AVERAGE PROP 6[plastics] = 229.4

HIS AVERAGE PROP 6[DFD] = 0.3

Units: kg/car

Is the historical average level of property in the sixth age-cohort.

(422) HIS AVERAGE PROP 7[Mass] = 1445.1

HIS AVERAGE PROP 7[Ferrous] = 1124.1

HIS AVERAGE PROP 7[Nonferrous] = 91.7

HIS AVERAGE PROP 7[plastics] = 229.4

HIS AVERAGE PROP 7[DFD] = 0.3

Units: kg/car

Is the historical average level of property in the seventh age-cohort.

(423) HIS EQ HULK PRICE = 89.29

Units: \$/ton

Is the initial hulk price when starting at historical conditions.

(424) HIS INI SALES = 600000

Units: car/Month

Initial historical sales.

(425) HIS JUNK CAR PRICE = 80

Units: \$/car

Initial value of the junk car under historical conditions.

(426) His prop 1[property] = HIS AVERAGE PROP 1[property]\*HIS 0 TO 3

Units: kg

The initial level of the stock, under historical values, is the average historical property per car times the number of cars in the corresponding age-cohort.

(427) His prop 2[property] = HIS AVERAGE PROP 2[property]\*HIS 3 TO 6

Units: kg

The initial level of the stock, under historical values, is the average historical property per car times the number of cars in the corresponding age-cohort.

(428) His prop 3[property] = HIS AVERAGE PROP 3[property]\*HIS 6 TO 9

Units: kg

The initial level of the stock, under historical values, is the average historical property per car times the number of cars in the corresponding age-cohort.

(429) His prop level in market[property] = (HIS AVERAGE PROP 2[property]+HIS AVERAGE PROP 3[property])/half)\*vehicle

Units: kg/vehicle

The initial level of this stock is the average of historical properties 2 and 3.

(430) His property 4[property] = HIS AVERAGE PROP 4[property]\*HIS 9 TO 12

Units: kg

The initial level of the stock, under historical values, is the average historical property per car times the number of cars in the corresponding age-cohort.

(431) His property 5[property] = HIS AVERAGE PROP 5[property]\*HIS 9 TO 12

Units: kg

The initial level of the stock, under historical values, is the average historical property per car times the number of cars in the corresponding age-cohort.

(432) His property 6[property] = HIS AVERAGE PROP 6[property]\*HIS 15 TO 18

Units: kg

The initial level of the stock, under historical values, is the average historical property per car times the number of cars in the corresponding age-cohort.

(433) His property 7[property] = HIS 18 TO 21\*HIS AVERAGE PROP 7[property]

Units: kg

The initial level of the stock, under historical values, is the average historical property per car times the number of cars in the corresponding age-cohort.

(434) HIS SCRAP PRICE = 148

Units: \$/ton

Initial historical price for scrap.

(435) Ini Ds capacity = IF THEN ELSE(Switch to equilibrium stocks=1,INI Ds EQ CAPA,INI Ds HIS CAPA)

Units: hr/Month

The initial level of the stock can be either the corresponding to historical conditions or the one of an initial equilibrium.

(436) Ini Ds capacity on order = IF THEN ELSE(Switch to equilibrium stocks=1,INI Ds EQ CAPA IN ORDER,INI Ds HIS CAPA IN ORDER)

Units: hr/Month

The initial level of the stock can be either the corresponding to historical conditions or the one of an initial equilibrium.

(437) INI Ds EQ CAPA = 632431

Units: hr/Month

Is the (calculated) equilibrium Ds capacity.

(438) INI Ds EQ CAPA IN ORDER = 84324

Units: hr/Month

Is the (calculated) equilibrium level of the stock.

(439) INI Ds HIS CAPA = 398475

Units: hr/Month

Is the estimated actual dismantlers' capacity.

(440) INI Ds HIS CAPA IN ORDER = 53130

Units: hr/Month

Is the estimated dismantlers' capacity on order, actual.

(441) Ini Ds hulks = IF THEN ELSE(Switch to equilibrium stocks=1,BASE MONTHS Ds HULKS DESIRED\*FLAT SALES\*OLD CAR RETIREMENT EQ FRACTION,BASE MONTHS Ds HULKS DESIRED\*HISTORICAL AVERAGE SALES\*OLD CAR RETIREMENT HIS FRACTION)

Units: car

The initial level of this stock depends on the desired month of inventory, the flat sales and the fraction of old cars.

(442) INI EQ CARS ON THE ROAD = 1.5976e+008

Units: car

Is the calculated number of cars on the road under equilibrium conditions.

(443) INI EQ HULK PRICE = 80

Units: \$/ton

Initial hulk price under equilibrium.

(444) INI EQ SCRAP PRICE = 125.6

Units: \$/ton

Initial scrap price under equilibrium.

(445) INI HIS CARS ON THE ROAD = 1.11045e+008

Units: car

Actual initial number of cars on the road.

(446) Ini hulk price = IF THEN ELSE(Switch to equilibrium stocks=1,INI EQ HULK PRICE

, HIS EQ HULK PRICE)

Units: \$/ton

The initial value of the hulk price can be the equilibrium or the historical one.

(447) Ini junk car price = IF THEN ELSE(Switch to equilibrium stocks=1,INI EQ JUNK CAR PRICE

, HIS JUNK CAR PRICE)

Units: \$/car

The initial value of the junk car price can be the equilibrium or the historical one.

- (448) Ini old car fraction = IF THEN ELSE  
(Switch to equilibrium stocks=1, OLD CAR RETIREMENT EQ  
FRACTION, OLD CAR RETIREMENT HIS FRACTION)  
Units: dimensionless  
The fraction of old cars can be the equilibrium of the historical one.
- (449) Ini prop 1[property] = IF THEN ELSE(Switch to turn  
to equilibrium levels in properties=1,  
Eq property 1[property], His prop 1[property])  
Units: kg  
Is the initial level of the corresponding stock of property. It  
varies based on the Switch to set equilibrium values.
- (450) Ini prop 2[property] = IF THEN ELSE(Switch to turn  
to equilibrium levels in properties=1, Eq property  
2[property], His prop 2[property])  
Units: kg  
Is the initial level of the corresponding stock of mass. It varies  
based on the Switch to set equilibrium values.
- (451) Ini prop 3[property] = IF THEN ELSE(Switch to turn  
to equilibrium levels in properties=1, Eq property  
3[property], His prop 3[property]) Units: kg  
Is the initial level of the corresponding stock of mass. It varies  
based on the Switch to set equilibrium values.
- (452) Ini prop 4 [property]= IF THEN ELSE(Switch to turn  
to equilibrium levels in properties=1, Eq property  
4[property], His property 4[property])  
Units: kg  
Is the initial level of the corresponding stock of mass. It varies  
based on the Switch to set equilibrium values.
- (453) Ini prop 5[property] = IF THEN ELSE(Switch to turn  
to equilibrium levels in properties=1, Eq property  
5[property], His property 5[property])  
Units: kg  
Is the initial level of the corresponding stock of mass. It varies  
based on the Switch to set equilibrium values.
- (454) Ini prop 6[property] = IF THEN ELSE(Switch to turn  
to equilibrium levels in properties=1, Eq property  
6[property], His property 6[property])  
Units: kg  
Is the initial level of the corresponding stock of property. It  
varies based on the Switch to set equilibrium values
- (455) Ini prop 7[property] = IF THEN ELSE(Switch to turn  
to equilibrium levels in properties=1, Eq property  
7[property], His property 7[property])  
Units: kg  
Is the initial level of the corresponding property stock. It varies  
based on the Switch to set equilibrium values.
- (456) Ini prop in hulks[dimproperty] = IF THEN ELSE  
(Switch to turn to equilibrium levels in properties=1, Ini Ds  
hulks\*(CONSTANT PROPERTY[dimproperty]-BASE  
DISMANTLING OF OLD CARS EQ[dimproperty]), Ini Ds  
hulks\*(HIS AVERAGE PROP 7[dimproperty]-BASE  
DISMANTLING DONE IN OLD CARS HIS[dimproperty]))  
Units: kg  
Evaluates the initial level of the stock. Considers the constant  
property level, the dismantling done in old cars, and the initial  
level in cars.
- (457) Ini prop in new cars to be processed[property] = Ini  
new deregistered cars\*CONSTANT PROPERTY[property]
- Units: kg  
Evaluates the initial level of this stock as a function of the stock  
level in car units and the constant property.
- (458) Ini prop in old cars to be processed[property] = Ini  
old deregistered cars\*CONSTANT PROPERTY[property]  
Units: kg  
The initial level of this stock is a function of the initial level of  
the stock in car units and the constant property.
- (459) Ini prop in sh raw mat[dimproperty] = IF THEN  
ELSE(Switch to turn to equilibrium levels in properties=1, Ini Sh  
rm inventory\*(CONSTANT PROPERTY[dimproperty]-BASE  
DISMANTLING DONE IN HULKS EQ[dimproperty]), Ini Sh  
rm inventory\*(HIS AVERAGE PROP 7[dimproperty]-  
BASE DISMANTLING DONE IN HULKS HIS[dimproperty]))  
Units: kg  
Evaluates the initial level of the stock Shredders Raw Material,  
considers the Constant property minus the average dismantling  
done and the Initial level of the inventory in cars.
- (460) Ini prop recovered by Sh[dimproperty] = IF THEN  
ELSE(Switch to turn to equilibrium levels in properties  
=1, Ini shredded hulks\*(CONSTANT PROPERTY[dimproperty]  
-BASE DISMANTLING DONE IN HULKS EQ[dimproperty]),  
Ini shredded hulks\*(HIS AVERAGE PROP 7[dimproperty]-  
BASE DISMANTLING DONE IN HULKS HIS[dimproperty]))  
Units: kg  
Evaluates the initial level of the stock Shredded Hulks, considers  
the Constant property minus the average dismantling done and  
the Initial level of the inventory in cars.
- (461) ini sales = IF THEN ELSE(Switch to equilibrium  
stocks=1, FLAT SALES, HIS INI SALES)  
Units: car/Month  
Initial sales are defined depending on the Switch to change to  
equilibrium conditions
- (462) Ini scrap price = IF THEN ELSE(Switch to  
equilibrium stocks=1, INI EQ SCRAP PRICE, HIS SCRAP  
PRICE)  
Units: \$/ton  
The initial scrap price is selected based on the switch to  
establish equilibrium conditions.
- (463) Ini Sh capa on order = IF THEN ELSE(Switch to  
equilibrium stocks=1, INI Sh EQ CAPA IN ORDER, INI Sh HIS  
CAPA IN ORDER)  
Units: ton/Month  
The initial shredders' capacity on order is selected based on the  
switch to establish equilibrium stocks
- (464) Ini Sh capacity = IF THEN ELSE(Switch to  
equilibrium stocks=1, INI S'n EQ CAPACITY, INI Sh HIS  
CAPACITY)  
Units: ton/Month  
The initial shredders' capacity is selected based on the switch to  
establish equilibrium stocks.
- (465) INI Sh EQ CAPA IN ORDER = 201070  
Units: ton/Month  
It is the equilibrium shredders' capacity in order when the  
simulation starts.
- (466) INI Sh EQ CAPACITY = 1.34047e+006  
Units: ton/Month  
It is the equilibrium initial shredders' capacity installed.



