Prospects for Automobile Recycling: An integrated Approach of Systems Dynamics and Life-Cycle Assessment

by

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Abstract:
An integrated approach of life-cycle assessment and systems dynamics is applied to analyze the current and inter-temporal effects of automobile recycling and to propose strategic policies for this issue. Life-cycle assessment is employed to identify the current automobile recycling problem, which results from the interactions among environmental concerns, regulatory mandates, technological innovations, and market economics. Systems dynamics is used to construct a computer simulation model in order to examine the effectiveness of different recycling policies.

The results of the model simulation show that the automobile industry would be capable of dealing successfully with regulatory and economic challenges from automobile recycling by efficiently adjusting the current market system. Europe's take-back legislation and deposit systems are not necessary in the United States. Additionally, policymakers should be careful about setting regulatory requirements, such as fixed recycling targets and classifying ASR as hazardous waste.

Currently, the domestic government and industry can adopt a wait-and-adjust policy and focus on technological development and information collecting. A joint effort from both the public and private sectors is needed in order to remove the barriers of automobile recycling, develop new technologies, improve the market economics, as well as arrive at a sustainable solution for the long-term development of the society.

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Chapter 1

Introduction

The recycling problem of automobiles, which arose in the 1960's[1] and spurred by recent European recycling imperatives[2], has been receiving significant attention these days. Recycling was recognized as the top issue by the 1992 Ward's Automotive Yearbook in the Material and Manufacturing section[3]. In February 1992, Ford Motor Co., Chrysler Corp., and General Motors Corp. jointly announced the formation of the Vehicle Recycling Partnership (VPR). Recycling has even become a new commercial term for the Saturn Corporation to improve its corporate image[4].

The interest in automobile recycling derives both from "resource exhaustion" concern (or a fashion term, sustainability) and from environmental concern. Each year, an estimated 9 million vehicles are scrapped in the United States[5], providing over 10 million metric tons of recycled ferrous scrap to the iron and

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[1] About the recycling problems of the 1960's, refer to M. Wohl, The Junk Vehicle Problem: Some Initial Thought, The Urban Institute, Washington, DC, 1970.
[2] Refer to Barrie, Chris, "Germany's recycling feats lead the European pack," Automotive News Insight, Automotive News, Crain Communications, August 6, 1990, p.10i.
[3] Ward's Automotive Yearbook, 1992
[4] "A different kind of company," the TV commercial of Saturn Co., 1994
[5] Ward's Automotive Yearbook, 1993.

steel industry[6], but also generating about 3 million tons of automotive solid waste to the environment[7]. As a result, the recycling of automobiles presents not only a profitable economic opportunity, but also a potential environmental challenge.

Under current technologies, about 75% of the weight of a vehicle is recycled, but it is almost exclusively metals: the steel, cast iron, and aluminum parts that are easily identified and salvaged, plus easily retrieved components such as tires and batteries. However, hundreds of pounds of other materials, including plastics, glass, fabric, and carpeting end up as what salvage yards call "fluff" or "Automobile Shredder Residue" (ASR) and are largely landfilled[8]. The fact is that even though the industry can reclaim some materials, such as glass or plastics from the automobile fluff, there currently is no market for them.

Today the automobile recycling problem in the United States has several dynamic features. First, it is an interdisciplinary problem that covers various research areas including environmental management, regulatory mandates, production and recycling technologies, and market economics. Second, it is an inter-sectoral problem that relates to every sector along the life cycle of automobiles, from manufacturers to dismantlers and shredders. Third, it is an inter-temporal problem that "design-for recycling" initiatives implemented today will generally take about 10 years to work their way through the life cycle of

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[6]B.J. Jody, E.J. Daniels, P.V. Bonsignore, and F.J. Dudek, "Recycling of Plastics in Automobile Shredder Residue," in Proceedings of the 25th Intersociety Energy Conversion Engineering Conference in Reno, Nevada, August 12-17, 1990, by the American Institute of Chemical Engineers (New York: American Institute of Chemical Engineers), 131.
[7]M.Fisher, The Council for Solid Waste Solutions, Remarks given at Reconstituting Plastics Forum, 1990 Society of Automotive Engineering Passenger Car Meeting and Exposition, September 18, 1990.
[8]Ward's Automotive Yearbook, 1992.

automobiles and impact on recyclability. Finally, it is an inter-jurisdictional problem when the international trade of automobiles is taken into account.

Several policy option aimed at dealing with the problem of scrap automobile recycling are proposed by both the public and private sectors, including technological resolutions, such as pyrolysis, hydrolysis and alcoholysis, economic resolution, such as polluters-pay principle and charge mechanism, and legislative resolutions, such as the requirement of extended producer responsibility and the regulation on "automotive hazardous wastes[9]." Since recycling issues are the most frequently mentioned new regulatory area[10], these prospective policies will have significant influence on the automotive industry in the near future.

1.1 Overview

In order to address the complex interactions among all the environmental, economic, technological, and regulatory issues and in order to "capture" all the dynamic features of the automobile recycling problem, this thesis will study the relevant industrial ecology and recycling infrastructure through a life-cycle framework. A computer model aimed at simulating the automotive material flow system will serve as a major analytic tool by which different recycling initiatives will be evaluated from an integrative approach of Systems Dynamics and Life-Cycle Assessment.

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[9]F.R. Field, III and J.P. Clark, "Recycling of US Automobile Materials: A Conundrum for Advanced Materials," in the 3rd International ATA Conference, June 1991.
[10]Delphi IV Forecast and Analysis of the U.S. Automotive Industry, University of Michigan, 1992, v.3, p.16.

Chapter 2 will examine the existing recycling infrastructure for scrap automobiles. Chapter 3 will describe current problems and challenges faced by the industry. Chapter 4 will evaluate the proposed recycling practices and policy options. Chapter 5 will present a simulation model that will be used to analyze the effects of different policy options. Chapter 6 will summarize the results of the model simulations. Chapter 7 will discuss the different policies around this issue. Chapter 8 will conclude with a discussion of the prospects for automobile recycling.

Chapter 2

The Current Recycling Infrastructure

2.1 Overview

The objective of this chapter is to establish the context for a life-cycle framework for the automotive material flow system. At each stage of the life cycle, the recycling infrastructure will be examined and the recycling activities will be described. In addition to material flows, special attention will be paid to the economic activities of the automobile recycling industry.

2.2 Life-Cycle Framework

Traditionally, the recycling of automobiles has been viewed merely as the inherent job of automobile dismantlers and shredders (or known as automobile salvage industry), who process and then dispose of the automotive scrap after the end use of cars. However, increasing emphasis on product recyclability and the complex market mechanism for recycled materials have forced us not only to confine our efforts to the end-of-use processors of automobiles, but also to turn our attention to some of the behind-the-scenes players of recycling activities. For example, it is nearly impossible for an automobile shredder to recycle a windshield as long as the manufacturer keeps using plastic/glass laminates, a complex mixed compound, as its material[11]. A shredder will never recycle PVC if the material suppliers are not willing to buy the recycled composite back. It turns out that extending the recycling concern to the whole life cycle of automobiles is of crucial importance in dealing with engineering unknowns and with the market uncertainties around the automobile recycling problem.

Life-cycle assessment, which addresses the complex technological and economic interconnections along with a product's life cycle from a life-cycle framework, has become one of the most powerful tools for the study and analysis of the automobile recycling problem. The life-cycle assessment is an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying materials used and wastes released to the environment, to assess the impact of those energy and materials uses and releases on the environment, and to evaluate and implement opportunities to affect environmental improvements[12]. The conception of life-cycle framework derives from its roots in traditional engineering and process analysis, and from the recognition, implicit in its formulation, that the consequences of technological undertakings are not limited to the performance of a single process or change.

[11]Ward's Automotive Yearbook, 1992, p.35.
[12]SETAC, "Executive Summary," A Technical Framework for Life-cycle Assessment, SETAC Foundation, 1991.

Rather, most of the consequences of any action can only be perceived when the entire range of consequences of that action are taken into consideration[13].

Methodologically, a life-cycle framework traces the flows of material through both the so-called productive pathways as well as the so-called waste routes in order to develop an understanding of the interactions between the economic and technological activities along the whole chain of production, consumption, and elimination[14]. The life-cycle based framework thus allows environmental threats and remedies to be identified according to the "stage" in which they occur. Figure 2.1 illustrates the typical stages for a product's life cycle. It can further be divided into two streams: the "upstream," including raw materials extraction, manufacture, distribution, and consumption, and the "downstream," including collection, processing, and disposal[15].

For the purpose of establishing a life-cycle framework for the automotive material flow system, an automobile can be considered as a collection of materials. According to the Material Balance Principle, materials are neither created nor destroyed by extraction, production, consumption, or recycling at each stage of the life cycle, but just change their forms[16]. Figure 2.2 illustrates the life-cycle framework for automotive materials. Each stage represents a specific role or activity in the material flow system, and has its specific influence on the

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[13]F.R. Field III, J.A. Isaacs, and J.P. Clark, "Life Cycle Analysis and Its Role in Product and Process Development," in the 2nd International Congress on Environmentally Conscious Manufacturing, August 29, 1993.
[14]J.R. Ehrenfeld, "The Potential for Life Cycle Assessment to Reshape Corporate Practice," in MIT Conference on Life Cycle Assessment: From Inventory to Action, November 4-5, 1993.
[15]R.J. Lifset, "Take It Back: Extended Producer Responsibility as a Form of Incentive-based Environmental Policy," in Conference on Economic Incentive for Environmental Management, Air & Waste Management Association and U.S. Environmental Protection Agency, November 1993.
[16]E.S. Mills and P.E. Graves, The Economics of Environmental Quality (New York: Norton), 1986, p.11

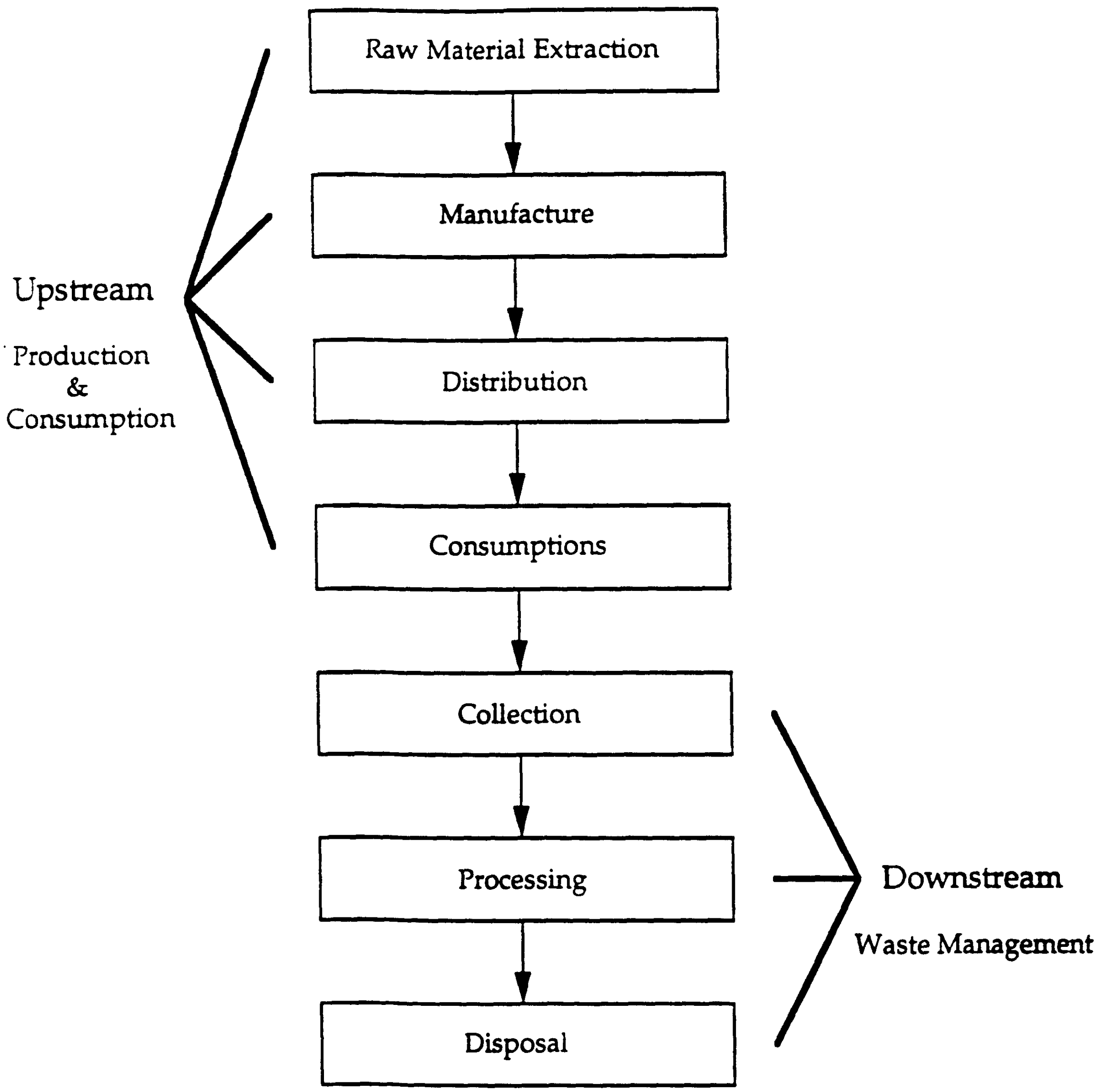

Figure 2.1: Typical Stages of Product's Life Cycle

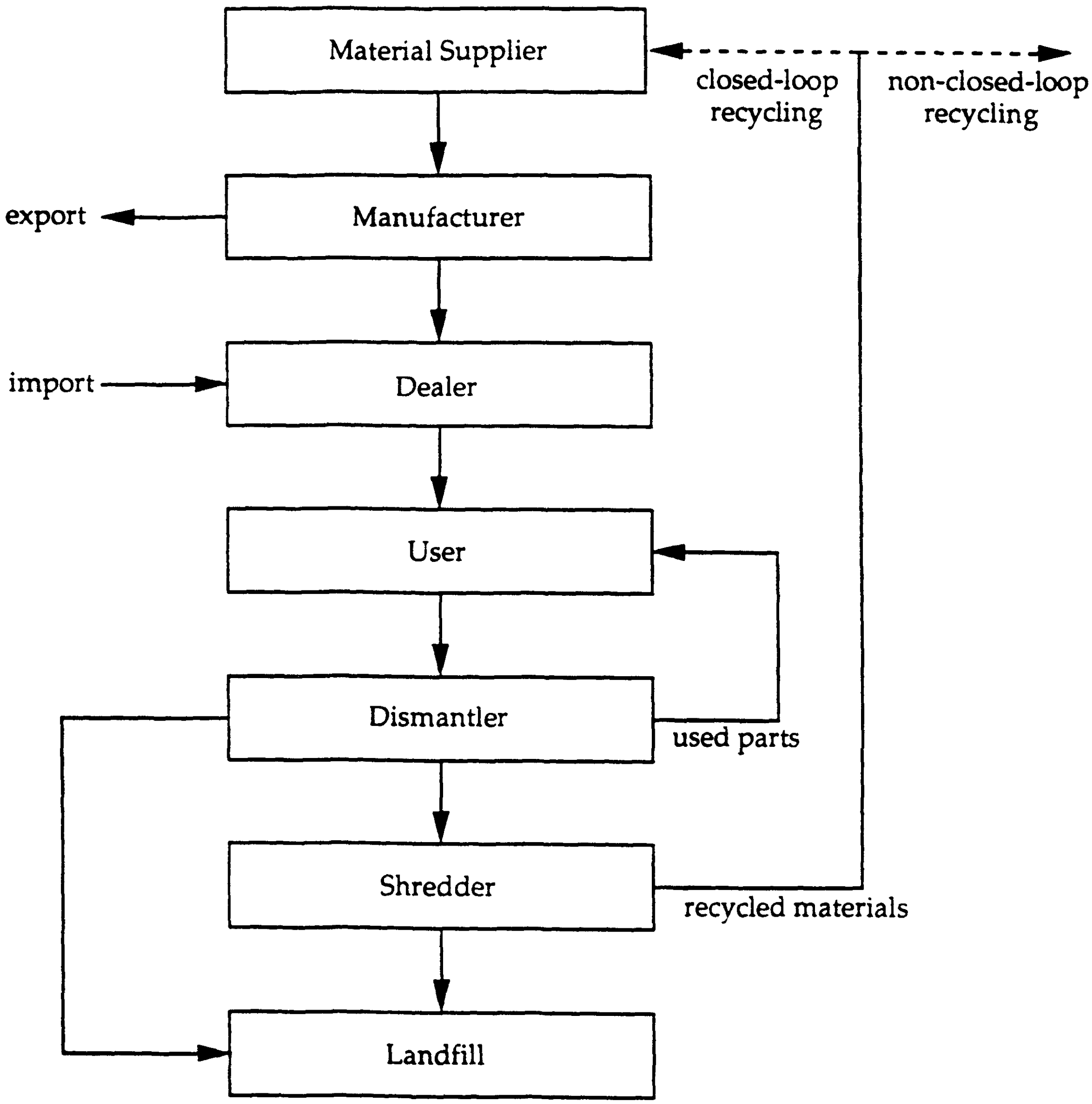

Figure 2.2: Life-Cycle Framework for Automobiles

recycling of automobiles. For the "upstream," the major stages include material supplier (raw materials extraction), automobile maker (manufacture), automobile dealer (distribution), and users (consumption). For the "downstream," the major stages include automobile dismantler and shredder (collection and processing) and landfill (disposal). All these stages constitute the current recycling infrastructure for automobiles under a life-cycle framework.

2.3 Upstream: Production and Consumption Stages

Although not directly involved in waste end activities, the actors in the upstream of the life cycle of automobiles play an important role in automobile recycling. These actors include material suppliers, manufacturers, dealers, and users. The following subsections will discuss their physical and economic activities that affect the whole recycling infrastructure of scrap automobiles.

2.3.1 Material Supplier

At the very first stage of an automobile's life cycle are material suppliers. The automotive material suppliers provide the qualified materials needed to achieve the specified performance of an automobile's parts. Traditionally, these materials can be divided into two groups: (1) raw materials, the virgin materials extracted from the natural environment, and (2) scraps, which refer to materials recovered from industrial processes or from post-customer products. Scraps can be further categorized into three groups: (1) post-customer scrap, the materials recycled from the end-of-life automobiles, (2) home scrap, the material that is an unavoidable nonproduct output of the material-making operation, and (3) prompt scrap, the material that is a nonproduct output of automobile-making processes[17]. Figure 2.3 shows an example of the typical origin of materials used in making ferrous materials. Here the automotive post-customer scrap, with its large quantity, is of most concern to society.

The importance of material suppliers lies not only in their work of providing materials to the automotive industry, but also in their willingness to form a market for post-customer automotive materials, especially when a closed-loop recycling practice is taken into account. Currently, the willingness for material suppliers to adopt a recycled automotive material depends mostly on the quality and the relative price of this material. For example, the automobile derived steel scrap is graded as No. 1 Heavy Melting Steel and No. 2 Bundles. The connotation is that "No. 2" scrap, which refers to the class of all obsolete steel scrap, is not as clean as "No. 1" scrap, which refers to the class of all nonobsolete steel scrap. The major limitation of the recycled No. 2 scrap is the metallic impurities that would usually result in low quality steels[18], and additional reprocessing is needed in order to achieve the same quality level of No.1 scrap. The fact that most steel suppliers are unwilling to accept any bundles that contain too many impurities presents a major difficulty for introducing recycled materials into the market.

However, due to the aggressive competition in the market of automotive materials, many material suppliers have now turned their attention to recycled automotive materials. The development of advanced automotive materials has

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[17]J.W. Sawyer, Jr, Automotive Scrap Recycling Processes, Prices, and Prospects, 1974.
[18]F.R. Field, III and J.P. Clark, "Recycling of US Automobile Materials: A Conundrum for Advanced Materials," in the 3rd International ATA Conference, June 1991.

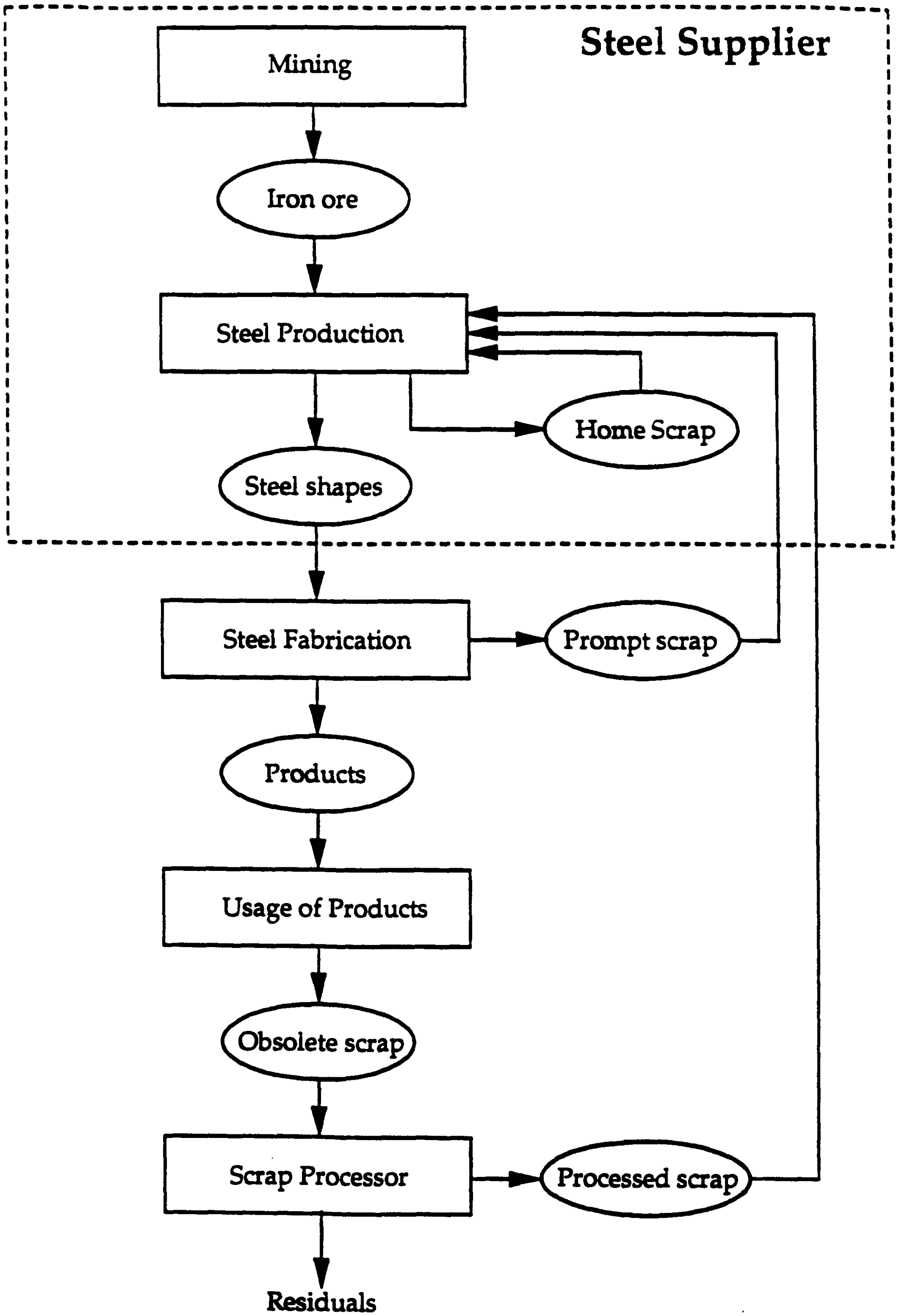

Figure 2.3: Material Flow Diagram of Steel Supply System

brought about a new battle of material selection among material suppliers. This material tug-of-war involves steel, aluminum, plastics, powder metal, and many others[19]. Among all the virtues praised by materials suppliers, recyclability has become one of the decisive factors. For example, recyclable materials such as steel and iron gained their dominant ground in material selection in 1992 because recycling was the top issue that year[20]. The polymer suppliers, especially the thermoplastic polymer suppliers, have been claiming that the recycling of plastics is technically feasible. As a consequence, the competition of material selection among material suppliers will have a significant effect on automobile recycling in the future.

2.3.2 Manufacturer

From the viewpoint of material flow, the job of automobile manufacturers is to design, fabricate, and assemble different kinds of materials into operational vehicles. The material composition of a typical automobile can be categorized into four groups: (1) ferrous metals, (2) non-ferrous metals, (3) plastics, and (4) miscellaneous materials[21] (refer to Figure 2.4). During the design and manufacturing processes, manufacturers employ these materials to build automobiles that meet the desired quality and performance. The actual development process of an automobile, however, is full of constraints, uncertainties, and conflicting goals.

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[19] Ward's Automotive Yearbook, 1993.
[20] Ward's Automotive Yearbook, 1992.
[21] Refer to Ward's Automotive Yearbook, Material Composition Chart.

Two factors currently governing the U.S. manufacturer' design and production are regulation and competition[22]. Figure 2.4 shows the general design and manufacturing processes for an automobile. The success or failure of the development of a passenger car depends heavily on whether it can meet the specified regulatory and competitive qualifications. However, these qualifications are usually conflicting, and it is difficult for manufacturers to satisfy them simultaneously. As a result, most manufacturers are forced to prioritize and compromise among all these qualifications. Unfortunately, during this kind of negotiation process, recyclability has not usually been high on the priority list of manufacturers.

On the regulatory side, emission controls[23] and fuel economy[24] standards are of primary concern. Automobile manufacturers currently respond to these regulatory requirements by changing material bases, using energy efficient materials, and increasing the complexity of products with the ultimate goal of weight reduction. However, these measures generally increase the recycling difficulty of automotive scraps. Advanced materials, such as plastics and ceramics, are technologically or economically non-recyclable at this time. In addition, the complexity of modern automobile structure presents the recycling industry with several problems in dismantling and removing processes[25]. The fact is that recyclability is usually outweighed by other regulatory considerations.

On the competitive side, automobile manufacturers are trying to integrate market effects into the product's development process. Key competitive factors include

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[22]F.R. Field, III and J.P. Clark, "Recycling of US Automobile Materials: A Conundrum for Advanced Materials," in the 3rd International ATA Conference, June 1991.
[23]Refer to Clean Air Act, Subchapter II--Emission Standards for Moving Sources.
[24]Refer to Corporate Average Fuel Economy Standards.
[25]For details, refer to Chapter 3.

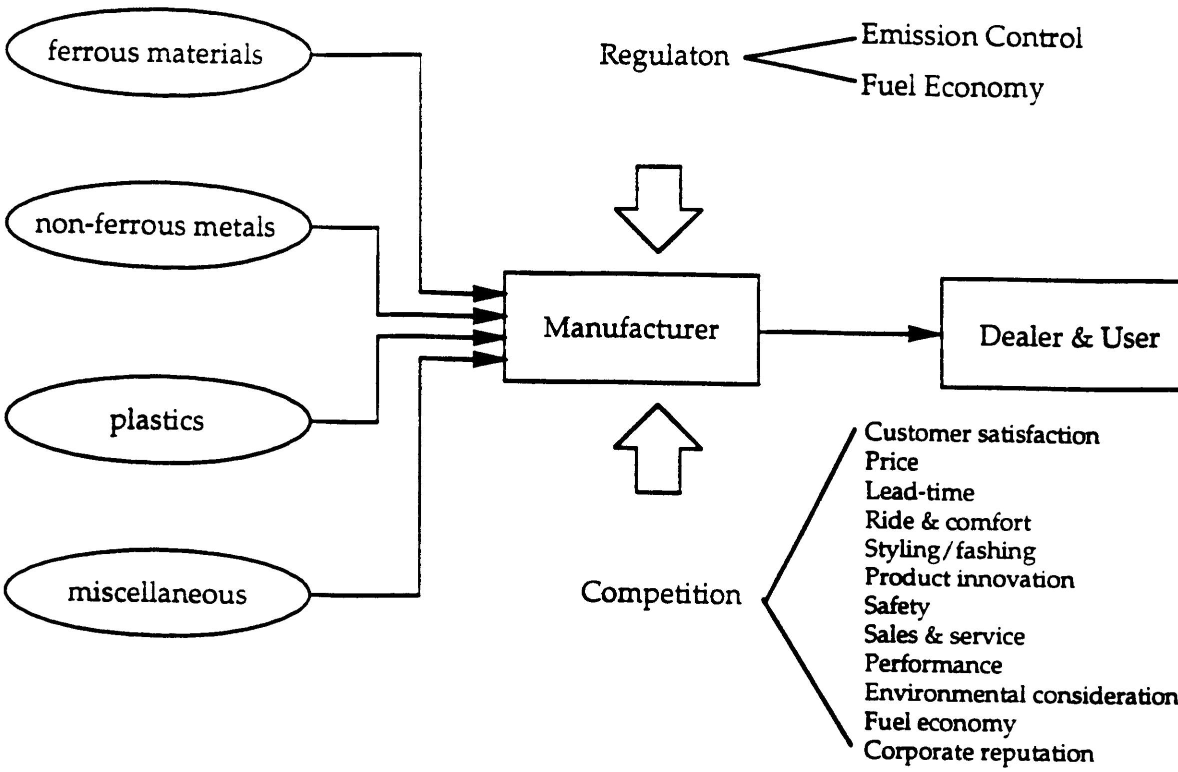

Figure 2.4: Material Flow Diagram of Manufacturing Stage

Basic of Competition: Key Elements	**Ranking**
Customer Satisfaction	1.5
Price	2.7
Lead Time	3.5
Ride & Comfort	4.0
Styling/Fashion	4.4
Product Innovation	4.7
Safety	5.0
Sales & Service	5.1
Performance	5.3
Environmental Considerations	6.5
Fuel Economy	6.7
Corporate Reputation	7.6

* Order from 1 to 9 (with 1=most important)

Table 2.1: Ranking of Competition Elements for U.S. Manufacturer

customer satisfaction, styling, safety, and price. However, recyclability still does not gain a strong ground among these marketing considerations. Table 2.1 illustrates a survey of manufacturers' ranking of key competition elements in the automobile industry. Environmental considerations such as recycling are currently not a priority for most automobile manufacturers[26].

Currently, it is apparent that "design for recycling" is not an essential design principle for the U.S. automobile manufacturer, in both regulatory and competitive considerations. Moreover, some conflicting goals, such as weight reduction and product complexity, yield negative effects on automobile recycling. However, the U.S. automaker has been aware of these negative effects and has started to work on recycling issues. In 1992, Ford Motor Co., Chrysler Corp., and General Motors Corp. jointly announced the formation of the Vehicle Recycling Partnership (VRP). The objective of VRP is to increase the amount of recyclable materials in vehicles and to develop guidelines such as material selection and compatibility, and design for dismantling. It turns out that the concern of recyclability is likely to increase its importance in vehicle design and manufacturing in the future.

2.3.3 Dealer and User

In an automobile's life cycle, dealer and user are positioned at the stages of distribution and consumption respectively. Although not directly involved in recycling activities, dealer and user have a significant influence on scrap

[26] Delphi IV Forecast and Analysis of the U.S. Automotive Industry, University of Michigan, 1992, v.2.

automobile recycling: they determine the number and characteristics of automobiles that are in operation as active vehicles as opposed to those which are retired from transportation fleet. In other words, they control the supply of material flow from the upstream to the downstream along an automobile's life cycle.

Figure 2.5 shows the general relationship among new motor vehicle sales, the size of fleet population, and the supply of scrappage. New vehicles enter the on-road fleet population first, are used for a finite period of time, and are eventually removed from service as a result of wear, tear, or accident. Here the dealer's sales are the inputs; the number of on-road vehicles is the stock; and the scrappage supply is the output. This inter-relationship determines the material flow from the production stage, through the consumption stage, and finally into the waste management stage. Figure 2.6 presents the yearly data of dealers' new car sales, cars in operation, and car scrapped in the United States from 1980 to 1990. The number of cars in operation kept increasing as dealers' sales continued to exceed the scrapped cars during this period[27].

The supply of scrapped passenger cars can be related to several factors, including customer preference, population, the distribution of population (for example, the proportion of children in the total population), the price of operating automobiles, the general economic condition, and a host of other factors[28]. Some of these factors are subjective and hard to measure. However, the overall effect of all these factors can be summarized by the average survival data of cars produced in a specific model year. Figure 2.7 shows an example of the estimated

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[27]Ward's Automotive Yearbook, 1980-1993.
[28]J.W. Sawyer, Jr., Automotive Scrap Recycling Processes, Prices, and Prospects, 1974.

