A Product Lifecycle Framework for Environmental Management and Policy Analysis:

Case Study of Automobile Recycling

by

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Abstract

An analytical framework has been developed to integrate product recycling into industry's environmental management strategy and its financially driven operating structure. This approach advocates the explicit consideration of cost and market relationships when evaluating environmental issues. Through process simulations, research has shown the current hulk shredder based automobile recycling infrastructure in the United States to be financially robust and exceptionally tolerant of the automobile's changing material content. For those markets with higher landfill cost structures, hulk shredding complemented by selective disassembly and various shredder residue treatment processes can still offer stable post-use management options. While it is relatively straightforward to financially promote particular recycling schemes, the environmental justifications for such manipulations are often ambiguous. Mandating increased recycling can adversely affect the attainment of other environmental goals.

In order to better articulate the rationales behind environmental initiatives, this thesis employs a product lifecycle methodology to resolve seemingly conflicting environmental objectives and to rationalize product design decisions. By assessing the environmental and economic effects of public policy and product design decisions throughout all stages of a product's existence, one can begin to move towards a globally optimal solution. Thus, this research has been able to demonstrate recycling policies' potential drawbacks and short-sightedness. By narrowly defining environmental problems within a landfill conservation argument, it is easy to justify recycling's benefits. If instead analyses are undertaken from a systems perspective like the lifecycle concept, trade-off possibilities among the diverse environmental objectives become clear. Each product design possesses its unique environmental impact profile. Furthermore, these designs have varying financial effects on the business entities throughout the different lifecycle stages. A cogent environmental management approach therefore must focus on facilitating these various trade-offs among the diverse environmental and economic issues.

Thesis Supervisor: Dr. Joel P. Clark
Title: Professor of Materials Engineering

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Table of Contents

List of Figures

List of Tables

1. Overview

This thesis examines the environmental and economic implications of recycling. While recycling may often be regarded as an environmental panacea by regulators, the public, non-government organizations, and even industries, this confidence is based on tenuous assumptions. Recycling certainly has appealing potential benefits. Its ability to direct the post-use waste stream away from landfills is a principal attraction in solid waste management strategies. It should in theory also achieve broader resource conservation objectives by substituting virgin materials with recovered ones in production processes. These perceptions regarding recycling's capabilities may be intuitively straightforward but are inadequately substantiated. Recycling is an industrial process that has its own impacts on the environment. By focusing only on its potential benefits without consideration of the possible drawbacks, arguments for recycling may be unrealistically optimistic. Nevertheless, such qualitative and incomplete assessments have been used to rationalize a wide range of policies to increase post-use recycling.

Economic considerations in undertaking recycling similarly have suffered from superficial analyses. Despite the current unprofitability of many recycling schemes, such adverse conditions are routinely dismissed by arguing that recycling costs will drop as process volume increases and technology is refined. Stabilization of secondary material markets is assumed to occur as recyclate quality and availability increase. Better knowledge of recyclates' performance and processing properties presumably can provide further recyclate price support. Such cursory assessments ignore the cost structures and market dynamics of industrial processes. Recycling, like any other industrial undertaking, is driven by fundamental process considerations. Product yields are ultimately constrained by the laws of thermodynamics. Decreases in marginal production costs are critically dictated by the relationship between the process' fixed and variable costs. Market development for recyclates, while significantly determined by the material's performance characteristics and production function, also depends on a complex demand function reflecting product mix and feedstock substitution opportunities.

The major hypothesis of this work is that while recycling has the potential to offer dramatic environmental improvements and still allow financial profitability, a simple qualitative assessment of these features is an inadequate basis for policy rationalization. Recycling is a market-driven undertaking with system-wide environmental and product design implications. A quantitative approach is required to ascertain the attainability of recycling policies as well as their short and long-term compliance costs. From industry's perspective, definable cost parameters are necessary to operationalize environmental information and to formulate strategic responses. Furthermore, there is the need to verify recycling's environmental benefits. Regulations can undoubtedly force product recovery and material reclamation schemes to play a greater role in post-use management strategies regardless of their costs. Justifying such regulations, however, requires substantiation that recycling's resulting environmental benefits have values greater than their costs.

This thesis proposes and develops a new environmental management paradigm to move recycling issues beyond rhetorics and to pose them within a consistent analytical framework. Automobile post-use management, a major environmental concern, serves as a case study. Through process studies and computer simulations, the environmental and economic driving forces behind various automotive recycling schemes are identified and quantified. Results show that the automobile currently is very recyclable and extensively recycled. Although various alternative post-use management routes may more aggressively minimize the post-use automobile's landfill liability, there are broader economic and environmental issues that must also be addressed. Post-use management costs, as well as product manufacturing and use costs, may increase dramatically as a result of recycling initiatives. Furthermore, this thesis indicates that while recycling policies may be justifiable if environmental benefits are narrowly defined as landfill conservation, they can aggravate other environmental objectives.

To avoid the short-sighted environmental planning embodied in many recycling policies, this thesis provides a quantitative systems perspective that offers greater problem resolution, exposes previously unforeseen consequences, and identifies trade-off opportunities. Utilizing the concept of a product's lifecycle from raw material production through product manufacturing, use, and post-use, the thesis illustrates the interactions among the various lifecycle stages, business entities, and environmental objectives.

2. Background

2.1. Focus On Product Post-use

Packaging materials have been the focus of post-use regulations for the past several years. Most states in the U.S., as well as Japan and many European nations, have already adopted legislation aimed at increasing recycling rates of packaging materials.[1,2,3,4,5] Consumer durables, in particular automobiles, are widely recognized as the next major category of manufactured goods to be more specifically regulated.[6,7,8] Long vilified for its central role in petroleum depletion and air pollution during its use stage, the automobile is now under increasing environmental scrutiny at its post-use stage as well.[9] With approximately 9 million passenger vehicles junked every year in the U.S. alone, at an average mass of 1400 kilograms per vehicle, 12.6 million metric tons of automotive materials can enter the waste stream every year.[10] Technological and market factors have effectively addressed this waste stream by recovering roughly 75% of the vehicle by weight. The convergence of the electric arc furnace for steelmaking with the vehicle hulk shredder and separator for high throughput size reduction and materials segregation created the financial incentive to recycle the largely ferrous automobile.[11] The remaining 25%, termed automobile shredder residue (ASR) or fluff, is composed of organics (*e.g.* plastics, paper, wood), inorganics (*e.g.* dirt, glass), and moisture. Debate is now focused on whether to landfill or recycle this remaining 25%.