- (467) INI Sh HIS CAPA IN ORDER = 229451  
Units: ton/Month  
It is the historical shredders' capacity in order when the simulation starts.
- (468) INI Sh HIS CAPACITY = 1.52967e+006  
Units: ton/Month  
It is the historical shredders' capacity installed when the simulation starts.
- (469) Ini Sh rm inventory = IF THEN ELSE(Switch to equilibrium stocks=1,MONTHS FOR SHREDDERS RM INVENTORY\*FLAT SALES,MONTHS FOR SHREDDERS RM INVENTORY\*HISTORICAL AVERAGE SALES)  
Units: car  
Initial level of this stock, under equilibrium is the number of desired months in inventory times the flat sales and considering the initial dismantling ratio
- (470) Ini shredded hulks = IF THEN ELSE(Switch to equilibrium stocks=1,FLAT SALES\*BASE MONTHS OF SHREDDED MATL,HISTORICAL AVERAGE SALES\*BASE MONTHS OF SHREDDED MATL.)  
Units: car  
Initial level of this stock, under equilibrium is the number of desired months in inventory times the flat sales and considering the initial dismantling ratio.
- (471) sales to calculate initial stocks = IF THEN ELSE (Switch to equilibrium stocks=1,FLAT SALES,HISTORICAL AVERAGE SALES)  
Units: car/Month  
A value of average past sales has to be selected when the simulation starts to evaluate the initial level of the several stocks. This value varies according to initial conditions
- (472) Switch to turn to equilibrium levels in properties = 1  
Units: dimensionless  
Sets all-property-related stocks to the equilibrium initial condition when equal to 1
- .junkcarp**
- (473) change in junk car price = Junk car price gap/t for junk car price change  
Units: \$/(car\*Month)  
Is the monthly change in junk car price.
- (474) combined effect on junk car price = Effect of Ds inventory in junk car price  
\*profit effect on junk car price  
Units: dimensionless  
The combined effect of inventory management and profit is calculated.
- (475) Ds relative inventory = Dismantled hulks/Ideal Dismantled Hulks  
Units: dimensionless  
Actual level of inventories are compared to the desired level.
- (476) Dynamic junk car price = INTEG(change in junk car price,Ini junk car price)  
Units: \$/car  
Is the price offered for the junk cars
- (477) Effect of adequacy of inventory in price graph  
((0.001,0.5),(0.23,0.64),(0.45,0.85),(0.75,0.97),(1,1),(1.3,1.05),(1.533,1.11),(1.78,1.17),(2,1.22),(10,1.25))  
Units: dimensionless  
Relationship between inventory and price.
- (478) Effect of Ds inventory in junk car price = Effect of adequacy of inventory in price graph(Ds relative inventory)  
Units: dimensionless  
Effect of inventory management in junk car price.
- (479) Effect of utilization rates on prices graph ((-1,0.78),(-0.5,0.79),(-0.2,0.8),(-0.1,0.85),(-0.05,0.9),(0,1),(0.05,1.1),(0.1,1.15),(0.2,1.2),(0.5,1.21),(1,1.22))  
Units: dimensionless  
Relationship between utilization rates and prices.
- (480) Junk car price gap = target junk car price-Dynamic junk car price  
Units: \$/car  
Difference between desired junk car price and actual price
- (481) profit effect on junk car price = Relative profit effect on junk car price graph(Relative Ds margin per car sold)  
Units: dimensionless  
Effect of profit on junk car price.
- (482) Relative profit effect on junk car price graph  
((0,0.8),(0.56,0.85),(0.72,0.88),(0.8,0.92),(0.9,0.96),(1,1),(10,1.2))  
Units: dimensionless  
Relationship between profit and junk car price
- (483) SLOWER GAINS = 0.9  
Units: dimensionless  
Factor used to calibrate the time to correct price gap
- (484) t for junk car price change = t TO CHANGE JUNK CAR PRICE/SLOWER GAINS  
Units: Month  
Actual time used to correct junk car price gap
- (485) t TO CHANGE JUNK CAR PRICE = 6  
Units: Month  
This is the time the Dismantlers would like to take to correct the Junk car price (make it equal to the target Junk car price)
- (486) target junk car price = Dynamic junk car price\* combined effect on junk car price  
Units: \$/car  
The target junk car price considers the effect of inventories and profit
- .main**
- (487) BASE JUNK CAR PRICE FOR SELLING RATE = 50  
Units: \$/car  
Base price used to define selling rate.
- (488) BASE SUPPLY FRACTION = 0.15667  
Units: 1/Month  
Base fraction of the stock of deregistered cars that would be brought to the dismantlers for recycling each month.

- (489) Dismantled hulks = INTEG(dismantling rate-hulks selling rate,Ini Ds hulks)  
Units: car  
Number of hulks in the dismantlers' yards.
- (490) Fraction of old cars being retired = Old cars being retired/Total number of cars being retired  
Units: dimensionless  
The number of "old cars" being retired is compared to the total number of cars being retired.
- (491) His prop level in design[property] = HIS AVERAGE PROP 2[property]\*vehicle  
Units: kg/vehicle  
The initial level of this stock is assumed to be the level of "His average prop 2".
- (492) HISTORICAL AVERAGE SALES = 788044  
Units: car/Month  
This is the historical average of sales per month.
- (493) hulks selling rate = IF THEN ELSE(Switch to turn hulks transferring constant=1,dismantling rate, MIN(Possible hulk transferring,Desired Ds hulk transferring))  
Units: car/Month  
The dismantling rate is the minimum of the dismantlers' capacity and the rate at which cars are brought to them.
- (494) INI EQ JUNK CAR PRICE = 50  
Units: \$/car  
Initial equilibrium price of junk cars.
- (495) Junk car price and supply fraction graph ((-2,0.0106),(-0.4,0.0213),(-0.17,0.0319), (0,0.0532), (0.23,0.5532), (0.44,0.734), (0.62,0.8511), (0.82,0.9255), (1,1), (1.32,1.0638), (1.68,1.1064), (1.96,1.1277), (2.4,1.1596), (3,1.1702), (5,1.2234))  
Units: dimensionless  
Relationship between the junk car price and the supply fraction
- (496) Mass ton shredded = Prop shredded hulks[Mass]/Ton  
Units: ton  
Is the finished (shredded) material at the Shredders site. This material is ready to be sold or sent to the landfill. Expressed in tons. Is a conversion from the corresponding stock in the Property Sector.
- (497) MONTHS UNWANTED CARS = 6.382  
Units: Month  
Note: this is the level such that with the graph to relate junk car price and dismantling the equilibrium is achieved. If the graph is changes we'd need to change this also.
- (498) OLD CAR RETIREMENT EQ FRACTION = 0.783  
Units: dimensionless  
Under equilibrium 78.3% of the vehicles being retired are "old".
- (499) OLD CAR RETIRMENT HIS FRACTION = 0.734  
Units: dimensionless  
Under historical conditions 73.4% of the cars being retired are "old".
- (500) Perceived junk car = IF THEN ELSE(Switch to change junk car price=1,DELAY3(Variable junk car price, t TO PERCEIVE JUNK CAR PRICE),INI EQ JUNK CAR PRICE)  
Units: \$/car  
The junk car price is perceived with a 3rd order delay.
- (501) Percent of cars not dismantled = (1-Ratio of cars dismantled)\*100  
Units: dimensionless  
Evaluates the percent of the retired vehicles that are not processed by dismantlers.
- (502) prop into chain [property]=  
IF THEN ELSE(Switch to allow changes in property into chain[property] = 1, Variable property[property], CONSTANT PROPERTY[property])  
Units: kg/car  
When the switch to change property equals 1, the property used is the variable one, otherwise is a constant number (disconnected from the rest of the model).
- (503) random generator = RANDOM NORMAL()  
Units: dimensionless  
Vensim's random generator
- (504) Ratio of cars dismantled = (dismantling rate+dismantling of new cars)/Total number of cars being retired  
Units: dimensionless  
Evaluates the efficiency of the Recycling Industry in "capturing and processing" cars being retired. Compares the rate at which the cars get processed versus the actual retirement rate.
- (505) Relative junk car price = Perceived junk car/BASE JUNK CAR PRICE FOR SELLING RATE  
Units: dimensionless  
The actual junk car price is compared to a standard.
- (506) Relative supply fraction = Junk car price and supply fraction graph(Relative junk car price)  
Units: dimensionless  
The relative junk car price is used to evaluate the supply fraction.
- (507) Sh transferring material in cars = Transferring shredded ton materials  
\*Ton/Average prop shredded hulks[Mass]  
Units: car/Month  
Is the Shredded material transferring expressed in cars/month. Conversion done using the average weight of hulks in the stock Shredded hulks.
- (508) Shredded hulks FGI = INTEG(+shredding car rate-Sh transferring material in cars,Ini shredded hulks)  
Units: car  
Quantifies the level of inventory of shredded material in "hulk units".
- (509) Shredders raw mat inventory = INTEG(+hulks selling rate+dismantling of new carshredding car rate,Ini Sh rm inventory)  
Units: car  
Quantifies the number of hulks waiting to be shredded at the shredding sites.Note that it considers both "old" and "new" cars
- (510) shredding car rate = IF THEN ELSE(Switch to turn shredding rate constant=1,hulks selling rate+dismantling of new cars,Shredding ton rate/(Average prop in Sh raw mat inv[Mass]/Ton))  
Units: car/Month  
Is the shredding rate expressed in car units. Uses the mass per hulk at the Sh raw material level to make the conversion.

(511) step junk car price = step(10,100)+step(-10,200)

Units: \$/car

Creates a step function for the junk car price. For testing.

(512) Supply fraction = BASE SUPPLY

FRACTION\*Relative supply fraction

Units: 1/Month

Is the actual fraction of the stock of cars deregistered that will be offer to dismantlers at any junk car price.

(513) Supply of cars = Supply fraction\*Old deregistered cars

Units: car/Month

(514) Switch to change hulk price = 1

Units: dimensionless

Allows to set hulk price constant if equal to 0.

(515) Switch to change junk car price = 1

Units: dimensionless

Allows the Junk Car price o change if equal to 1. Used for testing purposes.

(516) Switch to dynamically calculate hulk price = 1

Units: dimensionless

Allows for use of the dynamically calculated hulk price.

(517) Switch to dynamically calculate junk car price = 1

Units: dimensionless

Allows for use of the dynamically calculated junk car price.

(518) Switch to step retirement of old cars = 0

Units: dimensionless

Creates a step function in old cars being retired for testing purposes.

(519) Switch to turn dismantling rate constant = 0

Units: dimensionless

Sets the dismantling rate equal to the retirement of old cars if equal to 1 Used for testing purposes.

(520) Switch to turn hulks transferring constant = 0

Units: dimensionless

Sets the variable hulks transferring constant if equal to 1 Used in testing.

(521) Switch to turn selling shredded mat constant = 0

Units: dimensionless

Sets selling recovered material constant if equal to 1. Used for testing only.

(522) Switch to turn sh capacity constant = 1

Units: dimensionless

Disconnects shredders' capacity form the rest of the model if equal to 1.

(523) Switch to turn shredding rate constant = 0

Units: dimensionless

Sets shredding rate constant if equal to 1 Used for testing only

(524) Switch to turn to constant parts dismantling = 0

Units: dimensionless

Sets dismantling parts constant if equal to 1.