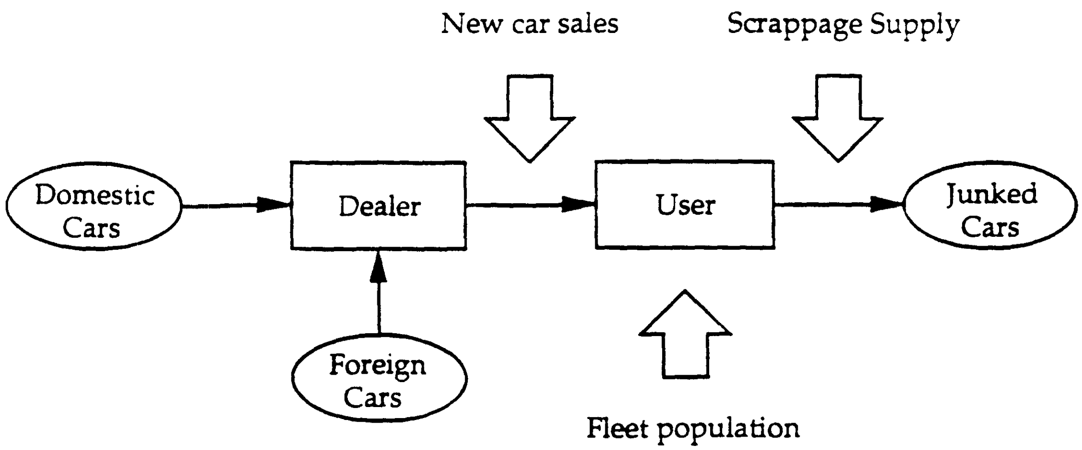

Figure 2.5: Material Flow Diagram of Consumption Stage

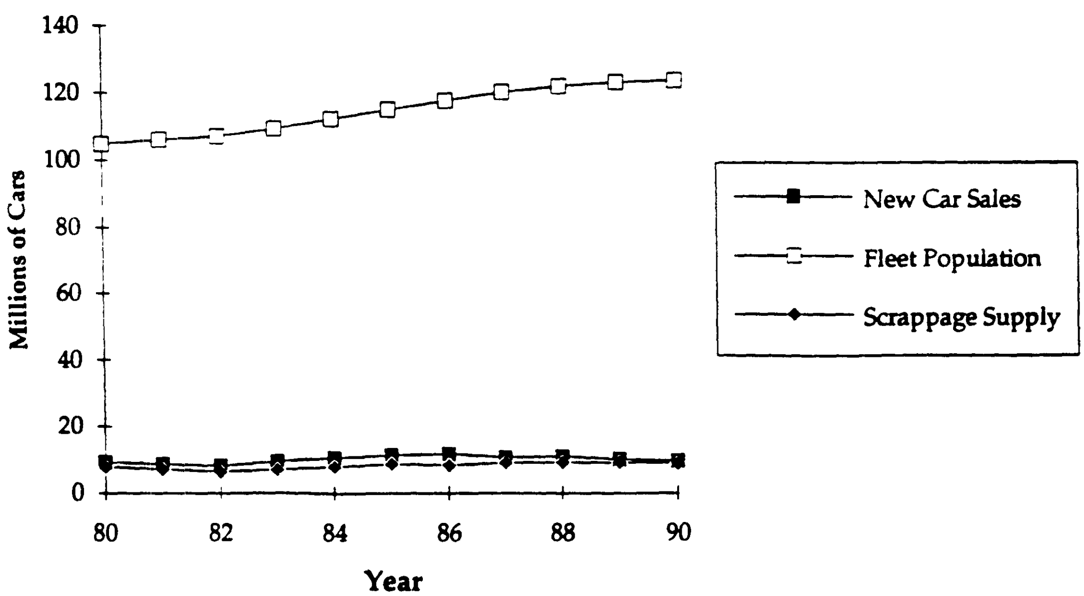

Figure 2.6: Fleet Population from 1980-1990

Year of Service, n	Percent of Cars Still in Service	Percent of Cars Removed in nth year
5	89.0%	
6	87.4%	1.6
7	84.7%	2.7
8	82.0%	2.7
9	78.0%	4.0
10	72.0%	6.0
11	64.1%	7.9
12	55.6%	8.5
13	46.2%	9.4
14	37.3%	8.9
15	29.8%	7.5

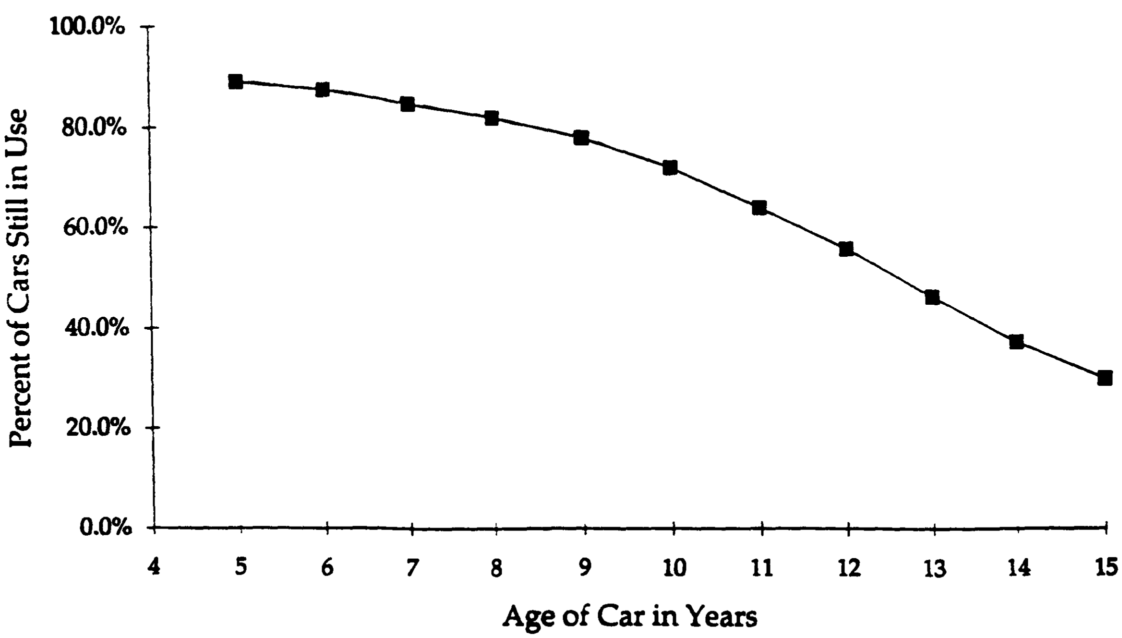

Figure 2.7: Percent of Total Car Production Surviving

percentage of 1976 cars still in use during a given period (5-15 years)[29]. Since different cars have different life spans, the characteristics of junked cars are determined by the distributional percentage of a specific model year's vehicles in the total junked car population.

After an automobile goes through its useful life, and is eventually deregistered, it is transported into the next stage of its life cycle: the waste management stage. Direct recycling activities thus take place in the downstream of the automotive material flow system.

2.4 Downstream: Waste Management Stages

When an automobile's service life is over, it may still be valuable depending on the method of disposal. The scrapped vehicles are processed by the automobile recycling industry, including about 12,000 dismantlers and 200 shredders[30]. The dismantling and shredding industry is well established in the recovery of metal components that typically account for 70 to 75 percent of vehicle mass[31]. Their recycling activities are described in the following sections.

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[29]Calculated from Ward's Automotive Yearbook, 1990.
[30]M.Fisher, The Council for Solid Waste Solutions, Remarks given at Reconstituting Plastics Forum, 1990 Society of Automotive Engineering Passenger Car Meeting and Exposition, September 18, 1990.
[31]H.Hock and M.A.Maten, Jr., A Preliminary Study of the Recovery and Recycling of Automotive Plastics, 1992.

2.4.1 Dismantler

The dismantling industry, also known as automobile wrecking industry, has focused primarily on the recovery of valuable parts from scrapped vehicles. The industry's main business includes obtaining discarded cars, salvaging their useful parts, and then selling the stripped hulks to automobile shredders. The automobile dismantling industry is not only the major source of parts for maintaining older vehicles in service, but also the main channel through which junked cars flow into the downstream of the life cycle of automobiles.

There are some 12,000 dismantlers, widely distributed in the United States. Most of then are small, with usually 10 or fewer employees. Land and buildings account for most of a dismantler's capital investment because they represent the storage space for junked cars being dismantled and for removed parts. In addition, equipment represents the rest at about 20% of the capital investment. Typical equipment includes trucks (tow truck, boom truck, flat bed truck, or pick up truck), a crane, tractors, crushers, etc. There is also extensive use made of hand tools and cutting torches[32].

The operation begins with the dismantler's acquisition of a junked car by paying the last owner. The general value of a junked car varies from $50 to $300, depending on its age and general condition. Once a scrapped car is in a dismantler's junk yard, it will go through two major removing processes: primary removing and secondary removing. The primary removing refers to the operation of taking off the "bad" parts from a junked car, including batteries,

[32]R.Kaiser, R.P.Wasson, A.C.W. Daniels, Automobile Scrappage and Recycling Industry Study, Overview Report, H.H.Aerospace Design Company, Inc., 1977.

tires, catalytic converters, radiators, fuel tanks, air bag canisters, fluids, and anything else that will damage the equipment or contaminate the material stream. The secondary removing refers to the operation of taking off the "good" parts from the car, including engine blocks, transmissions, reusable or remanufacturable spare parts, radios, some fluids, and anything else of marketable value[33]. Parts from primary removing are usually recycled (like batteries) or carted away (like gas tanks) by a specific contractor and used for landfill. The valuable parts from secondary removing are generally cleaned, tested, or rebuilt first, and then classified and stored for future sale. Many dismantlers now handle their inventory with computer systems in order to meet the demand of a variety of used parts in different brands of passenger cars[34]. After all salvageable parts have been removed, the residue, or so-called automobile hulk, is flattened to reduce the transportation space and then sold as a byproduct to the shredding industry. Figure 2.8 is a summary of the general material flows within the dismantling industry[35].

It is of interest how a dismantler decides to remove a specific part from a scrapped car and if the "dismantling for the environment" concept accounts for this decision. The general rule is that, for a specific part m, if the sale price of this part exceeds the costs of removal, rebuilding, storage, etc., and if the market condition favors the resale of it, then remove part m. If not, leave it in the car body[36]. That is, economic incentive is the major drive for dismantlers to remove a used part. However, the above rule does not work on the parts from primary

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[33]J.R. Dieffenbach and A.E. Mascarin, Cost Simulation of the Automobile Recycling Infrastructure: The Impact of Plastics Recovery, Society of Automotive Engineers (#930557).
[34]Information from the Automotive Recyclers Association, Virginia.
[35]Joseph Nissenbaum, Nissenbaum's Recycled Auto Parts Co. (Somerville, MA), interview with author.
[36]J.W. Sawyer, Jr, Automotive Scrap Recycling Processes, Prices, and Prospects, 1974, chapter 5.

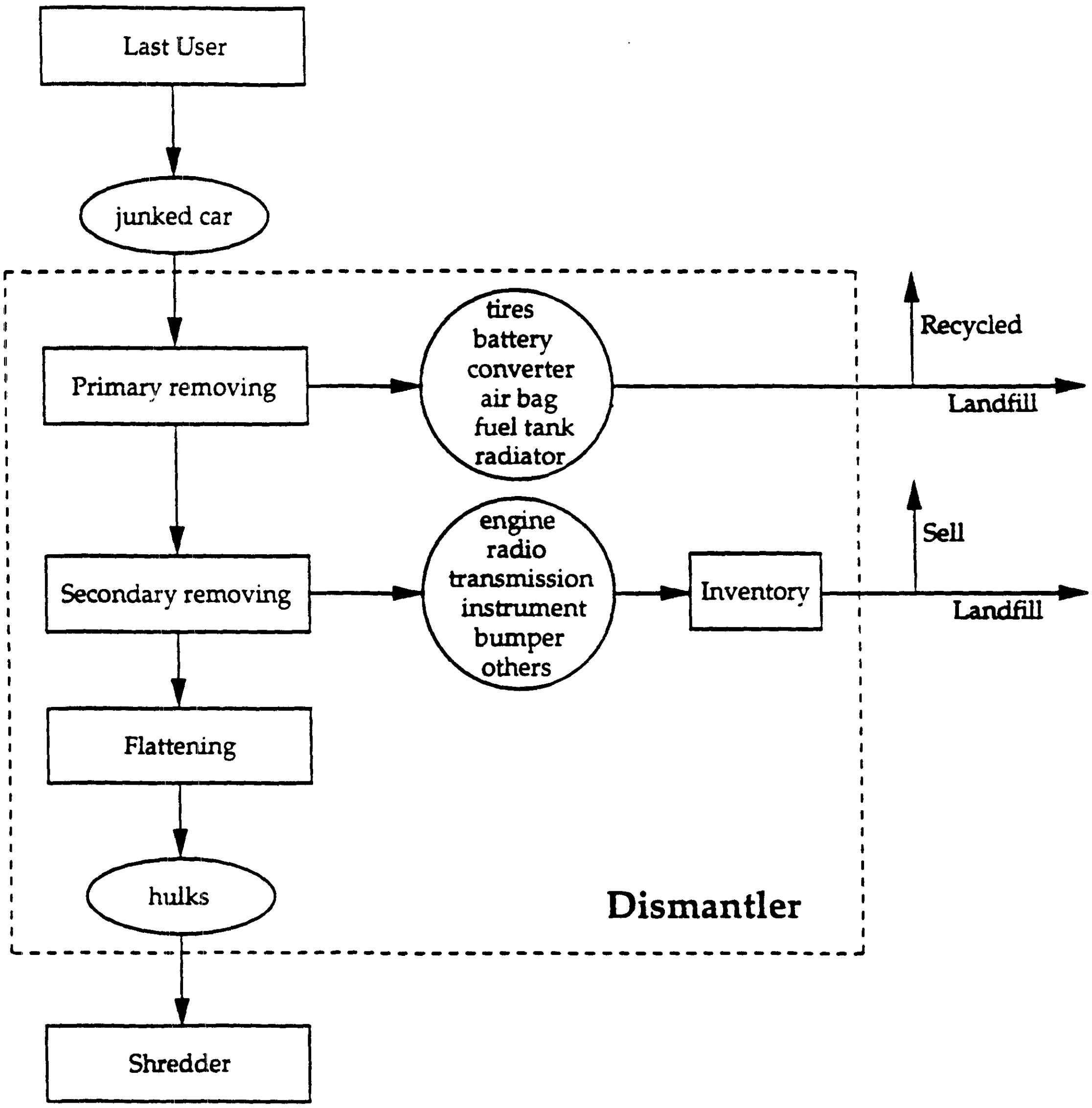

Figure 2.8: Material Flow Diagram for Dismantler

removing because the removal of those parts are required by regulation for recycling (like batteries) or by shredders in order to maintain the material quality and thus the higher selling price for hulks. It turns out that the dismantling process is currently dominated by economic factors rather than by regulatory requirements or environmental consciousness.

2.4.2 Shredder

The shredding industry is primarily focused on the recovery of valuable materials from automobile hulks. The main business of shredders is obtaining stripped and compacted automobile residues from dismantlers, processing the residues to recover their material value, and then selling the recycled materials to material suppliers. From the viewpoint of an automobile's life cycle, the shredding industry is the last stage through which automotive materials are either recycled for further use or disposed of as automotive wastes.

The shredding operation begins with the shredder placing the entire hulk onto a moving belt into a shredder machine that breaks the car into small, fist-sized pieces. These pieces then pass through a series of separation devices using magnetic, air, and aqueous separation techniques. Air classifiers separate the non-magnetic waste from the magnetic portion, and magnetic separators segregate the chunks into ferrous and non-ferrous scrap. The non-ferrous scrap is further recovered by either shredder operators themselves, or by non-ferrous metal separators. The shredding process thus produces three streams of materials: ferrous metals, non-ferrous metals, and automotive shredder residue

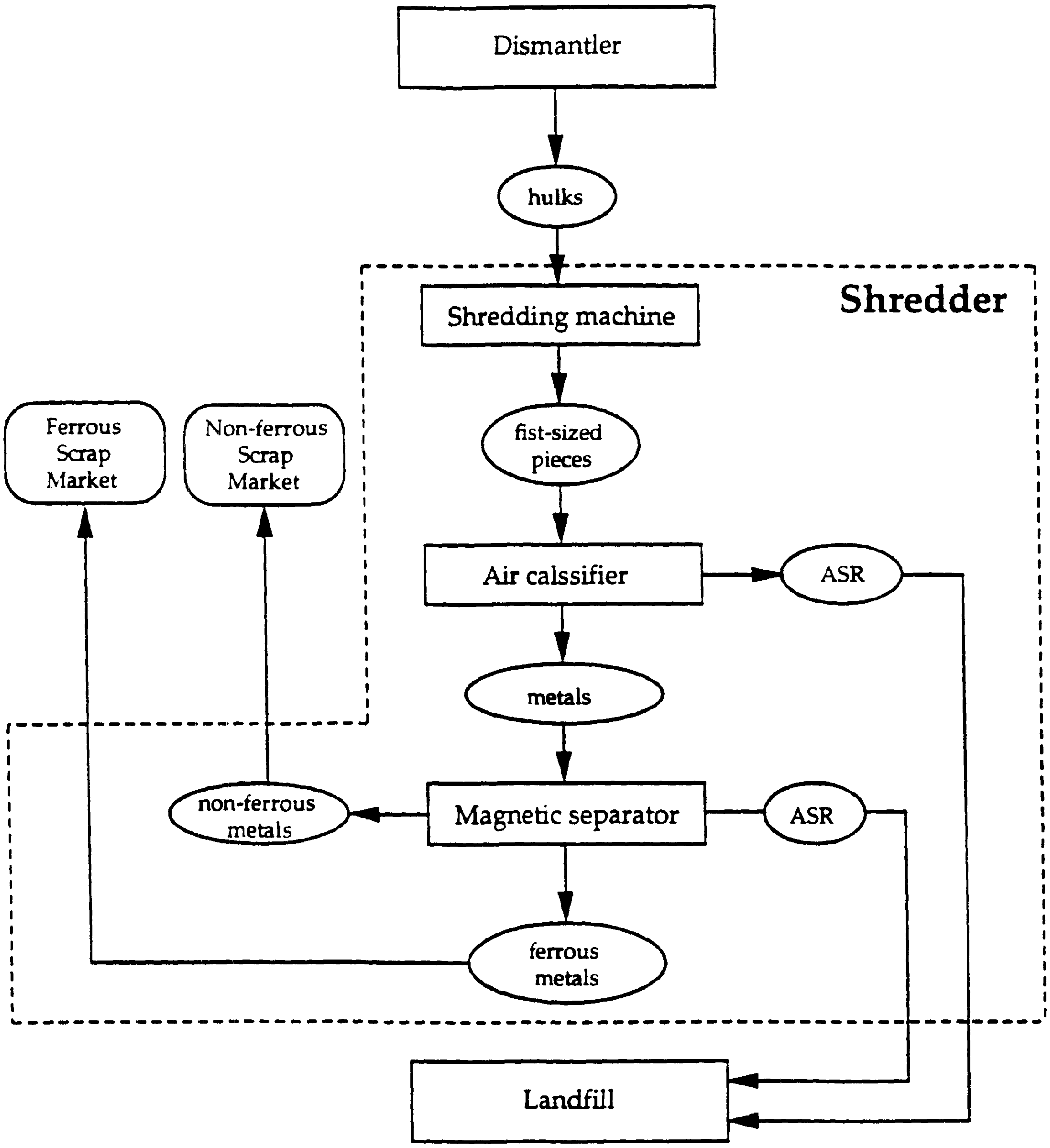

Figure 2.9: Material Flow Diagram for Shredder

(ASR), the remaining commingled residue. Figure 2.9 is a summary of the material flows with the shredding industry.

By mass, about 96% of ferrous metals and up to 60% of non-ferrous metals are currently recovered by shredders[37] and sold as post-customer scrap to material suppliers. Newly developed technologies, such as heavy duty shredders, dry separation systems, pre-shredder process equipment, and even hand picking[38], have been largely adopted in the industry, and have greatly improved the recovery percentage and the quality of recycled ferrous and non-ferrous metals[39].

However, the automotive shredder residue, made up of a number of materials including plastics, glass, fluids and dirt, presents a major challenge to the industry. While the overwhelming majority of ASR is currently landfilled, the presence of fluids and heavy metals that exist in the ASR poses disposal problems for the automobile shredding industry. As a result, increasing environmental pressure has compelled shredders to consider some disposal options like pyrolysis and incineration for the purpose of recovering more from the material stream or changing the basic form of ASR. The technological and economic feasibility of these options will have substantial effects on shredding processes in the future[40].

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[37]M.Rousseau and A.Melin, "The Processing of Non-Magnetic Fractions from Shredded Automobile Scrap: A Review," Resources, Conservation and Recycling, Vol. 2, 1989, P.142.
[38]J.Holusha, "An Afterlife for Automobiles," NYU, June 16, 1991.
[39]"Shredding with a Newell Super Heavy Duty Shredder," marketing book of Newell Industries, Inc., April, 1990.
[40]For details, refer to Chapter 3.

2.4.3 A Summary of Recycling Activities

Along an automobile's life cycle, the process of automotive materials is viewed not only as the flow of materials, but also as the flow of financial assets from one stage to another. As described before, the current recycling industry is driven primarily by economic opportunity, rather than by environmental concerns or regulatory imperatives. Therefore, an integrative understanding of both material flow and monetary flow through the life cycle of automobiles is of crucial importance in order to address the current recycling problem.

Figure 2.10 illustrates both the material flow system and market mechanism of the existing recycling infrastructure[41]. The automotive material flows from the material supplier, through the manufacturer, the user, the dismantler, and the shredder and finally reaches its environmental fate: the landfill. The transfer of material from one stage to another is accompanied by a reciprocal flow of financial assets, and the transfer of waste requires a parallel flow of cash[42]. As a consequence, an effective recycling practice should address not only how to recycle certain amount of materials from the automotive material stream, but also how to provide the economic incentive for the recycling industry.

The recycling of automobiles is related to every sector of the automotive industry. A life-cycle framework serves as a basic tool in order to identify the problems in each sector, to understand the interactions among these problems, and to propose effective policies for dealing with these problems. Based on the

[41]Refer to F.R. Field, III, and J.P. Clark, "Automobile Recycling: Environmental Policymaking in a Constrained Marketplace," February, 1994.
[42]There are two assumptions for Figure 2.11: (1) close-loop recycling, (2) non-ferrous metals are recovered by shredders.

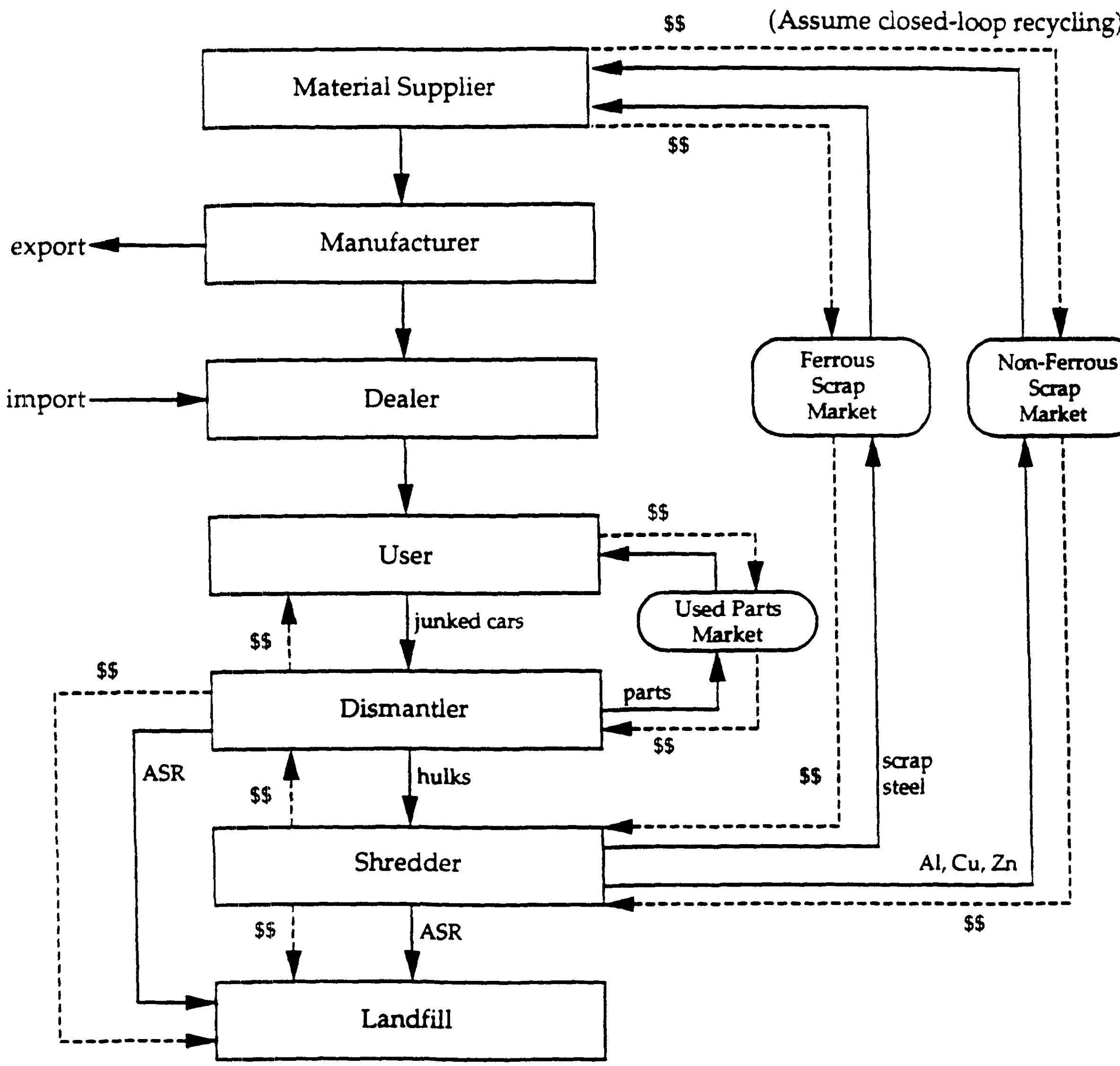

Figure 2.10: Material & Financial Flow Diagram for Automobile Recycling

life-cycle framework developed in this chapter, the following chapters will examine current challenges faced by the industry and analyze different policies for resolving the automobile recycling problem.

Chapter 3

Current Recycling Challenges for the Automobile Industry

3.1 Overview

The objective of this chapter is to examine current recycling challenges faced by the U.S. automobile industry. Derived from environmental concerns, the automobile recycling problem is also subject to regulatory, technological, and economic constraints. The following sections will inspect the environmental necessity, technological trends, and economic feasibility of automobile recycling in the United States.

3.2 Recycling: An Environmental Necessity

One of the primary reasons for most recycling practices is environmental concerns. In the past few decades, there has been a significant shift of the society's environmental attention from the traditional end-of-pipe control to so-called sustainable development. Under this new context, recycling has been playing a more and more important role in the national environmental agenda of the United States.

3.2.1 Toward a Sustainable Environment

During the last two decades there has been a growing concern that the consumption of manufactured products places a great demand on natural resources and has a considerable impact on the environment. In response to this concern, the context for environmental management has progressed from the traditional problem-solving and compliance approach, to the emissions and source reduction practices, and finally toward the subject of sustainable development[43]. Since the Earth Summit in Rio de Janeiro in 1992, sustainable development, which refers to an ultimate goal that economic progress be in harmony with environmental protection, has been exclaimed as a primary goal for both public and private sectors in dealing with their development issues[44].

Modern industrial economics was founded on the use of vast quantities of materials and energy, and the economic health of nations has often been equated to the amount they consumed. However, the increasing extraction of raw materials, the extensive use of energy, and the massive disposal of wastes have forced us to extend our attention from the consumption stage to the whole life cycle of a product[45]. Generally speaking, a successful environmental strategy to

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[43]A.J. Hoffman and J.R. Ehrenfeld, "Becoming a Green Company: The Importance of Culture in the Greening Process," in the Greening of Industry Conference: Designing the Sustainable Enterprise, November 14-16, 1993.
[44]J.L. Greeno, G.S. Hedstrom, and W.E. Wescott II, "The Message from Rio," Arthur D. Little Inc., Prism, 3rd Quarter, 1992.
[45]J.E. Young, "Discarding the Throwaway Society," Worldwatch Paper 101, January 1991.

achieve sustainability should deal effectively with the dynamic relationship of raw material depletion, energy usage, and waste management along a product's life cycle.

Recycling, which is defined as the recovery and conversion of waste materials into new products, has been recognized as one of the most effective methods of sustainable waste management[46]. Recycling addresses not only the need for waste reduction, but also the problem of material and energy conservation, and thus provides a practical measure for achieving sustainability. As a result, today recycling has become an environmental necessity in most of the countries of the world.

3.2.2 Material Recycling: The Virtue of Necessity

Considered one of the most powerful tools for resolving the problem of modern material consumption, recycling has several prominent advantages. First, recycling reduces the extraction of raw materials. One unit of material recovery represents one unit fewer of raw material depletion. The over-extraction of virgin materials over the past few centuries has raised the concern of "limit to growth" all over the world. The result is that the availability of iron, aluminum, and wood, which are always considered among mankind's most important materials for a sustainable future, is full of uncertainties now. By encouraging the reuse of these materials or their products, recycling provides a basic solution for dealing with the "limit to growth" problem resulting from the over extraction of such natural resources.

[46]D. Anderson and L. Burnham, "Toward Sustainable Waste Management," 1991.

Second, recycling saves energy, which is vital to the development of our society. For example, world steel production alone consumes as much energy annually as Saudi Arabia produces. If the worldwide per capita use of metal increases to the level of the United States, the output of seven Saudi Arabias is needed. Recycling, fortunately, can cut the energy required in materials production by 50 to 90 percent[47], and thus help lessen the exhaustive problem of energy consumption.

Third, recycling reduces pollution from mining and producing raw materials. For example, using coke in iron ore reduction produces copious quantities of airborne particulates, including carcinogenic substances such as benzopyrene. Recycling iron and steel reduces these particulate emissions by about 11 kilograms per metric ton of steel produced, and thus abates the air pollution problem associated with steel production[48].

Finally, recycling reduces the final spoil or solid wastes generated from the disposal of consumption goods. The economic burden and political difficulty of expanding city dumps frequently prompt communities to turn to recycling. Solid waste disposal costs represent a major budget item for many cities in the United States, and residents often react strongly in favor of the NIMBY syndrome and against having dumps located near their homes[49]. As a resolution, recycling offers a substantial reduction both in the space needed to dispose of solid wastes, as well as in the cost of waste management.

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[47]W.U. Chandler, "Materials Recycling: The Virtue of Necessity," Worldwatch Paper 56, October, 1983.
[48]R.C. Ziegler, "Environmental Impacts of Virgin and Recycled Steel and Aluminum," 1976.
[49]National Solid Waste Management Association, "Solid Waste Disposal Overview," 1993.

	Paper	Aluminum	Iron & Steel
Energy Use Reduction	30-55	90-95	60-70
Spoil & Solid Waste Reduction	130	100	95
Air Pollution Reduction	95	95	30

Note: (1) Percent reduction in BTUs, tons of waste, tons of particulates, etc., per ton of material produced from waste. (2) More than a 100 percent reduction is possible because 1.3 pounds of waste paper is required to produce one pound of recycled paper.

Table 3.1: U.S. Environmental Benefits of Recycling

Table 3.1 presents an estimation of the environmental benefits from recycling in the United States[50]. For the three vital materials, paper, aluminum, and ferrous metals, recycling achieves substantial reductions in BTUs, tons of particulate, and tons of material produced from wastes. This table summarizes our discussion that recycling is necessary for our society in order to achieve a sustainable development by alleviating exhaustion, saving energy, abating pollution, and reducing waste along a product's life cycle.

3.3 The Dilemma of Automobile Recycling

The processing of scrap automobiles was once considered one of the most profitable and environmentally efficient recycling industries in the United States. The automobile recycling industry has primarily been established to recycle two of the three vital materials, steel and aluminum, for the society. It is generally agreed that the overall aim of automobile recycling is to reduce America's solid and hazardous wastes, to reduce our energy consumption, and to reduce the

[50] W.U. Chandler, "Materials Recycling: The Virtue of Necessity," Worldwatch Paper 56, October, 1983.

long-term demand for virgin materials[51]. However, soaring landfill costs and conflicting environmental goals between fuel economy and recyclability have turned the industry into a future full of technological and economic uncertainties. As a result, recycling has presented the automobile recycling industry with a dilemma associated with environmental concerns, regulatory mandates, technological availability, and economic feasibility.

3.3.1 The Rising ASR Disposal Cost

Recently, automotive shredder residue (ASR) has become a major financial burden to the automobile recycling industry that is responsible for its disposal. The problem of ASR results from both the unavailability of its disposal space and its hazardous content.

While most of ASR is currently landfilled, landfill space in the United States has been less and less available these days. The number of landfill facilities in the United States decreased from 18,000 in 1970 to 9,000 in 1980. According to an estimation by the EPA, half of the nation's 5,400 landfills will be closed by 1995 and that by 2006, only 1,235 landfill facilities will be available[52]. The increasing scarcity of landfill space has therefore escalated the tipping fee of the ASR from about five dollars per ton in 1985 to over one hundred dollars in some areas now.

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[51]General Agreement in the Recycling of Durable Conference, MIT, March 1993. Refer to Lindsay Brook, "Recycling: What's Next," Environment MIT, 1993.

[52]C.N. Cucuras, A.M. Flax, W.D. Graham, and G.N. Hartt, "Recycling of Thermoset Automotive Components," SAE Paper, No.910387.

As mentioned in Chapter 2, ASR is made up of a number of materials including plastics, glass, fluids, dirt and metals. The presence of several unwanted materials, such as waste oils, lead, and PCBs, presents some disposal problems. The EPA and individual states have imposed some special performance and permitting regulations on the disposal of ASR. For example, because of the unacceptable lead levels in the waste, ASR has been regulated as a hazardous waste in California since 1984, which has driven the tipping fees to over $270 per ton[53]. If this practice continues to expand, the more and more stringent regulatory standards on ASR will further increase disposal costs in the near future.

If recyclability is the only goal for the automobile industry, decreasing the amount of ASR generated and increasing the amount of materials recycled from the automotive material streams seem to be the best policies for dealing with soaring landfill costs. Adopting more and more recyclable materials in new vehicles is necessary in order to achieve this goal. Unfortunately, the real development process of automobiles is full of conflicting goals other than recyclability, and the automobile industry has thus been facing a dilemma when choosing automotive materials.

3.3.2 Stricter Fuel Economy and Emission Standards

As Chapter 2 describes, two factors currently governing the U.S. automakers' design and production are regulation and competition. To automobile manufacturers, regulatory mandates, which are strictly upheld by the

[53]Los Angeles Times, July 20, 1987.

government, are of crucial importance, and their primary consideration is focused on the engineering and economics of meeting these regulations[54]. Two major regulations that greatly affect the automobile industry are fuel economy standards and emission limits.