The perception of landfill scarcity has prompted this drive towards an even more complete vehicle recycling scheme. The number of landfills in the U.S. has dwindled from approximately 20,000 in 1979 to 6,600 by 1989 as existing sites reach capacity and new sites become more difficult to locate.[12] While arguments for increased recycling commonly refer to this decline in the number of existing sites, a more realistic perspective is the total landfill capacity. Whether expressed in terms of tons, cubic meters, or years-to-fill, a capacity figure accounts for the fact that larger and more modern landfills continue to exist or even to expand as older and smaller dumps close. Total landfill capacity thus may not be decreasing nearly as rapidly as the site count indicates.[13] Nevertheless, the perception of a landfill crisis, regional space shortages, and stricter landfill maintenance standards all have contributed to increasing landfill charges. In Midwest U.S., for example, tipping fees have climbed over 20% to approximately $24/mton in the 1988 to 1990 period. There are also regional variations with the Northeast at about $70/mton.[14] While ASR is currently disposed in Resource Conservation and Recovery Act (RCRA) Subtitle D landfills, *i.e.* conventional municipal solid waste landfills, there is growing pressure for more stringent disposal requirements due to ASR's potential cadmium, zinc, and lead content.[15,16] Disposal costs may then skyrocket.

Another important factor for the increased attention to automobile's post-use stage is the apprehension that vehicles' changing material contents may jeopardize the existing ferrous scrap driven automobile recycling infrastructure. The dramatic change in a typical automobile's material content over the past 2 decades is evident in the next graph.[17] Since a change in material accounting methodology occurred after 1989, the figures before and after 1990 are not directly comparable. Nevertheless, the increasing usage of nonferrous metals and plastics is evident. Environmental regulations have dramatically changed the design and manufacture of the automobile. Air emission and fuel efficiency mandates have led to the use of novel materials and processing approaches. The result is that today's car has evolved from a predominantly spot welded ferrous product into one with material composition and joining techniques of unprecedented diversity. The average mass of vehicles has decreased from 1709 kgs in 1976 to less than 1441 kgs in 1994 as part of the strategic response to develop fuel efficient automobiles. Some of this lightweighting has come from vehicle downsizing. The other major factor has been the replacement of traditional ferrous materials with lower density alternatives. Polymer applications in particular have experienced rapid growth in the automotive sector with today's vehicle averaging 112 kgs of plastic materials, up from 73 kgs in 1976. This represents a rise of more than 50%.

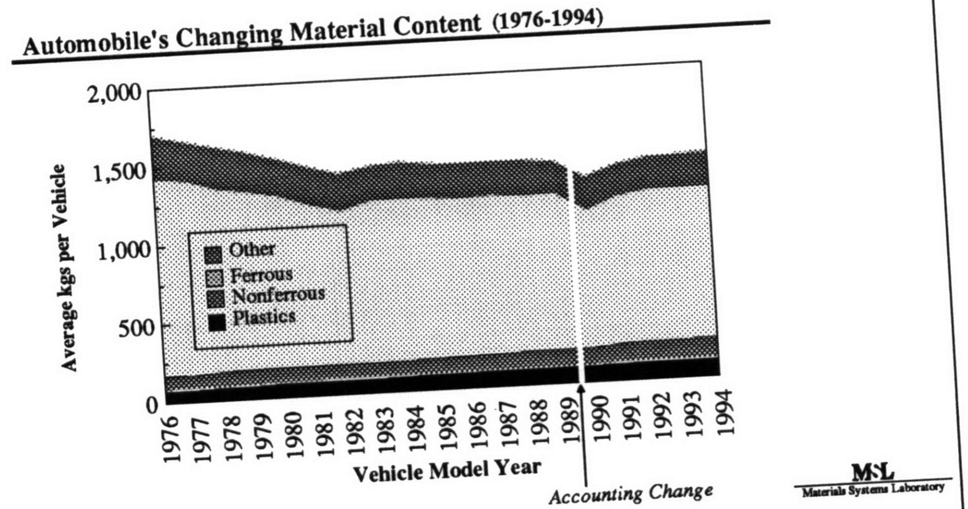

Figure 2.1: Changing Material Content of the Automobile

There have been numerous arguments that polymers are red herrings in environmental, especially landfill, debates.[18,19] Data indicate that plastics account for only 8% by weight of the municipal solid waste stream with automotive plastics making up only 1.2% by weight.[20,21,22] For the specific case of post-use automotive materials, the approximately 3 million metric tons of shredder residue generated each year is small relative to the 200+ million metric tons of municipal solid waste. Nevertheless, automotive polymers attract a seemingly disproportionate amount of attention. The combination of lower overall vehicle mass, smaller ferrous fraction, and larger polymer fraction potentially leads to the typical post-use automobile with a lower ferrous revenue and a higher fluff landfill cost liability than previous year models. This continuing trend, seen in the next figure, has prompted warnings that the existing vehicle recycling infrastructure may eventually collapse.[23,24,25,26,27,28]