(525) t TO DISMANTLE NEW CARS = 3

Units: Month

Delay used to calculate the dismantling rate of "new cars".

(526) t TO PERCEIVE JUNK CAR PRICE = 9

Units: Month

Delay in perceiving changes in junk car price.

(527) Ton = 1000

Units: kg/ton

Conversion factor to relate kg and tons.

(528) Total number of cars being retired = New cars being retired+Old cars being retired

Units: car/Month

Sum of vehicles being retired.

(529) unit = 1

Units: dimensionless

Conversion factor.

(530) Variable junk car price = IF THEN ELSE(Switch to dynamically calculate junk car price=1,Dynamic junk car price,INI EQ JUNK CAR PRICE+step junk car price)

Units: \$/car

Dynamic junk car price is the internally calculated price dismantlers are willing to pay for the cars.

## .Mdl

(531) dirproperty :Mass, Ferrous, Nonferrous, plastics

(532) property :Mass, Ferrous, Nonferrous, plastics, DFD

## .newcars

(533) BASE COST OF NEW CARS = 1837.6

Units: \$/car

Researched average value of "new cars".

(534) conv5 = 1

Units: \$/car

Conversion factor.

(535) conv6 = 1

Units: sec/car

Conversion factor

(536) Cumulative margin of new cars dismantling = INTEG(monthly margin from new cars,0)

Units: \$

Margin on dismantling of new cars is accumulated for reporting purposes.

(537) FREQUENCY OF NEW CARS = 0.5

Units: dimensionless

It is assumed that about 50% of the new cars would have most of the parts intact and there would be a market for these parts.

(538) In0 = 16578.4

Units: dimensionless

Coefficient from the DOE.

(539) In1 = 793.11

Units: dimensionless

Coefficient from the DOE.	(555) $p n5 = 68.242$ Units: dimensionless Coefficient from the DOE.
(540) $l n2 = -139.03$ Units: dimensionless Coefficient from the DOE.	(556) $p n6 = -69.075$ Units: dimensionless Coefficient from the DOE.
(541) $l n3 = 110.3$ Units: dimensionless Coefficient from the DOE.	(557) $p n7 = 66.942$ Units: dimensionless Coefficient from the DOE.
(542) $l n4 = -344.99$ Units: dimensionless Coefficient from the DOE.	(558) $p n8 = 344.075$ Units: dimensionless Coefficient from the DOE.
(543) $l n5 = 0$ Units: dimensionless Coefficient from the DOE.	(559) $\text{precalc dismantling labor cost per new car} = l n0 + l n1 * \text{DFD level in new cars} + l n2 * \text{nonferrous level in new cars} + l n3 * \text{plastic level in new cars} + l n4 * \text{Nonferrous price level 4} + l n5 * \text{Plastic price level 5} + l n6 * \text{Landfill cost level 6} + l n7 * \text{Labor cost level 7} + l n8 * \text{Price of parts level 8}$ Units: dimensionless Equation obtained in the design of experiments using the DMA.
(544) $l n6 = -155$ Units: dimensionless Coefficient from the DOE.	(560) $\text{Precalc revenue from parts on Dismantling New Cars} = p n0 + p n1 * \text{DFD level in new cars} + p n2 * \text{nonferrous level in new cars} + p n3 * \text{plastic level in new cars} + p n4 * \text{Nonferrous price level 4} + p n5 * \text{Plastic price level 5} + p n6 * \text{Landfill cost level 6} + p n7 * \text{Labor cost level 7} + p n8 * \text{Price of parts level 8}$ Units: dimensionless Equation obtained in the design of experiments using the DMA.
(545) $l n7 = 201.69$ Units: dimensionless Coefficient from the DOE.	(561) $\text{revenue from ferrous in new cars} = \text{Auto scrap price in kg} * \text{Kg of ferrous recycled new cars}$ Units: \$/car Revenue generated from recycling ferrous materials from new cars.
(546) $l n8 = 468.74$ Units: dimensionless Coefficient from the DOE.	(562) $\text{revenue from nonferrous in new cars} = \text{Kg of nonferrous recycled new cars} * \text{Sh UNIT NONFERROUS PRICE}$ Units: \$/car
(547) $\text{Labor cost of dismantling new cars} = \text{time in to dismantling new cars} * \text{BASE UNIT DISMANTLING LABOR COST}$ Units: \$/car Labor cost of dismantling a "new car".	(563) $\text{revenue from parts in new car dismantled} = \text{FREQUENCY OF NEW CARS} * \text{Precalc revenue from parts on Dismantling New Cars} * \text{conv5}$ Units: \$/car Revenue generated from recycling non-ferrous materials from new cars
(548) $\text{margin per new car} = \text{total revenue per new car} - \text{total processing cost of new cars}$ Units: \$/car Revenue minus processing costs of "new cars" define the margin.	(564) $\text{revenue from recycling of new cars} = \text{revenue from ferrous in new cars} + \text{revenue from nonferrous in new cars}$ Units: \$/car Total revenue generated from material recovery in "new cars".
(549) $\text{monthly margin from new cars} = \text{dismantling of new cars} * \text{margin per new car}$ Units: \$/Month Coefficient from the DOE.	(565) $\text{time in to dismantling new cars} = \text{STANDARD TIME TO PROCESS A CAR} + \text{var labor into new cars dismantling in hours}$ Units: hr/car The optimized time plus the time to remove some mandated parts are added to calculate total dismantling time.
(550) $p n0 = 1163.57$ Units: dimensionless Coefficient from the DOE.	(566) $\text{total processing cost of new cars} = \text{BASE COST OF NEW CARS} + \text{Ds UNIT ENERGY COST} + \text{Labor cost of dismantling new cars}$ Units: \$/car
(551) $p n1 = 70.108$ Units: dimensionless Coefficient from the DOE.	
(552) $p n2 = -69.075$ Units: dimensionless Coefficient from the DOE.	
(553) $p n3 = -68.608$ Units: dimensionless Coefficient from the DOE.	
(554) $p n4 = -68.242$ Units: dimensionless Coefficient from the DOE.	

Processing cost considers cost of cars, energy cost and labor cost.

(567) total revenue per new car = revenue from recycling of new cars + revenue from parts in new car dismantled

Units: \$/car

Revenue from recycling is added to the revenue obtained from parts.

(568) var labor into new cars dismantling in hours = var labor into new cars dismantling in secs/hour

Units: hr/car

"Optimized" time in dismantling "new cars".

(569) var labor into new cars dismantling in secs = precalc dismantling labor cost per new car \* conv6

Units: sec/car

Labor going into dismantling "new cars".

### .prop

(570) Average prop 1[property] = Prop in 0 to 3[property]/Cars from 0 to 3 years

Units: kg/car

The Average mass in the cohort is calculated dividing the two levels of the stocks: Mass and Cars

(571) Average prop 2[property] = Prop in 3 to 6[property]/Cars from 3 to 6 years

Units: kg/car

The Average mass in the cohort is calculated dividing the two levels of the stocks: Mass and Cars.

(572) Average prop 3[property] = Prop in 6 to 9[property]/Cars from 6 to 9 years

Units: kg/car

The Average mass in the cohort is calculated dividing the two levels of the stocks: Mass and Cars

(573) Average prop 4[property] = Prop in 9 to 12[property]/Cars from 9 to 12 years

Units: kg/car

The Average property in the cohort is calculated dividing the two corresponding stocks: Property and Cars.

(574) Average prop 5[property] = Prop in 12 to 15[property]/Cars from 12 to 15 years

Units: kg/car

The Average property in the cohort is calculated dividing the two corresponding stocks: Property and Cars.

(575) Average prop 6[property] = Prop in 15 to 18[property]/Cars from 15 to 18 years

Units: kg/car

The Average property in the cohort is calculated dividing the two corresponding stocks: Property and Cars

(576) Average prop 7[property] = Prop in 18 to 21[property]/Cars from 18 to 21 years

Units: kg/car

The Average property in the cohort is calculated dividing the two corresponding stocks: Property and Cars.

(577) Average prop in hulks[dimproperty] = Prop in hulks[dimproperty]/Dismantled hulks

Units: kg/car

Average property level in dismantled hulks is calculated by dividing the corresponding stocks.

(578) Average prop in Sh raw mat inv [dimproperty] = Prop in Sh raw material inv

[dimproperty]/

Shredders raw mat inventory

Units: kg/car

The average level of properties in the hulks waiting to be shredded is calculated by dividing the corresponding stocks.

(579) Average prop shredded hulks [dimproperty] = Prop shredded hulks[dimproperty]/Shredded hulks FGI

Units: kg/car

The average level of properties in the shredded material is calculated by dividing the corresponding stocks.

(580) Average ton weight when retired = Average prop when retired old cars[Mass]/Ton

Units: ton/car

The average weight of the vehicles being retired is calculated (in tons)

(581) Average weight of old hulks transferred = Average prop in hulks[Mass]/Ton

Units: ton/car

This is the weight of hulks when sold to the shredders.

(582) BASE MONTHS Ds HULKS DESIRED = 18

Units: Month

Base dismantlers' coverage in hulks.

(583) BASE MONTHS OF SHREDDED MATL = 4

Units: Month

Base shredders' coverage in material shredded.

(584) error in input properties = prop into chain[Mass]-sum of masses into the chain

Units: kg/car

Keeps track of potential errors during the simulation. Testing purposes.

(585) error in landfill rates = sh prop landfill rate[Mass]-sum of landfill rates

Units: kg/Month

Keeps track of potential errors during the simulation. Testing purposes.

(586) error in materials as shredded hulks = Average prop shredded hulks[Mass]-sum of materials

Units: kg/car

(587) error in selling rates = selling prop rate shredded[Mass]-sum of selling rates

Units: kg/Month

Keeps track of potential errors during the simulation. Testing purposes.

(588) Mass landfilled[dimproperty] = INTEG(sh prop landfill rate[dimproperty]

,0)

Units: kg

Accumulates mass in the landfill. It receives material from Dismantlers and Shredders. Arbitrarily, its initial value is set at 1 million. Used for reporting reasons.

(589) MONTHS FOR SHREDDERS RM INVENTORY = 2

Units: Month

Inventory coverage used for the level of the stock Unwanted cars, to test the model

(590)  $\text{Prop in } 0 \text{ to } 3[\text{property}] = \text{INTEG}(\text{+prop incorp rate}[\text{property}]-\text{prop transfer } 1[\text{property}]-\text{prop retiring } 1[\text{property}], \text{Ini prop } 1[\text{property}])$

Units: kg

It is a cohort that accumulates mass associated to the cars being this age range. Considers the Mass incorporation rate and the mass transfer to the next, as well as the Mass retiring flow

(591)  $\text{Prop in } 12 \text{ to } 15[\text{property}] = \text{INTEG}(\text{+prop transfer } 4[\text{property}] - \text{prop retiring } 5[\text{property}] - \text{Prop transfer } 5[\text{property}], \text{Ini prop } 5[\text{property}])$

Units: kg

It is a cohort that accumulates mass associated to the cars being this age range. Considers the Mass incorporation rate and the mass transfer to the next, as well as the Mass retiring flow.

(592)  $\text{Prop in } 15 \text{ to } 18[\text{property}] = \text{INTEG}(\text{+Prop transfer } 5[\text{property}] - \text{prop retiring } 6[\text{property}] - \text{Prop transfer } 6[\text{property}], \text{Ini prop } 6[\text{property}])$

Units: kg

It is a cohort that accumulates mass associated to the cars being this age range. Considers the mass transfer (from previous cohort) and the mass transfer to the next, as well as the Mass retiring flow.