	Chrysler	Ford	GM	CAFE Standard
1978	18.4	18.4	19.0	18.0
1979	20.5	19.2	19.1	19.0
1980	22.3	22.9	22.6	20.0
1981	26.8	24.1	23.8	22.0
1982	27.5	25.0	24.6	24.0
1983	26.9	24.3	24.0	26.0
1984	27.8	25.8	24.9	27.0
1985	27.8	26.6	25.8	27.5
1986	27.8	27.0	26.6	26.0
1987	27.6	26.8	26.4	26.0
1988	28.4	26.4	27.6	26.0
1989	27.7	26.6	26.9	26.5
1990	27.1	26.4	27.1	27.5
1991	27.5	27.7	27.1	27.5
1992	27.8	27.3	26.8	27.5
1993	27.5	28.1	27.4	27.5

Unit: Miles/gallon

Table 3.2: Corporate Fuel Economy Standards & Big Three's Accomplishment

The fuel economy standards, Corporate Average Fuel Economy Standards (CAFE), was introduced soon after the energy crisis in the 1970's. In order to reduce the overall consumption of imported oil, a minimum average fuel efficiency for new automobiles was set, with penalties for failure to meet these goals. The CAFE has been more and more stringent during the last couple of decades, and has thus become the dominant manufacturing issue for the U.S.

[54]Frank R. Field, III, "Materials Technology: Automobile Design and the Environment," Report to the US Office of Technology Assessment, May 1991.

automobile industry. Table 3.2 presents the historical data of CAFE standards and the real fuel efficiency achieved by the Big Three from 1978 to 1993[55].

In addition to fuel economy standards, emission standards have also presented the automobile industry with several challenges. Since the enactment of the Clean Air Act, the U.S. Environmental Protection Agency has established a number of emission limits for mobile air pollution sources. For passenger cars, hydrocarbon, carbon monoxide and nitrogen oxides emissions are of the greatest concern. Figure 3.1-Figure 3.3 present the historical emission limits for hydrocarbon, carbon monoxide and nitrogen oxides emissions. As shown in these figures, the EPA has been tightening these limits since the 1970's[56], mostly because of the serious urban air pollution problem caused by passenger cars.

In response to regulatory challenges resulting from fuel economy standards and emission limits, the automobile manufacturers have been pursuing the ultimate objective of weight reduction in their design and production. Weight reduction has been considered the most effective method for meeting the goals of fuel economy and emission control. A 10% reduction in drag can generally yield a 2% increase in fuel efficiency. An improvement of fuel economy implies that energy is more efficiently extracted from the fuel. If so, a greater fraction of the available fuel is burned (thus reducing hydrocarbon emissions) and a larger fraction of the fuel is completely combusted (thus reducing the amount of carbon monoxide released)[57]. Weight reduction therefore achieves higher fuel efficiency and lower emissions level simultaneously.

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[55]Ward Automotive Yearbook, 1978-1993.
[56]Refer to Clean Air Act, Subchapter II--Emission Standards for Moving Sources.
[57]Frank R. Field, III, "Materials Technology: Automobile Design and the Environment," Report to the US Office of Technology Assessment, May 1991.

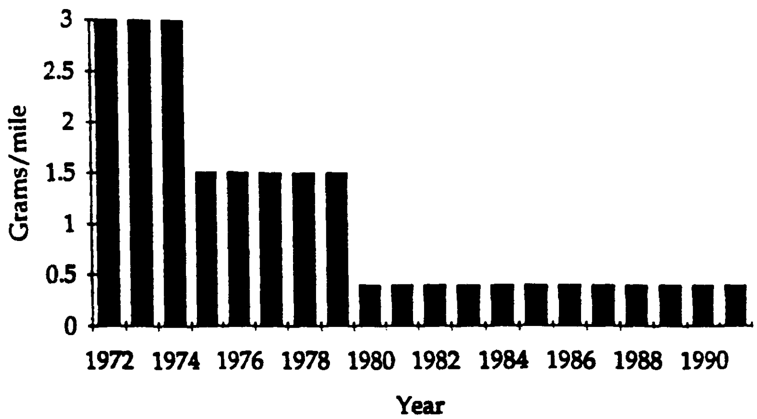

Figure 3.1: Emission Standards for HC, 1972-1991

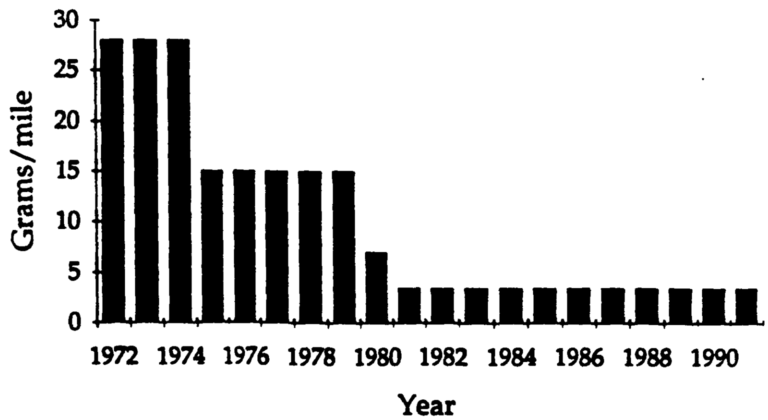

Figure 3.2: Emission Standards for CO, 1972-1991

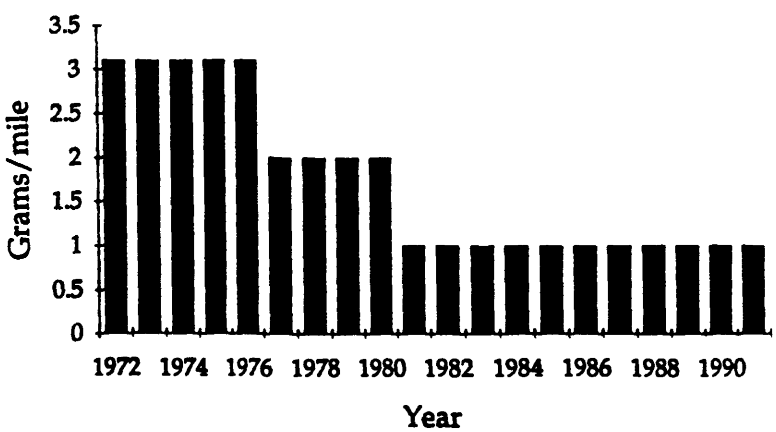

Figure 3.3: Emission Standards for NOx, 1972-1991

In order to achieve the goal of weight reduction, the automobile industry has been applying a two-pronged strategy to the development process of new automobiles: downsizing and advanced material substitution[58]. Downsizing, which refers to the diminishing of the sizes of automotive components such as engine, transmission, fuel tank, chassis, and the whole car body, is usually considered the most effective way of reducing vehicle weight and achieving higher levels of fuel efficiency. However, upon reducing the weight and "squeezing" the size of an automotive component, the specific material performance, such as strength, stiffness, and corrosion resistance, should not be sacrificed. Therefore, it is necessary to substitute the traditional automotive materials with some advanced materials that are on the one hand lighter and on the other hand capable of meeting the same (or even better) mechanical and competitive requirements of automotive parts.

As a result of downsizing and material substitution, both the weight and the traditional ferrous metal content in automobiles have been declining, while the content of non-ferrous metals and polymer composites have been greatly increasing. This material trend has been dominating the development of domestic cars for decades. Table 3.3 and Figure 3.4 present the historical data of the average material compositions in domestic passenger cars from 1975 to 1993. While the average weight has declined from 3,799 pounds to 3,128 pounds. The effects of weight reduction and material substitution are that the ferrous metal content has decreased from 2,889 pounds to 2,138 pounds (from 76% to 68% by weight), and that the material contents of non-ferrous metals and plastics have

[58]F.R. Field, III and J.P. Clark, "Recycling of US Automobile Materials: A Conundrum for Advanced Materials," in the 3rd International ATA Conference, June 1991.

	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984
conventional steel	2125	2075	1995	1880	1846	1737	1602	1479	1511	1488
high-strength steel	100	120	125	127.5	150	175	190	198.5	207	214
stainless steel	28	28	26	25	27	27.5	26.5	28.5	28	29
other steel	56	56	56	56	55	54	50	46	53	45
iron	580	562	540	503	498	484	470	452	474	454.5
aluminum	81	85.5	97	112	119	130	130	135.5	136	137
rubber	149	153	150	141.5	137	131	133	132	137	133.5
plastics/composites	155	162.5	168	176	185	195	198	202.5	200	206.5
glass	86	87.5	86	88	85	83.5	83	86	85	87
copper	33	32	35.5	39.5	28.5	35	27.5	39	39	44
lead	25	25	NA	NA	24	NA	22.5	NA	NA	NA
zinc die casting	50	44	38	28	25	20	17	14.5	17	17
powder matal parts	NA	NA	15.5	16	NA	17	NA	17.5	18	18.5
fluids and lubricants	180	190	200	189	189	178	175.5	179.5	183	180
magnesium castings	NA	NA	NA	NA	NA	1.5	NA	NA	NA	NA
other materials	151	140	133.5	112.5	107	94.5	103	91	103	88
total weight	3799	3761	3666	3494	3476	3363	3228	3102	3191	3142
ferrous metals	2889	2841	2742	2592	2576	2478	2339	2204	2273	2230
non-ferrous metals	189	186.5	186	195.5	196.5	203.5	197	206.5	210	216.5
plastics	155	162.5	168	176	185	195	198	202.5	200	206.5
others	566	570.5	569.5	531	518	487	494.5	488.5	508	488.5
ferrous %	76.0%	75.5%	74.8%	74.2%	74.1%	73.7%	72.4%	71.1%	71.2%	71.0%
non-ferrous %	5.0%	5.0%	5.1%	5.6%	5.7%	6.1%	6.1%	6.7%	6.6%	6.9%
plastics %	4.1%	4.3%	4.6%	5.0%	5.3%	5.8%	6.1%	6.5%	6.3%	6.6%
other %	14.9%	15.2%	15.5%	15.2%	14.9%	14.5%	15.3%	15.8%	15.9%	15.5%

Unit: Pounds

Table 3.3: Material Compositions in Domestic Cars, 1975-1984

	1985	1986	1987	1988	1989	1990	1991	1992	1993
conventional steel	1482	1446	1459	1337	1416	1246	1341	1379	1376
high-strength steel	217.5	221	228	227.5	234	233	240.5	247	259
stainless steel	29	30	32	31	31	31.5	37	41.5	43.5
other steel	54.5	47	55.5	46.5	47	53	41.5	42	48
iron	469	446.5	460	426.5	459	398	431	429.5	411.5
aluminum	138	141.5	146	150	155.5	158.5	166	173.5	177
rubber	135	131.5	135	130	134.5	128	135	133	134.5
plastics/composites	211.5	216	221.5	219.5	224.5	222	236	245	243
glass	85	86.5	86	86	85	82.5	86	88	88.5
copper	44	43	46	49.5	49.5	46	45	45	43.5
lead	NA	NA	NA	NA	NA	NA	NA	NA	NA
zinc die casting	18	17	18	19.5	20	19	17.5	16	16
powder matal parts	19	20	19.5	21.5	21.5	23	23.5	25	26
fluids and lubricants	184	182.5	183	176.5	179.5	167	174	177	188.5
magnesium castings	2.5	NA	NA	NA	NA	NA	5	6.5	6.5
other materials	99	89.5	88	89	83	88	70.5	89.5	86
total weight	3188	3118	3178	3010	3140	2896	3050	3138	3148
ferrous metals	2252	2191	2235	2069	2187	1962	2091	2139	2138
non-ferrous metals	221.5	221.5	229.5	240.5	246.5	247	257	266	269
plastics	211.5	216	221.5	219.5	224.5	222	236	245	243
others	503	490	492	481.5	482	465.5	465.5	487.5	497.5
ferrous %	70.6%	70.3%	70.3%	68.7%	69.6%	67.7%	68.6%	68.2%	67.9%
non-ferrous %	6.9%	7.1%	7.2%	8.0%	7.9%	8.5%	8.4%	8.5%	8.5%
plastics %	6.6%	6.9%	7.0%	7.3%	7.1%	7.7%	7.7%	7.8%	7.7%
other %	15.8%	15.7%	15.5%	16.0%	15.4%	16.1%	15.3%	15.5%	15.8%

Unit: Pounds

Table 3.3 (continue): Material Compositions in Domestic Cars, 1985-1993

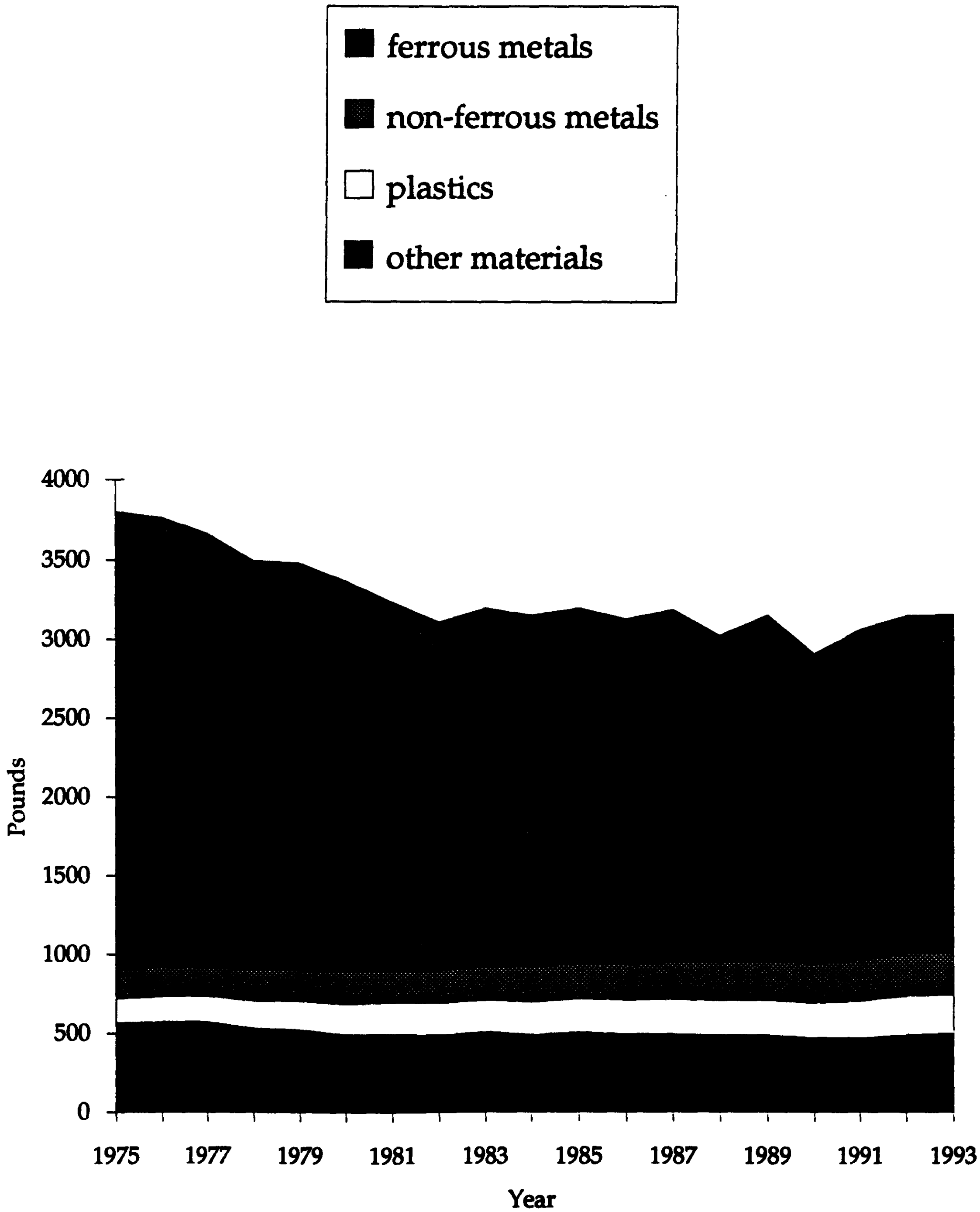

Figure 3.4: Material Compositions in Domestic Passenger Cars

increased from 189 pounds to 269 pounds and from 155 pounds to 243 pounds respectively[59].

It is of interest whether the material trends of weight reduction and material substitution will continue in the future. According to a recent survey result in the Delphi Forecast and Analysis of the U.S. Automotive Industry, over 88% of the panelists predicted that the CAFE standards would be more restrictive, and over 65% of the panelists predicted that the emission standards would be more restricted. Coincident with the above foreboding is Senate Bill 279, proposed by Senator Richard Bryan (D) and 34 other sponsors from both parties, requiring that every automaker selling to the U.S. market achieve a 20% increase in fuel economy by 1996, and a 40% increase by 2001 measured from the actual fuel economy achieved by each company in 1988[60]. Experts estimate that about 40% of weight reduction and 25% of downsizing will be needed in order to achieve this proposed fuel efficiency[61], and more and more non-ferrous metals and plastics will thus be adopted in new cars. It is very likely that the fuel economy standards and the emission standards will keep challenging the engineering and technological capability of the U.S. automobile industry in the future.

3.3.3 Conflicting Environmental Goals

As described in Chapter 2, the current U.S. automobile recycling industry is running under a market system. That is, the market opportunity is the main

[59]Ward's Automotive Yearbook (Material Composition Chart), 1975-1993.
[60]Maryann N. Keller, "Does It Take a War to Stop Waste?" 1991.
[61]Delphi IV Forecast and Analysis of the U.S. Automotive Industry, University of Michigan, 1992, v.2.

driving force for the industry to recycle useful parts and materials from the automotive material stream. The automobile dismantler removes useful parts from junked cars, and the automobile shredder recovers about 96% of ferrous metals and up to 60% of non-ferrous metals by mass from the automotive material stream. This recycling system has been working well for decades in the United States.

However, the environmental goal of automobile recycling and the current automotive material trends present the industry with a dilemma. On the one hand, greater environmental awareness and soaring landfill costs require the industry to recycle more from the material stream. On the other hand, the fuel economy standards and emission standards force the automaker to apply more and more advanced materials such as plastics and ceramics, which are considered not recyclable by the recycling industry. These conflicting environmental goals will continue to challenge the industry as landfill costs keep increasing and as the fuel economy standards become more stringent in the near future.

Additionally, downsizing and advanced material substitution have another negative effect on automobile recycling. Automotive parts made of advanced materials like polymer composites should generally go through a series of complicated and sophisticated fabrication processes, especially when automakers try to "squeeze" the size of these parts for the purpose of downsizing. The result is that the mechanical and material structures of modern automobiles have become more and more complex, and the automobile dismantler must therefore spend more time to salvage useful parts from the car body. More salvaging time means higher processing costs for dismantlers, and their recycling incentive is thus greatly affected. For example, most dismantlers are unwilling to recycle windshields, which are actually plastic/glass laminates, and rear windows, which often have embedded defogger wiring, because of the difficulty of identification, sorting and removing[62].

In short, the environmental goals of fuel economy and emission control, which lead to a substitution of advanced materials for traditional ferrous materials and to increasing complexity of automobile structure, have been in great conflict with the environmental goal of recycling, which requires more materials recovered and less ASR generated. As the polymeric fraction of the automobile keeps increasing because of the restrictive fuel economy standards, the economics of automobile recycling will eventually become unattractive if there is no breakthrough in the current recycling technology. It is possible that automobiles with high fluff content ultimately will not enter the recycling stream at all, since the value that the dismantler receives from the hulk and the value that the shredder receives from the materials cannot support the costs of processing the non-recyclable fraction[63]. This result is likely to cause the breakdown of the current market system, as well as the existing recycling infrastructure, and all the environmental virtues of automobile recycling would finally end up with nothing at all.

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[62] Ward's Automobile Yearbook, 1992.
[63] Frank R. Field, III, "Materials Technology: Automobile Design and the Environment," Report to the US Office of Technology Assessment, May 1991.

3.3.4 Technological and Economic Constraints

In order to overcome the dilemma of automobile recycling, many efforts have been focused on new recycling technology options. While there is no lack of technological solutions, such as pyrolysis, hydrolysis and alcoholysis, to the problem, none yet provides the recycling industry with the kind of profit opportunity necessary to implement them[64].

The fact is that recyclability is both a technological and an economic issue. On the technological side, recyclability requires the existence of technologies that can be applied to extract the constituent materials from an obsolete product. On the economic side, recyclability depends upon the existence of a market for the recycled materials. Most importantly, there must be a balance between the cost of employing the extraction technology and the profit from the recycled materials so that the recycling industry has an economic incentive to undertake the recycling. Therefore, the future task for the industry is not only to develop new material extraction and processing technologies, but also to address the complex market dynamics of the existing recycling infrastructure[65]. As a result, automobile recycling is challenging not only the industry's ability to respond to regulatory mandates, but also its capability of technological innovation and market adjustment.

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[64]F.R. Field, III and J.P. Clark, "Recycling of US Automobile Materials: A Conundrum for Advanced Materials," in the 3rd International ATA Conference, June 1991.
[65]F.R. Field, III, and J.P. Clark, "The Recycling of Automobiles: Conflicting Environmental Objectives in a Competitive Marketplace," in the Proceeding of the KIET International Seminar on Korea's Auto Industry, November 25-26, 1993.

3.4 A Summary of the Recycling Challenges

Automobile recycling is also an issue which concerns to the whole life cycle of an automobile. In order to understand the recycling problem in each stage of the life cycle and in order to formulate an effective resolution to deal with this issue, it is necessary to go through the life-cycle framework established in Chapter 2 and to identify the challenge at each stage of an automobile's life cycle.

Figure 3.5 presents a summary of the current challenges for the automobile industry. While environmental concerns require that the automobile industry recycle more from the material stream and extract less from the natural environment, the real automotive material trend is heading for the opposite direction. At the manufacturing stage, automakers are constrained by fuel economy and emission standards, and they respond to the regulatory mandates with the ultimate goal of weight reduction. Material substitution and increasing product complexity are two major strategies for achieving weight reduction. As a consequence, the new automobile transported to the dealer and user has less and less ferrous content, and its mechanical and material structures are more and more complicated. The complexity of the modern automobile makes the dismantling process more and more difficult, and the less ferrous content makes the shredding process less and less profitable. The result is that less and less automobile material is recycled, and that more and more ASR is generated. Unfortunately, the disposal cost for ASR is soaring, and the recycling industry is forced to innovate new extraction technologies to recover plastics from ASR. However, even though the new technologies are available, the following question remains: "who is going to buy the recycled plastics back." Finally, the extreme consequence is that if the industry fails to deal with the automobile

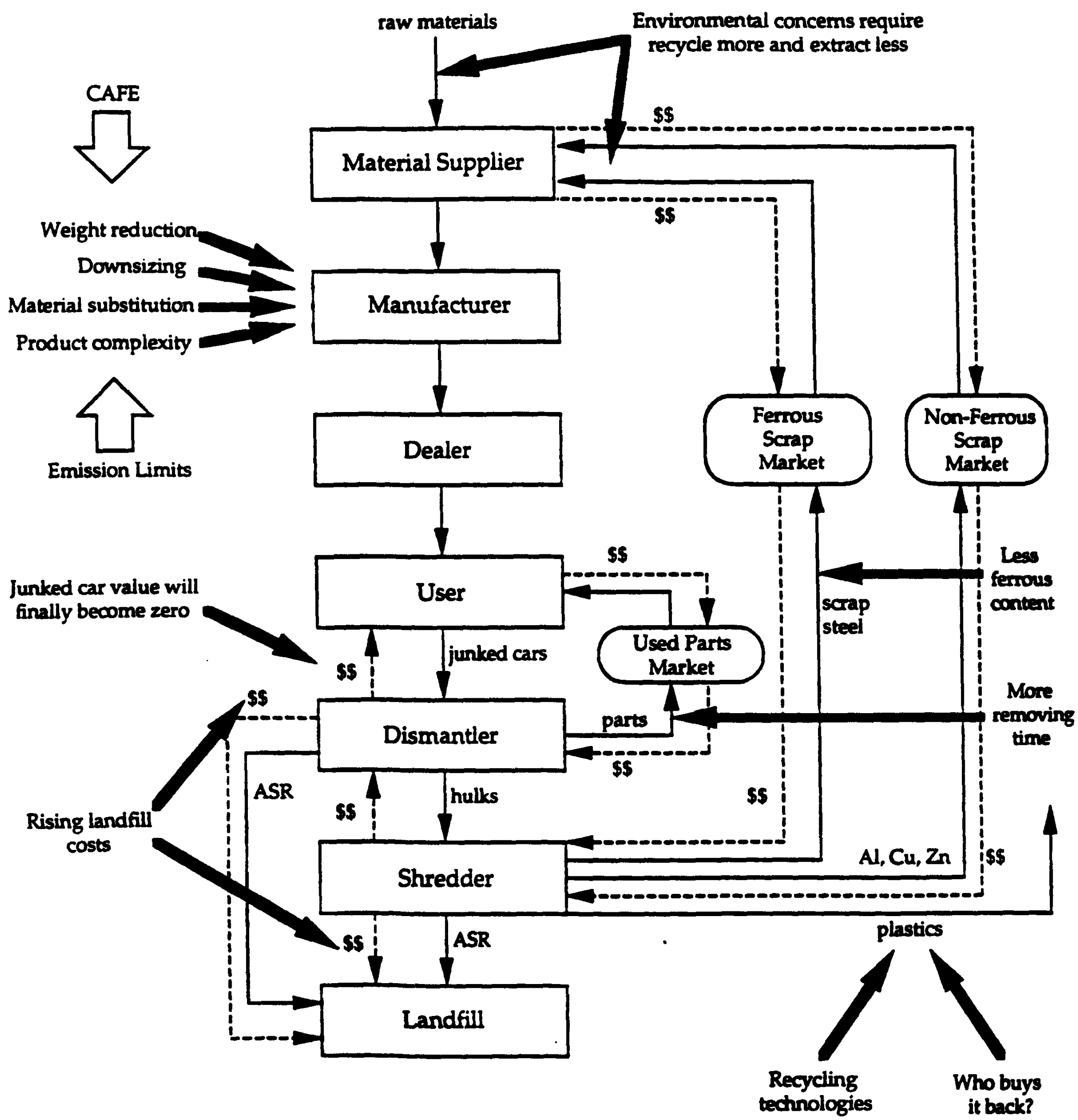

Figure 3.5: Summary of Recycling Challenges along Automobile's Life Cycle

recycling problem, future automobiles, which contain large portions of non-recyclable materials, will not enter the recycling stream at all because the profitability for the recycling industry is not enough to support the cost of disposing of the non-recycled fraction. The existing market system of automobile recycling would thus be strongly challenged.

Can the automobile industry survive the current challenges? Can the existing market system deal effectively with the automobile recycling problem? What kind of policies and in which stage of the life cycle are they needed in order to resolve this problem? These are the questions that the following chapters are going to answer.

Chapter 4

Resolutions for the Automobile Recycling Problem

4.1 Overview

Engineers and policy makers in the United State have responded to the automobile recycling problem with a variety of resolutions. As described in Chapter 3, the U.S. automobile recycling problem derives from environmental concerns, and is subject to regulatory, economic and technological constraints. Therefore, resolutions for the problem can generally be categorized into three groups: technological resolutions, economic resolutions, and legislative resolutions. In addition to domestic efforts, recent European recycling imperatives also have potential impacts on the projective policy options for automobile recycling. The following sections will examine the effectiveness of these domestic and foreign resolutions.

4.2 Technological Resolution

Technology plays a key role in solving the automobile recycling problem. Since the development of shredding and steelmaking technologies in the 1970's had successfully resolved the automobile recycling problem at that time, many people today have the same expectation for technological resolutions to solve the contemporary recycling problem. In response to the increasing non-recyclable content, especially plastics, in the automotive material stream, a broad range of technologies have been developed by the automobile industry. These technologies generally fall into three categories: (1) plastic recycling technologies, (2) ASR disposal options, and (3) designing and manufacturing for recycling.

4.2.1 Plastics Recycling Technology

The concept of recovering plastics from the material stream is appealing since the plastics content in automotive materials is expected to increase significantly plus the markets for plastic packaging and other recycled plastic products already exist. In fact, the major plastics suppliers, including duPont, Union Carbide, and Dow Chemical, have already participated in a variety of joint ventures to develop technologies for separating and processing plastics in the waste stream, most notably polyethylene terepthalate (PET) and high density polyethylene (HDPE)[66].

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[66]F.R. Field, III and J.P. Clark, "Recycling of US Automobile Materials: A Conundrum for Advanced Materials," in the 3rd International ATA Conference, June 1991.

Hoechst Celanese Corp., Eastman Chemical, duPont Co. are also working on recycling programs that employ hydrolysis and alcoholysis technologies. In these technologies, super-heated steam or alcohol is used to depolymerize the plastic material into its original state[67]. Additionally, Argonne National Laboratory has developed and is presently testing a process for the recycling the ASR contents. The Argonne process is to selectively extract specific plastics or groups of compatible plastics from ASR using solvents through four major steps: drying, mechanical separation, solvent extraction of the plastics, and regeneration of the solvents for reuse[68].

Pyrolysis has been receiving significant attention in the last few years. Demonstrated as an effective method for tire recycling, pyrolysis is now applied to the recovery of automotive plastic materials such as nylon, polypropylene, polyurethane foam, paint, paste and many other thermoplastics. The process is to heat plastics in an anaerobic environment until they break down into fuel oil and solid byproducts. Because of the anaerobic environment, once started with an outside fuel source, the process is generally self-sustaining. The energy content of flue gas byproducts may be marketable for home or industrial heating use. The solid byproducts may potentially be reused for making other plastic components[69]. With its technical prospects and market potential, pyrolysis has become one of the most preferable plastics recycling technologies for the industry.

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[67] Ward's Automotive Yearbook, 1992.
[68] Bassam J. Jody, Edward J. Daniels, Patrick V. Bonsignore, and Norman F. Brockmeier, "Recovering Recyclable Materials from Shredder Residue," February 1994.
[69] Irvin E. Poston, "The Future of Molded Composites for Automotive Bodywork," Presented at National Technology Workshop on Polymer Composites, April 1991.

Although a variety of technology options for plastics recycling exists, none of them has been demonstrated to be cost-effective for automotive materials. The primary problem is high processing costs. Many technologies require that plastic materials be identified and separated before further processes, and extra costs for sorting and even hand stripping of junk cars are therefore needed in addition to capital investments. Another problem lies in the non-existence of a secondary market for recycled plastics. It turns out that even though the industry can recycle most of the plastic contents, the current market economics do not support the adoption of these technologies.

4.2.2 ASR Disposal Options

Given soaring landfill costs and premature plastics recycling technologies, the automobile industry has been considering disposal options for ASR other than direct landfills. These waste management options are primarily aimed at changing the basic form of ASR or reducing its overall weight and volume.

Incineration, which refers to the burning of ASR in a conventional incinerator, is one of the most popular substitutes for landfills. This technique is to burn refuse at high temperatures and reduce its volume by as much as 90 percent. One advantage of incineration is that it generates electricity or steam, which can be sold for household or industrial heating use. These energy sales partly offset the capital and operation costs of a modern incinerator. Incineration may turn out to be an economical method for both waste reduction and energy recovery[70].

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[70]National Solid Waste Management Association, "Solid Waste Disposal Overview," 1993.

Although incineration seems like a feasible alternative to landfilling, its application to automotive wastes yields some difficulties. On the one hand, ASR is difficult to burn and, in many cases, incineration does little to reduce either its volume or its chemical potency. On the other hand, incinerating ASR might cause some other problems such as air pollution and hazardous waste. As a result, the ash residue from burning ASR must be buried in specified landfills.

Faced with rising disposal costs and the unavailability of landfill facilities, some automobile shredders are following the method of the nuclear power industry by storing their wastes on private land and waiting for the future development of disposal technology. Although this option merely shifts one cost (landfilling) to another (land), it may turn out to be a practical method prior to the availability of cost-effective recycling or disposal technologies[71].

4.2.3 Design for Recycling

The fundamental solution for automobile recycling is to reduce the amount of ASR generated in the first place by incorporating the concept of recyclability into vehicle design at the manufacturing stage. As described in Chapter 3, the critical issues of automobile recycling are the rising plastic content in the automotive material stream and the increasing complexity of the modern automobile structure. "Designing for recycling" means employing lower amounts of non-recyclable materials and fewer distinct types of individual material species in

[71]F.R. Field, III and J.P. Clark, "Recycling of US Automobile Materials: A Conundrum for Advanced Materials," in the 3rd International ATA Conference, June 1991.

each vehicle and in each component, as well as clearly labeling these components so that recyclers can easily identify and separate them before further processes.

There are a variety of manufacturing options for automakers to improve the recyclability of their products. These options include increasing the use of plastics that are both easy to recycle and that have an established secondary material market such as polypropylene, reducing the number of different resins used in vehicles, introducing stronger and lighter steels from the steel industry, and developing a standard labeling system for plastics so that sorting and recycling are eased. Additionally, during manufacturing processes, two-way snap-fits or snap-fits with break points are employed, and separation points are clearly marked. In order to minimize the number of screws needed, designers generally follow the principle of tight-tolerance and greater precision so that parts can fit together more tightly without fasteners. Furthermore, fewer parts are designed into each component in the first place to minimize the number of diverse pieces that must be removed during recycling processes[72].

Although "design for recycling" seems to be an effective resolution, it still has several limitations. The biggest difficulty is whether or not recyclability is able to gain its strong ground among a variety of conflicting environmental and competitive goals for automobile manufacturers. In addition, because "design for recycling" relates to all sectors along an automobile's life cycle, a joint effort of the whole industry, instead of the automaker's individual commitment, is necessary. Therefore, a coordinating association or even government intervention might be needed. Finally, even though the above problems are overcome, "design-for recycling" initiatives implemented today must take about

[72]Thomas J. David, "Designing for the Environment," Machine Design, 1991.