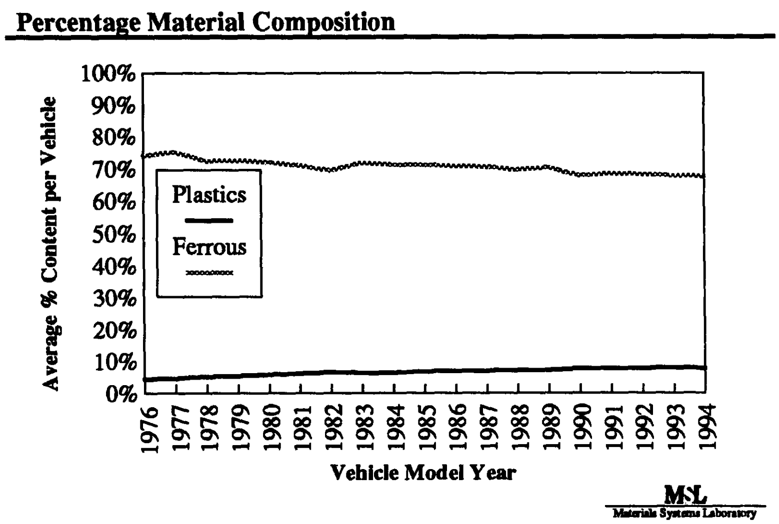

Figure 2.2: Plastics and Ferrous Contents in the Automobile

Polymers have been a major target of recycling efforts since they are not extensively recovered from the automobile and thus constitute a large fraction within the ASR stream. Unlike most metals, which enjoy relatively mature recovery procedures and established secondary markets, post-consumer plastics struggle to balance their recovery costs with often small residual market values. Polymer's high volume to mass ratio further exacerbates this material's landfill consumption potential. Schemes to improve automobile recycling thus often focus on developing cost effective solutions to treat the vehicle's polymer content.[29,30,31,32,33,34,35,36] Automakers are increasingly wary of polymer's disposal implications and are actively incorporating post-use management into the product development process. In particular, automakers and their suppliers are challenged to more thoroughly examine their material selection rationale and its post-use consequences. Public perceptions regarding a product's environmental friendliness and an industry's environmental responsibility certainly are factors for industry's growing awareness. Escalating regulatory pressures to reduce a product's post-use impacts and thwart any possibility of a recycling infrastructure collapse may be the more insistent stimulus.

2.2. Recycling's Resource Conservation Appeal

Recycling has become a prominently upheld environmental panacea based on its perceived resource usage sensibility. There are several indisputable facts that make arguments for recycling quite convincing. Material recovery undertakings certainly can redirect a particular waste stream, ostensibly leading to a net reduction in landfill consumption. Recycling, therefore, has been an often touted solution to various post-use management goals. Moreover, there is a broader resource conservation appeal. The observation that the resource requirements to produce a given material from its basic precursor are greater than those from some intermediate feedstock stage is often cited as one of recycling's inherent benefits.[37,38,39] Energy, in particular, is a resource that is often identified during resource conservation discussions. For materials with energy intensive ore refining steps, such as aluminum, the potential energy savings through the reuse of scrap materials may be substantial. Some potential energy savings are presented in the next table.[40,41] The data is intended only for comparisons between a specific material's virgin and recycled grades. Comparisons among the different material classes, *i.e.* the rows in the table, may be dangerous given that different testing and accounting procedures are employed.

Material	Energy Requirement for Virgin Material (MJ/kg)	Energy Requirement for Recycled Material (MJ/kg)
Aluminum	341	62
Carbon Steel	64	39
Zinc	106	65
RIM Polyurethane	98	34

Table 2.1: Potential Energy Savings From Recycling

Recycled material's resource savings are not surprising since materials production and processing are a series of value-added and resource-added steps. This concept is shown schematically for energy in the next figure. This energy-added chain shows the major stages in a material's lifecycle with returning arcs indicating some recycling possibilities.

The further upstream to which the material is returned, the greater the energy not recovered and thus the greater the energy required to bring the material back to a useful form. This chain can be viewed from whichever resource perspective is of interest (*e.g.* petroleum consumption, CO_2 emission). Alternatively, a value chain can provide insights into a material's economic inputs and outputs (*i.e.* financial resources). A particularly attractive implication is that recycling can perhaps produce materials with lower costs relative to their virgin counterparts by bypassing those process steps required only by virgin materials.