(593)  $\text{Prop in } 18 \text{ to } 21[\text{property}] = \text{INTEG}(\text{+Prop transfer } 6[\text{property}] - \text{prop retiring } 7[\text{property}], \text{Ini prop } 7[\text{property}])$

Units: kg

It is a cohort that accumulates mass associated to the cars being this age range. Considers the mass transfer (from previous cohort) and the Mass retiring flow.

(594)  $\text{Prop in } 3 \text{ to } 6[\text{property}] = \text{INTEG}(\text{+prop transfer } 1[\text{property}] - \text{prop retiring } 2[\text{property}] - \text{prop transfer } 2[\text{property}], \text{Ini prop } 2[\text{property}])$

Units: kg

It is a cohort that accumulates mass associated to the cars being this age range. Considers the mass transfer (from previous cohort) and the mass transfer to the next, as well as the Mass retiring flow

(595)  $\text{Prop in } 6 \text{ to } 9[\text{property}] = \text{INTEG}(\text{+prop transfer } 2[\text{property}] - \text{prop retiring } 3[\text{property}] - \text{prop transfer } 3[\text{property}], \text{Ini prop } 3[\text{property}])$

Units: kg

It is a cohort that accumulates mass associated to the cars being this age range. Considers the mass transfer (from previous cohort) and the mass transfer to the next, as well as the Mass retiring flow.

(596)  $\text{Prop in } 9 \text{ to } 12[\text{property}] = \text{INTEG}(\text{+prop transfer } 3[\text{property}] - \text{prop retiring } 4[\text{property}] - \text{prop transfer } 4[\text{property}], \text{Ini prop } 4[\text{property}])$

Units: kg

It is a cohort that accumulates mass associated to the cars being this age range. Considers the mass transfer (from previous cohort) and the mass transfer to the next, as well as the Mass retiring flow.

(597)  $\text{Prop in hulks}[\text{dimproperty}] = \text{INTEG}(\text{prop in hulks rate old}[\text{dimproperty}] - \text{prop in selling hulks}[\text{dimproperty}], \text{Ini prop in hulks}[\text{dimproperty}])$

Units: kg

The average level of the properties in the stock of dismantled hulks

(598)  $\text{prop in new hulks after dismantling}[\text{Mass}] = \text{Average prop of new cars to be processed}[\text{Mass}] - \text{Total kg dismantled in new cars}$

$\text{prop in new hulks after dismantling}[\text{Ferrous}] = \text{Average prop of new cars to be processed}[\text{Ferrous}] - \text{kg of ferrous reused or recycled in new cars}$

$\text{prop in new hulks after dismantling}[\text{Nonferrous}] = \text{Average prop of new cars to be processed}[\text{Nonferrous}] - \text{kg of nonferrous reused or recycled in new cars}$

$\text{prop in new hulks after dismantling}[\text{plastics}] = \text{Average prop of new cars to be processed}[\text{plastics}] - \text{kg of plastics reused or recycled in new cars}$

$\text{prop in new hulks after dismantling}[\text{DFD}] = \text{Average prop of new cars to be processed}[\text{DFD}]$

Units: kg/car

Hulks of new cars get transferred with this level of property. It represents what the car originally had minus what was removed at the dismantling stage.

(599)  $\text{prop in selling hulks}[\text{dimproperty}] = \text{Average prop in hulks}[\text{dimproperty}] * \text{hulks selling rate}$

Units: kg/Month

Traces the follows (per property) associated with selling recovered material.

(600)  $\text{Prop in Sh raw material inv}[\text{dimproperty}] = \text{INTEG}(\text{prop in selling hulks}[\text{dimproperty}] + \text{prop in hulks rate new}[\text{dimproperty}] - \text{prop shredding rate}[\text{dimproperty}], \text{Ini prop in sh raw mat}[\text{dimproperty}])$

Units: kg

Accumulates properties in the Inventory of Raw Materials. Increased by the transferring of old and new hulks, from the dismantlers, and decrease as a function of the prop transfer associated to the shredder operation.

(601)  $\text{prop incorp rate}[\text{property}] = \text{prop into chain}[\text{property}] * \text{car sales}$

Units: kg/Month

Is the rate at which the pipeline incorporates properties. It is a parallel flow based on the physical (cars) flow and the property level of cars being sold at which cars are being sold.

(602)  $\text{prop old hulks after dismantling}[\text{Mass}] = \text{Average prop of old cars to be processed}[\text{Mass}] - \text{Mass being recycled in old cars}$

$\text{prop old hulks after dismantling}[\text{Ferrous}] = \text{Average prop of old cars to be processed}[\text{Ferrous}] - \text{Kg ferrous recycled from old cars}$

$\text{prop old hulks after dismantling}[\text{Nonferrous}] = \text{Average prop of old cars to be processed}[\text{Nonferrous}] - \text{Kg of nonferrous recycled from old cars}$

$\text{prop old hulks after dismantling}[\text{plastics}] = \text{Average prop of old cars to be processed}[\text{plastics}] - \text{Kg plastics recycled from old cars}$

$\text{prop old hulks after dismantling}[\text{DFD}] = \text{Average prop of old cars to be processed}[\text{DFD}]$

Units: kg/car

The hulks from old cars get transferred with this level of the property. It is the level the cars had when processed minus what was removed by the dismantlers.

(603) prop retiring 1[property] = retiring 1 \* Average prop 1[property]

Units: kg/Month

The mass being retired from this cohort is a function of the Retiring(i) flow and the Average mass in the cohort. It is a parallel flow.

(604) prop retiring 2[property] = retiring 2 \* Average prop 2[property]

Units: kg/Month

The mass being retired from this cohort is a function of the Retiring(i) flow and the Average mass in the cohort. It is a parallel flow.

(605) prop retiring 3[property] = retiring 3 \* Average prop 3[property]

Units: kg/Month

The mass being retired from this cohort is a function of the Retiring(i) flow and the Average mass in the cohort. It is a parallel flow.

(606) prop retiring 4[property] = retiring 4 \* Average prop 4[property]

Units: kg/Month

The mass being retired from this cohort is a function of the Retiring(i) flow and the Average mass in the cohort. It is a parallel flow.

(607) prop retiring 5[property] = retiring 5 \* Average prop 5[property]

Units: kg/Month

The mass being retired from this cohort is a function of the Retiring(i) flow and the Average mass in the cohort. It is a parallel flow.

(608) prop retiring 6[property] = Average prop 6[property] \* retiring 6

Units: kg/Month

The mass being retired from this cohort is a function of the Retiring(i) flow and the Average mass in the cohort. It is a parallel flow.

(609) prop retiring 7[property] = (aging 7 + retiring 7) \* Average prop 7[property]

Units: kg/Month

The mass being retired from this cohort is a function of the Retiring(i) flow and the Average mass in the cohort. It is a parallel flow.

(610) Prop shredded hulks[dimproperty] = INTEG(prop shredding rate[dimproperty] - selling prop rate shredded[dimproperty] - sh prop landfill rate[dimproperty], Ini prop recovered by Sh[dimproperty])

Units: kg

Is the property recovered at the Shredder level. It is accumulated here before selling it to the material recycling industry and before landfilling the corresponding fraction.

(611) prop shredding rate[dimproperty] = Average prop in Sh raw mat inv[dimproperty] \* shredding car rate

Units: kg/Month

The mass shredding rate is the shredding rate (in cars) expressed in mass (kg) terms. Uses the hulk weight to make the conversion.

(612) prop transfer 1[property] = aging 1 \* Average prop 1[property]

Units: kg/Month

It is the rate at which mass gets transferred from one cohort to the next. It is a parallel flow based on the aging(i) flow and the average mass in the corresponding cohort.

(613) prop transfer 2[property] = aging 2 \* Average prop 2[property]

Units: kg/Month

It is the rate at which mass gets transferred from one cohort to the next. It is a parallel flow based on the aging(i) flow and the average mass in the corresponding cohort.

(614) prop transfer 3[property] = aging 3 \* Average prop 3[property]

Units: kg/Month

It is the rate at which mass gets transferred from one cohort to the next. It is a parallel flow based on the aging(i) flow and the average mass in the corresponding cohort.

(615) prop transfer 4[property] = aging 4 \* Average prop 4[property]

Units: kg/Month

It is the rate at which mass gets transferred from one cohort to the next. It is a parallel flow based on the aging(i) flow and the average mass in the corresponding cohort.

(616) Prop transfer 5[property] = aging 5 \* Average prop 5[property]

Units: kg/Month

It is the rate at which mass gets transferred from one cohort to the next. It is a parallel flow based on the aging(i) flow and the average mass in the corresponding cohort.

(617) Prop transfer 6[property] = aging 6 \* Average prop 6[property]

Units: kg/Month

It is the rate at which mass gets transferred from one cohort to the next. It is a parallel flow based on the aging(i) flow and the average mass in the corresponding cohort.

(618) Step property into property chain[Mass] = step(280,100) + step(-280,200)

Step property into property chain[Ferrous] = prop into chain[Mass] - prop into chain[Nonferrous] - prop into chain[plastics]

Step property into property chain[Nonferrous] = step(-14,100) + step(14,200)

Step property into property chain[plastics] = step(70,50) + step(-70,150)

Step property into property chain[DFD] = step(-10,50)

Units: kg/car

Creates a step input in the property in cars being sold.

(619) sum of landfill rates = sh prop landfill rate[Ferrous] + sh prop landfill rate[Nonferrous] + sh prop landfill rate[plastics]

Units: kg/Month

Testing calculations.

(620) sum of masses into the chain = prop into chain[Ferrous] + prop into chain[Nonferrous] + prop into chain[plastics]

Units: kg/car

Testing calculations

(621) sum of materials = Average prop shredded hulks[Ferrous]+Average prop shredded hulks[Nonferrous]+Average prop shredded hulks[plastics]  
Units: kg/car  
Testing calculations

(622) sum of selling rates = selling prop rate shredded[Ferrous]  
+selling prop rate shredded[Nonferrous]+selling prop rate shredded[plastics]  
Units: kg/Month  
Testing calculations

(623) Switch to allow changes in property into chain[Mass] = 1  
Switch to allow changes in property into chain[Ferrous] = 1  
Switch to allow changes in property into chain[Nonferrous] = 1  
Switch to allow changes in property into chain[plastics] = 1  
Switch to allow changes in property into chain[DFD]= 1  
Units: dimensionless  
Controls the input property. If equal to 1, the property level of the cars being sold is kept constant.