10 years (a car's service life) to work their way through the life cycle of automobiles and thus impact on recyclability. It turns out that the automobile recycling problem is not likely to be solved directly by a single technological resolution.

4.3 Legislative Resolution

The legislative approach is often considered the most power tool for achieving environmental goals. Fuel economy standards and emission control regulations are two obvious examples. While the European government is currently taking the lead in regulating the automobile industry on recyclability, the proposed recycling mandates in the United States are largely driven by perceptions of the potential impacts of the European efforts[73]. Among all these recycling imperatives, fixed recycling target, deposit system, and extended producer responsibility are of the greatly concern.

4.3.1 Fixed Recycling Target

Recyclability has usually been viewed as the most possible "new area" of legislative activity on the automobile industry[74]. Setting fixed recycling targets for the industry is one of the most straightforward methods for achieving desired recycling objectives. The proposed recycling targets include the fixed fraction of

[73]F.R. Field, III, and J.P. Clark, "The Recycling of Automobiles: Conflicting Environmental Objectives in a Competitive Marketplace," in the Proceeding of the KIET International Seminar on Korea's Auto Industry, November 25-26, 1993.
[74]Delphi IV Forecast and Analysis of the U.S. Automotive Industry, University of Michigan, 1992, v.3, p.16.

plastics recycling and the upper limit of non-recyclable content on percent Gross Vehicle Weight (GVW), which aim at pushing the innovation of recycling technologies, as well as at directing the material selection for the industry.

The National Recycling Markets Act of 1991, also known as the House of Representatives Bill No. HR-2746, has proposed a goal of recycling 30%-40% of plastics in vehicles by 1995. Similarly, the upcoming Congressional consideration of reauthorizing the Resource Conservation and Recovery Act has asked the Office of Technology Assessment to evaluate the current automotive material trends and how they affect recyclability[75]. In addition to regulatory activities at the federal level, individual states have also proposed several mandates on recyclability. The potential legislative areas include the disposal of automotive fluids and the requirement of identification and coding standards for part separation. It is likely that regulations will eventually mandate recycling targets not only at particular stages, but also along the entire life cycle of an automobile.

However, directly setting recycling targets might present several difficulties for both the government and the industry. Such fixed targets generally assume that the government can accurately find the "optimal" level of industrial activities that balance the environmental benefits and the market economics of automobile recycling. Unfortunately, given the nature of the current recycling problem, which is associated with a wide range of market and technological uncertainties, the "optimal" level usually ends up with arbitrariness. Germany's recent experience in regulating the recycling of packaging materials shows that failure

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[75]F.R. Field, III and J.P. Clark, "Recycling of US Automobile Materials: A Conundrum for Advanced Materials," in the 3rd International ATA Conference, June 1991.

to find the optimal level can lead to some serious consequences[76]. It turns out that the initiation of any of the above recycling imperatives needs further consideration of the domestic regulatory and competitive environments for the existing recycling industry.

4.3.2 Deposit System

Both Norway and Sweden have conducted deposit systems since the 1970's. The deposit approach, which is based on the polluter pays principle, aims at promoting national automobile recycling by owners of vehicles. When the consumer purchases a new car, the deposit is added to the price of each new vehicle. The deposit fee is used by the government to finance the national collection infrastructure and a system of cash reimbursement for every recycled vehicle. The prepayment from consumers can offset the deficit (if any) from collecting and processing scrap cars with high non-recyclable contents, and the deposit system thus solves the unprofitable problem of scrap car recycling[77].

Perhaps the biggest problem for a deposit system lies in the controversy of "who is the polluter." Automobile recycling, which relates to every stage along a vehicle's life cycle, is not merely the responsibility of consumers. Unilaterally demanding that consumers pay for automobile recycling might cause some strong political resistance. In addition, most European deposit systems require a national vehicle registration and collection program. In the United States,

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[76]Refer to F.R. Field, III, and J.P. Clark, "Automobile Recycling: Environmental Policymaking in a Constrained Marketplace," February, 1994.
[77]For details, refer to J. Thompson, Economic Instruments in Solid Waste Management, "Annex III: The Recovery of Car Hulks in Norway," 1981.

however, vehicle registration is normally handled at state and local levels. As a consequence, introducing a deposit system would bring about a great deal of federal intervention into the existing automobile market, which is very unlikely to happen in the United States.

4.3.3 Extended Producer Responsibility

One of the most controversial recycling practices is Germany's "take-back" legislation. The take-back legislation, also known as extended producer responsibility, requires that producers retain legal or even physical responsibility for their product from cradle to grave. The objective of this legislation is to force producers to incorporate waste management-related concerns into product design and marketing decision-making[78]. According to this new context, automakers are responsible for the processing and disposal of scrap cars along the whole life cycle of vehicles. Therefore, under the coordination of manufacturers, it is likely that the automobile industry will have a systematic approach to resolve the recycling problem.

The German experience of the take-back legislation shows that automakers are responding with several ambitious plans to reorganize and rationalize the existing recycling infrastructure. On the one hand, automakers have been nurturing an "ethic" of recycling within their design engineering departments towards using more green (recyclable) materials, more dismantler-friendly

[78]R.J. Lifset, "Take It Back: Extended Producer Responsibility as a Form of Incentive-based Environmental Policy," in Conference on Economic Incentive for Environmental Management, Air & Waste Management Association and U.S. Environmental Protection Agency, November 1993.

fastener types, and fewer types of plastics[79]. On the other hand, they have been establishing their partnership with suppliers, dismantlers, and shredders. They will not only provide the recycling industry with disassembly manuals, detailing dismantling procedures, and material composition for major components, but also request their suppliers to take back many of these disassembled components for parts or material recovery and disposal[80].

Nevertheless, the European experience with extended producer responsibility shows an unexpected side effect. The above partnership between manufacturers and the recycling industry can be maintained only if the designated dismantling and shredding processes are profitable to the existing recyclers. If not, however, instead of driving automakers to explore new uses for the dismantled components and secondary materials, the take-back legislation might merely drag the manufacturers into the dismantling and shredding business because the existing recyclers would not be willing to conduct these unprofitable recycling processes. In the United States, where the existing recycling infrastructure is already well established and distributed, it is not likely that the automakers could do a better job than the existing dismantlers and shredders. Moreover, the manufacturer's taking over the business of the existing recyclers could even damage or destroy the current recycling infrastructure[81]. As a result, extended producer responsibility may end up with a bold legislation full of risks and uncertainties.

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[79]Presentation of the VW/Audi and BMW representatives in the Recycling of Durable Conference, MIT, March 1993. Refer to Lindsay Brook, "Recycling: What's Next," Environment MIT, 1993.
[80]F.R. Field, III, and J.P. Clark, "The Recycling of Automobiles: Conflicting Environmental Objectives in a Competitive Marketplace," in the Proceeding of the KIET International Seminar on Korea's Auto Industry, November 25-26, 1993.
[81]Opinions of the representatives from Big Three in the Recycling of Durable Conference, MIT, March 1993. Refer to Lindsay Brook, "Recycling: What's Next," Environment MIT, 1993.

4.4 Economic Resolution

The primary impetus for automobile recycling in the United States is market economics. Under the current market system, the incentive for the industry to recycle scrap automobiles comes primarily from economic profitability. Therefore, economic resolutions for the automobile recycling problem are generally aimed at dealing effectively with existing market economics, as well as at providing market incentives for the automobile industry.

4.4.1 Adjustment of Existing Market System

In spite of the recent impacts of European recycling imperatives, many people maintain that the existing U.S. automobile industry can still handle the recycling problem successfully for at least the perceivable future. While the processing of scrap automobiles is still considered one of the most profitable and environmentally efficient recycling industries in the United States, the current recycling challenges may be resolved merely by the adjustment of the existing market system[82].

There are several reason for this optimism. First, American cars traditionally contain more recyclable ferrous metals and less non-recyclable plastics than their European counterparts, and landfill costs in the United States are relatively lower than those in Europe. Therefore, the net material value of U.S. cars is higher than that of European cars. Second, the economics of automobile recycling depend

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[82]For examples, refer to Ben Teplitz, "No plans to recycle plastics," American Metal Market, V.98, No.98, May 1990.

not only on the value of marketable recycled materials, but also on the recycling capacity of the industry and the transfer prices inside it. Although there are fewer and fewer valuable metals in the automotive material stream, the industry can still respond with adjusting transfer prices between different sectors. For example, shredders can pay dismantlers less for hulks as the material value from recyclable metals decreases. In turn, dismantlers can pay last users less for junked cars which have too many non-recyclable contents. As long as the recycling technology can keep the net material value of cars above zero, it will always be profitable for the current recycling industry to continue its business. Finally, European automakers are currently being forced to take the risks implicit in redefining their product strategy and in reorganizing their industrial infrastructure. Until the result of their successes and failures come out, it will be safer for the U.S. automobile industry to adopt a wait-and-adjust policy[83].

Certainly, this wait-and-adjust policy is not without its own risks. It depends heavily on the inter-temporal aggravating effect of the current recycling problem, especially the chronic interaction between rising disposal costs and unfavorable material trends over time. Generally speaking, if the current recycling problem can be solved by technological development before the net material value of scrap cars decreases to zero, "wait and adjust" seems like a prudent policy. If it cannot be solved by technological development, however, we may lose the most precious opportunity to solve the problem in time. Consequently, the wait-and-adjust policy needs a precise prediction of the capability of the recycling industry, as well as the risks associated with the inter-temporal effect of the automobile recycling problem.

[83]Frank R. Field, III, "Materials Technology: Automobile Design and the Environment," Report to the US Office of Technology Assessment, May 1991.

4.4.2 Market Incentive Scheme

As described before, automobile recycling in the United States is primarily driven by economic opportunity, rather than by environmental or technological necessity. Deliberate technological innovations and regulatory requirements might encourage the recycling of some currently non-recyclable materials. However, nothing is truly recyclable if there is no market for the recyclate[84]. Therefore, a new secondary market for potentially recyclable materials, especially plastics, is necessary in order to incorporate new recycling practices into the current market mechanism of automobile recycling.

There are a variety of economic approaches for creating a new secondary market. On the waste end side, ASR can be classified as a hazardous waste just as has happened in California and in Quebec, Canada. Because of the special performance and permitting regulations accompanying hazardous wastes, the disposal costs for ASR would sharply rise, and thus place pressure on the industry to explore new recycling technologies and secondary markets for the originally non-recyclable materials. On the materials supply side, a tax on virgin materials may encourage the use of recyclable materials. If the price discrepancy between raw materials and scrap materials is high enough, automakers will adjust their material usage and adopt more recyclable materials in their design in order to reduce material costs. Moreover, many European recycling imperatives are accompanied by a restriction on the export of scrap iron and other secondary materials[85]. According to market theory, sufficient domestic supply would result

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[84] F.R. Field, III, and J.P. Clark, "Automobile Recycling: Environmental Policymaking in a Constrained Marketplace," February, 1994.
[85] For examples, refer to William U. Chandler, "Materials Recycling: The Virtue of Necessity," Conservation and Recycling, Vol.9 No.1, 1986.

in lower prices for recycled materials, and the financial incentive for the industry to buy secondary materials would thus increase.

The major problem associated with market incentive approaches lies in the difficulty of "designing" a market system. For example, finding the optimal tax level on virgin materials requires accurate information about market demand and supply, which is usually unavailable. Restricting the export of scrap materials might confront some social and political resistance. It turns out that a complete analysis of all the micro- and macro-economic effects is needed in order to conduct a market incentive scheme.

4.5 A Summary of Resolutions

Due to the dynamic features of the automobile recycling problem, we again use the life-cycle framework to identify the relationship between recycling problems and their resolutions along the life-cycle of automobiles. Figure 4.1 and Figure 4.2 summarize our discussions about the challenges and resolutions for automobile recycling.

As described in Chapter 3, the automobile recycling problem take its root from the conflicting goals between environmental concerns of recycling and fuel economy and emission control standards. In order to meet fuel economy and emission control standards, automakers are pursuing the ultimate goal of weight reduction by both advanced material substitution and increasing the complexity of their products. As a result, there is less and less recyclable content in the automotive material stream, and the overall value of junked cars is diminishing

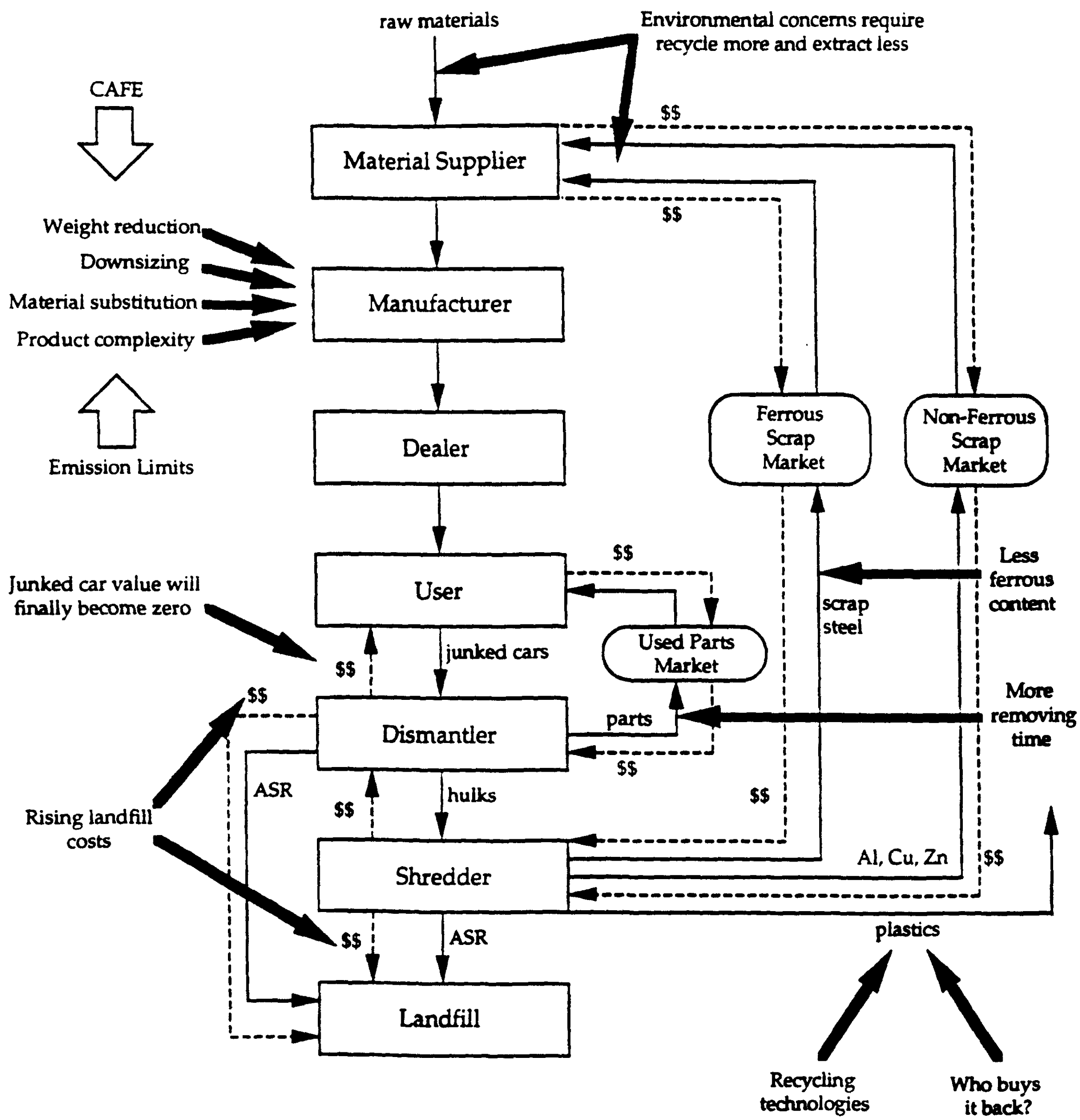

Figure 4.1: Summary of Recycling Challenges along Automobile's Life Cycle

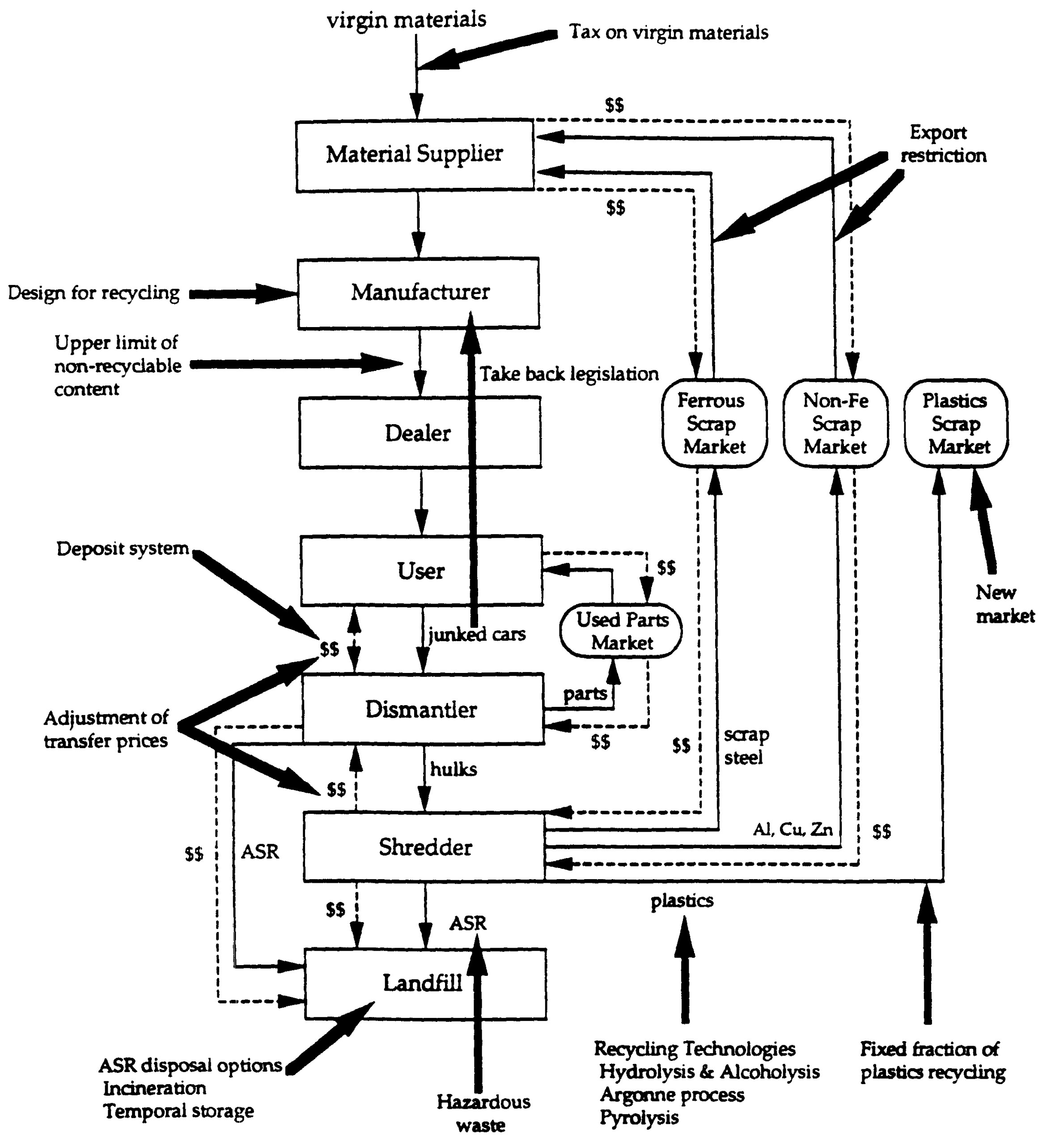

Figure 4.2: Summary of Resolutions along Automobile's Life Cycle

to zero. Additionally, rising landfill costs further aggravate this problem because the industry is forced to bear higher disposal costs for the non-recyclable automotive materials. Furthermore, due to technological and economic constraints, the industry is still struggling for the development of a cost-effective technique in order to recycle plastics from the material stream, as well as to find a secondary market to sell the recyclate.

In response to the challenges above, a variety of technological, legislative, and economic resolutions are proposed by both the public and private sectors. At the manufacturing stage, "design for recycling" is viewed as an effective method for solving the problem by fundamentally changing the automotive material base and manufacturing processes. Setting the upper limit of non-recyclable material content in vehicles is a possible legislative approach for pushing a "design for recycling" practice. A more ambitious take-back legislation, which would require the producers to be responsible for their products along the whole life cycle, is currently conducted in Germany and may possibly be introduced to the United States.

At the transaction stage between users and dismantlers, a new system, the deposit system, is aimed at dealing with the recycling problem of the diminishing value of junked cars. As opposed to the new system, many people maintain that the current market system can take care of the recycling problem by adjusting the transfer prices inside the industry.

At the shredding stage, several plastic recycling technologies, such as pyrolysis, hydrolysis and alcoholysis, are currently developed by the industry. For the purpose of technology forcing, regulatory requirements like fixed fraction of plastics recycling are currently proposed by the government. Economic approaches, such as export restriction and virgin material tax, are also possible in order to develop (or design) a new secondary market for the recycled plastics.

Finally, at the disposal stage (landfill), classifying ASR as a hazardous waste, which will sharply increase ASR disposal costs, is aimed at providing the industry with an overall incentive to recycle more as well as contaminate less. In addition, ASR disposal options such as incineration and temporal storage provide the industry with a variety of alternatives for waste management.

In order to evaluate the effectiveness of different policy options and formulate the best resolution for the automobile recycling problem, a simulation model developed under the concept of life-cycle assessment and system dynamics will be presented in the following chapters.

Chapter 5

A Simulation Model for Automobile Recycling

5.1 Overview

This chapter will present a simulation model in order to evaluate different policy options for automobile recycling. Section 5.2 will first discuss the background and general ideas of the simulation model. Section 5.3 will then describe the material flow system, mathematical structure, as well as basic assumptions of the model. Finally, Section 5.4 will test the model by running a sample case of policy options.

5.2 Model Background

Selecting a simulation model for policy analysis is not only a technique, but also an art. We should consider both the nature of the specific problem and its accompanying policy environment. Most importantly, the selected model should illustrate the process of simulation in a clear and friendly way.

One of the most popular modeling methodologies for simulation is "spreadsheet modeling." Spreadsheet modeling has traditionally had advantages in the sense of reducing the apparent complexity of problems by quantifying complicated processes and calculations into a set of real numbers, which are considered friendly to most decision-makers. However, the primary disadvantage of spreadsheet modeling results from its over-simplification of problems[86]. The real decision environment is always full of dynamic variables and uncertain risks. By simply presenting numbers, spreadsheet modeling fails to analyze the interactions between the inter and outer decision environments, as well as to predict future changes or explore desirable solutions. Additionally, instead of showing the process that a problem or a decision really goes through, spreadsheets can only provide a cell-by-cell peek at a set of abstract formulas. Furthermore, spreadsheet modeling is usually static. Therefore, it is not suitable for evaluating the long-term effects of problems.

The fact is that automobile recycling today has several dynamic features, which can not be easily simulated by spreadsheets. First, it is an interdisciplinary problem which is affected by the interactions among environmental concerns, regulatory mandates, technological innovation, and market economics. Second, it is an inter-temporal problem. People are not only asking "what's the effect of a specific regulatory mandate?" or "what's the influence of a breakthrough in plastics recycling technology?", but also "what would be the overall effect by the year 2005 if we adopt a specific recycling mandate today and achieve a technological breakthrough in the year 2000?" Therefore, a qualified simulation model should be capable not only of generating static outputs but also of

[86]Michael Schrage, "Spreadsheets: Bulking up on Data," Los Angeles Times, 1991.

presenting the effect of chronic interactions among all the dynamic variables. Finally, automobile recycling is an inter-sectoral problem that concerns every sector of the automobile industry. As a consequence, a qualified simulation model should explicitly present the process of material flows along an automobile's whole life cycle.

In order to capture the complex interactions among all the dynamic variables of automobile recycling, as well as describe the automotive material flow system from one stage to another in a friendly way, a computer systems dynamics model is chosen. The power of the systems dynamics model lies in its capability to simulate the problems of resources depletion and recycling, which are usually time-dependent and have complex interactions among several dynamic variables. The systems dynamics model is capable of analyzing the interrelationships among all the inter-temporal "causal factors" for automobile recycling, such as fuel economy and emission control standards, automotive material trends, manufacturing and recycling technologies, economics for the recycling industry, environmental concerns, and landfilling costs. In addition, the "mapping" function of computer systems dynamics provides users with a friendly way of understanding the nature of problems[87]. Furthermore, rather than presenting a set of static numbers, the systems dynamic model processes under a web of "loops," which provides an effective way of incorporating the concept of life-cycle assessment, the major analytic tool for this thesis. In short, the objective of the model is to simulate the dynamics of the automobile recycling system through the integrative approach of Life-Cycle Assessment and Systems Dynamics.

[87]Introduction to System Thinking and ithink, High Performance System Inc., 1992.

5.2.1 Theoretical Concepts

The primary theoretical idea of the simulation model involves the integrative conception of Life-Cycle Analysis and Systems Dynamics. From the viewpoint of life-cycle analysis, an automobile can be viewed as a collection of materials which flow from one stage to another along the vehicle's life cycle. According to the Material Balance Principle, materials are neither created nor destroyed by extraction, production, consumption, and recycling at each stage of the life cycle, but merely change their forms. Life Cycle Analysis thus provides a basic approach for simulating the physical processes and interrelationships along an automobile's life cycle.

Applying Systems dynamics to simulation modeling for automobile recycling entails the so-called "system thinking," which considers the whole automotive material flow system as a closed system. This conceptually closed system serves as a "control volume" within which the Material Balance Principle is observed. Further, the system thinking can be applied to the whole life cycle by conceiving of each stage as a closed "subsystem." The Material Balance Principle is therefore observed not only in every stage along an automobile's life cycle, but also within the whole automotive material system as well. As a consequence, system thinking allows us to trace and then quantify materials used and wastes released through all the production, consumption, and waste-end stages. Additionally, once the materials which flow through each stage are identified, we can simultaneously trace the accompanying economic flows according to the characteristics of each specific recycling process. Integrating Life-Cycle Analysis and Systems Dynamics thus provides us with an effective way to identify all the physical and financial processes in the automotive material flow system.

5.2.2 Modeling Methodology

The simulation model uses the technology of computer systems dynamics (ithink™) to incorporate the theoretical concepts of Systems dynamics and Life-Cycle Analysis. Constructing the computer model involves the following five-step process:

(1) Choose a closed system as the "target system" (control volume) for the simulation model. The target system can be small, such as a city or a state. It can also be large, such as a country or the whole world.
(2) Within the target system, establish a life-cycle framework by tracing material flows at all the significant stages, including manufacturing, consumption, dismantling, shredding, and disposal (as what we have done in Chapter 2).
(3) Identify both the short-term and long-term interrelationships among all the dynamic variables of the problem, such as fuel economy and emission control standards, automotive material trends, manufacturing and recycling technologies, economics for the recycling industry, environmental concerns, and landfilling costs (as what we have done in Chapter 3).
(4) Build "stocks" and "flows," two major software elements, according to the information of material flow systems in (2). Build the model infrastructure according to the life-cycle framework[88].
(5) Build "converters," the elements used to control "stocks" and "flows", according to the information of interrelationships among dynamic variables in (3).

[88]Stocks represent the accumulations of materials, and flows represent the moving of materials; for details, refer to ithink Tutorial and Technical Reference, High Performance Inc., 1992.

Within the context of computer systems dynamics, stocks and flows are used to represent the material flows along the life cycle of automobiles. Converters are used to control and change the quantity of material flows. With stocks, flows, converters, and their interrelationship, the computer systems dynamics model thus simulates both the physical processes and the dynamic features of the automotive material flow system.

5.3 Model Description

The model simulates the material flow system along an automobile's life cycle, including product manufacturing, distribution, and consumption, as well as the waste collection, separation, recovery, and disposal. That is, the model will describe how automobiles are manufactured, exported, imported, sold, and used, as well as how they are junked, dismantled, shredded, and landfilled. At each stage of the life cycle, manufacturing and recycling processes are characterized by a set of computer components, which represent material accumulations or flows. Since the Material Balance Principle is observed at each stage, the overall material flow system should be in balance. The amount of material in each material flow stream at any time can thus be identified and the accompanying financial flow can also be calculated. Figure 5.1 presents an overview the main material flow system of the model[89].

For the purpose of policy analysis in this thesis, we choose the automotive material flow system in the United States as the "target system." The simulation time period is from 1990 to 2018, which is long enough for analyzing both the

[89]For details about the model infrastructure, refer to Appendix 2.

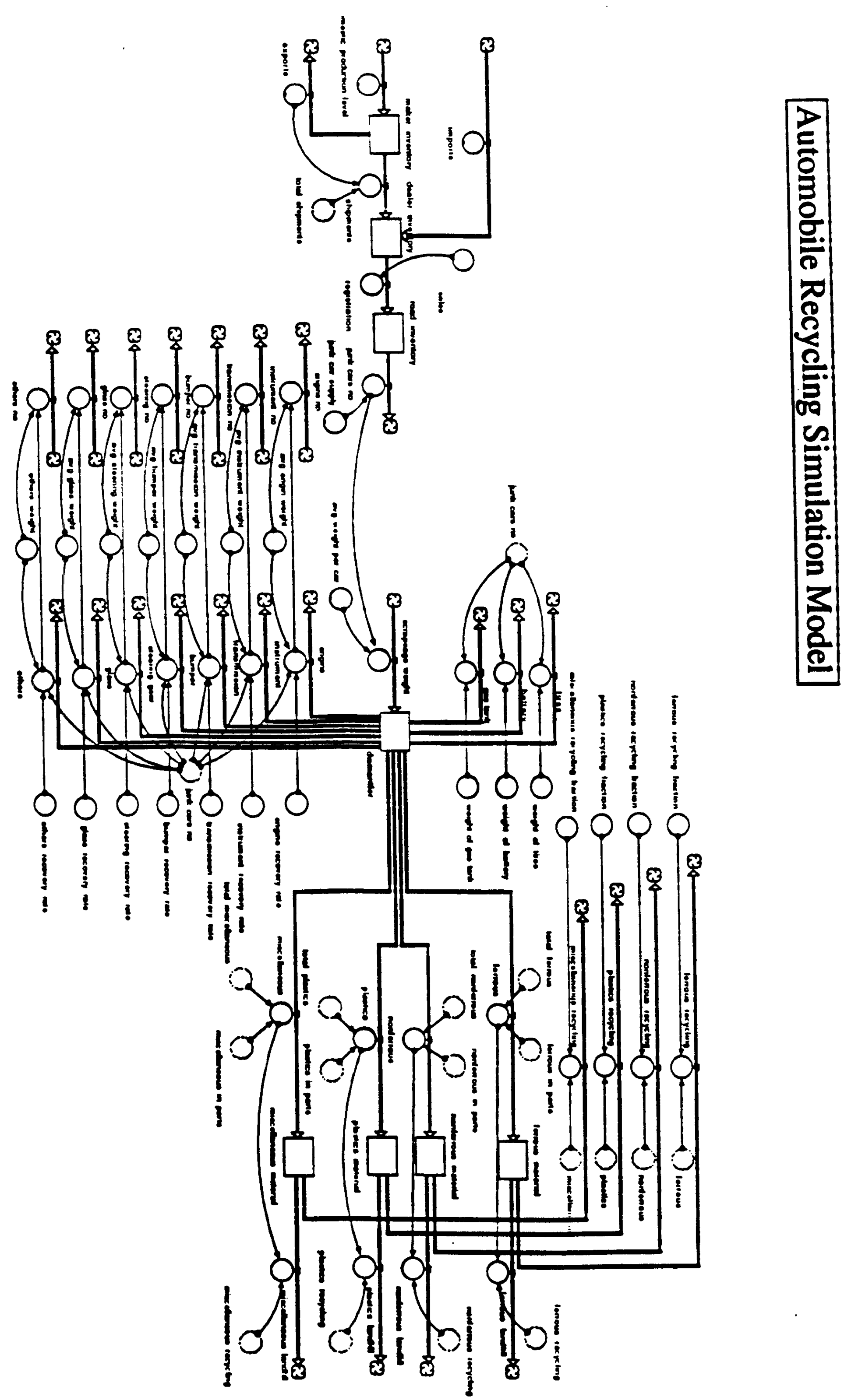

Figure 5.1: Overview of Automotive Material Flow System

short-term and long-term effects within the target system. All the data in this model will be processed over time so that the computer model can demonstrate the inter-temporal dynamic features of the automobile recycling problem.

The main structure of the simulation model can be divided into two parts: front end and rear end. The front end is aimed at simulating the quantity and the material characteristics of automobiles at the manufacturing and consumption stages. The rear end is aimed at simulating the recycling processes and the weight of different material species at the waste end stages. The following sections will describe the main material flow process, the mathematical structure, and the simulation environment within the model's infrastructure.

5.3.1 Front End

The objective of the front end is to simulate the quantity of vehicles at manufacturing and consumption stages. The major material flow streams include production, import, export, shipment, new car registration, and junked car deregistration. All the material streams flow through three major stocks (where materials are accumulated): maker inventory, dealer inventory, and road inventory.