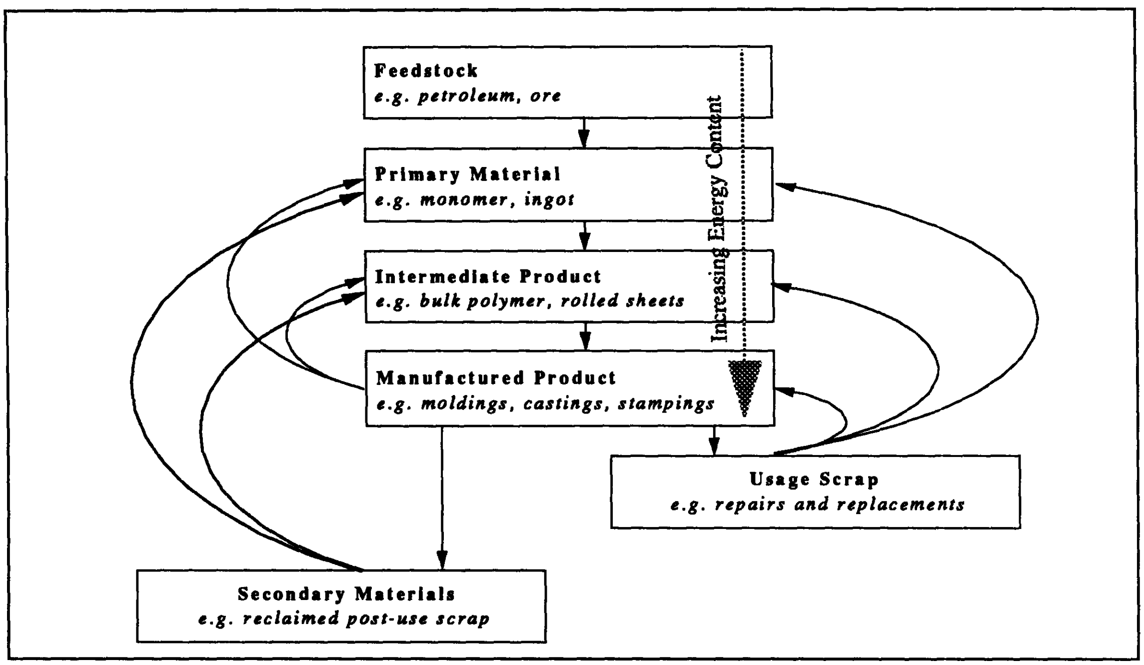

Figure 2.3: Energy-added Chain

The recycling alternatives represented by the various loops are often categorized into primary, secondary, tertiary, and quaternary recycling. Options for the specific case of polymers are shown in *Figure 2.4*. Primary recycling typically refers to reusing the recovered material in the same application from which it is derived. In this case, the waste usually must be meticulously segregated and cleaned. For polymers, primary recycling is most readily accomplished with remeltable thermoplastic scrap from the factory floor rather than post consumer waste. Secondary recycling refers to using the material in an application less demanding than the original. Slightly contaminated wastes thus can be tolerated. Construction shapes are typical end-uses. The reuse of automotive steel scrap in I-beams and polymeric scrap as plastic lumber are examples. Thermoset polymers are often reused as fillers. Tertiary recycling reclaims the material as its feedstock components. For polymers, this means the recycling process yields some type of petrochemical resin precursor (*e.g.* pre-polymer, monomer, oil, gas). Tertiary processes are usually quite tolerant of contaminations and are thus well suited to treating post consumer wastes and even highly heterogeneous mixtures such as automobile shredder residue. Quaternary recycling also brings the material back to its feedstock stage. Instead of recyclate materials, the corresponding heat of combustion is captured. That is, the waste is converted to energy.

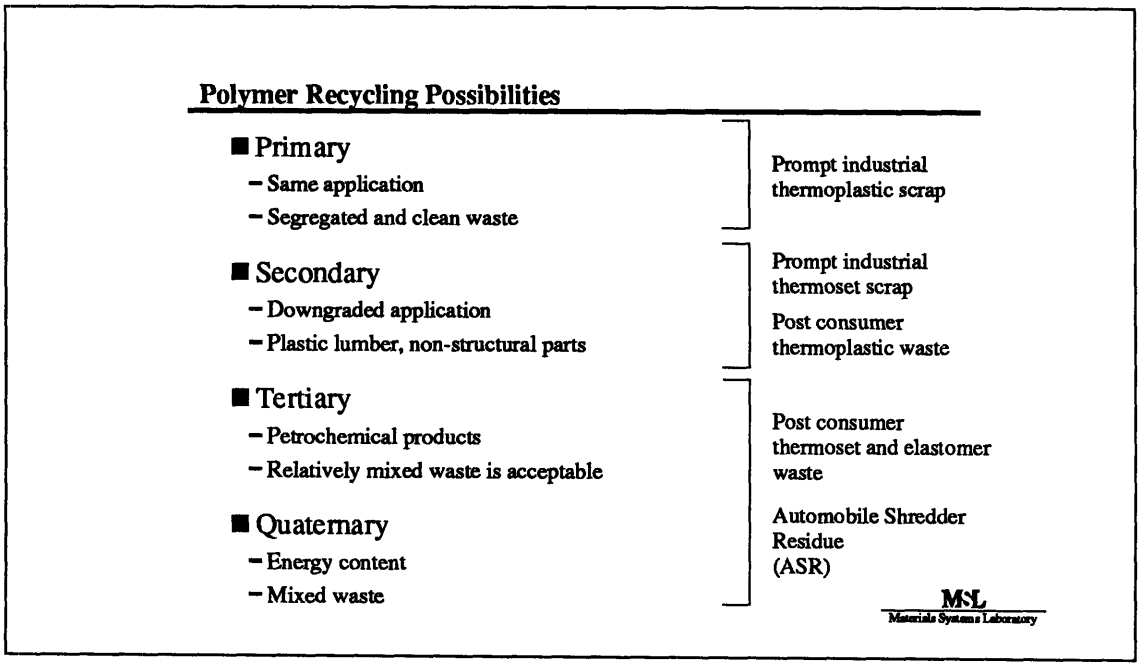

Figure 2.4: Recycling Alternatives for Automotive Polymeric Materials

Figures 2.3 and *2.4* show recycling's potential resource saving and processing routes, but also evidence recycling's problem of multiple and ambiguous definitions. There clearly are many approaches to recycling and each has different associated environmental results. Out of the intuitive observation that shorter return loops in the resource chain can lead to greater quantities of recoverable resources, a post-use management hierarchy has been widely promoted by government bodies such as the U.S. Environmental Protection Agency (EPA), the German Federal Environment Ministry (*Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit*, or BMU), as well as some segments of industry.[42,43,44,45,46,47] Commonly referred as the 3 R's of reduce-reuse-recycle, this hierarchy emphasizes a source reduction strategy. That is, using less material in the first place is deemed to be the most effective in reducing landfill consumption. Product re-use is given next priority followed by materials recycling. Incinerating for energy recovery and landfilling are to be undertaken only as a final options. Within the material recycling option, primary or closed loop recycling is often preferred. That is, the material must be reclaimed and reused in the original or similar requirement. This preference for recycling to be a closed loop process is a common fixture in environmental thinking. This idealistic view is often captured in a figure similar to the one below.