(624) Switch to dynamically calculate property[property] = 1  
Units: dimensionless  
When this switch equals 1, the Variable mass is calculated and used dynamically from the Automakers view. Otherwise has a step shape

(625) Variable property[Mass] =IF THEN ELSE(Switch to dynamically calculate property[Mass]=1, Property designed[Mass],CONSTANT PROPERTY[Mass]+Step property into property chain [Mass])  
Variable property[Ferrous] =IF THEN ELSE (Switch to dynamically calculate property[Ferrous]=1, Property designed[Ferrous],Step property into property chain[Ferrous])  
Variable property[Nonferrous] = IF THEN ELSE (Switch to dynamically calculate property[Nonferrous]=1, Property designed[Nonferrous],CONSTANT PROPERTY[Nonferrous] + Step property into property chain[Nonferrous])  
Variable property[plastics] = IF THEN ELSE (Switch to dynamically calculate property[plastics]=1, Property designed[plastics],CONSTANT PROPERTY[plastics]+Step property into property chain [plastics])  
Variable property[DFD] = IF THEN ELSE (Switch to dynamically calculate property[DFD]=1, Property designed[DFD],CONSTANT PROPERTY[DFD]+Step property into property chain [DFD])  
Units: kg/car  
When the switch to dynamically calculate property is 1, the variable property is obtained in the Automakers Sector. Otherwise, the variable property is a step function

### .scrap

(626) Automotive demand of steel = Estimated total demand of steel\*AUTOMOTIVE RELATIVE DEMAND OF STEEL  
Units: ton/Month  
The Automotive demand of steel is the total demand times the relative participation of the automotive industry ion the total steel consumption.

(627) AUTOMOTIVE RELATIVE DEMAND OF STEEL = 0.143

Units: dimensionless  
This is the relative share of the automotive industry in the steel consumption.

(628) BASE AUTOMOBILE FERROUS CONTENT = 980  
Units: kg/car  
Is the initial level of ferrous material in automobiles.

(629) BASE DEMAND OF STEEL = 7.4185e+006  
Units: ton/Month  
Base demand of steel (researched).

(630) change in scrap price =Scrap price gap/t for scrap price change  
Units: \$(ton\*Month)  
Is the monthly change in scrap price.

(631) Corrected Automotive demand of steel = Automotive demand of steel\*Correction for ferrous automotive usage\*sales adjustment effect  
Units: ton/Month  
The corrected steel demand of steel for automotive applications is a function of the calculated GDP-driven consumption and the usage of ferrous material in automobiles.

(632) Correction for ferrous automotive usage = prop into chain[Ferrous]/BASE AUTOMOBILE FERROUS CONTENT  
Units: dimensionless  
The change in the use of steel in cars have a direct effect of the level of steel consumption.

(633) DAMPENING EFFECT = 1.2  
Units: dimensionless  
Factor used to calibrate model. Changes the size of the price correction step.

(634) desired scrap fraction = IF THEN ELSE(Switch to equilibrium stocks=0,HIS SCRAP FRACTION,EQ SCRAP FRACTION OF STEEL DEMAND)  
Units: dimensionless  
Evaluates the desired scrap fraction depending on the initial conditions to be run.

(635) desired scrap price change = effect of scrap fraction on scrap price\* price conversion  
Units: \$/ton  
The target scrap price is calculated as the actual price times the effect of the scrap fraction gap.

(636) deviation in fraction of steel scrap = perceived scrap fraction/desired scrap fraction  
Units: dimensionless  
Is the deviation from the desired level of scrap flow as a percentage of steel production.

(637) effect of fraction of steel scrap on scrap price graph ((-1,27),(0,26),(0.5,25),(0.8,20),(0.9,10),(0.95,5),(1,0),(1.05,-5),(1.1,-10),(1.2,-20),(1.5,-25),(2,-28) )  
Units: dimensionless  
The gap in the scrap fraction on steel scrap creates an effect on the scrap price.

(638) effect of scrap fraction on scrap price = (effect of fraction of steel scrap on scrap price graph(deviation in fraction of steel scrap))/DAMPENING EFFECT  
Units: dimensionless



The effect of the gap in scrap fraction determines the effect on the target scrap price.

(639) EQ SCRAP FRACTION OF STEEL DEMAND = 0.853282

Units: dimensionless

It is the estimated equilibrium fraction of scrap compared to the total demand of steel.

(640) EQUILIBRIUM SCRAP PRICE =  $\ln_i$  scrap price

Units: \$/ton

Defines the equilibrium scrap price.

(641) Estimated total demand of steel = BASE DEMAND OF STEEL \* GDP

Units: ton/Month

The steel demand estimated follows the GDP development with an elasticity of 1

(642) HIS SCRAP FRACTION = 0.6815

Units: dimensionless

Researched scrap fraction

(643) perceived scrap fraction = DELAY3(scrap fraction of steel demand,  $\tau$  \* O PERCEIVE SCRAP FRACTION)

Units: dimensionless

(644) price conversion = 1

Units: \$/ton

Conversion factor

(645) sales adjustment effect = Sales/ $\ln_i$  sales

Units: dimensionless

Evaluates the change in automobile sales to correct demand of steel for automobiles

(646) scrap fraction of steel demand = Scrap supply/Corrected Automotive demand of steel

Units: dimensionless

This is the actual scrap fraction: the relative amount of scrap supplied to the steel industry compared to the estimated production of steel

(647) Scrap price gap = target price - Dynamic scrap price

Units: \$/ton

This is the difference between the desired scrap price and the actual price

(648) Scrap supply = selling prop rate shredded[Ferrous]/Ton

Units: ton/Month

The supply of scrap to the steel industry is the amount of ferrous material transferred from the shredders.

(649) step in scrap price = step(20,100)+step(-20,200)

Units: \$/ton

Creates a step function for the scrap price

(650)  $\tau$  for scrap price change =  $\tau$  TO ADJUST SCRAP PRICE/SLOWER GAINS

Units: Month

Desired time to close the gap between desired scrap price and actual

(651)  $\tau$  TO ADJUST SCRAP PRICE = 18

Units: Month

It is assumed that it would take approx. 18 months to correct deviations in scrap price.

(652)  $\tau$  TO PERCEIVE SCRAP FRACTION = 6

Units: Month

Delay in perceiving scrap fraction.

(653) target price = EQUILIBRIUM SCRAP

PRICE+desired scrap price change

Units: \$/ton

Desired scrap price.

### .shcapa

(654) Actual Sh capacity utilization = shredding car rate/Sh capacity in cars

Units: dimensionless

Is the fraction of the installed capacity being used by the Shredders at any point in time.

(655) Deviation in Sh utilization rate =

(Sh DESIRED CAPA UTILIZATION-Actual Sh capacity utilization)/Sh DESIRED CAPA UTILIZATION

Units: dimensionless

Evaluates changes in utilization rates.

(656) Effect of profit in Sh desired capacity graph ((-0.6),(-1,0.7),(0,0.8),(0.25,0.9),(0.48,0.95),(1,1),(1.1,1.04),(1.5,1.1),(10,1.2))

Units: dimensionless

This graph captures the relationship between the Shredders' relative profit and the desired capacity.

(657) Effect of profit in Sh ideal capacity = Effect of profit in Sh desired capacity graph(Relative Sh future profit)

Units: dimensionless

Evaluates the effect of Shredders' profit in desired capacity.

(658) Effect of Sh utilization rate in capacity = Effect of utilization rate on capacity graph(Deviation in Sh utilization rate)

Units: dimensionless

Utilization rates are considered to order shredding capacity.

(659) Expected shredder capacity gap = Sh indicated capacity - Dynamic Shredder capacity in tons

Units: ton/Month

Quantifies the gap between the desired Sh capacity and the actual capacity.

(660) Indicated Sh capacity change = Sh aging capacity rate + Sh capacity indicated increment + Sh correction for capacity in order

Units: ton/(Month\*Month)

This is the size of the monthly order for capacity desired. Considers expectations about the future, profit effect, level of capacity in order and aging of current facilities

(661) LIFETIME OF Sh CAPA = 240

Units: Month

It is the average lifetime of a Shredder facility (20 years)

(662) Relative Sh future profit = Expected future Sh profit per semester / Base Sh semester profit

Units: dimensionless

Defines the relative level of profits expected in the future versus an standard

(663) Sh capacity in cars = Dynamic Shredder capacity in tons/(Average prop in Sh raw mat inv[Mass]/Ton)  
Units: car/Month

The Shredders capacity in cars per month is calculated based on the capacity in tons and average weight of the hulks being processed

(664) Sh capacity in order gap = Sh indicated capa in order - Sh Capacity on order  
Units: ton/Month

Is the gap between the capacity that should be on order (to replace what gets old) and the actual level of this stock

(665) Sh capacity indicated increment = Expected shredder capacity, gap/t TO CORRECT Sh CAPA GAP  
Units: ton/(Month\*Month)

This is the first of the three elements considered to order Sh capacity. Quantifies the desired monthly increment in capacity necessary to satisfy future work

(666) Sh Capacity on order = INTEG(+Sh capacity order rate - Sh capa completion rate, Ini Sh capa on order)  
Units: ton/Month

The capacity in order is increased by new orders and reduced by completion of this facilities under construction

(667) Sh capacity order rate = MAX(Indicated Sh capacity change, 0)  
Units: ton/(Month\*Month)

The order of capacity may not be negative

(668) Sh correction for capacity in order = Sh capacity in order gap/t TO CORRECT Sh CAPA IN ORDER  
Units: ton/(Month\*Month)

This is the desired size of the correction to be implemented in one month to correct the level of the capacity in order. It is the third element to be considered to order capacity

(669) Sh DESIRED CAPA UTILIZATION = 0.95  
Units: dimensionless  
Shredders would like to have their facilities working at 95% capacity

(670) Sh indicated capa in order = Sh aging capacity rate \* t TO COMPLETE Sh CAPACITY  
Units: ton/Month

Given the time it takes to complete the Sh capacity in order, this is the ideal level of capacity in order (considering aging).

(671) Sh indicated capacity = (Sh expected future shredding in tons/Sh DESIRED CAPA UTILIZATION)\*Effect of profit in Sh ideal capacity\*Effect of Sh utilization rate in capacity  
Units: ton/Month

This is the Sh capacity required to handle the expected flow of materials considering the desired utilization level and the effect of profit

(672) Shredder capacity = IF THEN ELSE(Switch to turn sh capacity constant=1, BASE Sh CAPACITY\*2, Dynamic Shredder capacity in tons)  
Units: ton/Month

Shredder capacity can be set constants for testing purposes.

(673) t TO COMPLETE Sh CAPACITY = 36

Units: Month

It would take 3 years to complete a Shredders' facility.

(674) t TO CORRECT Sh CAPA GAP = 18

Units: Month

It is the time Shredders would like to take to correct the capacity gap, considering future work, profits, and actual capacity.

(675) t TO CORRECT Sh CAPA IN ORDER = 9

Units: Month

Shredders would like to correct the level of capacity in order in 9 months.

### .shfore

(676) Auto scrap price in kg = (IF THEN ELSE(Switch to change scrap price=1, Variable auto scrap price, CONSTANT AUTO SCRAP PRICE))/Ton

Units: \$/kg

The scrap price the Shredders get, expressed in kg

(677) Average hulk weight in tons = Average weight of hulks in kg/Ton

Units: ton/car

Is the average weight of hulks received by Shredders and expressed in tons.

(678) AVERAGE t FOR Sh FORECAST = 12

Units: Month

Number of past months the Dismantlers consider to make their forecast.

(679) Average weight of hulks in kg = (prop in new hulks after dismantling[Mass]\*dismantling of new cars+prop old hulks after dismantling[Mass]\*hulks selling rate)/Hulks bought by Sh  
Units: kg/car

The average weight of the hulks received by Shredders is the weighted average of new and old hulks.

(680) Expected future Sh profit per semester =

FORECAST(Sh perceived semester profit, AVERAGE t FOR Sh FORECAST, Sh HORIZON)

Units: \$

This is the profit forecast the Shredders use to take decisions. Based on perceived profits and taking into consideration 6 months of history and 6 months into the future.