Maker Inventory (MI)

The number of inventory by manufacturers at time t is determined by the previous maker inventory, domestic production level (DP), total shipments from plants (TS), and export level (X). The following equation represents this interrelationship.

$$MI(t) = MI(t-dt) + [DP(t) - TS(t) - X(t)]$$

Dealer Inventory (DI)

The inventory of dealers at time t is determined by the dealer's previous inventory, total shipments (TS), import level (I), and dealer's sales (S). The following equation represents this interrelationship.

$$DI(t) = DI(t-dt) + [TS(t) + I(t) - S(t)]$$

Road Inventory (RI)

The road inventory, or the total number of cars in service, at time t is determined by the previous road inventory, dealer's sales (S), and the supply of junked cars (J). The following equation represents this interrelationship.

$$RI(t) = RI(t-dt) + [S(t) - J(t)]$$

	1990	1995	2000	2005	2010	2015	2018
Domestic Production	6,078	6,750	8,175	9,150	9,825	10,500	10,950
Export	555	975	1,650	2,475	3,225	3,825	4,050
Import	3,014	4,050	4,425	4,725	2,950	5,100	5,250
Dealer's Sales	9,300	9,800	10,400	11,000	11,600	12,200	12,560
Junked Car Supply	8,565	9,310	9,880	10,450	11,020	11,590	11,932

Unit: 1,000 (Passenger Cars)

Table 5.1: Number of Passenger Cars in the United States, 1990-2018

Several assumptions about the quantity of passenger cars have been made in order to set up the simulation environment of the front end. Table 5.1 shows the historical and predicted data of domestic production, import, export, dealer's sale, and junked cars supply. Data from 1990 to 1993 are based on the historical figures[90]. Data after 1994 are based on the prediction in Delphi Forecast and Analysis of the U.S. Automotive Industry[91], and the same five-year trend is assumed to continue till 2018.

5.3.2 Transaction Stage

At the transaction stage between the front end and rear end, the simulation unit is transferred from "the number of cars" (J) to "the total weight of automotive wastes" (TW). In order to analyze the material flows of different material species, the total weight of automotive wastes is further categorized into four groups: ferrous metals (W_f), non-ferrous metals (W_n), plastics (W_p), and miscellaneous materials (W_m).

Different vehicles have different life spans. For example, among all the junked cars of 1990, some vehicles are 1975 models, some are 1980 models, and some are 1985 models. Therefore, the characteristics of the total junked car population depend not only on the total number of junked cars (J), but also on the percentage of a specific model year's vehicles (P^Y, in model year Y) in the overall junked car population.

[90] Ward's Automotive Yearbook, 1990-1993.

[91] Delphi IV Forecast and Analysis of the U.S. Automotive Industry, University of Michigan, 1992, v.1, p.49.

Average Weight

The average weight of junked cars (AW) is determined by the vehicle weight in a specific model year Y (W^Y) and the percentage of this model year's vehicles in the junked car population (P^Y).

$$AW(t) = \sum_Y \left[P^Y(t) \times W^Y(t)\right]$$

Average Material Composition

In turn, the average material composition in vehicle (AC_i) of a specific material species (i) is determined by the material composition in model year Y (C_i^Y) and the percentage of this model year's vehicles in the junked car population (P^Y).

$$AC_i(t) = \sum_Y \left[P^Y(t) \times C_i^Y(t)\right]$$

Total Weight

The total weight of automotive wastes (TW) is the product of the average weight per car (AW) and the supply of junked cars (J).

$$TW(t) = J(t) \times AW(t)$$

The total weight of each material specie in the material stream (W_i) is the product of total weight (TW) and the average percentage of material composition in vehicles for the specific material (AC_i).

$$W_i(t) = TW(t) \times AC_i(t) \qquad where\ i = f,\ n,\ p,\ m$$
$$TW(t) = \sum_i W_i(t)$$

Several assumptions about the characteristics of passenger cars have been made in order to set up the simulation environment of the transaction stage. The first assumption is about the average vehicle weight (W^Y) and the material composition (C_i^Y) in a specific model year Y, which are shown in Table 5.2. Note that data before 1993 are based on historical figures[92]. Data after 1994 (including 1994) are based on the prediction in Delphi Forecast and Analysis of the U.S.

[92]Ward's Automotive Yearbook, 1975-1993.

Automotive Industry[93], and the same five-year trend is assumed to continue until 2018. The second assumption is about the percentage of a specific model year's vehicles in the total junked car population (P^Y), which is shown in Table 5.3. Note that the assumption is based on the historical data in 1990[94], but vehicles that have less than 4-year or more than 15-year life span are neglected because the quantity is quite small.

	Ferrous (%)	Non-ferrous (%)	Plastics (%)	Others (%)	Total Weight (ton)
1975	76.05%	4.97%	4.08%	14.90%	1.725
1976	75.55%	4.96%	4.32%	15.17%	1.707
1977	74.81%	5.07%	4.58%	15.54%	1.664
1978	74.17%	5.60%	5.04%	15.20%	1.586
1979	74.12%	5.65%	5.32%	14.90%	1.578
1980	73.67%	6.05%	5.80%	14.48%	1.527
1981	72.44%	6.10%	6.13%	15.32%	1.466
1982	71.06%	6.60%	6.53%	15.75%	1.480
1983	71.23%	6.58%	6.27%	15.92%	1.449
1984	70.99%	6.89%	6.57%	15.55%	1.426
1985	70.64%	6.95%	6.64%	15.78%	1.447
1986	70.25%	7.10%	6.93%	15.72%	1.416
1987	70.32%	7.22%	6.97%	15.48%	1.443
1988	68.72%	7.99%	7.29%	16.00%	1.367
1989	69.65%	7.85%	7.15%	15.35%	1.426
1990	67.73%	8.53%	7.67%	16.07%	1.315
1991	68.57%	8.43%	7.74%	15.26%	1.385
1992	68.28%	8.48%	7.81%	15.54%	1.424
1993	67.93%	9.18%	7.72%	15.81%	1.429
1995	65.06%	9.90%	9.35%	15.58%	1.311
2000	61.75%	11.12%	12.03%	15.13%	1.245
2005	58.02%	12.27%	14.83%	14.88%	1.175
2010	54.47%	13.42%	14.48%	14.48%	1.105

Note: Weight is in metric ton

Table 5.2: Material Composition (C_i^Y) and Vehicle Weight (W^Y), 1975-2010

[93]Delphi IV Forecast and Analysis of the U.S. Automotive Industry, University of Michigan, 1992, v.3, p.44.
[94]Refer to "U.S. Summary: Cars in Operation by Model Year," Ward's Automotive Yearbook, 1993, p.243.

Life Span (Year)	4	5	6	7	8	9	10	11	12	13	14	15
Percentage (%)	1.2%	2.4%	4.2%	7.1%	10.8%	14.0%	15.2%	14.5%	14.0%	8.8%	5.1%	2.7%

Table 5.3: Life-Span Distribution of Junked Cars

5.3.3 Rear End

The objective of the rear end is to simulate the recycling processes of scrap automobiles. Two kinds of recycling processes are addressed in the model: dismantling and shredding. In general, the effect of the dismantling and shredding processes is comparable to extracting a certain amount (weight) of materials from the material stream. Based on the Material Balance Principle and the economic conditions (cost and revenue) of recyclers, the material flows and the accompanying financial flows at dismantling and shredding stages can therefore be calculated.

Dismantler

Dismantlers remove used parts (D^j) from junked cars. Here, we should make distinction between so-called "primary removing" and "secondary removing." The secondary removing refers to the operation of taking off the "good" parts from the car, including engine blocks (D^1), transmissions (D^2), instruments (D^3), bumpers (D^4), steering gear boxes (D^5), glass (D^6), and anything else (D^7) of selling value. If a used part is deemed to have no selling value, however, dismantlers will just leave it in the car body. Therefore, there is a "recovery rate" (R^j) for each type of used part j. The primary removing refers to the operation of taking off the "must-be-removed" parts which will damage the equipment or contaminate the material stream, including batteries (D^8), tires (D^9), catalytic converters (D^{10}), fuel tanks (D^{11}), air bag canisters (D^{12}). All these parts, without exception, mist be removed from the car body (R^j=0, j=8~12).

The effect of the dismantling processes is comparable to removing a certain amount of weight from the automotive material stream. The weight of a specific material species i in the material stream being removed (DW_i) is determined by the number of junked cars (J), the weight of the material i in part j, and the recovery rate (R^j).

$$DW_i(t) = \sum_j \left[J(t) \times R^j(t) \times WD_i^j(t) \right] \quad \textit{where } WD_i^j\textit{: weight of material i in part j}$$

The total weight of material species i in the material stream after dismantling is determined by the weight before dismantling and the weight removed.

$$W_i(t) = W_i(t-dt) - DW_i(t)$$

	Ferrous (%)	N-ferrous (%)	Plastics (%)	Others (%)	Weight (kg)	Rj
Engine	95%	5%	0%	0%	200	0.10
Transmission	70%	30%	0%	0%	70	0.35
Instrument	0%	20%	80%	0%	3	0.10
Bumper	5%	0%	95%	0%	35	0.45
Gear Box	55%	40%	0%	5%	4	0.35
Glass	0%	0%	0%	100%	4	0.30
Others	45%	19%	15%	21%	80	0.10
Battery	0%	65%	30%	5%	13	1.00
Tires	10%	0%	0%	90%	40	1.00
Converter	10%	85%	0%	5%	12	1.00
Fuel Tank	95%	5%	0%	0%	20	1.00
Air Bag Can.	10%	0%	90%	0%	5	1.00

Table 5.4: Material Composition and Recovery Rate of dismantled Part

Several assumptions about the dismantling process have been made in order to set up the simulation environment at this stage. The first assumption is about the material weight and composition in used parts (WD_i^j). The second assumption is about the recovery rates of parts (R^j). Table 5.4 is a summary of all these data[95].

Shredder

Shredders recover valuable materials from the materials stream after dismantling processes. Because of technological constraints, shredders can only recover a specific fraction of each material species. Multiplying material weight (W_i) by recycling fraction (RF_i) will give us the weight of materials recovered by shredders (WR_i). After dismantling and shredding, the remaining materials (WL_i) are landfilled.

$$WR_i(t) = W_i(t) \times RF_i(t) \qquad where\ i = f,\ n,\ p,\ m$$
$$WL_i(t) = W_i(t) \times \left[1 - RF_i(t)\right]$$

Table 5.5 shows the assumption of recovery rates for different materials[96]. Note that plastics and miscellaneous materials are not recycled by shredders under current technologies, and both ferrous and non-ferrous metals are assumed to be recycled by shredders.

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[95]Information from (1) J.W. Sawyer, Jr., Automotive Scrap Recycling Processes, Prices, and Prospects and (2) Joseph Nissenbaum, Nissenbaum's Recycled Auto Parts Co. (Somerville, MA), interview with author.

[96]Information from (1) M. Rousseau and A. Melin, "The Processing of Non-Magnetic Fractions from Shredded Automobile Scrap: A Review," Resources, Conservation and Recycling, 1989, v.2, p.142. and (2) "Shredding with a Newell Super Heavy Duty Shredder," marketing book of Newell Industries, Inc., April, 1990.

	Recovery Rate (%)	Average Price ($/ton)
Ferrous Metals	**96%**	**120**
steel	96%	90-506
iron	96%	60-140
Non-Ferrous Metal	**60%**	**600**
aluminum	53%	330-1211
copper	39%	1541-2220
zinc	98%	44-2510
lead	100%	176-300
platinum group	95%	350-550/troy oz.
other N-Fe	73%	NA
Plastics	0%	0
Miscellaneous	0%	0

Note: $/ton (metric ton)

Table 5.5: Recycled Percentage and Material Price for Shredding

Economics of Recycling Industry

Once the amounts of material flows in the whole recycling system are identified, we can use this information to calculate dismantler's profit (P_d) and shredder's profit (P_s). In general, the profit for the recycling industry depends on the material revenue (MR, from selling used parts or recycled materials), material cost (MC), investment cost (IC), operating cost (OC), and landfilling cost (LC).

$$P_d(t) = MR_d(t) - MC_d(t) - IC_d(t) - OC_d(t) - LC_d(t)$$

$$MR_d(t) = \sum_j \left[J(t) \times R^j(t) \times P^j(t) \right] \qquad where\ p^j\text{: price of part } j$$

$$P_s(t) = MR_s(t) - MC_s(t) - IC_s(t) - OC_s(t) - LC_s(t)$$

$$MR_s(t) = \sum_i \left[WR_i(t) \times P_i(t) \right] \qquad where\ P_i\text{: price of material } i$$

$$LC_s(t) = \sum_i \left[WL_i(t) \times LC_i(t) \right]$$

Several assumptions about the economics for the recycling industry have been made in order to set up the simulation environment of financial flows in the model. Table 5.6 and Table 5.7 present the price list for used parts and the cost summaries for dismantling processes[97]. Table 5.5 and Table 5.8 present the price list for recycled materials and the cost summary for shredding processes[98]. Note that all the monetary values in these tables are in 1990 value so that the inflation factor will not affect the simulation results of this model.

	Recovery Rate (%)	Average Price ($/vehicle)
Engine	10%	250
Instrument	10%	30
Transmission	35%	100
Bumper	45%	100
Steering Gear Box	35%	75
Glass	30%	100
Others	10%	50

Table 5.6: Recovery Rate and Price List for Used Parts

	Cost ($/vehicle)
Junked Cars & Transportation	50
Investment Cost	15
Operating Cost	75
Disposal Cost	6

Table 5.7: Dismantling Cost Summary

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[97]Information from (1) J.R. Dieffenbach and A.E. Mascarin, "Cost Simulation of the Automobile Recycling Infrastructure: The Impact of Plastics Recovery," Society of Automotive Engineers (#930557) and (2) Joseph Nissenbaum, Nissenbaum's Recycled Auto Parts Co. (Somerville, MA), interview with author. Note that the dismantling investment cost is under the following assumptions: (1) Yearly total investment: $31,000/year, and (2) Average monthly throughput: 180 vehicles/month.

[98]Information from (1) J.R. Dieffenbach and A.E. Mascarin, "Cost Simulation of the Automobile Recycling Infrastructure: The Impact of Plastics Recovery," Society of Automotive Engineers (#930557), (2) Helmut Hock and Allen Maten, Jr., "A Preliminary Study of the Recovery and Recycling of Automotive Plastics," Society of Automotive Engineers (#930561), and (3) "Shredding with a Newell Super Heavy Duty Shredder," marketing book of Newell Industries, Inc., April, 1990. Note that the shredding investment cost is based on the following assumptions: (1) Average monthly throughput: 7000 tons/month, (2) Total Investment cost: $2,500,000/project, and (3) Life of project: 7 years.

	Cost ($/ton)
Hulks & Transportation	48
Investment Cost	6
Operating Cost	10
Landfilling Cost	35

Table 5.8: Shredding Cost Summary

Since the real industrial processes and market conditions vary from time to time, from region to region, and from business to business, one of the most challenging parts of modeling activities is to establish the simulation environment according to the realistic situation. Although the system dynamic model is capable of analyzing the changing dynamic variables for automobile recycling, a series of "base values" are defined here in order to simplify the model simulation. These "base values," which are derived from the relevant literature and adjusted for the realistic industrial process, are aimed at representing the average values from the overall industrial base. Note that precise values are unrealistic because costs and processes are diverse in practice. However, the system dynamic model does have the powerful function of sensitivity testing and parameterization, which provide us an effective way to deal with uncertainties in model simulation.

5.4 Running the Simulation Model

There are four steps in running the simulation model: (1) choose a simulation scenario from any of the recycling policy options, (2) define and change the values of the dynamic variables according to the conditions of the selected scenario, and (3) run the computer model, and the model will generate the desired outputs automatically.

One of the computer systems dynamics model's powerful characteristics is its ability to conduct sensitivity analysis for different policy options. Choosing simulation scenarios is the groundwork for sensitivity analysis. Different policy options will have different inner and outer environments, different interactions between dynamic variables, and, certainly, different simulation results. Therefore, choosing a simulation scenario not only includes selecting a target system which we aim to analyze, but also concerns connecting the characteristics of the specific policy option with the computer components of the model.

Setting up the simulation environment means defining or assuming the value of each component (or variable) in the model. The primary work is distinguishing among the three basic types of dynamic variables: (1) "input variables," the variables which we will enter into different values to conduct sensitivity analysis, (2) "background variables," the variables which are independent to different model formulation, and (3) "output variables," the variables which we will use to demonstrate the simulation results. Theoretically, every component in the computer simulation model can serve as any of the three types of variables above. Therefore, the work of establishing the simulation environment not only entails defining the fixed or changing values of model component according to the conditions of the selected scenario, but also an appropriate selection of different types of variables. In general, too many "background variables" can reduce the complexity of the specific problem, but they can also lead to unrealistic results. Too many "input variables" can simulate the dynamic situations of the problem, but may also blur the sensitivity effect of the specific variable that we aim to observe. It turns out that setting up the simulation environment requires a set of well-balanced definitions among all the dynamic variables in the model.

After the scenarios for model simulation are chosen, and the simulation environment is well established, we are ready to run the computer simulation model. The next chapter will present the model's overall simulation process and results, as well as its application to the analysis of different policy options for automobile recycling.

Chapter 6

Model Simulation For Policy Analysis

6.1 Overview

This chapter will employ the system dynamic simulation model to analyze the effects of different policy options for automobile recycling. Section 6.1 will first describe the simulation environment for policy analysis. Section 6.2 will set up the designated conditions for different simulation scenarios. Finally, section 6.3 will present and interpret the results of the model simulation.

6.2 Simulation Environment

The primary work of the model simulation is the sensitivity analysis of different policy options. Sensitivity analysis is the process of investigating the dependence of the simulation results on changes in the way that a problem is formulated[99]. As described in the previous chapter, the groundwork for sensitivity testing is to establish the simulation environment, including choosing

[99]Richard de Neufville, Applied Systems Analysis, Engineering Planning and Technology management (McGraw-Hill, 1990), ch.6.

the target policy scenarios that we aim to analyze and defining a set of dynamic variables according to realistic policy circumstances. The following section will discuss the simulation environment for policy analysis in this chapter.

6.2.1 Selecting Simulation Scenarios

Automobile recycling is a problem which is affected by the interactions among fuel economy standards, environmental concerns, market economics, landfilling costs, and technological development. In practice, we will process all these dynamic factors differently in the following ways.

(1) Fuel economy standards are mostly decided by energy conservation consideration, but not by any recycling schemes. Therefore, the effect of fuel economy standards on the current and future automotive material trends are treated as the "outside force" to the model, which is independent of any of the recycling policy options.

(2) Since recycling technology and automotive waste disposal are two of the most possible areas for future policy action, we choose "plastics recycling technology" and "ASR disposal cost" as two dynamic variables with which to conduct sensitivity analysis for different policy options.

(3) Environmental and economic consequences are two of our major concerns. Therefore, we choose "amounts of landfills" (environmental result) and "profits for the recycling industry" as the target outputs for sensitivity analysis.

6.2.2 Defining Dynamic Variables

As mentioned in the previous chapter, there are three basic types of dynamic variables for the model: (1) "input variables," the variables which we will enter into different values to conduct sensitivity analysis, (2) "background variables," the variables which are independent to different model formulation, and (3) "output variables," the variables which we will use to demonstrate the simulation results. In practice, we run the model by changing the values of "input variables" and controlling the values of "background variables." The model will then process the data automatically and generate the desired outputs. The definitions of these variables for policy analysis are described as follows.

Input Variables:

As mentioned before, the dynamic variables that are chosen to conduct sensitivity analysis are "plastics recycling technology" and "ASR disposal cost." Here we define three technology conditions and two disposal conditions for policy analysis.

(1) Plastics Recycling Technology

-- Condition 1: Base Case--No Plastics Recycling

The base case simulates the current condition that no plastics are recycled by the industry. The values of dynamic variables are the same as those defined in the previous chapter.

Plastics Recycling Fraction (RF_i):	0% (1990-2018)
Plastics Market Price (P_p):	\$0/ton (1990-2018)
Investment Costs (IC_s):	\$6/ton (1990-2018)
Operating Costs (OC_s):	\$10/ton (1990-2018)

-- Condition 2: Fixed Recycling Target--Current Technology

This case simulates the condition that there is a regulatory mandate which requires the shredding industry to recycle 25% of plastics from ASR beginning in 2000. Since no new technology is available, the industry is forced to apply the current technology (pyrolysis) to recycle plastics without a secondary market to sell the recyclate[100].

Plastics Recycling Fraction (RF_i):	0% (1990-1999), 25% (2000~)
Plastics Market Price (P_p):	$0/ton (1990-2018)
Investment Costs (IC_s):	$6/ton (1990-1999), $10/ton (2000~)
Operating Costs (OC_s):	$10/ton (1990-1999), $25/ton (2000~)

-- Condition 3: Fixed Recycling Target: Best Technology

This case simulates the condition that there is a regulatory mandate which requires the industry to recycle 25% of plastics from ASR beginning in 2000. In response to this regulatory change, the industry will achieve a breakthrough in the development of a cost-effective technology to supply the recyclate with higher quality in 2005. A secondary market for recycled plastics will therefore be formed at that time.

Plastics Recycling Fraction (RF_i):	0%/ton (1990-1999), 25% (2000~)
Plastics Market Price (P_p):	$0/ton (1990-2004), $250/ton (2005~)
Investment Costs (IC_s):	$6/ton (1990-1999), $10/ton (2000~)
Operating Costs (OC_s):	$10/ton (1990-1999), $25/ton (2000~)

[100] Assume the market values of the solid by-products (char) and the pyro-oil are zero.

(2) ASR Landfilling Costs

-- Condition 1: Increasing Landfilling Cost

This case simulates the condition that the ASR landfilling cost will steadily rise by \$4/ton each year after 1993 in response to the increasing scarcity of landfilling space.

ASR Landfilling Cost (LC_S): \$35/ton (1990-1993),
Increase by \$4/ton-year (1994~)

-- Condition 2: Hazardous Waste

The case simulates the condition that ASR is classified as hazardous waste after 2000. The ASR landfilling cost will therefore increase sharply at that time.

ASR Landfilling Cost (LC_S): \$35/ton (1990-1999), \$150/ton (2000~)

Background Variables:

The designated values of all dynamic variables, as defined in Chapter 5, will serve as "background variables," except for the elements that are chosen as "input variables." For example, the future automotive material trends, as defined in Table 5.3 (material compositions from 1990-2018), will not change under different simulation scenarios.

Output Variables:

Two kinds of simulation results are of interest: the environmental consequence and the economic impact. In order to observe the environmental consequence under different policy options or recycling schemes, the amounts of ASR landfilled and materials recycled will be plotted as the model outputs. In turn, for the purpose of examining economic impact under different simulation scenarios, the profits for dismantlers and shredders are plotted as the model outputs as well. As a result, the environmental and economic results generated by the computer model will serve as the comparison basis for different policy scenarios.

6.3 Description of Simulation Scenarios

The simulation scenarios are derived from the interactions between the model's two major dynamic variables: the plastics recycling technology and the ASR landfilling cost. Because there are three different conditions for plastics recycling technology and two different conditions for ASR landfilling cost, we have six different combinations of simulation scenarios. Additionally, for the purpose of testing the adjusting ability of the current recycling industry, additional scenarios for simulating the effects of "economic adjustments" of the industry will also be presented in some cases. Table 6.1 is a summary of all these simulation scenarios.

6.4 Model Simulation and Result Interpretation

This section will present and discuss the process of model simulation and the resulting model outputs. For each of the scenarios of policy analysis, the simulation condition will be described, and the environmental and economic consequences will be exhibited. A brief interpretation of the simulation results will be presented to discuss the effects of different policy options as well.

<table>
<tr><th>Plastics Recyciig Technology
ASR Landfill Cost</th><th>Base Case
No Plastics Recycled</th><th>Current Technology
25% Plastics Recycled</th><th>Best Technology
25% Plastics Recycled</th></tr>
<tr><td rowspan="2">Steady Increasing Landfilling Cost</td><td rowspan="2">Scenario 1</td><td>Scenario 2</td><td rowspan="2">Scenario 3</td></tr>
<tr><td>Subscenario 2-1
Market Adjustment
($22 of transfer cost)</td></tr>
<tr><td rowspan="2">Hazardous Waste</td><td>Scenario 4</td><td>Scenario 5</td><td>Scenario 6</td></tr>
<tr><td>Subscenario 4-1
Market Adjustment
($30 of transfer price)</td><td>Subscenario 5-1
Market Adjustment
(no transfer price)</td><td>Subscenario 6-2
Market Adjustment
($40 of transfer price)</td></tr>
</table>

Table 6.1: A Summary of Simulation Scenarios

6.4.1 Scenario 1: Increasing Landfill Cost vs. No Plastics Recycling

This scenario simulates the condition that no plastics are (or will be) recycled by the industry, and that the ASR landfilling cost will increase steadily over time. The results of this simulation scenario will illustrate the effect of interactions between the current plastics recycling practice and the challenge of rising landfilling costs.

Simulation Conditions:

ASR Landfilling Cost (LC_s):	\$35/ton (1990-1993),
	Increase by \$4/ton-year (1994~)
Plastics Recycling Fraction (RF_i):	0% (1990-2018)
Plastics Market Price (P_p):	\$0/ton (1990-2018)
Investment Costs (IC_s):	\$6/ton (1990-2018)
Operating Costs (OC_s):	\$10/ton (1990-2018)

Simulation Results:

Figure 6.1 presents the environmental consequences (amount of landfills) and the economic impacts (profits for dismantlers and shredders) of this scenario. On the environmental side, the total amount of landfills will increase by about 50% (from 1990 to 2018), mostly because the amount of plastics in ASR keep increasing over time. On the economic side, the increasing ASR and its rising landfilling cost will make the shredding process less and less profitable over time and eventually become unprofitable in 2014. The recycling system is likely to break down at that time.

6.4.2 Scenario 2: Increasing Landfill Cost vs. Current Technology

This scenario simulates the condition that the industry will apply the current technology (as defined in Section 6.1.2) to recycle plastics in 2000 because of the regulatory requirement of the fixed recycling target (25%), and that the ASR landfilling cost will increase steadily over time. The results of this simulation scenario will illustrate the effect of the fixed recycling target policy under the situation that there is no cost-effective technology available for the industry.

Simulation Conditions:

ASR Landfilling Cost (LC_s):	\$35/ton (1990-1993),
	Increase by \$4/ton-year (1993~)
Plastics Recycling Fraction (RF_i):	0% (1990-1999), 25% (2000~)
Plastics Market Price (P_p):	\$0/ton (1990-2018)
Investment Costs (IC_s):	\$6/ton (1990-1999), \$10/ton (2000~)
Operating Costs (OC_s):	\$10/ton (1990-1999), \$25/ton (2000~)

Simulation Results:

Figure 6.2 presents the environmental consequences and the economic impacts of this scenario. On the environmental side, the total amount of landfills will decrease by about 500,000 tons each year after 2000 (compared to Scenario 1). However, this environmental achievement is not without its serious economic consequences. On the economic side, shredders will begin to lose their profitability soon after the recycling scheme becomes effective, and the shredding process will eventually be unprofitable by 2006. It turns out that arbitrarily setting a fixed recycling target without consideration of technological availability is likely to result in the breakdown of the recycling system.

Sub-Scenario 2-1: Adjustment of Market System

As described in Chapter 4, many people believe that the recycling problem can be solved by adjustment of the market economic system. The sub-scenario here simulates the condition that after the effectiveness of the fixed recycling target regulation in 2000, shredders will pay dismantlers less for hulk purchase. In turn, dismantlers will pay the last owners less for their junked cars. The overall effect of the market adjustment is comparable to passing the additional shredding cost of plastics recycling back to consumers. Note that the effect of this sub-scenario is also similar to that of a deposit system because the additional recycling cost is paid by consumers in both cases.

Cost for Hulks (MC_s): $48/ton (1990-1999), $18/ton (2000~)

Cost for Junked Cars (MC_d): $50/car (1990-1999), $20/car (2000~)

Figure 6.3 presents the environmental consequences and the economic impacts of this sub-scenario. The environmental consequence is the same as that of Scenario 2. However, the profits for the recycling industry are very different. The dismantling industry can still maintain its stable profit margin, and the shredding industry is rescued from breaking down because of savings from the material cost of hulks. The result is that the adjustment of the market system is likely to maintain the profitability of the recycling industry. However, we should keep in mind that it is the consumer who pays for the additional cost of plastics recycling.

6.4.3 Scenario 3: Increasing Landfill Cost vs. Best Technology

This scenario simulates the condition that the regulatory mandate of a fixed recycling target requires the industry to recycle 25% of plastics beginning in 2000, and that the ASR landfilling cost will increase steadily over time. In response to the regulatory requirement, the industry will achieve a technological breakthrough (as defined in Section 6.1.2) in plastics recycling in 2005, and find a secondary market to sell the recycled plastics. The result of this scenario will illustrate the effects of technological innovation and the importance of a secondary market for the recyclate.

Simulation Conditions:

ASR Landfilling Cost (LC_s):	\$35/ton (1990-1993),
	Increase by \$4/ton-year (1994~)
Plastics Recycling Fraction (RF_i):	0% (1990-1999), 25% (2000~)
Plastics Market Price (P_p):	\$0/ton (1990-1999), \$250/ton (2000~)
Investment Costs (IC_s):	\$6/ton (1990-1999), \$10/ton (2000~)
Operating Costs (OC_s):	\$10/ton (1990-1999), \$25/ton (2000~)

Simulation Results:

Figure 6.4 presents the environmental consequences and the economic impacts of this scenario. On the environmental side, the total amount of landfills will decrease by about 500,000 tons each year after 2000 (compared to Scenario 1). On the economic side, shredders will regain some profitability in 2005, and the technological breakthrough will give the industry about 7 more years before the shredding process become unprofitable in 2013 (compared to 2006, the result of Scenario 2). It turns out that the technological innovation for plastics recycling can delay the serious effects of the problem and give the industry some precious time for finding other solutions. However, the result of this scenario also illustrates that the automobile recycling problem is not likely to be solved directly by a single technological resolution.

6.4.4 Scenario 4: Hazardous Waste vs. No Plastics Recycling

This scenario simulates the condition that no plastics are (or will be) recycled by the industry, and that the ASR is classified as hazardous waste in 2000, and the ASR landfilling cost will therefore increase sharply at that time. The results of this simulation scenario will illustrate the effect of a "bold" regulation for the ASR disposal on the current recycling industry.

Simulation Conditions:

ASR Landfilling Cost (LC_s):	\$35/ton (1990-1999), \$150/ton (2000~)
Plastics Recycling Fraction (RF_i):	0% (1990-2018)
Plastics Market Price (P_p):	\$0/ton (1990-2018)
Investment Costs (IC_s):	\$6/ton (1990-2018)
Operating Costs (OC_s):	\$10/ton (1990-2018)

Simulation Results:

Figure 6.5 presents the environmental consequences and the economic impacts of this scenario. On the environmental side, the total amount of landfills is the same as that of Scenario 1. On the economic side, the profit for shredding will become zero soon after the effectiveness of the hazardous waste regulation. On the one hand, classifying ASR as hazardous waste is likely to result in the immediate breakdown of the recycling system. This explains why some shredders in California, where ASR is a hazardous waste, try to store the waste or ship it to Mexico to avoid the high landfilling cost[101]. On the other hand, if we try to accomplish "technology forcing" by classifying ASR as hazardous waste, it might provide the industry with a strong incentive for technological development. However, the results of "technology forcing" schemes are always hard to control.

[101]The ASR landfilling cost in California is about \$270/ton, refer to Los Angeles Times, July 20, 1987.

The following sub-scenario will present a possible consequence of the hazardous waste regulation.

<u>Sub-Scenario 4-1: Adjustment of Market System</u>

We will again test the industry's adjustment ability of market system. In this sub-scenario, shredders will pay \$20/ton less to dismantlers for hulks, and dismantlers will pay \$20/vehicle less to last owners for scrap cars after 2000. The result of this sub-scenario will show the industry's capability of market adjustment to deal with the sharply increased landfilling cost.

Cost for Hulks (MC_s):	\$48/ton (1990-1999), \$28/ton (2000~)
Cost for Junked Cars (MC_d):	\$50/car (1990-1999), \$30/car (2000~)

Figure 6.6 presents the environmental consequences and the economic impacts of this sub-scenario. The environmental consequences are the same as those of Scenario 4. The economic result shows that the industry can survive the challenge of sharply increased landfilling cost by adjusting the current market system. The result of this scenario implies that employing recycling schemes for "technology forcing", such as classifying ASR as hazardous waste, would not definitely lead to the desired consequence. In contrast, sometimes the outcome of "technology forcing" would merely turn into the consequence of "market adjustment forcing" within the current market system.

6.4.5 Scenario 5: Hazardous Waste vs. Current Technology

This scenario simulates the condition that the industry will apply the current technology (as defined in Section 6.1.2) to recycle plastics in 2000 because of the regulatory requirement of the fixed recycling target (25%), and that the ASR is classified as a hazardous waste at the same time. The results of this simulation scenario will illustrate the effect of the worst situation for the industry. That is: the overall consequence of the extremely high landfilling cost, the fixed recycling target, and the unavailability of cost-effective technologies.

Simulation Conditions:

ASR Landfilling Cost (LC_s):	\$35/ton (1990-1999), \$150/ton (2000~)
Plastics Recycling Fraction (RF_i):	0% (1990-1999), 25% (2000~)
Plastics Market Price (P_p):	\$0/ton (1990-2018)
Investment Costs (IC_s):	\$6/ton (1990-1999), \$10/ton (2000~)
Operating Costs (OC_s):	\$10/ton (1990-1999), \$25/ton (2000~)

Simulation Results:

Figure 6.7 presents the environmental consequences and the economic impacts of this scenario. On the environmental side, the total amount of landfills is the same as that of Scenario 2. On the economic side, however, the profits for the industry are very different. The shredding process will become absolutely unprofitable after 2000. It is unlikely that shredders would like to stay in the recycling industry and suffer about $200 million in losses each year. The breakdown of the recycling system seems to be inevitable in this case.

Sub-Scenario 5-1: Adjustment of Market System--No Transfer Price

We will again test the industry's adjustment ability of market system. Since Scenario 5 represents the worst situation for the industry, we will also choose the extreme case of market adjustment: no transfer price. Under this circumstance, shredders pay nothing to dismantlers for hulks after 2000. In turn, dismantlers pay nothing to last owners for junked cars (perhaps a last owner will be even required to pay for the transportation fee of his scrap car). The result of this sub-scenario will show whether the recycling industry is capable of dealing with the "worst" situation of technological availability, market economics, and regulatory mandates.