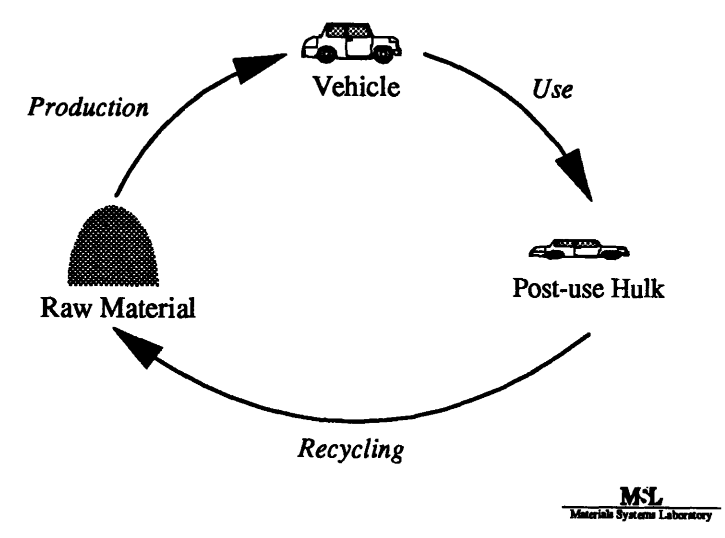

Figure 2.5: Simplistic View of Recycling As a Closed Loop Process

Closed-loop recycling's appeal lies not only in its potential energy savings as outlined in *Figure 2.3*, but also in its potential for raw material conservation. Intuitively, this type of recovery exploits the most of recycling's resource conservation potential by allowing an one-time infusion of raw material to be recirculated throughout multiple product lives. This loop ideally should have a lower associated economic and environmental burden than a production route starting from virgin materials. Ultimately, closed-loop recycling is upheld as a solution towards resource sustainability. While there are many schools of thought about the roles of resource substitution, technological development, and conservation in achieving sustainable development, recycling is generally viewed favorably.[48,49,50,51,52] As part of a paradigm to offer equivalent product functionality at reduced resource consumption, recycling has the potential to ease the manufacturing industry's burden on the environment. The next figure schematically shows an automobile's consumption levels for some arbitrary resource over three product lives.

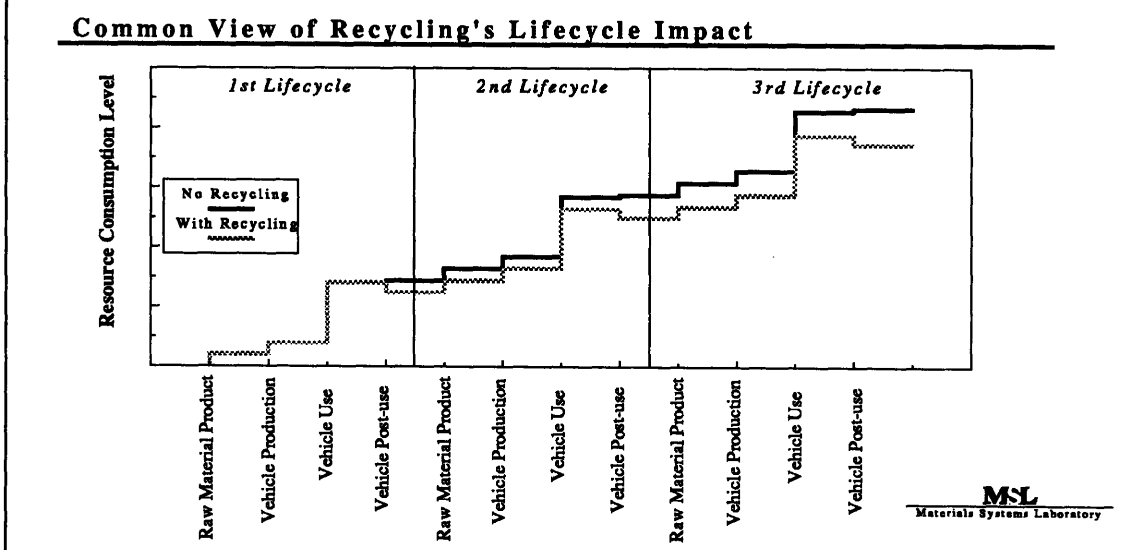

Figure 2.6: Idealized View of Recycling's Impact on Resource Consumption Pattern

Each lifecycle is broadly classified into raw material production, vehicle production, use, and post-use. The darker line indicates the consumption pattern given a no-recycling paradigm. The lighter line indicates the use of recyclates in place of virgin materials for the next product life. Through the vehicle use stage in the first lifecycle, the two lines follow identical paths. At the post-use stage, the lines begin to diverge. While the no-recycling scheme continues to utilize some small amount of resources in the disposal undertaking (*e.g.* energy), the recycling alternative should offer some net resource recovery. Over multiple product lifecycles, the divergence between a no-recycling versus a recycling approach becomes greater. The self-sufficiency implication of the closed loop in *Figure 2.5* can be translated into the lower resource consumption trajectory seen in *Figure 2.6*. Offering tantalizing resource conservation benefits, including the potential to significantly reduce landfill usage, recycling is being aggressively promoted through legislatory and consumer awareness campaigns.

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3. Policy Initiatives to Increase Recycling

3.1. Policy Rationales

Recycling's ability to dramatically redirect the post-use waste stream and potentially lead to a product with lower resource consumption patterns is based on engineering arguments. Some environmental benefits attainable from recycling thus can be, at least theoretically, substantiated. Yet, especially for post-consumer materials, recycling is neither an inherently routine nor feasible undertaking. In fact, out of the 188 million mtons of municipal solid waste generated in 1993, only 22 percent is composted or recycled for materials reclamation. An additional 16 percent is combusted, usually for energy recovery.[53]

This disparity between recycling's potential environmental benefits and the limited degree of post-consumer recycling has prompted policymakers to focus their attention on disposal issues. Faced with an uncertain market for recyclates, individual firms may be unwillingly to commit financially towards widespread post-consumer recycling. The basic policy objective, for packaging or automotive materials, is therefore to create and stabilize markets for recyclates. In terms of the familiar supply-demand curve seen in *Figure 3.1*, policymakers wish to push down the supply curve and/or pull up the demand curve to allow some equilibrium market price to exist. At such a price (P^*), some corresponding quantity of recyclates (Q^*) will be marketed.