(681) Expected Sh ferrous income per car = Sh expected future ferrous fraction\*(Sh expected future kg hulk weight)\*Sh expected scrap price\*Sh FERROUS RECOV FRACTION  
Units: \$/car

This is the ferrous income per car that the Shredders expect to get in the future.

(682) Expected Sh nonferrous income per car = Sh expected nonferrous fraction\*(Sh expected future kg hulk weight)\*Sh expected nonferrous price\*Sh NONFERROUS RECOV FRACTION  
Units: \$/car

This is the nonferrous income per car that the Shredders expect to get in the future.

(683) Sh expected cost of hulks per car = Sh expected price of hulks\*Sh expected future ton hulk weight

Units: \$/car

This is what the Shredders forecast they will be paying for the hulks in the future.

(684) Sh expected cost per car = Sh expected landfill cost per car + Sh expected processing cost per car + Sh expected cost of hulks per car

Units: \$/car

The Shredder estimate their cost per car as the sum of the hulk, landfill and operation cost.

(685) Sh expected future ferrous fraction = FORECAST(Sh perceived ferrous fraction, AVERAGE t FOR Sh FORECAST, Sh HORIZON)

Units: dimensionless

Shredders forecast the ferrous fraction considering 6 months into the future and into the past.

(686) Sh expected future kg hulk weight = Sh expected future ton hulk weight \* Ton

Units: kg/car

Is the expected hulk weight to the shredders expressed in kg per car.

(687) Sh expected future shredding in tons = Sh expected future ton hulk weight \* Sh expected hulks transferring

Units: ton/Month

The tonnage the shredders expect to be process in the future is the expected hulks received times the expected weigh of the hulks they get.

(688) Sh expected future ton hulk weight = FORECAST(Sh perceived ton hulk weight, AVERAGE t FOR Sh FORECAST, Sh HORIZON)

Units: ton/car

Shredders forecast the weight of the hulks they are going to receive in the future considering 6 months of past history and 6 months into the future

(689) Sh expected hulks transferring = FORECAST(Sh perceived hulks transferring, AVERAGE t FOR Sh FORECAST, Sh HORIZON)

Units: car/Month

The Shredders estimate supply of hulks based on their perceived supply and considering 6 months into the past and 6 months into the future.

(690) Sh expected income per car = Expected Sh ferrous income per car + Expected Sh nonferrous income per car

Units: \$/car

This is the total income Shredders expect to get per car in the future.

(691) Sh expected landfill cost = FORECAST(BASE UNIT LANDFILL COST, AVERAGE t FOR Sh FORECAST, Sh HORIZON)

Units: \$/ton

Shredders forecast the unit landfill cost.

(692) Sh expected landfill cost per car = Sh expected future ton hulk weight \* Sh expected shrinkage fraction \* Sh expected landfill cost

Units: \$/car

This is the expected cost of landfill, according to the Shredders

(693) Sh expected nonferrous fraction = FORECAST(Sh perceived nonferrous fraction, AVERAGE t FOR Sh FORECAST, Sh HORIZON)

Units: dimensionless

Shredders forecast the nonferrous fraction considering 6 months into the future and into the past.

(694) Sh expected nonferrous price = FORECAST(Sh UNIT NONFERROUS PRICE, AVERAGE t FOR Sh FORECAST, Sh HORIZON)

Units: \$/kg

Shredders forecast the price of nonferrous materials.

(695) Sh expected price of hulks = FORECAST(Corrected hulk price, AVERAGE t FOR Sh FORECAST, Sh HORIZON)

Units: \$/ton

Shredder forecast the price they will be paying for the hulks.

(696) Sh expected processing cost per car = FORECAST(Sh perceived processing cost, AVERAGE t FOR Sh FORECAST, Sh HORIZON)

Units: \$/car

Shredders forecast the processing cost.

(697) Sh expected scrap price = FORECAST(Auto scrap price in kg, AVERAGE t FOR Sh FORECAST, Sh HORIZON)

Units: \$/kg

Shredders forecast the scrap price.

(698) Sh expected shrinkage fraction = FORECAST(Sh perceived landfill fraction, AVERAGE t FOR Sh FORECAST, Sh HORIZON)

Units: dimensionless

Shredders forecast the percentage of automobiles they will need to landfill in the future.

(699) Sh ferrous fraction = Average prop in Sh raw mat inv[Ferrous] / Average prop in Sh raw mat inv[Mass]

Units: dimensionless

The ferrous fraction that the Shredders perceive is calculated by dividing the amount of ferrous material on average in the hulks at the Sh inventory, by the average mass of hulks at that stage.

(700) Sh HORIZON = 12

Units: Month

Time the Shredders consider into the future to make their forecast.

(701) Sh nonferrous fraction = Average prop in Sh raw mat inv[Nonferrous] / Average prop in Sh raw mat inv[Mass]

Units: dimensionless

The nonferrous fraction that the Shredders perceive is calculated by dividing the amount of nonferrous material on average in the hulks at the Sh inventory, by the average mass of these hulks at that stage.

(702) Sh operation cost = Sh processing cost + Sh transportation cost

Units: \$/Month

Is the sum of transportation and processing cost.

(703) Sh operation cost per car = Sh operation cost / shredding car rate

Units: \$/car

Is the operation cost per car.

(704) Sh perceived ferrous fraction = SMOOTH(Sh ferrous fraction, Sh t TO PERCEIVE MATERIAL COMPOSITION)  
Units: dimensionless  
The actual ferrous fraction is perceived by Shredders with certain delay.

(705) Sh perceived hulks transferring = SMOOTH3((hulks selling rate+dismantling of new cars), Sh t TO PERCEIVE HULKS TRANSFERRING)  
Units: car/Month  
Shredders perceive the rate of hulks being transferred as a third order delay of the actual transferring rate.

(706) Sh perceived landfill fraction = SMOOTH(Shrinkage factor for shredders, Sh t TO PERCEIVE MATERIAL COMPOSITION)  
Units: dimensionless  
The actual landfilled fraction is perceived by Shredders with certain delay.

(707) Sh perceived nonferrous fraction = SMOOTH(Sh nonferrous fraction, Sh t TO PERCEIVE MATERIAL COMPOSITION)  
Units: dimensionless  
The actual nonferrous fraction is perceived by Shredders with certain delay.

(708) Sh perceived processing cost = SMOOTH(Sh operation cost per car, t TO PERCEIVE Sh ACCOUNTING INFO)  
Units: \$/car  
The operation cost per car is perceived by Shredders with certain delay.

(709) Sh perceived semester profit = SMOOTH(Shredder semester profit, t TO PERCEIVE Sh SEMESTER PROFIT)  
Units: \$  
Shredders perceive their semester profit with certain delay.

(710) Sh perceived ton hulk weight = SMOOTH(Average prop in Sh raw mat inv[Mass]/Ton, Sh t TO PERCEIVE WEIGHT)  
Units: ton/car  
Shredders perceive changes in the average weight of hulks they get with a delay equal to the Sh time to perceive weight.

(711) Sh processing cost = Sh energy cost+Sh variable maintenance cost  
Units: \$/Month  
The direct Sh processing cost is the sum of the energy and variable maintenance cost.

(712) Sh t TO PERCEIVE HULKS TRANSFERRING = 3  
Units: Month  
Shredders perceived the rate of hulks they received with this time delay.

(713) Sh t TO PERCEIVE WEIGHT = 6  
Units: Month  
Is the delay in the perception of the average weight of the hulks the shredders receive.

(714) Sh t TO PERCEIVE MATERIAL COMPOSITION = 4  
Units: Month  
This is the estimated delay in the Shredders perception of composition.

(715) Sh UNIT NONFERROUS PRICE = 0.4816  
Units: \$/kg  
This is the average price the Shredders get for the non ferrous metals (researched). This is a simplification because in reality it depends on the composition, and the prices of each metal.

(716) Shredder semester profit = INTEG(in rate Sh semester profit-out rate Sh semester profit, Base Sh semester profit)  
Units: \$  
The average semester profit for shredders is quantified to smooth out monthly noise.

(717) t TO PERCEIVE Sh ACCOUNTING INFO = 6  
Units: Month  
It is the time it takes the Shredders to perceive changes in accounting information.

(718) t TO PERCEIVE Sh SEMESTER PROFIT = 6  
Units: Month  
The delay in Shredder to perceive changes in the semester profit is 6 months.

### .shprofit

(719) Auto scrap revenue = selling prop rate shredded[Ferrous]\*Auto scrap price in kg  
Units: \$/Month  
The income associated to the ferrous scrap is the multiplication of the flow of ferrous material being sold times the scrap price.

(720) BASE SH PROFIT PER CAR = 6.3  
Units: \$/car  
This is the basic expectation of profit per car on the shredders' operation.

(721) Base Sh semester profit = BASE SH PROFIT PER CAR\*Hulks bought by Sh\*SEMESTER  
Units: \$  
Standard shredders' profit per semester.

(722) BASE UNIT LANDFILL COST = 22.4  
Units: \$/ton  
Is the cost of landfill per ton (researched), based on \$12.5/cubic yard and an ASR density of 1,250lb/cubic yard.

(723) Capacity for Sh accounting = IF THEN ELSE(Switch to disconnect profit and capacity=1, 1.34047e+006, Dynamic Shredder capacity in tons)  
Units: ton/Month  
Is the Sh capacity that generates a fixed cost.

(724) Hulks bought by Sh = dismantling of new cars+hulks selling rate  
Units: car/Month  
Is the amount of cars that the Shredders receive (and pay) in one month. Is the sum of new and old dismantled hulks.

(725) Hulks cost = Average hulk weight in tons\*Hulks bought by Sh\*Corrected hulk price  
Units: \$/Month  
Is the cost of buying Hulks.

(726) in rate Sh semester profit = Shredder profit  
Units: \$/Month

The rate at which the semester profit is calculated is the monthly profit.

(727)  $\text{out rate Sh semester profit} = \text{Shredder semester profit}/\text{SEMESTER}$   
Units: \$/Month

(728)  $\text{Sh energy cost} = \text{Shredding ten rate} * \text{Sh INI UNIT ENERGY COST}$   
Units: \$/Month  
The monthly energy cost is calculated multiplying the unit cost times the shredding rate (expressed in ton/month).

(729)  $\text{Sh fixed cost} = \text{Capacity for Sh accounting} * \text{Sh INI UNIT CAPACITY COST}$   
Units: \$/Month  
The fixed cost of Shredder is a function of their installed capacity and the unit capacity cost.

(730)  $\text{Sh INI UNIT CAPACITY COST} = 12.3$   
Units: \$/ton  
Calculated capacity cost based on interviews and direct research Value calculated at 1/96. Presented in terms of dollars/unit of capacity.

(731)  $\text{Sh INI UNIT ENERGY COST} = 0.2106$   
Units: \$/ton  
Is the researched energy cost per ton of material Shredded.

(732)  $\text{Sh INI UNIT VAR MAINTANCE COST} = 1.9917$   
Units: \$/ton  
Researched maintenance cost per ton of material Shredded.