Cost for Hulks (MC_s): $48/ton (1990-1999), $0/ton (2000~)

Cost for Junked Cars (MC_d): $50/car (1990-1999), $0/car (2000~)

Figure 6.8 presents the environmental consequences and the economic impacts of this sub-scenario. The environmental consequences are the same as those of Scenario 5. The economic result shows that the industry can not only survive the "worst" situation in Scenario 5, but also maintain an acceptable profit margin. It turns out that the current market system is capable of dealing with the recycling problem by adjusting the transfer prices along the life-cycle of automobiles.

6.4.6 Scenario 6: Hazardous Waste vs. Best Technology

This scenario simulates the condition that the regulatory mandate of the fixed recycling target requires the industry to recycle 25% of plastics beginning in 2000, and that the ASR is classified as hazardous waste at that time. In response to the regulatory requirement, the industry will achieve a technological breakthrough (as defined in Section 6.1.2) in plastics recycling in 2005, and find a secondary market to sell the recycled plastics. The result of this scenario will illustrate the effect of technological innovation in dealing with the sharply increased landfilling cost and the fixed-target recycling scheme.

Simulation Conditions:

ASR Landfilling Cost (LC_s): $35/ton (1990-1999), $150/ton (2000~)

Plastics Recycling Fraction (RF_i): 0% (1990-1999), 25% (2000~)

Plastics Market Price (P_p): $0/ton (1990-1999), $250/ton (2000~)

Investment Costs (IC_s): $6/ton (1990-1999), $10/ton (2000~)

Operating Costs (OC_s): $10/ton (1990-1999), $25/ton (2000~)

Simulation Results:

Figure 6.9 presents the environmental consequence and the economic impacts of this scenario. On the environmental side, the total amount of landfills is the same as that of Scenario 5. On the economic side, shredders will regain some profitability after 2005. However, regaining profitability is not enough to offset shredders' overall losses. This result implies that even though the industry can accomplish a certain level of technological development under the "technology forcing" scheme of classifying ASR as hazardous waste, the new technology would not be able to support the overall economics of scrap car processing.

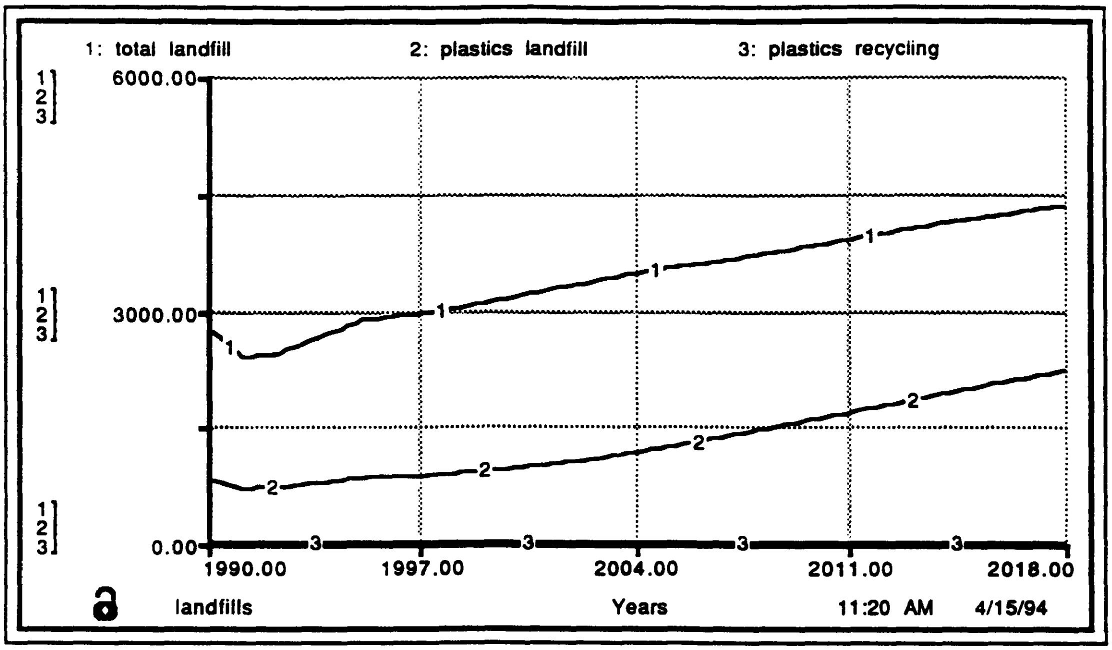
Sub-Scenario 6-1: Adjustment of Market System

We will again test the industry's adjustment ability of market system. In this sub-scenario, shredders will pay $40/ton less to dismantlers for hulks, and dismantlers will pay $40/vehicle less to last owners for scrap cars after 2000. The result of this sub-scenario will show the industry's capability of market adjustment to deal with the increasing landfilling cost and the fixed-target recycling requirement.

Cost for Hulks (MC_s):	$48/ton (1990-1999), $8/ton (2000~)
Cost for Junked Cars (MC_d):	$50/car (1990-1999), $10/car (2000~)

Figure 6.10 presents the environmental consequences and the economic impacts of this sub-scenario. The environmental consequences are the same as those of Scenario 6. The economic result shows that shredders can regain their original profit margin after 2005 by both the technological innovation and market adjustment. The simulation of this sub-scenario illustrates an important fact: by proper market adaptation and technological development, it is possible to recycle more and contaminate less without serious damage to the existing recycling system. As a result, this sub-scenario pictures a desirable prospect for automobile recycling in the future.

I. Environmental Consequence (unit: 1,000 ton)



II. Economic Consequence (unit: $1,000)

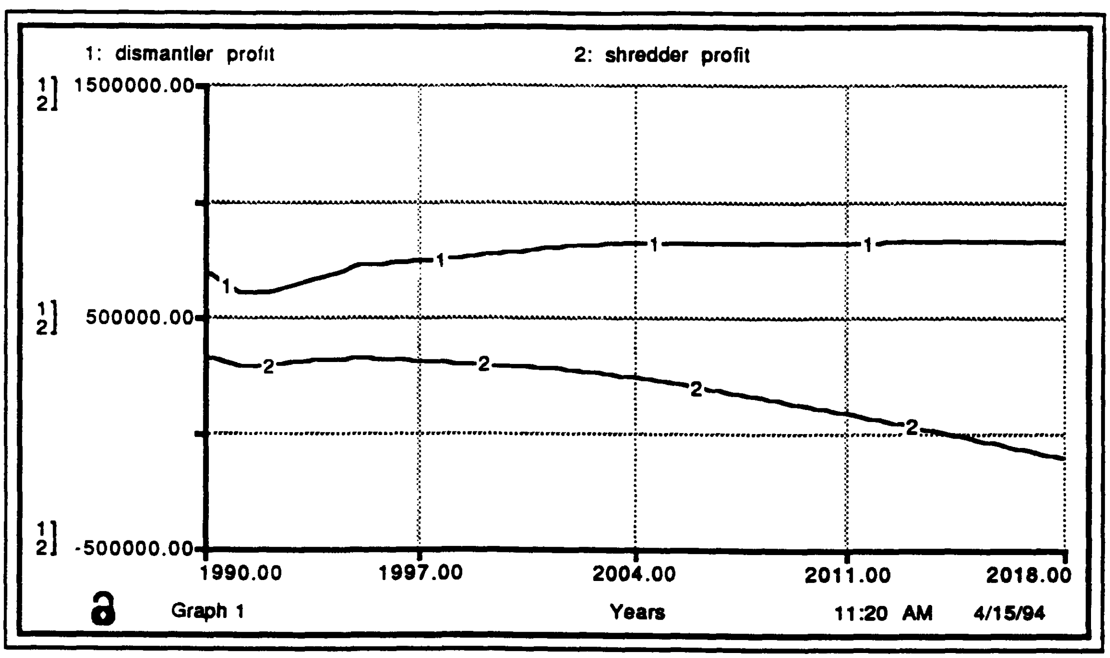
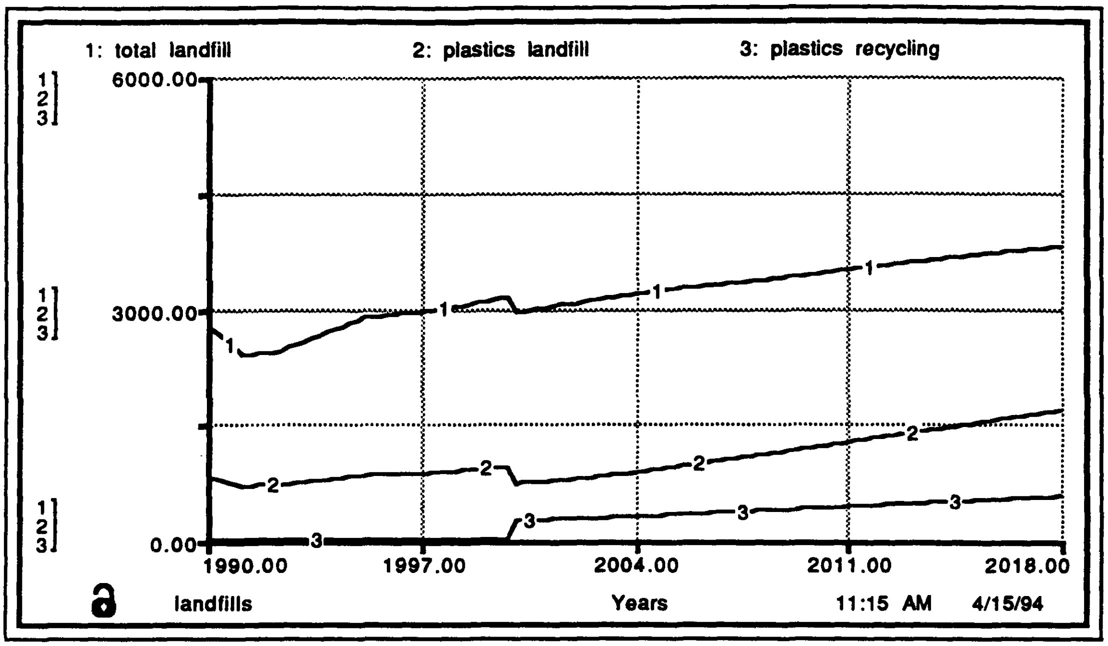


Figure 6.1: Scenario 1–Increasing Landfill Cost vs No Plastics Recycling

I. Environmental Consequence (unit: 1,000 ton)



II. Economic Consequence (unit: $1,000)

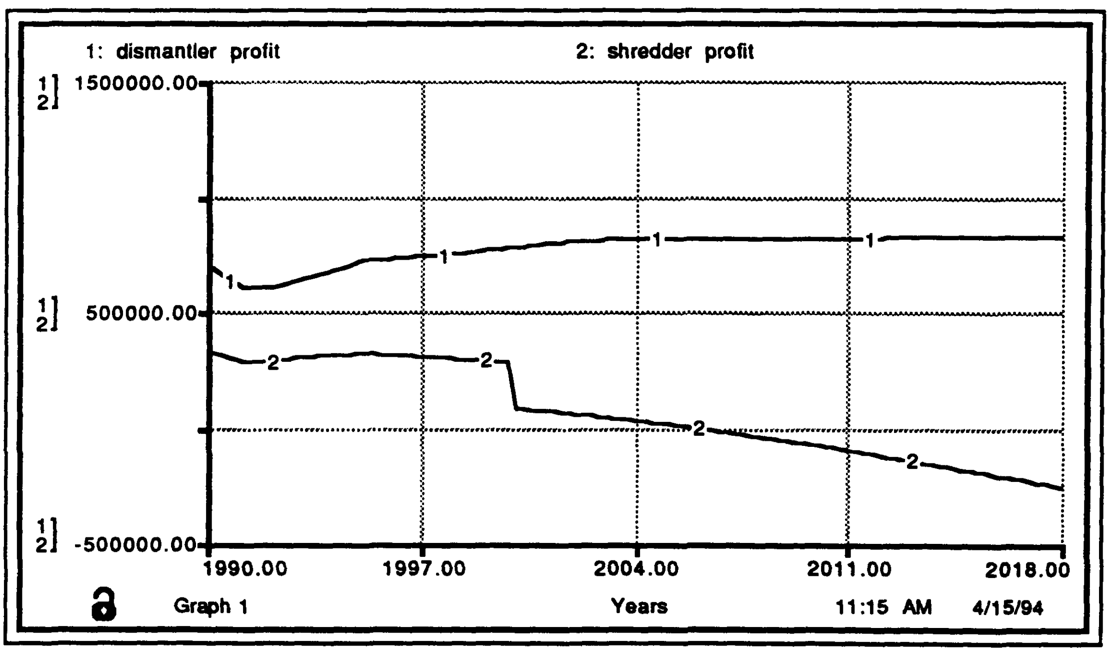
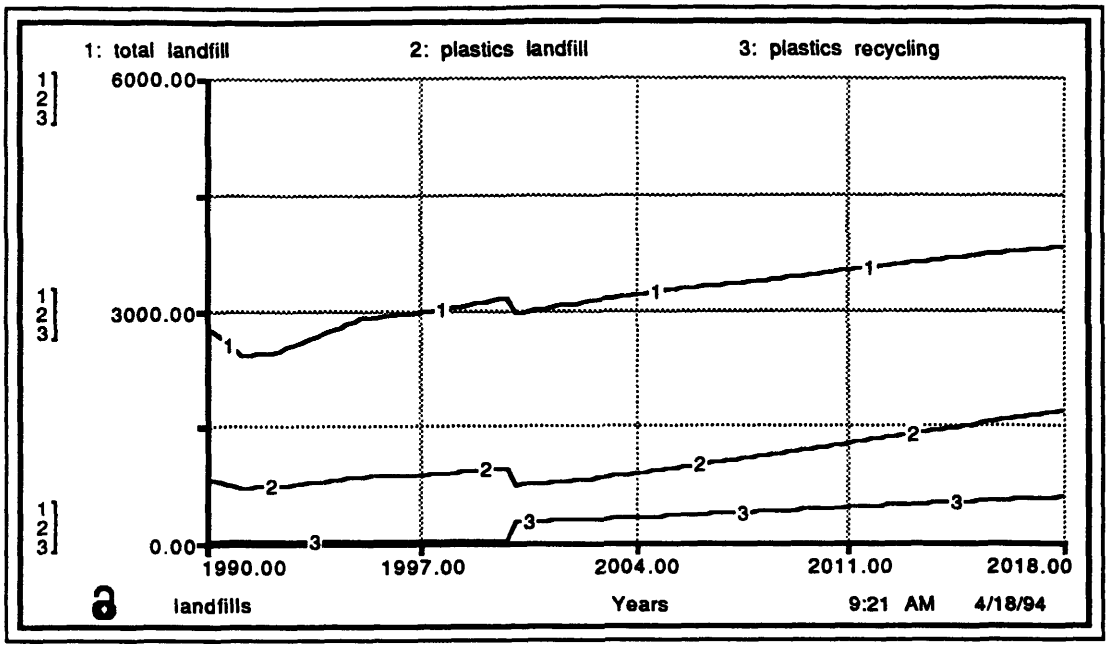


Figure 6.2: Scenario 2--Increasing Landfill Cost vs Current Technology

I. Environmental Consequence (unit: 1,000 ton)



II. Economic Consequence (unit: $1,000)

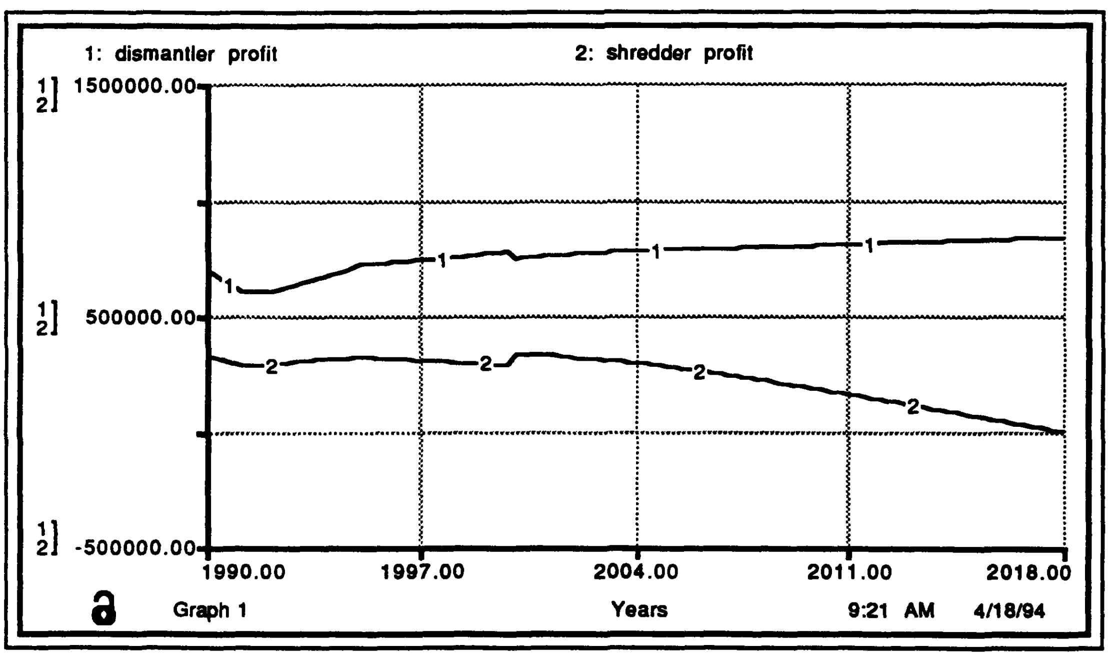
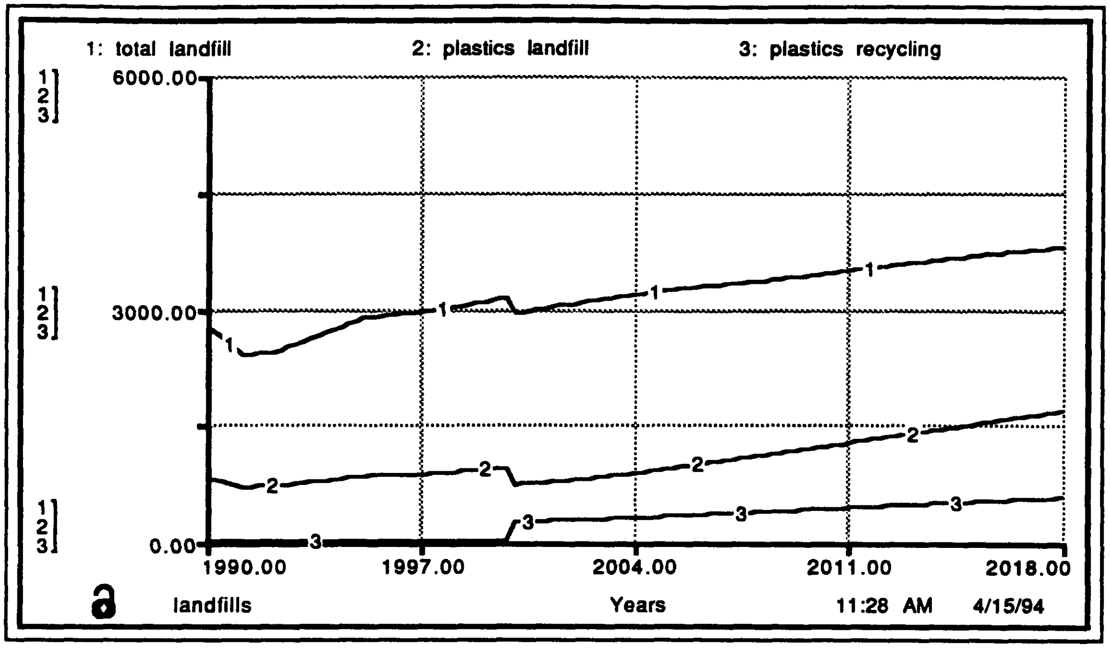


Figure 6.3: Sub-Scenario 2-1--Increasing Landfill Cost vs Current Technology (Market Adjustment)

I. Environmental Consequence (unit: 1,000 ton)



II. Economic Consequence (unit: $1,000)

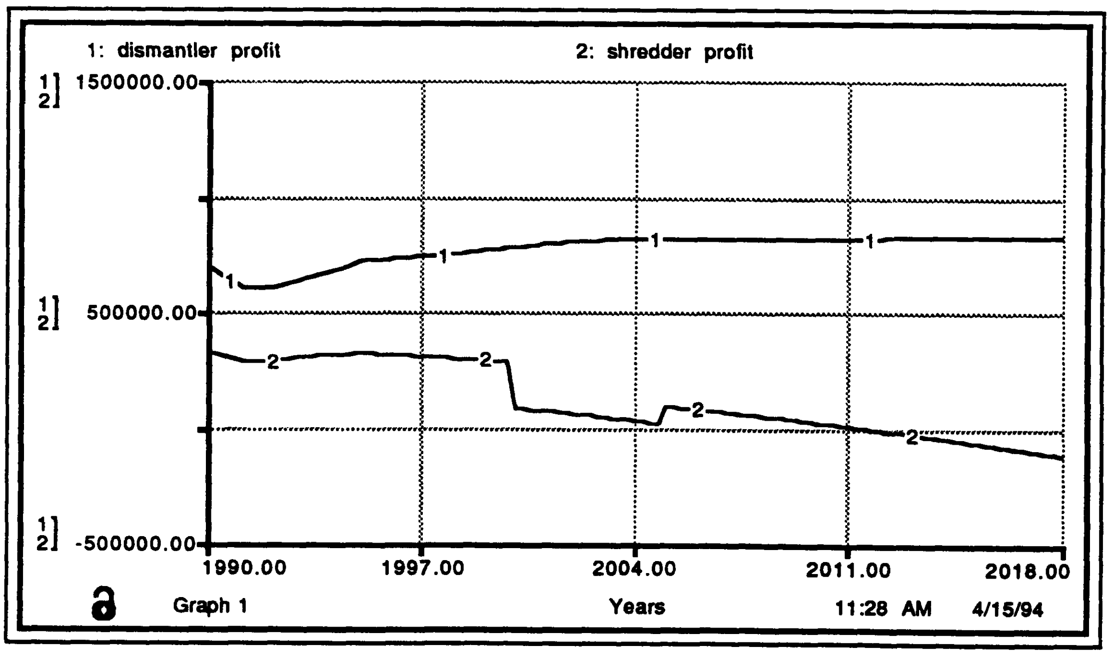
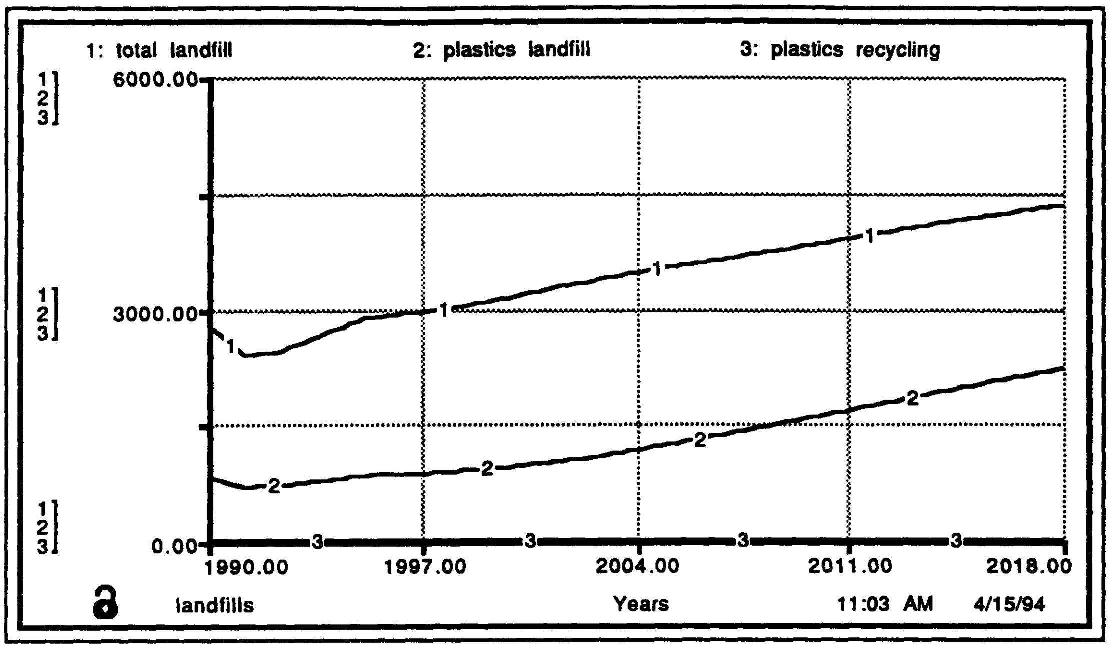


Figure 6.4: Scenario 3--Increasing Landfill Cost vs Best Technology

I. Environmental Consequence (unit: 1,000 ton)



II. Economic Consequence (unit: $1,000)

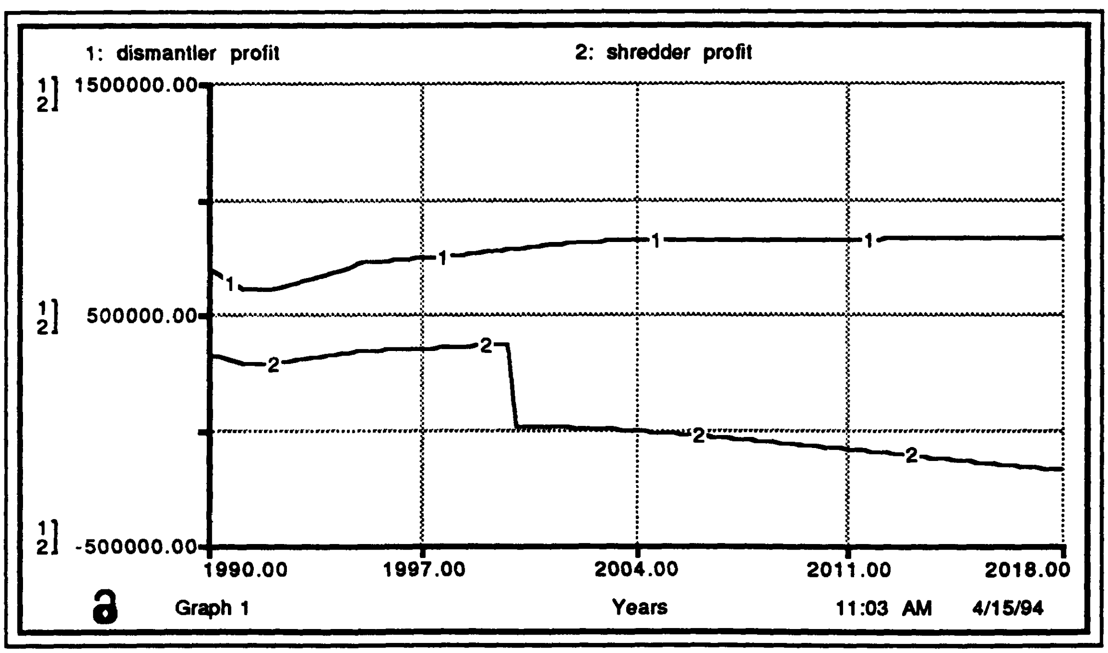
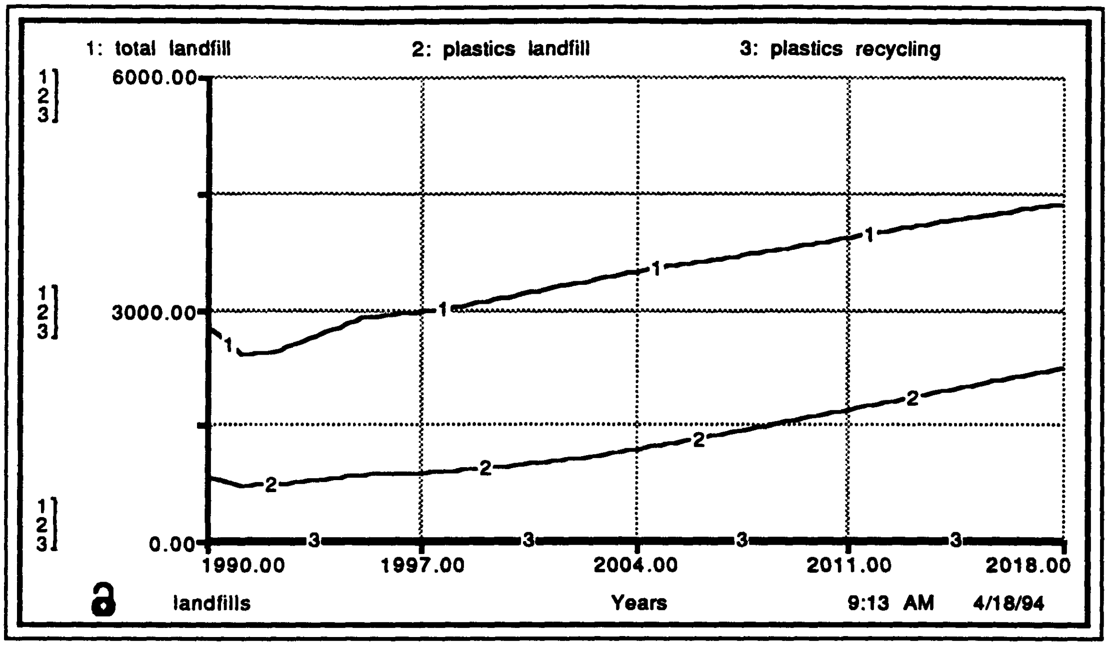


Figure 6.5: Scenario 4–Hazardous Waste vs No Plastics Recycling

I. Environmental Consequence (unit: 1,000 ton)



II. Economic Consequence (unit: $1,000)

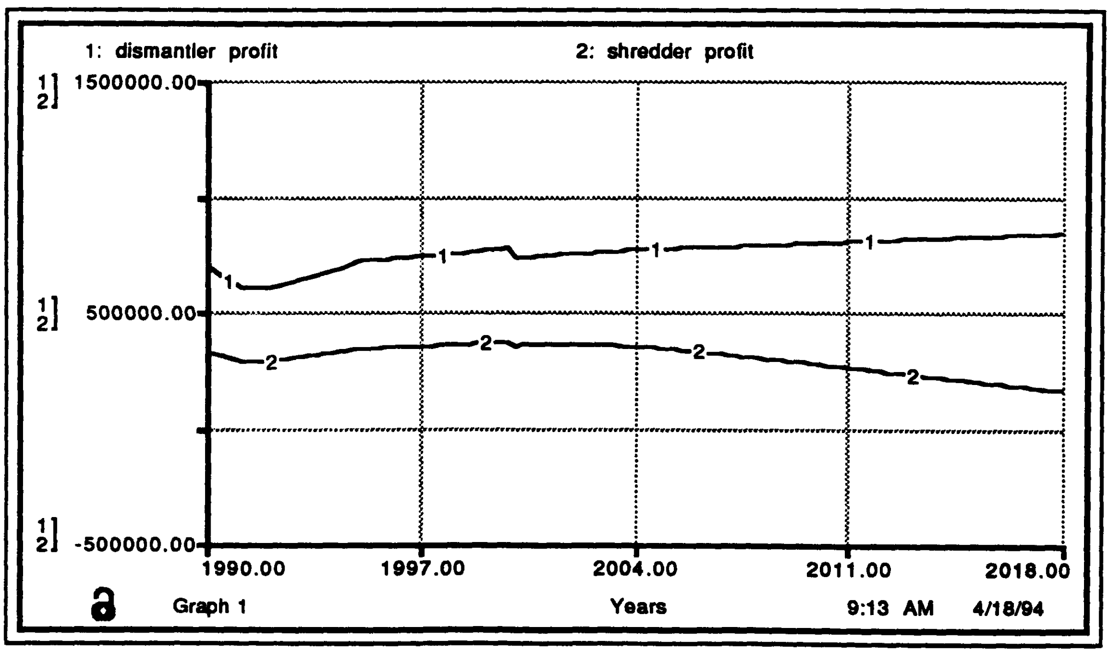
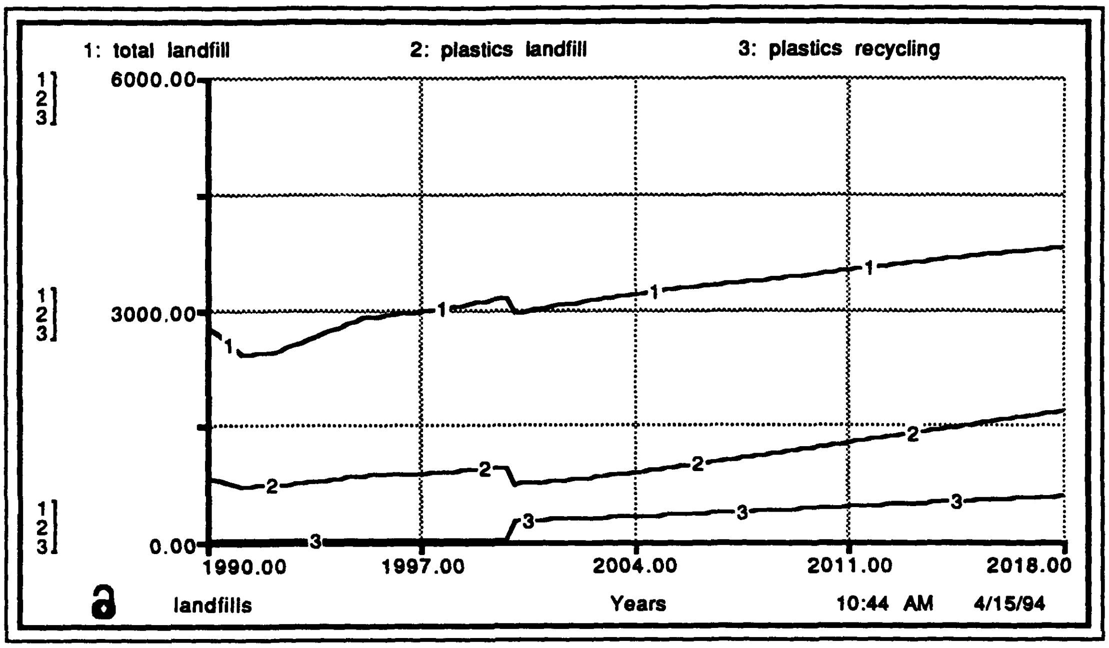