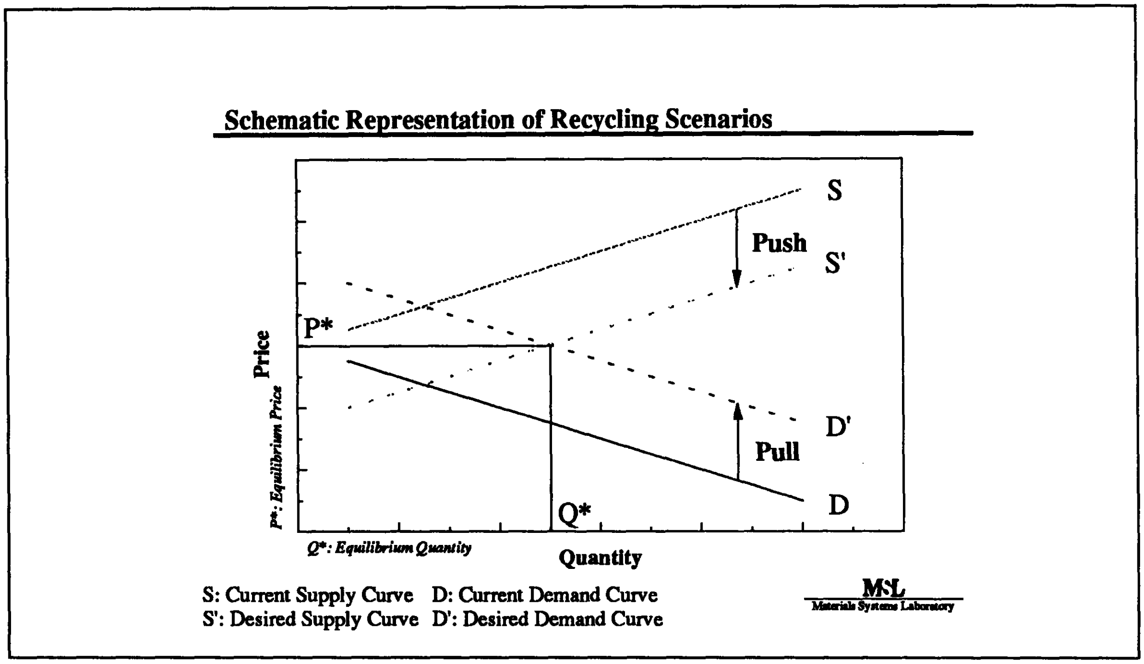

Figure 3.1: Recycling Policy's Market Creation Objective

There are two rationales behind such supply and demand curve manipulations. The first is based on the theory of economic externalities. An externality is said to exist whenever an individual's utility or production functions include nonmonetary variable, whose values are chosen by others without particular attention to the effects on this individual's welfare.[54] For post-consumer recycling, the externality is grounded on the notion that the present rate of landfill consumption is too high. Since landfill cost is usually funded through a broad tax base and is not related to an individual's waste generation pattern, there is no incentive for the individual to conserve landfill space. Yet, each individual's continued landfill use does impact society at large by reducing the availability of this public good (thus satisfying the above definition). A more expansive view of disposal's externalities considers not only the over-use of landfill space, but also the under-use of resources contained in the waste. The argument is that the external costs of virgin materials consumption and disposal (*e.g.* deforestation, wildlife habitat loss, noise, odor, property value decline, aquifer contamination, air and water pollution, health problems related with industry) are not directly carried by the cost originator. Therefore, non-optimal production, consumption, and disposal patterns may result (*e.g.* overconsumption of landfill and virgin materials, underconsumption of secondary materials).

This idea potentially has major repercussions on economic activities. Essentially, the externality argument reflects the opinion that existing market prices are based on incomplete information. Regulations therefore, should be enacted to correct this market failure. In the case of automobile post consumer wastes, the costs of producing, using, and disposing the vehicle's material content are viewed as being not fully carried by the manufacturers and users. That is, there are external costs not captured by definitive market prices but nevertheless borne as losses by society as a whole. By shifting the solid waste disposal burden traditionally borne by municipal governments to those parties directly responsible for the waste, policymakers are seeking to internalize those external costs associated with product disposal.[55] Industry, in particular, has been singled out as an appropriate point of cost internalization. This decision is based not so much on manufacturers being the principal generators of post-consumer waste (after all, product consumers are the ones directly responsible), but rather on manufacturers' ability to leverage design in addressing post-use issues.[56,57] If product manufacturers are directly confronted with the responsibility of product disposal, they should then have the financial incentives to enact alternative design, production routes, and material recovery schemes in order to decrease their products' post-use environmental burden. Recycling may then become an economically feasible undertaking in more instances.

The second justification for supply-demand curve manipulations is based on an economies-of-scale argument. Recycling, like any industrial process, requires capital investments. The profit potential of processes with large fixed costs (*e.g.* equipment) relative to variable costs (*e.g.* labor), can be characterized by a curve similar to that in *Figure 3.2*.