(733)  $\text{Sh nonferrous revenue} = \text{Sh UNIT NONFERROUS PRICE} * \text{selling prop rate shredded[Nonferrous]}$   
Units: \$/Month  
Shredders revenue associated to nonferrous metals recovery

(734)  $\text{Sh total cost} = \text{Hulks cost} + \text{Sh operation cost} + \text{Shredder landfill cost} + \text{Sh fixed cost}$   
Units: \$/Month  
The total Shredders' cost is the sum of the cost of acquiring the hulks, the processing cost, the landfill cost, the transportation and fixed costs.

(735)  $\text{Sh total revenue} = \text{Auto scrap revenue} + \text{Sh nonferrous revenue}$   
Units: \$/Month  
Total monthly shredders' revenue is the sum of the revenues from ferrous plus non-ferrous metals.

(736)  $\text{Sh transportation cost} = \text{Sh UNIT TRANSPORTATION COST} * \text{Transferring shredded ton materials}$   
Units: \$/Month  
It is the monthly cost in transportation for the Shredders (note: there is a simplification here. Shredders wouldn't probably pay transportation on top of the landfill cost, however the effect is small, specially is one considers that the cost of bringing material into the facility is not being considered)

(737)  $\text{Sh UNIT TRANSPORTATION COST} = 3.1411$   
Units: \$/ton  
Is the average (researched) unit cost that the Shredders pay to transport their product to their customers.

(738)  $\text{Sh variable maintenance cost} = \text{Sh INI UNIT VAR MAINTANCE COST} * \text{Shredding ton rate}$   
Units: \$/Month  
The monthly cost of Variable Maintenance is a function of the Shredding and the unit cost.

(739)  $\text{Shredder cumulative profit} = \text{INTEG}(\text{Shredder profit}, 0)$   
Units: \$  
Profit for shredders is accumulated during the simulations for reporting purposes.

(740)  $\text{Shredder landfill cost} = (\text{sh prop landfill rate}[\text{Mass}/\text{Ton}] * \text{Unit landfill cost})$   
Units: \$/Month  
The landfill cost is a function of the unit landfill cost and the flow of material being landfilled

(741)  $\text{Shredder profit} = \text{Sh total revenue} - \text{Sh total cost}$   
Units: \$/Month  
Monthly profit for shredders is the difference between revenues and total cost.

(742)  $\text{Switch to disconnect profit and capacity} = 0$   
Units: dimensionless  
Allows to use constant shredding capacity when equal to 1. Used for testing purposes.

(743)  $\text{Unit landfill cost} = (\text{Landfill c index}/100 + 1) * \text{BASE UNIT LANDFILL COST}$   
Units: \$/ton  
Is the landfill cost. Uses the index variable to allow for changes during the simulations.

### .shrate

(744)  $\text{Auto scrap price and desired shredded matl inventory graph} ((0, 1, 12), (0, 27, 6), (0, 42, 4), (0, 6, 2, 65), (0, 78, 1, 7), (1, 1), (1, 33, 0, 75), (1, 6, 0, 6), (1, 7, 0, 55), (1, 8, 0, 45), (2, 0, 25), (2, 5, 0, 13), (3, 0, 13))$   
Units: dimensionless  
Estimated relationship between the price Shredders believe they can get for their inventory and the level of inventory they want to keep

(745)  $\text{Auto scrap price perceived by shredder per ton} = \text{IF THEN ELSE}(\text{Switch to change scrap price} = 1, \text{Variable auto scrap price}, \text{CONSTANT AUTO SCRAP PRICE})$   
Units: \$/ton  
Is the price the Shredder believes he can get for his inventory of material if he offered it all.

(746)  $\text{BASE Sh CAPACITY} = 1.127e+007$   
Units: ton/Month  
Initial, estimated shredding capacity.

(747)  $\text{CONSTANT AUTO SCRAP PRICE} = 125.6$   
Units: \$/ton  
Standard auto scrap price.

(748) Desired months of shredded matl = Relative shredded matl inv desired \* BASE MONTHS OF SHREDDED MATL  
Units: Month  
The number of months on desired inventory is calculated using the relative number of months (function of the price they observe) and a standard number of months

(749) Desired transferring of shredded material = MAX(Transferring required to correct shredded material + Shredding ton rate, Sh transferring on storage limitations)  
Units: ton/Month

The desired rate of transferring materials out of the shredders facilities is the maximum between the shredding rate plus the correction to adjust inventories to the desired level, or the transferring defined by the storage limitations

(750) Dynamic scrap price = INTEG(change in scrap price, Ini scrap price)  
Units: \$/ton  
Is the internally calculated scrap price.

(751) Dynamic Shredder capacity in tons = INTEG(Sh capa completion rate - Sh aging capacity rate, Ini Sh capacity)  
Units: ton/Month  
The Shredders capacity increases as the capacity on order gets in place and decreases as the actual facilities age.

(752) Ideal shredded matl inventory = Sh expected future shredding in tons \* Desired months of shredded matl  
Units: ton  
The indicated level of the stock is calculated as a function of the desired number of months and their perception about the future shredding.

(753) Max shredding ton rate = MIN(Possible shredding based inv, Shredder capacity)  
Units: ton/Month  
Prevents shredding from being more than what capacity would allow.

(754) Possible selling of sh materials = MAX(Mass ton shredded/Month, 0)  
Units: ton/Month  
Defines an upper limit to transfer material out: What is in the stock.

(755) Possible shredding based inv = MAX(0, (Shredders ton rm inventory/Month))  
Units: ton/Month  
Defines the maximum rate of shredding possible based on the hulks to be shredded.

(756) Relative auto scrap price = Auto scrap price perceived by shredder per ton / CONSTANT AUTO SCRAP PRICE  
Units: dimensionless  
Shredders compare the price they can get to a standard price.

(757) Relative shredded matl inv desired = Auto scrap price and desired shredded matl inventory graph(Relative auto scrap price)  
Units: dimensionless  
Shredders define a relative level of inventory as a function of the relative price they can get.

(758) Sh aging capacity rate = MAX(Dynamic Shredder capacity in tons / LIFETIME OF Sh CAPA, 0)  
Units: ton/(Month\*Month)  
It is the rate at which the Shredders facilities would be retired.

(759) Sh capa completion rate = Sh Capacity on order / t TO COMPLETE Sh CAPACITY  
Units: ton/(Month\*Month)  
Is the rate at which the actual capacity of shredders increases. It is a function of the capacity that has been ordered and the speed at which those plans are executed.

(760) Sh STORAGE CAPACITY = 1.5576e+007  
Units: ton  
Is the maximum materials that can be stored at the Shredders facilities. Calculated as 12 months (monthly sales of 1.6 car/mo) and the equilibrium weight of hulks at the Shredded hulks inventory and at the Sh raw material inventory (same): 1298 kg/car.

(761) Sh storage usage = Total ton Sh inventory / Sh STORAGE CAPACITY  
Units: dimensionless  
Is the fraction of the Storage capacity being used; ratio of used/available.

(762) Sh transferring on storage limitations = Sh storage usage \* Shredding ton rate  
Units: ton/Month  
Defines a rate to take into consideration the storage limitations. If for any reason, the usage is more than one (too much inventory) this variable would define the transferring (out) of shredded material. It will keep the total inventory equal to the maximum by transferring out more material.

(763) Shredded matl gap = Mass ton shredded - Ideal shredded matl inventory  
Units: ton  
The indicated level of stock is compared to the actual level.

(764) Shredders ton rm inventory = Prop in Sh raw material inv [Mass] / Ton  
Units: ton  
Is the amount of tons (of total material) in the Raw Material Inventory of Shredders, expressed in tons. Is a conversion from the Property [Mass] corresponding stock.

(765) Shredding ton rate = MIN(Max shredding ton rate, (dismantling of new cars + hulks selling rate) \* Average prop in Sh raw mat inv [Mass] / Ton)  
Units: ton/Month  
Shredding rate is: everything they can get, considering capacity limitations and availability of raw material.

(766) Switch to change scrap price = 1  
Units: dimensionless  
Allows to keep scrap price constant when equal to 1.

(767) Switch to dynamically calculate scrap price = 1  
Units: dimensionless  
Allows to use the internally calculated scrap price when equal to 1.

(768) t TO CORRECT Sh INVENTROY = 6  
Units: Month  
It is the time Shredders would like to take to correct their inventory gap.

(769) Total ton Sh inventory = Mass ton shredded + Shredders ton rm inventory

Units: ton

This is the total amount of material sitting at the Shredders facilities. Is the material in its raw and shredded form.

(770) Transferring required to correct shredded material = Shredded matl gap/t TO CORRECT Sh INVENTROY

Units: ton/Month

Is the transferring rate component that would help to correct the inventory gap.

(771) Transferring shredded ton materials = IF THEN ELSE(Switch to turn selling shredded mat constant=1, shredding car rate \* Average prop shredded hulks[Mass]/Ton, MIN(Possible selling of sh materials, Desired transferring of shredded material))

Units: ton/Month

The actual transferring of shredded material would be the desired rate as long as it does not exceed what is available

(772) Variable auto scrap price = IF THEN ELSE(Switch to dynamically calculate scrap price=1, Dynamic scrap price, CONSTANT AUTO SCRAP PRICE + step in scrap price)

Units: \$/ton

Selects a scrap price that changes over time (not constant). It can be the dynamic price of a step function.

## .shredcalc

(773) ASR landfill versus processed = sh prop landfill rate[Mass]/(Average prop of new cars to be processed[Mass] \* dismantling of new cars + Average prop of old cars to be processed[Mass] \* dismantling rate)

Units: dimensionless

Evaluates the generation of ASR. Compares the rate at which material is sent to the landfill to the average monthly dismantling rate, in mass units.

(774) ASR versus retirement = sh prop landfill rate[Mass]/(Grand property average when retired[Mass] \* Total number of cars being retired)

Units: dimensionless

Evaluates the generation of ASR. Compares the rate at which material is sent to the landfill to the average monthly retirement rate, in mass units.

(775) Average dismantling industry mass recovery rate = (dismantling rate/Cars being dismantled) \* Mass recycled rate in old cars per car + (dismantling of new cars/Cars being dismantled) \* Mass reuse or recycled rate in new cars per car

Units: kg/car

Evaluates the average mass recovered by the dismantling industry.

(776) Average prop when retired new cars[property] = (Average prop 1[property] \* retiring 1 + Average prop 2[property] \* retiring 2 + Average prop 3[property] \* retiring 3)/New cars being retired

Units: kg/car

Evaluates the grand average property on "new cars" being retired. Weighed by the retirement rates at difference age cohorts.

(777) Average prop when retired old cars[property] = (Average prop 4[property] \* retiring 4 + Average prop 5[property] \* retiring 5 + Average prop 6[property] \* retiring 6 + Average prop 7[property] \* (retiring 7 + aging 7))/Old cars being retired

Units: kg/car

The Average property of the old cars being retired is the weighted average of the property of cars being retired from each cohort. The relative weight is given by the number of cars retiring at each flow.

(778) Cars being dismantled = dismantling of new cars + dismantling rate

Units: car/Month

Sum of dismantling of "old" plus "new" cars.

(779) Dismantlers Industry Recovery rate versus processed = (Average dismantling industry mass recovery rate)/(Average dismantling industry mass recovery rate + prop in hulks rate new[Mass]/dismantling of new cars + prop in hulks rate old[Mass]/dismantling rate)

Units: dimensionless

Evaluates how much material the dismantling industry is recovering as a fraction of the mass being processed (by dismantlers).