Figure 6.6: Sub-Scenario 4-1--Hazardous Waste vs No Plastics Recycling (Market Adjustment)

I. Environmental Consequence (unit: 1,000 ton)



II. Economic Consequence (unit: $1,000)

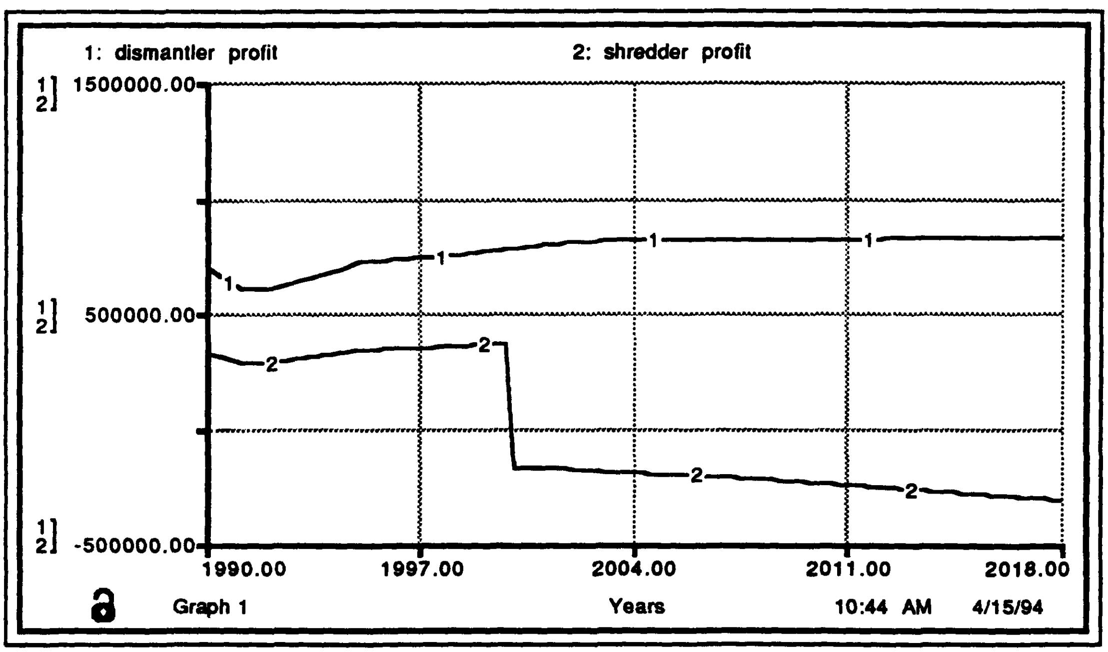
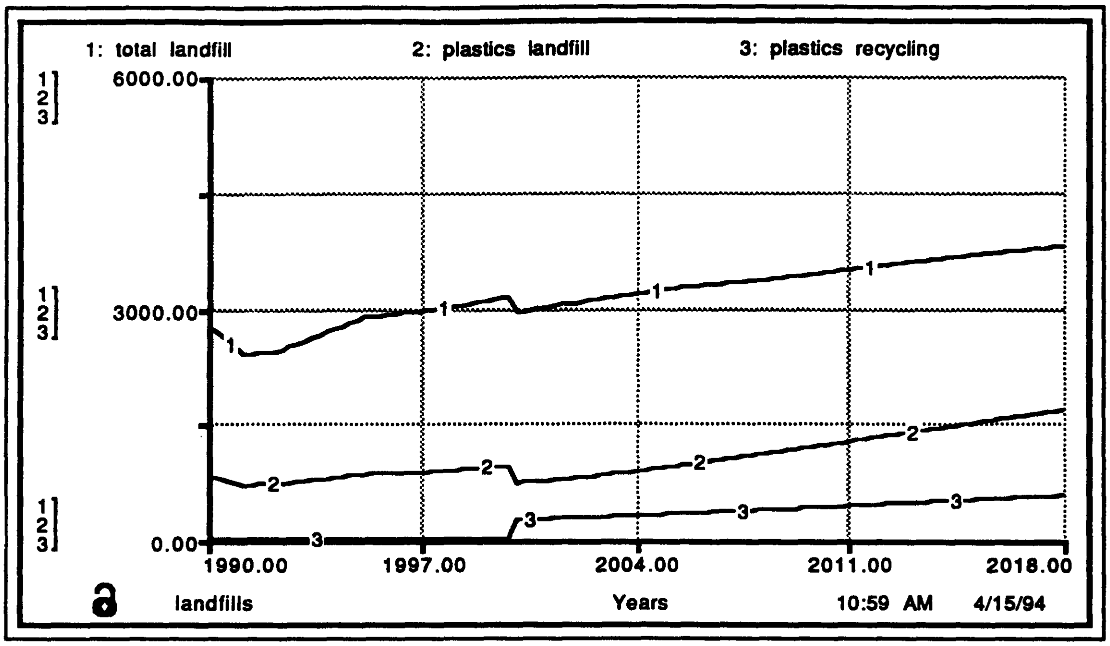


Figure 6.7: Scenario 5--Hazardous Waste vs Current Technology

I. Environmental Consequence (unit: 1,000 ton)



II. Economic Consequence (unit: $1,000)

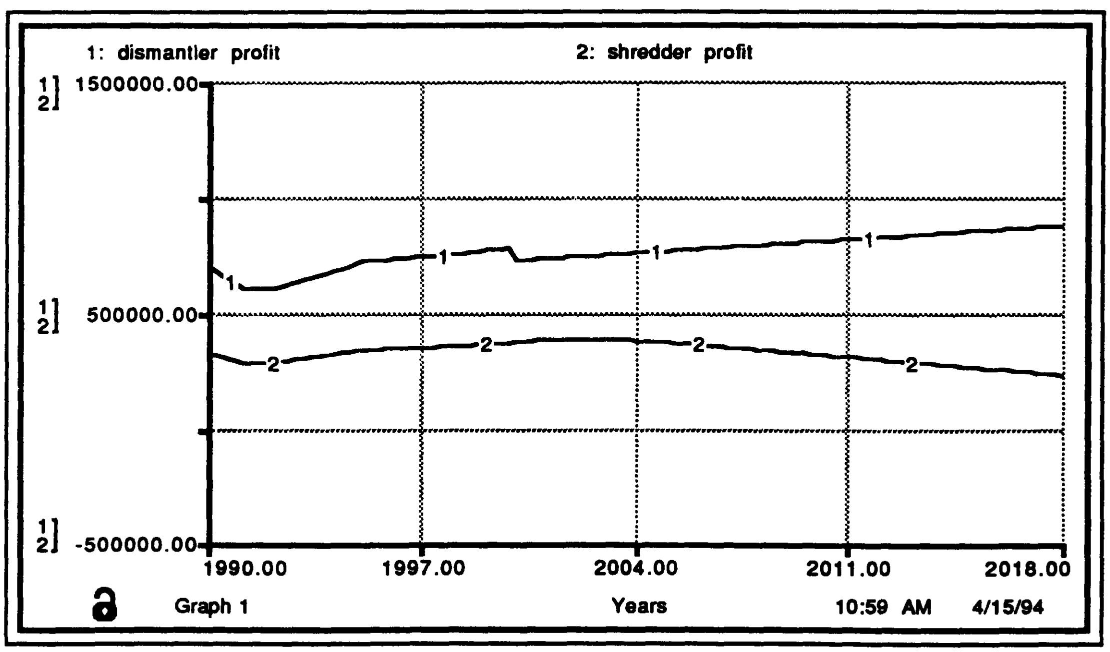
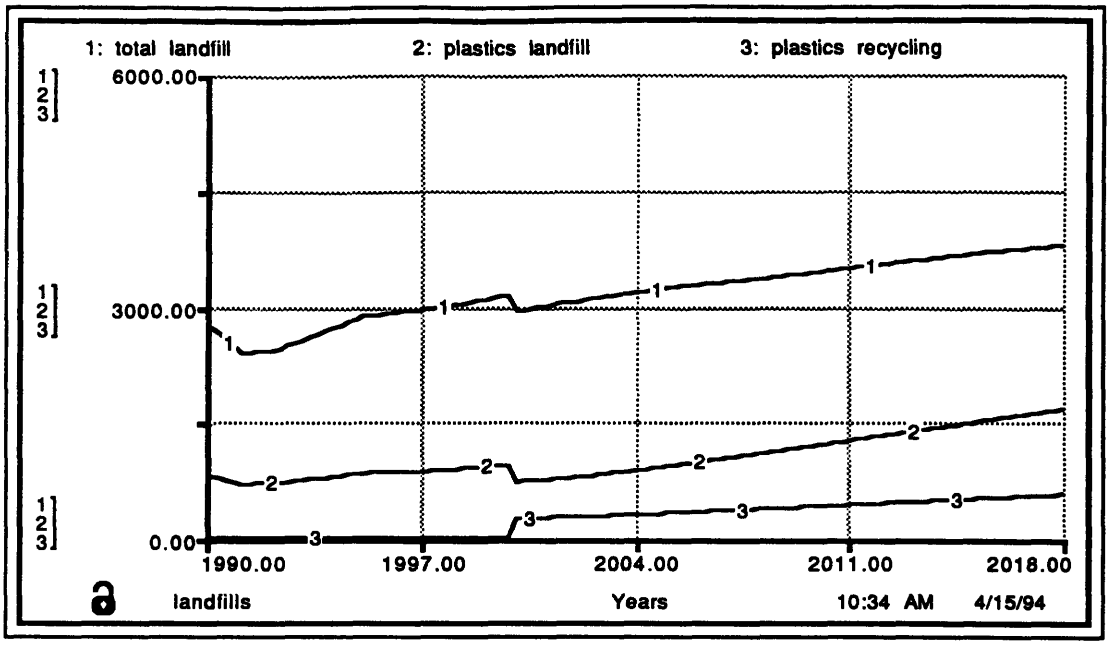


Figure 6.8: Sub-Scenario 5-1--Hazardous Waste vs Current Technology (Market Adjustment)

I. Environmental Consequence (unit: 1,000 ton)



II. Economic Consequence (unit: $1,000)

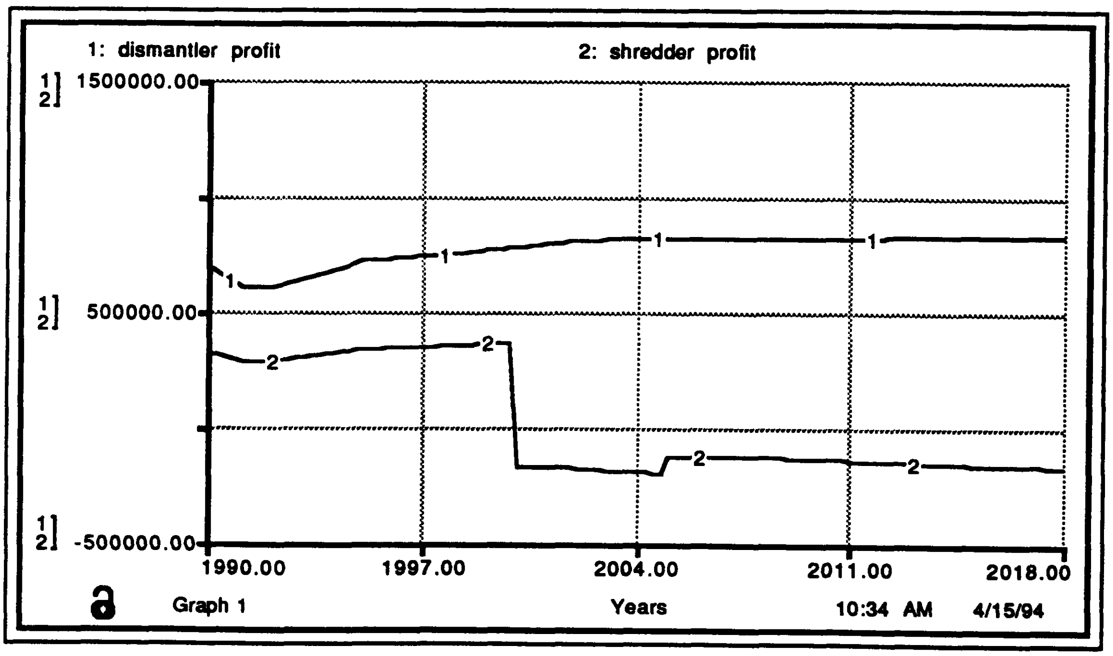
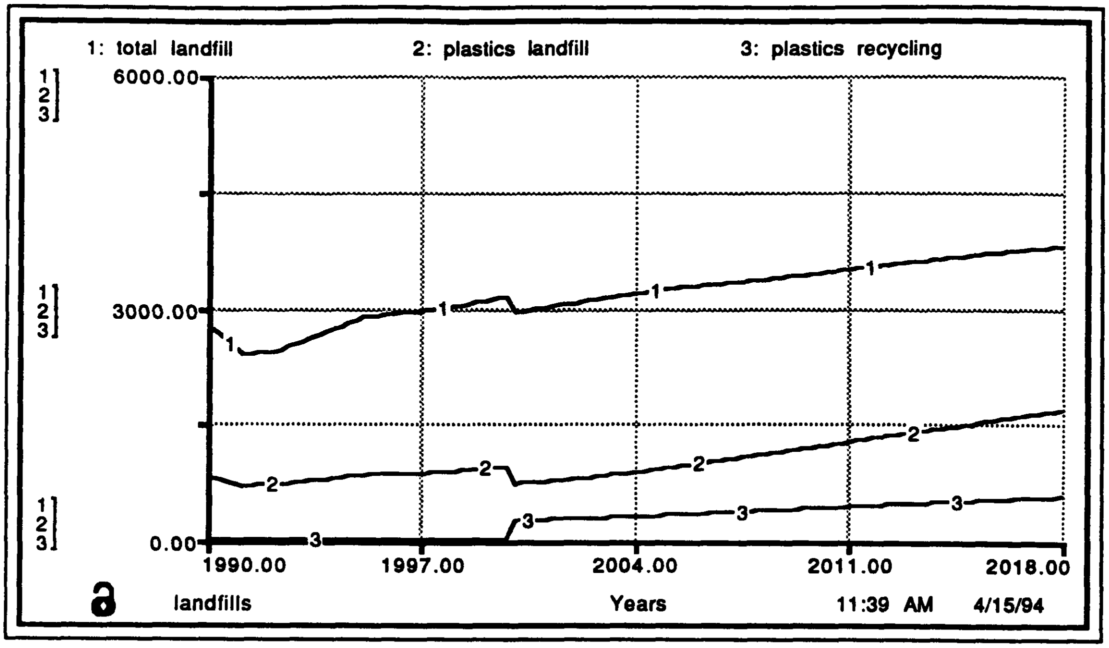


Figure 6.9: Scenario 6--Hazardous Waste vs Best Technology

I. Environmental Consequence (unit: 1,000 ton)



II. Economic Consequence (unit: $1,000)

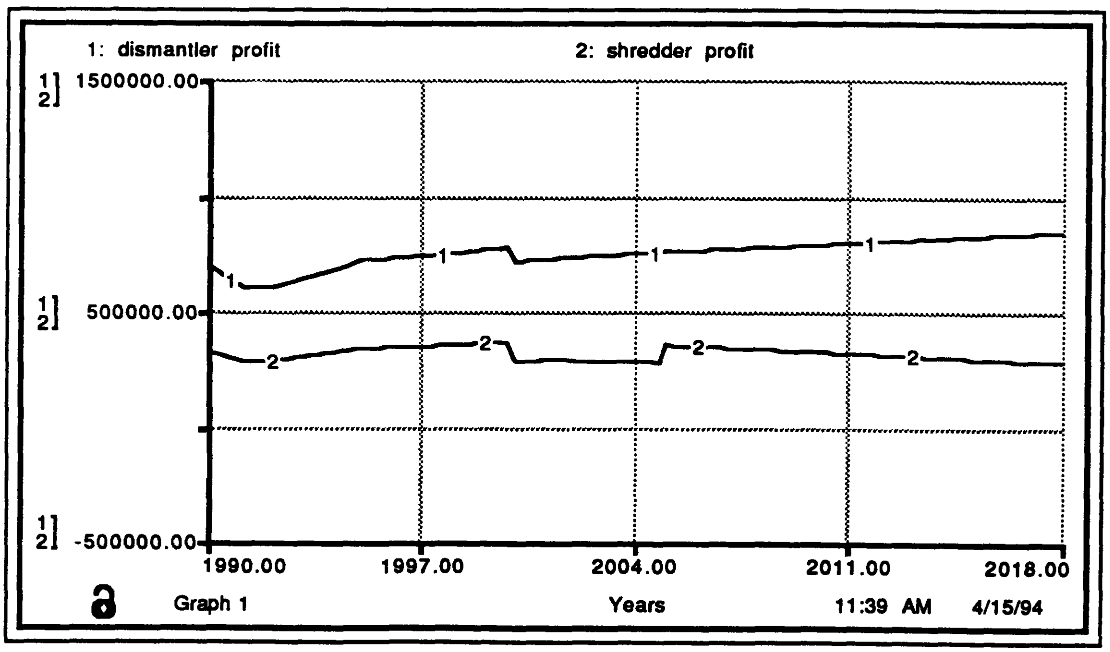


Figure 6.10: Sub-Scenario 6-1--Hazardous Waste vs Best Technology (Market Adjustment)

Chapter 7

Policy Recommendations for Automobile Recycling

7.1 Overview

The complexity, uncertainties, and risks associated with the automobile recycling problem reinforce the call for policy actions on this issue. In order to arrive at a sustainable solution for the society as a whole, effective governmental and industrial policies are of crucial importance. This chapter will discuss and propose policy recommendations for both the public and private sectors based on the analysis and simulation of the previous chapters.

7.2 Policy Recommendation: Public Sector

Automobile recycling is one of the most frequently mentioned new areas of governmental action. The potential subjects include legislative mandates and deliberated recycling schemes. In general, the objective of public policy for automobile recycling is to pursue the long-term and sustainable solution for this problem. In addition, public policy usually incurs certain levels of benefits and costs to the society. Therefore, the policy-maker should not only focus on the deliberated objective of a specific policy, but also pay attention to the society's overall benefits and costs, such as environmental performance, technology forcing, economic impact, and industrial profitability. Based on the principle above, the following sections will discuss and propose strategic policy options for the public sector.

7.2.1 Recognize the Nature of Problem

Understanding the nature of a problem is the first step in formulating public policies. Automobile recycling is not only a technical issue or an environmental performance, but also an economic practice. Recyclability is a characteristic that has both technological and economic implications[102]. The fact is that current recycling activities are primarily driven by economic opportunity rather than by technological or environmental necessity. Therefore, pursuing the goal of recyclability not only entails the availability of recycling technologies, but also relates to the economic feasibility for the existing recycling industry. The simulation results in the previous chapter clearly indicate that arbitrarily requiring a certain environmental or technological performance without addressing the industry's economic profitability will lead to serious consequences, such as the breakdown of the existing recycling system[103].

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[102]F.R. Field, III, and J.P. Clark, "Automobile Recycling: Environmental Policymaking in a Constrained Marketplace," February, 1994.
[103]For details, refer to the simulation results of Scenario 2, Scenario 4, and Scenario 5 in Chapter 6.

7.2.2 Identify Recycling Barriers from System Prospects

Automobile recycling is a problem that relates to every sector along a vehicle's life cycle. The barriers which prevent the industry from achieving a higher level of recyclability should be identified from the prospect of the whole automotive system. If any of the elements in the overall system are missing or pose technological or economic barriers, the objective of the public policy to encourage recycling will never be achieved. Therefore, one of the government's primary tasks upon enforcing public policies is to locate and then remove all the obstacles standing in the way of "recovering the maximum amount of resources from the automotive material stream." Instead of unilaterally focusing on a single sector of the industry, the policy-maker should apply a system approach in order to address all the problems along the whole life cycle of automobiles, including product design, manufacturing and consumption, as well as waste separation, recovery, and disposal. As demonstrated by the results of the simulation model in the previous chapter, it is the dynamics within the whole system, not a single process at an individual stage, that decide the overall consequence of automobile recycling.

7.2.3 Be Prudent about Taking Bold Regulatory Actions

Regulatory approaches are usually considered the most straightforward way of achieving the desired objectives of public policies. The proposed legislative imperatives include setting fixed recycling targets for the industry, classifying ASR as hazardous waste, and many other market incentive schemes. However, a policy-maker should be fully aware that there are always potential societal risks and uncertainties associated with regulatory changes.

The regulatory approaches does not always lead to the desired outcome. Instead, it might cause some serious side-effects. The simulation results in the previous chapter under the scenario of "classifying ASR as hazardous waste" indicate that the "technology forcing" regulation might merely end up with the "adjustment forcing" of the current market system[104]. Additionally, bold legislative approaches might sometime result in serious consequences. The simulation results under the scenario of "setting a fixed recycling target" (25% of plastics) imply that arbitrarily taking regulatory action without consideration of the industry's technological and economic feasibility might bring about the breakdown of the existing recycling infrastructure[105]. It turns out that the policy-maker should be very careful upon applying legislative approaches either to "design" or regulate the market economics and industrial processes within the automobile recycling system.

7.2.4 Avoid Regulating Industrial Changes Directly

Extended producer responsibility (take-back policy) and deposit systems, two national recycling policies currently conducted by several European governments to "design" or "change" the automobile industry's fundamental infrastructure and market economics, may have considerable impacts on the domestic regulatory climate. In general, the basic conception behind both the

[104]For details, refer to the results of Scenario 4, Scenario 5, and Scenario 6.
[105]For details, refer to the results of Scenario 2 and Scenario 5.

take-back policy and deposit system is the "polluters-pay principle." As the processing of scrap automobiles becomes unprofitable, consumers or producers are required by the governments to internalize the extra cost for scrap car processing so that they will adopt or incorporate the waste management related concerns into the decision-making of product consumption and design. Rightly or wrongly, these policies have potential attractiveness to domestic policy-makers.

However, the simulation analysis in the previous chapter suggests that it is not necessary for U.S. policy-makers to "import" these European policies, at least for now and the near future. First of all, since American cars traditionally contain more recyclable ferrous metals and less non-recyclable plastics than their European counterparts, and because landfilling cost in the United States is generally lower than in Europe, the processing of scrap automobiles is now and will continue to be profitable for the foreseeable future. The simulation result of Scenario 1 in the previous chapter indicates that the processing of scrap cars is likely to remain profitable until around 2014 under the interactions between the current automotive material trends and rising landfilling costs. Therefore, domestic policy-makers may still adopt a wait-and-see policy before the final results of the European policies come out. Additionally, even though there might be some regulatory changes in the future, such as fixed recycling targets or classifying ASR as hazardous waste, the domestic industry can still handle the situations well by adjusting the current market system[106]. Finally, as mentioned before, the effect of adjusting the market system is comparable to passing the extra processing cost back to consumers, which is similar to a deposit system. Since the overall value of scrap cars is still above zero, the industry can simply

[106]For details, refer to Sub-Scenario 2-1, Sub-Scenario 4-1, Sub-Scenario 5-1, and Sub-Scenario 6-1.

deduct the extra processing fee from the payment to the last owners for their junked cars. Therefore, a deposit system is not needed to collect the money from consumers.

7.2.5 Perceive Macroeconomic and Political Effects

One of the primary concerns of public policy is the potential macroeconomic and political impacts on society, especially when the government is trying to conduct centralized recycling schemes, such as the take-back policy and deposit system. As shown in the simulation results of market adjustment in the previous chapter, the extra costs paid by consumers for plastics recycling are likely to solve the automobile recycling problem in the future. However, even though the extra cost for each consumer seems to be low, the aggregation effect can be surprisingly tremendous. For example, if the government requires each consumer to pay $40/vehicle of extra cost, the total extra cost will be $360,000,000 per year for the U.S. consumers (assume there are 9 million junked cars per year). The resulting macroeconomic and political effects, such as income redistribution and citizen reaction, will have a substantial influence on the society.

The fact is that the recycling system for automobiles in the United States is already economically viable. The take-back legislation, which might drag automakers into the scrap car recycling business, would damage or destroy the existing independent dismantlers and shredders. In addition, the take-back policy is likely to cause economic inefficiency to the society. According to an estimation of a Big Three official, the independent recyclers' costs are about 25%

of what OEM's would be[107]. Furthermore, the regulatory, administrative, and legal interventions and controls exercised by the government might incur huge costs for the society[108]. Therefore, policy makers should perceive the potential macroeconomic effects of income redistribution, unemployment, social inefficiency, and high transaction costs.

The political impacts of centralized policies would also have a potential influence on the society. As described in Chapter 4, most European deposit systems require a national vehicle registration and collection program. In the United States, however, vehicle registration is normally handled at state and local levels. As a consequence, introducing a deposit system would bring about a great deal of federal intervention into regional affairs. The political reactions from local governments and citizens should be taken into account. It turns out that a thorough consideration of all the macroeconomic and political effects is necessary in order to formulate a flexible and evolutionary public policy for the domestic automobile recycling problem.

7.3 Policy Recommendation: Private Sector

The objective for most industrial policies is to deal with the risks and uncertainties associated with regulatory requirements and market economics, as well as to maintain the overall profitability of industry. However, the recent call from the general public for environmentalism has placed considerable pressure

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[107]Opinions of the representatives from Big Three in the Recycling of Durable Conference, MIT, March 1993. Refer to Lindsay Brook, "Recycling: What's Next," Environment MIT, 1993.
[108]Charles Wolf, Jr., Market or Governments: Choosing Between Imperfect Alternatives, (Cambridge: MIT Press, 1988), ch.7.

on the industry to pursue "greening" goals such as pollution prevention and material recycling. As a result, effective policies for the automobile industry should not only deal with uncertainties from regulatory and economic constraints, but also pursue a higher level of environmental performance. The following sections will discuss these proposed policies.

7.3.1 Develop Cost-Effective Technologies

Technological development is usually viewed as the best way to achieve environmental performance and avoid regulatory pressure. As mentioned before, the development of shredding and steelmaking technologies in the 1970's had successfully resolved the automobile recycling problem at that time. Today technology, especially plastics recycling technology, will continue to play a key role in solving the problem.

Material recycling, however, is not only a technological attribute, but also an economic and marketing practice. As demonstrated in the simulation results, applying the current technologies, which are not cost-effective, to plastics recycling will cause some serious economic damage to the recycling industry[109]. Therefore, the industry should keep improving the economics of the current recycling technologies. Additionally, the industry should explore applications that can use the recyclate and then develop a market for the secondary material. Such efforts will not only resolve the impending problem of automobile

[109]For details, refer to the results of Scenario 2 and Scenario 5.

recycling, but also provide a market opportunity which may be transferable to other industrial applications of material recycling[110].

7.3.2 Design for Recycling

Design for recycling is always considered the fundamental solution for most recycling problems. For automobile recycling, design for recycling means that the material concerns must be addressed early in design and product development. Given the future regulatory climate and consumer emphasis on environmentalism, the industry should be fully aware of future recycling demands and any possible legislated material bans and incorporate the conception of recyclability into product design and manufacturing processes.

As mentioned in Chapter 4, the critical works of design for recycling include reducing the diversity of materials employed in the automobile, applying lower amounts of non-recyclable materials, clearly labeling different material species in all components, and adopting more dismantler-friendly techniques in automobile manufacturing so that used parts and secondary materials can be easily identified and recovered by dismantlers and shredders. Additionally, automakers should establish their partnership with material suppliers, dismantlers, and shredders so that all the technological and economic factors that affect recyclability can be taken into account. Most importantly, manufacturers should enhance the importance of recycling-related concepts among their design and production considerations.

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[110]F.R. Field, III, and J.P. Clark, "Automobile Recycling: Environmental Policymaking in a Constrained Marketplace," February, 1994.

7.3.3 Adjust Market Systems Efficiently

Adjusting the current market system to deal with the regulatory and market uncertainties and risks is one of the potential solutions for automobile recycling. As indicated in the previous chapter, the transfer prices between different sectors of the life cycle could play some "magic" roles under various simulation scenarios[111]. Efficiently adjusting the transfer prices according to different regulatory, technological, and economic conditions may not only rescue the industry from breaking down in some circumstances, but also maintain the industry's overall profitability. In practice, the transfer prices (or the industry's willingness to pay for junked cars and hulks) should be efficiently adjusted to the net values of scrap cars.

However, the real market economics for the industry are composed of a complex "web" of financial flows, including the prices of junked cars, used parts, and secondary materials, as well as the costs for dismantling, processing, and disposal. Therefore, the industry should maintain a market system that is able to reflect the correct market signals of all the financial flows, as well as to balance the willingness to pay and willingness to accept within the whole system. Only with sufficient information and an effective market infrastructure can the industry efficiently adjust its economic system in response to all the uncertainties and risks associated with automobile recycling.

[111]For details, refer to the simulation results of Sub-scenarios 2-1, 4-1, 5-1, and 6-1.

7.3.4 Encourage Inter-Sectoral Cooperation

Automobile recycling is an inter-sectoral problem that relates to every sector along an automobile's life cycle. In order to resolve the problem from a system approach, it is necessary to encourage inter-sectoral cooperation among all the actors in the industry. In practice, a strong partnership should be established among materials suppliers, manufacturers, dismantlers, shredders or even consumers. Material suppliers can highlight the positive and minimize the negative attributes of materials. Dismantlers and shredders can provide manufacturers with separation and processing expertise so that the automakers can incorporate the concept of "design for recycling" into their design and production processes. Consumers can express their concerns on product consumption and environmental quality. Additionally, material suppliers and manufacturers can work closely to create secondary markets and explore applications that can encourage closed-loop recycling.

Currently, there have already been a variety of associations working on the recycling issue, including the Vehicle Recycling Partnership (manufacturers), the Automobile Recycler Association (dismantlers), the American Plastics Council (material suppliers, dismantlers, and shredders), and many other associations formed with the automotive industry. However, an inter-sectoral organization that can coordinate all the parties in the system is still unavailable at this time. It turns out that more dialogue and cooperation across all sectors of the life cycle are of crucial importance for solving the automobile recycling problem.

7.4 Joint Effort: Toward a Sustainable Solution

Perhaps the first step in implementing the proposed policies is to bring together government, industry, and the public in order to understand their positions and interests on the issue of automobile recycling. Information always plays a crucial role in formulating both public and private policies. A critical problem of the current policy-making process for automobile recycling is poor communication among all the affected parties[112]. Therefore, it is crucial to employ joint efforts from the government, the automobile industry, the recycling industry, and the general public in order to identify and then remove the barriers within the whole system, as well as to discuss and then understand the resulting costs and benefits of prospective recycling schemes.

In addition, the government and the industry should support and fund the R&D for automobile recycling, not only in the field of technological development, but also in the areas of economic analysis, market survey, and even the policy evaluation of foreign recycling imperatives. It turns out that the more technological and market information we control, the fewer risks and uncertainties will be involved in our decision-making processes.

Finally, all the affected parties should pursue the same objective: to reduce the solid wastes generated, decrease the virgin materials extracted, and support the long-term development of the society. Under the same belief and through the joint effort by the government, the automotive industry, and the general public, a

[112] F.R. Field, III, and J.P. Clark, "Automobile Recycling: Environmental Policymaking in a Constrained Marketplace," February, 1994.

sustainable solution for the domestic automobile recycling problem will be on its way.

Chapter 8

Conclusion

Automobile recycling is not only an environmental or technological performance, but also an economic practice. The success or failure of automobile recycling depends on the long-term development of a stable, technologically effective, and economically feasible infrastructure to carry both the material and financial flows along the life cycle of automobiles. Due to the dynamic features of automobile recycling, a system approach which addresses all the problems along the life cycle is needed to formulate effective policies for dealing with the issue.

Two critical elements are of crucial importance in the policy-making process. The first is the benefits and costs of different policy options. The second is the information and uncertainty that affect the quality of a decision-making process. On the one hand, policy-makers should formulate flexible and sustainable policies that can balance the overall environmental benefits and economic costs. On the other hand, policy-makers should keep improving the quality and availability of information for the purpose of dealing with the dynamic risks and uncertainties associated with the automobile recycling problem.

On the cost-benefit side, the government should be careful about taking bold regulatory action, such as classifying ASR as hazardous waste and setting fixed recycling targets for pursuing environmental performance without considering the economic impact on the industry. Additionally, the take-back policy and deposition system are not currently necessary because the industry is capable of adjusting the existing market system to deal with regulatory and economic uncertainties. Moreover, technological development of plastics recycling technology and design for recycling practice will play a key role in solving the problem in the future. Most importantly, policymakers should perceive the potential macroeconomic and political impacts on the society when formulating recycling policies.

On the information side, inter-sectoral communication within the industry should be encouraged. The government and the industry should support and fund the R&D in the areas of technological, economic, and policy studies. Most importantly, joint efforts by the government, the industry, and the general public are important in order to identify and then remove the risks and barriers within the whole recycling system.

Where there is risk, there is always opportunity. The overall aim of automobile recycling is to reduce America's solid and hazardous wastes, to reduce energy consumption and the demand for virgin materials, and to support the long-term development of the society. Under this belief, we will not only perceive the potential environmental impacts, technological challenges, and economic uncertainties associated with automobile recycling, but also discover enormous opportunities for environmental improvement, technological innovation, economic profitability, and an overall benefit for sustainable development .