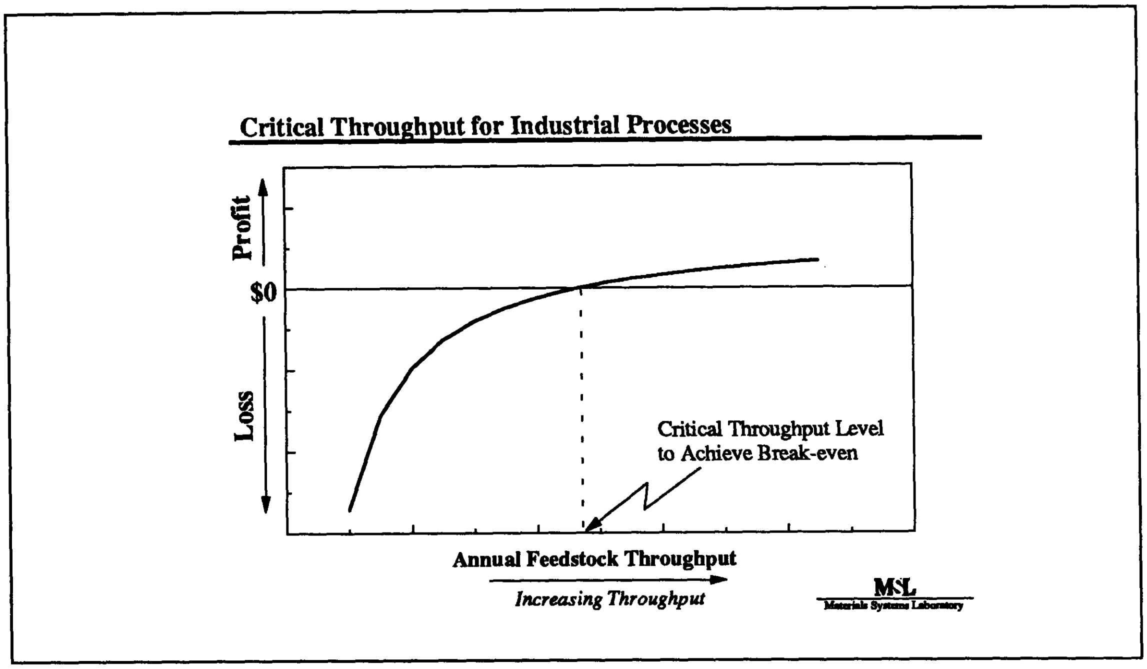

Figure 3.2: Critical Throughput To Allow Recycling Process to Reach Break-even

As feedstock throughput increases, whether it is number of vehicles or metric tons of post-consumer waste, the fixed capital investment can be distributed among more units. The fixed cost per unit thus decreases geometrically. Combining this decreasing fixed cost with the constant variable cost component, and revenue, a net income curve like the one above can be generated. At some critical process volume, the unit cost can be lowered enough to achieve a financial break-even. A major obstacle to improving recycling economics, some would argue, is achieving this critical throughput threshold. The opportunity to exploit a recycling process' economies-of-scale is not straightforward given that post consumer wastes are generated by geographically disperse and non-uniform households. Collection and transportation costs may prohibit an adequate volume of recycling process feedstock to be acquired. These variable costs, together with the potentially large fixed costs required to set up processing facilities, may represent significant barriers-to-entry into the recycling business. Many policies intended to stimulate recycling activities thus are designed to ensure that enough feedstock can be consolidated for the recycling industry to reach the break-even operating level.

3.2. Current Policies

Seeking to internalize environmental costs and cultivate the recycling industry, several solid waste recovery policies have been proposed and implemented. These policy initiatives to increase recycling can be broadly categorized into "push" and "pull", corresponding respectively to supply and demand shifts. Schematic illustrations of these policy concepts can be seen in the next figure.

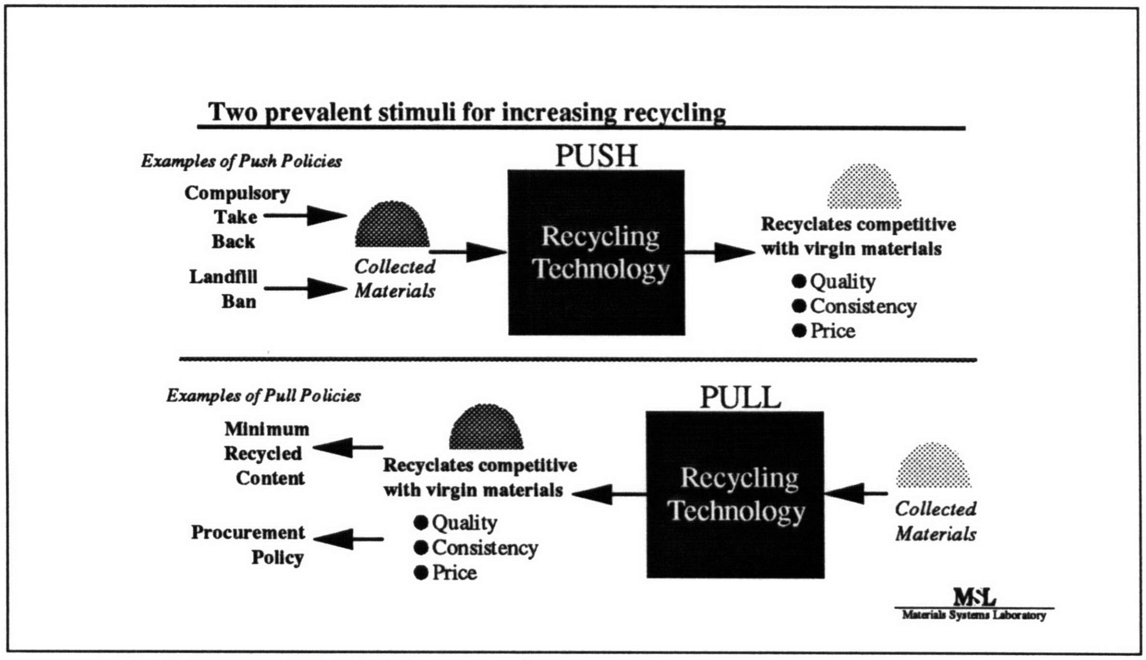

Figure 3.3: Schematic Representation of Common Policy Thinkings

The push approach, exemplified by take back mandates and landfill ban policies, seeks to drive technological developments by enforcing post-consumer materials collection. Faced with a potentially staggering amount of collected waste, industry will be compelled to develop the necessary technology and establish the necessary infrastructure to process these materials. Ostensibly, valuable recyclates will be produced according to businesses' financial best interests. The pull approach, exemplified by material content and procurement policies, addresses the demand side. By forcibly creating a market for recyclates, industry should in turn create the technology and infrastructure to exploit this profit opportunity. The basic premise behind both the push and pull approaches is that such mandates internalize post-use management cost into the manufacturer's operating structure and thus will spur novel processes and product designs incorporating recycled materials. Imbedded in these legislations are assumptions regarding technology drivers that can determine whether increased recycling can indeed be accomplished through public policy manipulations. The next figure illustrates potential technology development routes.