(780) Dismantlers Industry Recovery rate versus retirement = Average dismantling industry mass recovery rate/Grand property average when retired

[Mass]

Units: dimensionless

Evaluates how much material the dismantling industry is recovering as a fraction of the mass being retired.

(781) Grand property average when retired[property] = (1 - Fraction of old cars being retired) \* Average prop when retired new cars[property] + Fraction of old cars being retired \* Average prop when retired old cars[property]

Units: kg/car

Grand property average is a weighed average for each property.

(782) Mass recycled rate in old cars per car = prop recycled rate in old cars[Mass]/Old cars being retired

Units: kg/car

Kilograms per car being dismantled in "old cars".

(783) Mass reuse or recycled rate in new cars per car = prop reuse or recycled rate new cars[Mass]/New cars being retired

Units: kg/car

Kilograms per car being dismantled in "new cars"

(784) prop in hulks rate new[property] = dismantling of new cars \* prop in new hulks after dismantling[property]

Units: kg/Month

Evaluates the average property in new hulks considering the dismantling practice and their previous stage.

(785) prop in hulks rate old[Mass] = prop old hulks after dismantling[Mass] \* dismantling rate

prop in hulks rate old[Ferrous] = prop old hulks after

dismantling[Ferrous] \* dismantling rate

prop in hulks rate old[Nonferrous] = prop old hulks after

dismantling[Nonferrous] \* dismantling rate

prop in hulks rate old[plastics] = prop old hulks after

dismantling[plastics] \* dismantling rate

prop in hulks rate old[DFD] = prop old hulks after dismantling[DFD]\*dismantling rate

Units: kg/Month

Evaluates the average property in old hulks considering the dismantling practice and their previous stage

(786) prop outflow from shredded material[dimproperty] = Average prop shredded hulks[dimproperty]\*Sh transferring material in cars

Units: kg/Month

Properties get transferred out of the Shredders' Finished Product Inventory with the average property (at the shredded hulks level) and at the rate defined by the Transferring material in cars variable

(787) prop recycled rate in old cars[Mass] = Mass being recycled in old cars\*dismantling rate

prop recycled rate in old cars[Ferrous] = Kg ferrous recycled from old cars\*dismantling rate

prop recycled rate in old cars[Nonferrous] = Kg of nonferrous recycled from old cars\*dismantling rate

prop recycled rate in old cars[plastics] = Kg plastics recycled from old cars\*dismantling rate

prop recycled rate in old cars[DFD] = 0

Units: kg/Month

Evaluates the streams of material being recycled in "old cars".

(788) prop reuse or recycled rate new cars[Mass] = dismantling of new cars\*Total kg dismantled in new cars

prop reuse or recycled rate new cars[Ferrous] =dismantling of new cars\*kg of ferrous reused or recycled in new cars

prop reuse or recycled rate new cars[Nonferrous] =dismantling of new cars\*kg of nonferrous reused or recycled in new cars

prop reuse or recycled rate new cars[plastics] =dismantling of new cars\*kg of plastics reused or recycled in new cars

prop reuse or recycled rate new cars[DFD] = 0

Units: kg/Month

Evaluates the total amount of materials dismantled from "new cars".

(789) selling prop rate shredded[Mass] = prop outflow from shredded material[Mass]-sh prop landfill rate[Mass]

selling prop rate shredded[Ferrous] = prop outflow from shredded material[Ferrous]-sh prop landfill rate[Ferrous]

selling prop rate shredded[Nonferrous] = prop outflow from shredded material[Nonferrous]-sh prop landfill rate[Nonferrous]

selling prop rate shredded[plastics] = prop outflow from shredded material[plastics]-sh prop landfill rate[plastics]

Units: kg/Month

Rate at which the shredder sell their material. Conversion from the selling rate in ton units.

(790) Sh FERROUS RECOV FRACTION = 0.99

Units: dimensionless

Estimated shredder efficiency in ferrous recovery.

(791) Sh NONFERROUS RECOV FRACTION = 0.98

Units: dimensionless

Estimated shredder efficiency in non-ferrous recovery.

(792) Sh PLASTICS RECOV FRACTION = 0

Units: dimensionless

Estimated shredder efficiency in non-metals recovery.

(793) sh prop landfill rate[Mass] = prop outflow from shredded material[Ferrous]\*(1-Sh FERROUS RECOV FRACTION)+prop outflow from shredded

material[Nonferrous]\*(1-Sh NONFERROUS RECOV FRACTION)+prop outflow from shredded material[plastics]\*(1-Sh PLASTICS RECOV FRACTION)

sh prop landfill rate [Ferrous]=(1-Sh FERROUS RECOV FRACTION)\*prop outflow from shredded material[Ferrous]

sh prop landfill rate [Nonferrous] =prop outflow from shredded material[Nonferrous]\*(1-Sh NONFERROUS RECOV FRACTION)

sh prop landfill rate [plastics] =prop outflow from shredded material[plastics]\*(1-Sh PLASTICS RECOV FRACTION)

Units: kg/Month

It is assumed that shredders sell and dispose mass in the corresponding composition. This is the sum of all the materials that are transferred out and not recovered

(794) Shrinkage factor for shredders = sh prop landfill rate[Mass]/prop outflow from shredded material[Mass]

Units: dimensionless

The comparison of how much material is being landfilled as a fraction of the total amount of material transported out of the Shredders' inventories.

(795) Total material recovered by Shredders and Dismantlers = Average dismantling industry mass recovery

rate\*(dismantling of new cars+dismantling rate)+selling prop rate shredded[Mass]

Units: kg/Month

Adds the total amount of material per month that the recycling industry is recovering.

## .xlevel

(796) Average prop of new cars to be processed[property] = Prop in new cars to be processed[property]/New deregistered cars

Units: kg/car

Average property of "new cars" is calculated by dividing the corresponding stocks.

(797) Average prop of old cars to be processed [property]= Prop in old cars to be processed[property]/Old deregistered cars

Units: kg/car

Average property of "old cars" is calculated by dividing the corresponding stocks.

(798) Base Labor Cost Index = 0

Units: dimensionless

It represents a cost level for scenario and sensitivity analysis. 0 represents the base case scenario. A number such as 10, would represent that the labor cost is 10% higher than in the base case scenario. A number such as -50 would represent that the cost is half of the one used for the base case scenario.

(799) Base Landfill Cost Index = 0

Units: dimensionless

It represents a cost level for scenario and sensitivity analysis. 0 represents the base case scenario. A number such as 10, would represent that the landfill cost is 10% higher than in the base case scenario. A number such as -50 would represent that the cost is half of the one used for the base case scenario.



(800) Base Nonferrous Price Index = 0

Units: dimensionless

It represents a price level for scenario and sensitivity analysis. 0 represents the base case scenario. A number such as 10, would represent that material prices are 10% higher than in the base case scenario. A number such as -50 would represent that the prices are half of those used for the base case scenario

(801) Base Parts Price Index = 20

Units: dimensionless

(802) Base Plastic Price Index = 0

Units: dimensionless

It represents a price level for scenario and sensitivity analysis. 0 represents the base case scenario. A number such as 10, would represent that material prices are 10% higher than in the base case scenario. A number such as -50 would represent that the prices are half of those used for the base case scenario.

(803) conv1 = 1

Units: kg/car

Conversion factor.

(804) DFD level in new cars n1 = (Average prop of new cars to be processed[

DFD])/conv1-2

Units: dimensionless

Is the value the equations from the DMA use to evaluate dismantling behavior. Is a conversion of the corresponding Index to change the scale to (-1,1)

(805) DFD level in old cars o1 = (Average prop of old cars to be processed[

DFD])/conv1-2

Units: dimensionless

Is the value the equations from the DMA use to evaluate dismantling behavior. Is a conversion of the corresponding Index to change the scale to (-1,1)

(806) Labor c index = IF THEN ELSE(Switch to use trend in indexes=1,labor cost index trend,Base Labor Cost Index)

Units: dimensionless

Allows to have labor cost changing along the simulation

(807) labor cost index trend

Units: dimensionless

Estimated future labor cost (to create scenarios)

(808) Labor cost level 7 = 20\*Labor c index/700-3/7

Units: dimensionless

Is the value the equations from the DMA use to evaluate dismantling behavior. Is a conversion of the corresponding Index to change the scale to (-1,1)

(809) Landfill c index = IF THEN ELSE(Switch to use trend in indexes=1,landfill cost index trend,Base Landfill Cost Index)

Units: dimensionless

Allows to have landfill cost changing along the simulation.

(810) landfill cost index trend

Units: dimensionless

Estimated future landfill cost (to create scenarios)

(811) Landfill cost level 6 = 5\*Landfill c index/300-2/3

Units: dimensionless

Is the value the equations from the DMA use to evaluate dismantling behavior. Is a conversion of the corresponding Index to change the scale to (-1,1).

(812) Nonferrous fraction in new cars being processed = Average prop of new cars to be processed[Nonferrous]/Average prop of new cars to be processed[Mass]

Units: dimensionless

Is the fraction of nonferrous materials in new cars when they get into the dismantling industry.

(813) Nonferrous fraction in old cars being processed = Average prop of old cars to be processed[Nonferrous]/Average prop of old cars to be processed[Mass]

Units: dimensionless

Is the fraction of nonferrous materials in old cars when they get into the dismantling industry.

(814) nonferrous level in new cars n2 = nonferrous level graph(Nonferrous fraction in new cars being processed)

Units: dimensionless.

Evaluates the "level of non-ferrous in new cars".

(815) nonferrous level in old cars o2 = nonferrous level graph(Nonferrous fraction in old cars being processed)

Units: dimensionless

Evaluates the "level of non-ferrous in old cars".

(816) Nonferrous p index = IF THEN ELSE(Switch to use trend in indexes=1,nonferrous price index trend,Base Nonferrous Price Index)

Units: dimensionless

Allows to have non-ferrous price changing along the simulation

(817) nonferrous price index trend

Units: dimensionless

Estimated future non-ferrous price (to create scenarios).

(818) Nonferrous price level 4 = ((Nonferrous p index+100)/100)-2

Units: dimensionless

Is the value the equations from the DMA use to evaluate dismantling behavior. Is a conversion of the corresponding Index to change the scale to (-1,1).

(819) nonferrous level graph ((0,-5),(0.034,-1.01),(0.05,-0.61),(0.0951,0.05),(0.1,0.1),(0.15,0.51),(0.2,0.81),(0.22,0.91),(0.25,1.04),(0.255,1.06),(0.3,1.22),(0.35,1.38),(0.4,1.52),(0.45,1.64),(0.5,1.75),(0.55,1.84),(0.6,1.93),(0.65,2.02),(0.7,2.09),(0.75,2.16),(0.8,2.23),(0.85,2.29),(0.9,2.35),(0.95,2.4),(1,2.46))

Units: dimensionless

Relationship to convert car composition to a "level" to be used by the DOE equations.

(820) Parts p index = IF THEN ELSE(Switch to use trend in indexes=1,parts price index trend,Base Parts Price Index)

Units: dimensionless

Allows to have part prices changing along the simulation

(821) parts price index trend

Units: dimensionless

Estimated future part price (to create scenarios)

(822) Plastic fraction in new cars being processed = Average prop of new cars to be processed[plastics]/Average prop of new cars to be processed[Mass]

Units: dimensionless