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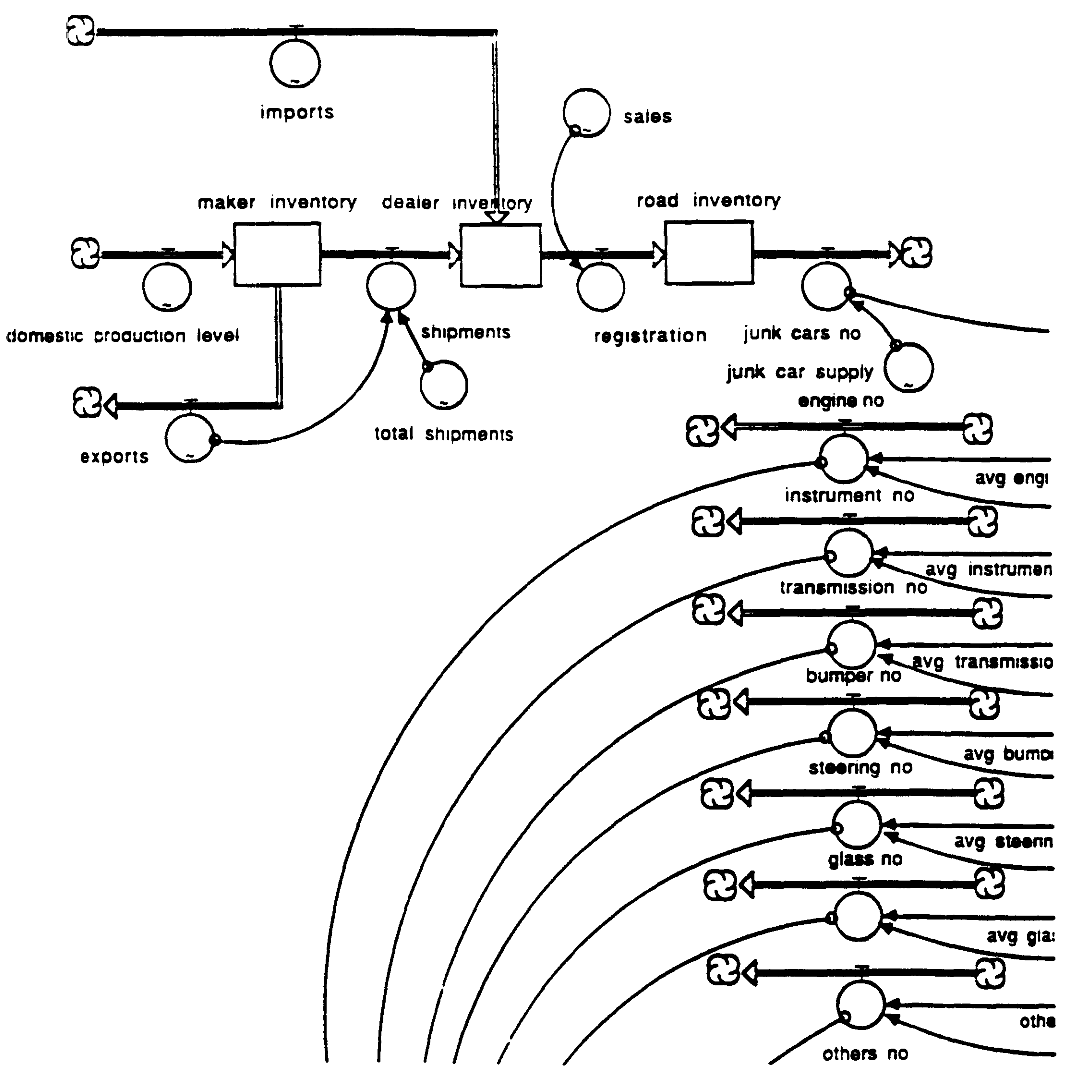
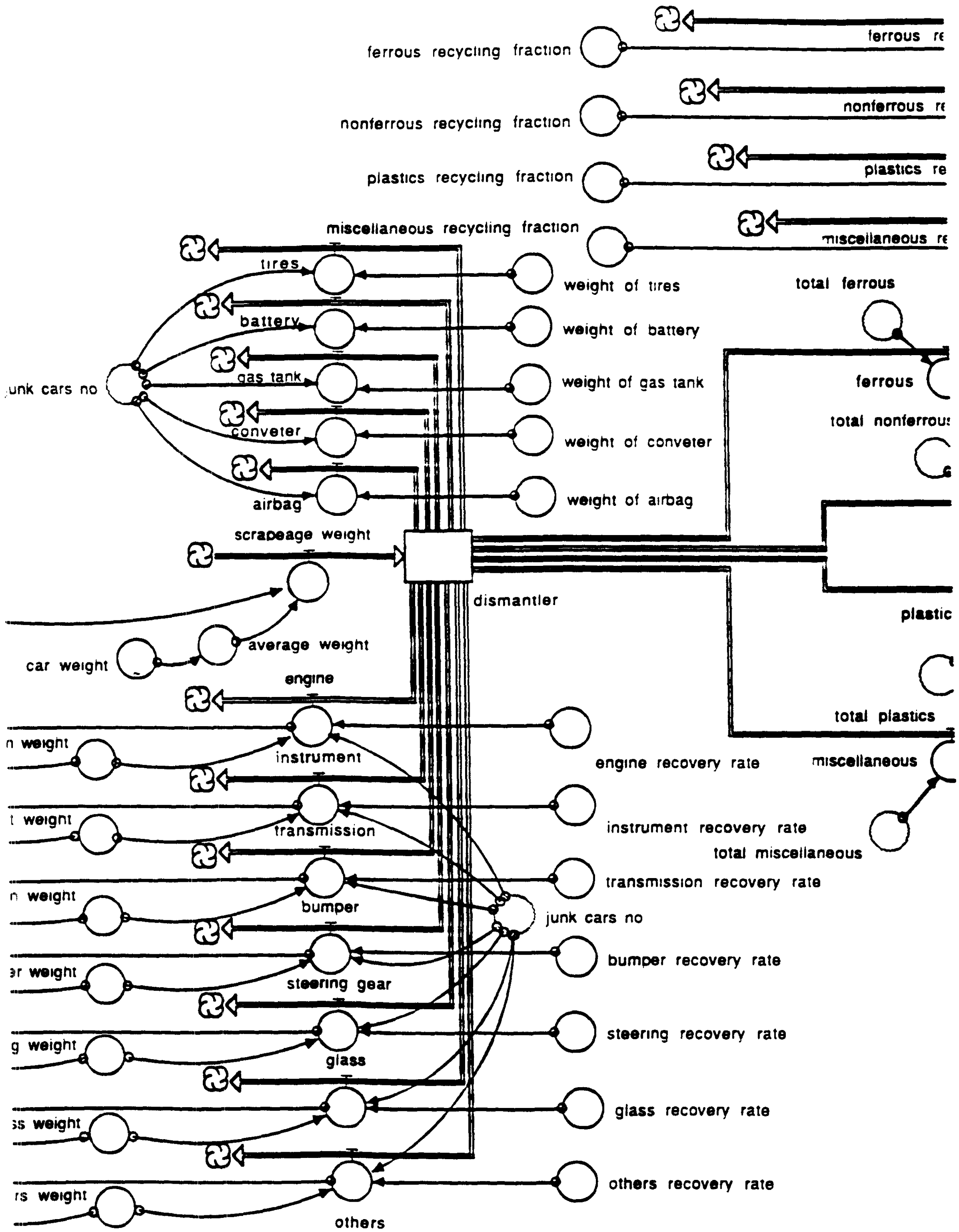
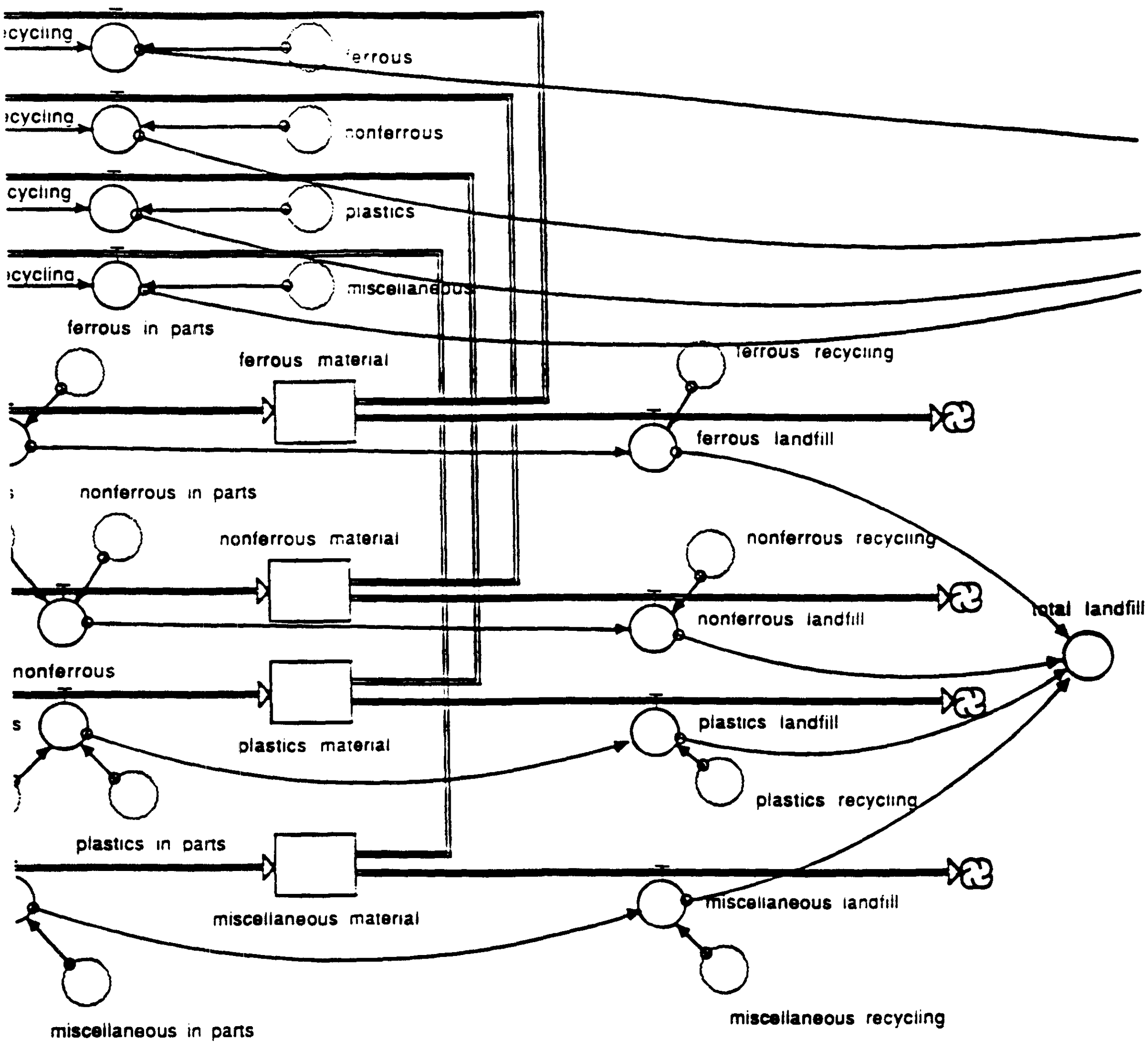
Appendix 2: Systems Dynamics Model and Reference




ferrous re
ferrous recycling fraction
nonferrous re
nonferrous recycling fraction
plastics re
plastics recycling fraction
miscellaneous re
miscellaneous recycling fraction
tires
weight of tires
total ferrous
battery
weight of battery
junk cars no
gas tank
weight of gas tank
ferrous
conveter
weight of conveter
total nonferrous
airbag
weight of airbag
scrapeage weight
dismantler
plastic
average weight
car weight
engine
total plastics
n weight
instrument
engine recovery rate
miscellaneous
t weight
transmission
instrument recovery rate
total miscellaneous
n weight
bumper
transmission recovery rate
junk cars no
er weight
steering gear
bumper recovery rate
g weight
glass
steering recovery rate
ss weight
glass recovery rate
rs weight
others
others recovery rate



ferrous
nonferrous
plastics
miscellaneous
ferrous in parts
ferrous material
ferrous recycling
ferrous landfill
nonferrous in parts
nonferrous material
nonferrous recycling
nonferrous landfill
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plastics landfill
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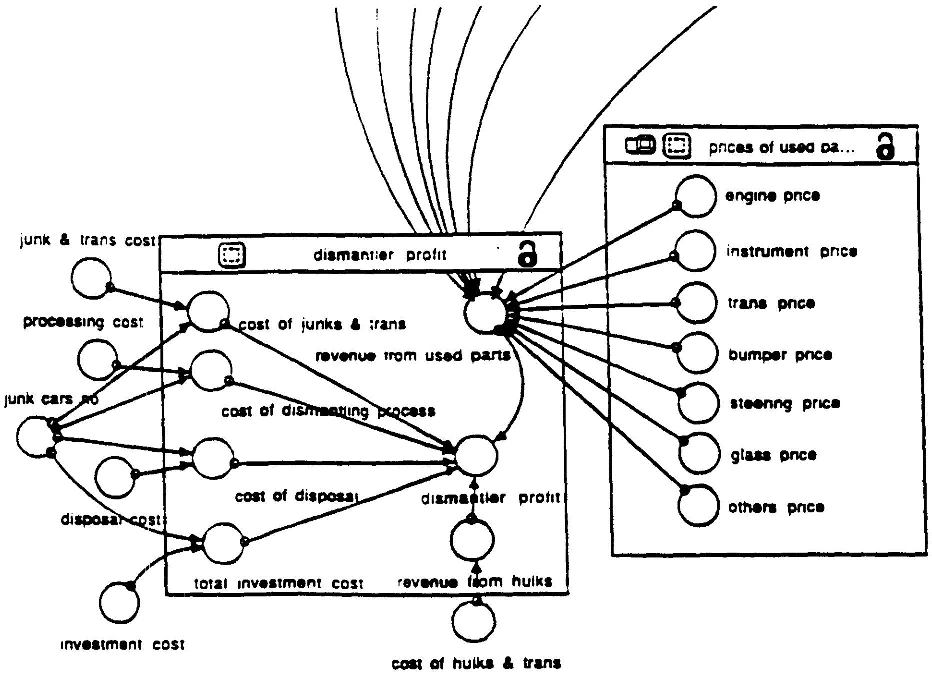
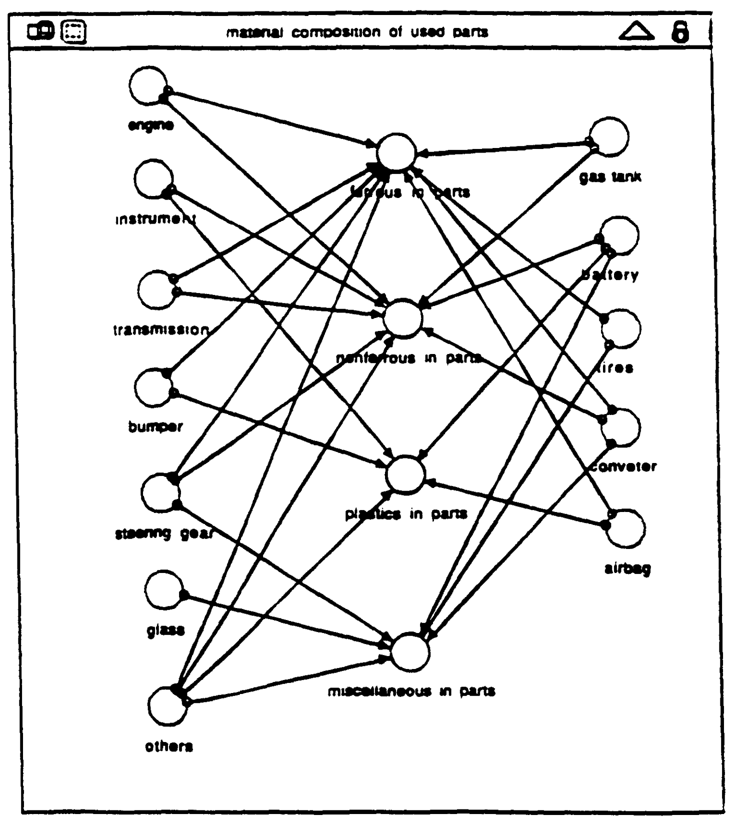
miscellaneous material
miscellaneous recycling
miscellaneous in parts


dismantler profit
prices of used pa...
junk & trans cost
processing cost
junk cars no
disposal cost
investment cost
cost of junks & trans
revenue from used parts
cost of dismantling process
cost of disposal
dismantler profit
total investment cost
revenue from hulks
cost of hulks & trans
engine price
instrument price
trans price
bumper price
steering price
glass price
others price


material composition of used parts
engine
instrument
transmission
bumper
steering gear
glass
others
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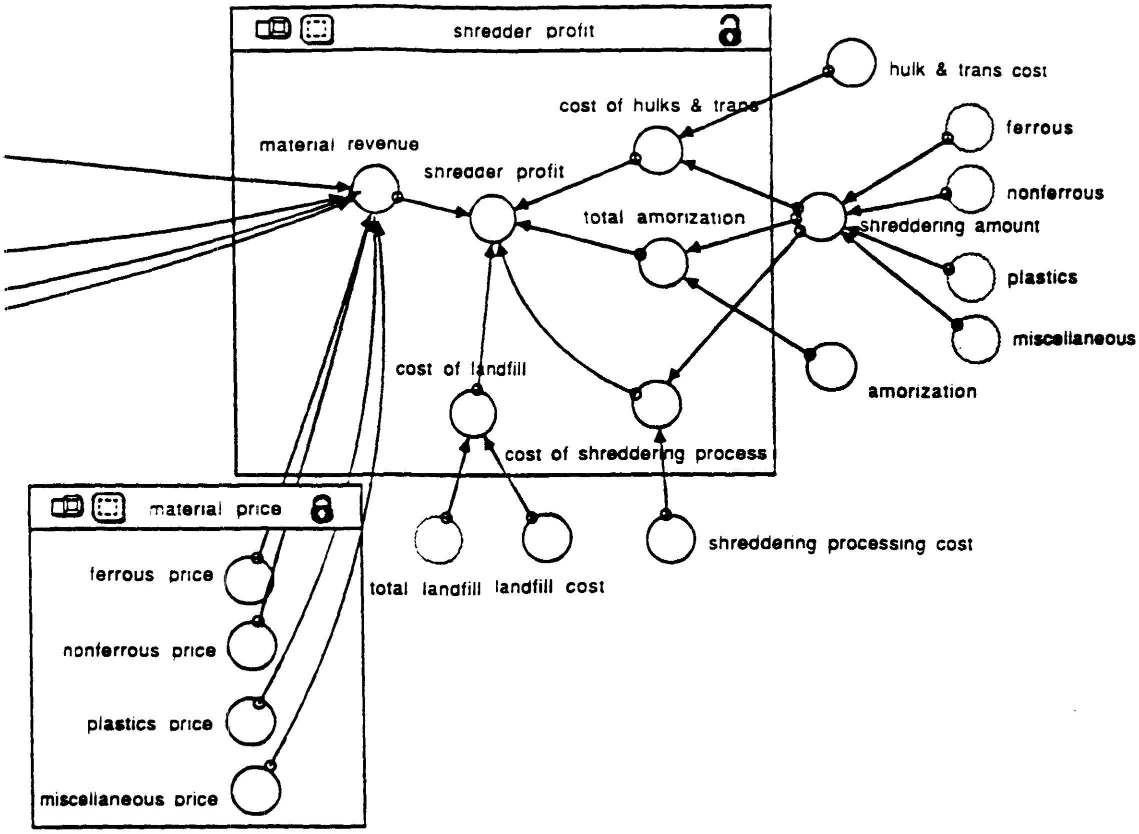
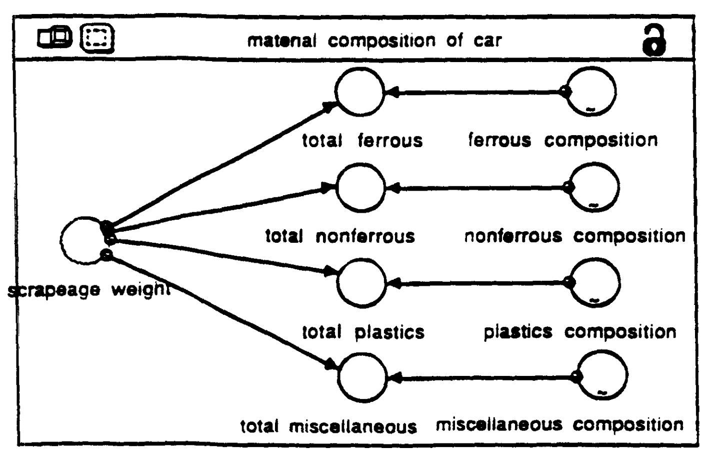
plastics in parts
miscellaneous in parts
gas tank
battery
tires
conveter
airbag



shredder profit
hulk & trans cost
cost of hulks & trans
ferrous
material revenue
shredder profit
nonferrous
total amorization
shreddering amount
plastics
miscellaneous
cost of landfill
amorization
cost of shreddering process
material price
ferrous price
nonferrous price
plastics price
miscellaneous price
total landfill
landfill cost
shreddering processing cost



material composition of car
total ferrous
ferrous composition
total nonferrous
nonferrous composition
scrapeage weight
total plastics
plastics composition
total miscellaneous
miscellaneous composition

dismantler profit

- cost_of_dismantling_process = processing_cost*junk_cars_no
- cost_of_disposal = disposal_cost*junk_cars_no
- cost_of_junks_&_trans = junk_&_trans_cost*junk_cars_no
- dismantler_profit = revenue_from_used_parts+revenue_from_hulks-cost_of_dismantling_process-total_investment_cost-cost_of_junks_&_trans-cost_of_disposal
- revenue_from_hulks = cost_of_hulks_&_trans
- revenue_from_used_parts = engine_no*engine_price+instrument_no*instrument_price+transmission_no*trans_price+bumper_no*bumper_price+steering_no*steering_price+glass_no*glass_price+others_no*others_price
- total_investment_cost = investment_cost*junk_cars_no

material composition of car

- total_ferrous = scrapeage_weight*(0.012*DELAY(ferrous_composition,4)+0.024*DELAY(ferrous_composition,5)+0.042*DELAY(ferrous_composition,6)+0.071*DELAY(ferrous_composition,7)+0.108*DELAY(ferrous_composition,8)+0.14*DELAY(ferrous_composition,9)+0.152*DELAY(ferrous_composition,10)+0.145*DELAY(ferrous_composition,11)+0.14*DELAY(ferrous_composition,12)+0.088*DELAY(ferrous_composition,13)+0.051*DELAY(ferrous_composition,14)+0.027*DELAY(ferrous_composition,15))
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- ferrous_composition = GRAPH(TIME)
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material composition of used parts

ferrous_in_parts = 0.95*engine+0.7*transm.ssion+0.05*bumper+0.55*steering_gear+0.45*others+0.95*gas_tank+0.1*conveter+0.1*tires+0.1*airbag

miscellaneous_in_parts = 0.05*steering_gear+glass+0.21*others+tires+0.05*battery+0.05*conveter

nonferrous_in_parts = 0.05*engine+0.2*instrument+0.3*transmission+0.4*steering_gear+0.19*others+0.65*battery+0.05*gas_tank+0.85*conveter

plastics_in_parts = 0.8*instrument+0.95*bumper+0.15*others+0.3*battery+0.9*airbag

material price

ferrous_price = 120

miscellaneous_price = 0

nonferrous_price = 600

plastics_price = 0

prices of used parts

bumper_price = 100

engine_price = 250

glass_price = 100

instrument_price = 30

others_price = 50

steering_price = 75

trans_price = 100

shredder profit

cost_of_hulks_&_trans = hulk_&_trans_cost*shreddering_amount

cost_of_landfill = landfill_cost*total_landfill

cost_of_shreddering_process = shreddering_processing_cost*shreddering_amount

material_revenue =
ferrous_recycling*ferrous_price+nonferrous_recycling*nonferrous_price+plastics_recycling*plastics_price+miscellaneous_recycling*miscellaneous_price

shredder_profit =
material_revenue-cost_of_hulks_&_trans-cost_of_shreddering_process-cost_of_landfill-total_amorization

total_amorization = shreddering_amount*amorization

Not in a sector

dealer_inventory(t) = dealer_inventory(t - dt) + (shipments + imports - registration) * dt
INIT dealer_inventory = 1691
INFLOWS:
- shipments = total_shipments-exports
- imports = GRAPH(TIME)
(1990, 3014), (1991, 2567), (1992, 2353), (1993, 3525), (1994, 3825), (1995, 4050), (1996, 4125), (1997, 4200), (1998, 4275), (1999, 4350), (2000, 4425), (2001, 4500), (2002, 4575), (2003, 4650), (2004, 4650), (2005, 4725), (2006, 4725), (2007, 4800), (2008, 4875), (2009, 4875), (2010, 4950), (2011, 4950), (2012, 4950), (2013, 4950), (2014, 5025), (2015, 5100), (2016, 5175), (2017, 5175), (2018, 5250)

OUTFLOWS:
- registration = sales

dismantler(t) = dismantler(t - dt) + (scrapeage_weight - engine - instrument - transmission - bumper - steering_gear - glass - others - ferrous - miscellaneous - nonferrous - plastics - battery - tires - gas_tank - conveter - airbag) * dt
INIT dismantler = 8000
INFLOWS:
- scrapeage_weight = junk_cars_no*average_weight

OUTFLOWS:
- engine = junk_cars_no*avg_engin_weight*engine_recovery_rate
- instrument = junk_cars_no*avg_instrument_weight*instrument_recovery_rate
- transmission = junk_cars_no*avg_transmission_weight*transmission_recovery_rate
- bumper = junk_cars_no*avg_bumper_weight*bumper_recovery_rate
- steering_gear = junk_cars_no*avg_steering_weight*steering_recovery_rate
- glass = junk_cars_no*avg_glass_weight*glass_recovery_rate
- others = junk_cars_no*others_weight*others_recovery_rate
- ferrous = total_ferrous-ferrous_in_parts
- miscellaneous = total_miscellaneous-miscellaneous_in_parts
- nonferrous = total_nonferrous-nonferrous_in_parts
- plastics = total_plastics-plastics_in_parts
- battery = junk_cars_no*weight_of_battery
- tires = junk_cars_no*weight_of_tires
- gas_tank = junk_cars_no*weight_of_gas_tank
- conveter = junk_cars_no*weight_of_conveter

airbag = junk_cars_no*weight_of_airbag

ferrous_material(t) = ferrous_material(t - dt) + (ferrous - ferrous_landfill - ferrous_recycling) * dt
INIT ferrous_material = 6000
INFLOWS:
ferrous = total_ferrous-ferrous_in_parts
OUTFLOWS:
ferrous_landfill = ferrous-ferrous_recycling
ferrous_recycling = ferrous*ferrous_recycling_fraction

maker_inventory(t) = maker_inventory(t - dt) + (domestic_production_level - shipments - exports) * dt
INIT maker_inventory = 1500
INFLOWS:
domestic_production_level = GRAPH(TIME)
(1990, 6078), (1991, 5439), (1992, 5667), (1993, 6075), (1994, 6450), (1995, 6750), (1996, 7125), (1997, 7425), (1998, 7650), (1999, 7950), (2000, 8175), (2001, 8400), (2002, 8625), (2003, 8775), (2004, 9000), (2005, 9150), (2006, 9225), (2007, 9375), (2008, 9525), (2009, 9600), (2010, 9825), (2011, 9900), (2012, 10125), (2013, 10200), (2014, 10350), (2015, 10500), (2016, 10650), (2017, 10800), (2018, 10950)
OUTFLOWS:
shipments = total_shipments-exports
exports = GRAPH(TIME)
(1990, 555), (1991, 542), (1992, 520), (1993, 600), (1994, 750), (1995, 975), (1996, 1125), (1997, 1275), (1998, 1425), (1999, 1575), (2000, 1650), (2001, 1800), (2002, 1950), (2003, 2100), (2004, 2325), (2005, 2475), (2006, 2625), (2007, 2850), (2008, 3000), (2009, 3150), (2010, 3225), (2011, 3375), (2012, 3525), (2013, 3600), (2014, 3750), (2015, 3825), (2016, 3900), (2017, 3975), (2018, 4050)

miscellaneous_material(t) = miscellaneous_material(t - dt) + (miscellaneous - miscellaneous_landfill - miscellaneous_recycling) * dt
INIT miscellaneous_material = 850
INFLOWS:
miscellaneous = total_miscellaneous-miscellaneous_in_parts
OUTFLOWS:
miscellaneous_landfill = miscellaneous-miscellaneous_recycling
miscellaneous_recycling = miscellaneous*miscellaneous_recycling_fraction

nonferrous_material(t) = nonferrous_material(t - dt) + (nonferrous - nonferrous_landfill - nonferrous_recycling) * dt
INIT nonferrous_material = 550
INFLOWS:
nonferrous = total_nonferrous-nonferrous_in_parts
OUTFLOWS:
nonferrous_landfill = nonferrous-nonferrous_recycling
nonferrous_recycling = nonferrous*nonferrous_recycling_fraction

plastics_material(t) = plastics_material(t - dt) + (plastics - plastics_landfill - plastics_recycling) * dt
INIT plastics_material = 700
INFLOWS:
plastics = total_plastics-plastics_in_parts

OUTFLOWS:

plastics_landfill = plastics-plastics_recycling

plastics_recycling = plastics*plastics_recycling_fraction

road_inventory(t) = road_inventory(t - dt) + (registration - junk_cars_no) * dt
INIT road_inventory = 123276
INFLOWS:

registration = sales

OUTFLOWS:

junk_cars_no = registration*retire_rate

amorization = 6

average_weight =
0.012*DELAY(car_weight,4)+0.024*DELAY(car_weight,5)+0.042*DELAY(car_weight,6)+0.071*DELAY(car_weight,7)+0.108*DELAY(car_weight,8)+0.14*DELAY(car_weight,9)+0.152*DELAY(car_weight,10)+0.145*DELAY(car_weight,11)+0.14*DELAY(car_weight,12)+0.088*DELAY(car_weight,13)+0.051*DELAY(car_weight,14)+0.027*DELAY(car_weight,15)

avg_bumper_weight = 0.035

avg_engin_weight = 0.2

avg_glass_weight = 0.004

avg_instrument_weight = 0.0028

avg_steering_weight = 0.0036

avg_transmission_weight = 0.07

bumper_recovery_rate = 0.45

disposal_cost = 6

engine_recovery_rate = .1

ferrous_recycling_fraction = 0.96

glass_recovery_rate = 0.3

hulk_&_trans_cost = 48

instrument_recovery_rate = 0.1

investment_cost = 15

junk_&_trans_cost = 50

miscellaneous_recycling_fraction = 0

nonferrous_recycling_fraction = 0.55

others_recovery_rate = 0.1

others_weight = 0.08

plastics_recycling_fraction = 0

processing_cost = 75

retire_rate = 0.95

shreddering_amount = ferrous+nonferrous+plastics+miscellaneous

shreddering_processing_cost = 10

steering_recovery_rate = 0.35

total_landfill = ferrous_landfill+nonferrous_landfill+plastics_landfill+miscellaneous_landfill

transmission_recovery_rate = 0.35

weight_of_airbag = 0+STEP(0.005,2002)

weight_of_battery = 0.013

weight_of_conveter = 0.012

weight_of_gas_tank = 0.02

weight_of_tires = 0.040

car_weight = GRAPH(TIME)
(1975, 1.72), (1976, 1.71), (1977, 1.66), (1978, 1.59), (1979, 1.58), (1980, 1.53), (1981, 1.47), (1982, 1.41), (1983, 1.45), (1984, 1.43), (1985, 1.45), (1986, 1.42), (1987, 1.44), (1988, 1.37), (1989, 1.43), (1990, 1.31), (1991, 1.38), (1992, 1.42), (1993, 1.43), (1994, 1.37), (1995, 1.31), (1996, 1.30), (1997, 1.28), (1998, 1.27), (1999, 1.26), (2000, 1.25), (2001, 1.23), (2002, 1.22), (2003, 1.20), (2004, 1.19), (2005, 1.18), (2006, 1.16), (2007, 1.15), (2008, 1.13), (2009, 1.12), (2010, 1.10), (2011, 1.09), (2012, 1.08), (2013, 1.06), (2014, 1.05)

landfill_cost = GRAPH(TIME)
(1990, 35.0), (1991, 35.0), (1992, 35.0), (1993, 35.0), (1994, 39.0), (1995, 43.0), (1996, 47.0), (1997, 51.0), (1998, 55.0), (1999, 59.0), (2000, 63.0), (2001, 67.0), (2002, 71.0), (2003, 75.0), (2004, 79.0), (2005, 83.0), (2006, 87.0), (2007, 91.0), (2008, 95.0), (2009, 99.0), (2010, 103), (2011, 107), (2012, 111), (2013, 115), (2014, 119), (2015, 123), (2016, 127), (2017, 131), (2018, 135)

sales = GRAPH(TIME)
(1990, 9300), (1991, 8175), (1992, 8213), (1993, 8742), (1994, 9271), (1995, 9800), (1996, 9920), (1997, 10040), (1998, 10160), (1999, 10280), (2000, 10400), (2001, 10520), (2002, 10640), (2003, 10760), (2004, 10880), (2005, 11000), (2006, 11120), (2007, 11240), (2008, 11360), (2009, 11480), (2010, 11600), (2011, 11720), (2012, 11840), (2013, 11960), (2014, 12080), (2015, 12200), (2016, 12320), (2017, 12440), (2018, 12560)

total_shipments = GRAPH(TIME)
(1990, 6065), (1991, 5407), (1992, 5925), (1993, 6375), (1994, 6675), (1995, 6900), (1996, 7200), (1997, 7425), (1998, 7650), (1999, 7725), (2000, 7950), (2001, 8175), (2002, 8400), (2003, 8625), (2004, 8775), (2005, 8925), (2006, 9150), (2007, 9300), (2008, 9375), (2009, 9600), (2010, 9750), (2011, 9975), (2012, 10200), (2013, 10350), (2014, 10500), (2015, 10650), (2016, 10800), (2017, 10950), (2018, 10950)