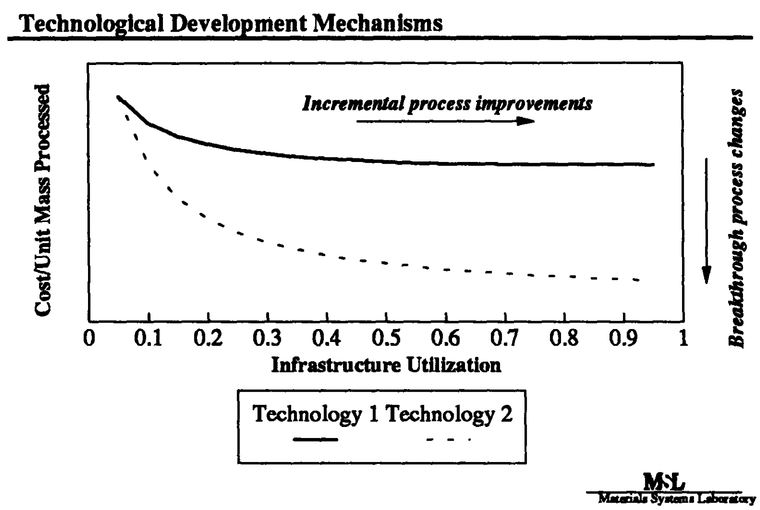

Figure 3.4: Effect of Technological Change on Process Cost

Technology, including those related to recycling, can develop via either breakthrough technical or incremental processing advances. The desired result is the lowering of the recyclate's recovery cost, and eventually in a competitive market, the selling price. Incremental process improvements are the result of process and design refinements and more efficient capacity usage. Roughly grouped together under the term infrastructure utilization, the basic idea is that a more fully utilized recycling scheme will lead to a gradual decrease in operating cost (*i.e.* economies-of-scale). This concept is a familiar one since it underlies any large-scale manufacturing (and to a lesser extent, service) undertaking.

A breakthrough improvement, rather than a series of gradual refinements, is a radical approach to dramatically lower process costs. Represented by a jump from technology curve 1 to 2 in *Figure 3.4*, a technology breakthrough can lead to a new cost reduction path. Of course, incremental improvements can still follow. It is important to note that technology changes can refer to both process and design innovations. Arguments for recycling mandates are driven by the underlying conviction that such technological developments can be forced (*i.e.* guided from the upper left region of *Figure 3.4* to the bottom right). The combination of stimulating demand for recycled materials (pull) and reducing recycling's costs (push), some recycling advocates argue, will drive the formation of secondary material markets. While external forces may be required to initiate recycling, an equilibrium-seeking market should evolve as consumer appreciation of recycled materials increases, and more crucially, as product and production technologies develop.

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4. Research Objectives

4.1. Cost Analysis of Recycling Processes

Regardless of its potential environmental benefits, a particular recycling technology's economic feasibility is necessarily the critical determinant in a firm's decision to undertake that recycling process. Certainly, from a competitive advantage standpoint, firms always have sought cost-effective operations. Even if recycling is undertaken only to satisfy specific regulations, a detailed understanding of processing costs is still required to facilitate asset allocation and cash flow calculations. Regulators also should be concerned with the costs of recycling to better gauge a particular statute's attainability. The push and pull initiatives described earlier simplistically treat technology as a black box. The assumption that technology development and process feasibility can be indiscriminately dictated has potentially disastrous implications. Recycling is a financially driven undertaking and a resource consumer just like any other material processing scheme. Thus, while any arbitrary degree of recycling is probably technically achievable, the associated net economic and environmental benefits can be ambiguous. Nevertheless, recycling's potential environmental benefits have usually been heralded as absolute and without stipulation.

One major premise in arguments for recycling is that the resource savings due to material reclamation is realistically achievable. The energy savings commonly touted, like those in *Table 2.1*, in actuality do not consistently account for the energies expended during recovery processes such as disassembly, shredding, segregation, cleaning, and transportation. Likewise, other categories of resource expenditures (environmental or economic) associated with these recovery processes may significantly alter the financial and/or environmental cross-over point in the choice between recycled and virgin materials. Yet, arguments for recycling often stipulate specific end-use applications and recyclate contents without assessing their corresponding cost and benefit characteristics. Economic feasibility, even if not presently achievable, is assumed to be inevitable as process volume increases and recyclate markets expand. Justifying recycling initiatives simply through comparisons between virgin and recycled materials' resource consumption intensities can lead to unforeseen cost and environmental consequences. The economic viability, and even environmental sensibility, to driving recycling undertakings through policy initiatives needs to be quantitatively substantiated. A move away from treating recycling as a technology black box and towards a better understanding of recycling's cost structure necessitates detailed process analyses.

As many of the policy initiatives suggest, the incongruity between recycling's potential benefits and the extent those benefits are exploited can be explained by the lack of financial incentives to undertake recycling. A qualitative appreciation of these issues, however appealing, is a dubious basis for market manipulating public policies. A recycling infrastructure is a dynamic economic engine and its driving forces demand closer scrutiny. It is important to realize that the resource recovery potential illustrated by the chain in *Figure 2.3* has associated financial transactions. Each box in *Figure 2.3* usually represents a different economic player. As material is transformed from raw feedstock to finished good during the product creation process, value is added at each step. More significantly, this value can be translated into a selling price some further downstream processor is willing to pay. For this economic chain to be sustainable, the revenue derived from the selling price at each step must be larger than the processing cost so as to yield a net profit. For the automobile manufacturing industry, such relationships exist throughout the supplier-customer network. A key feature of such an infrastructure is the existence of market signals that provide information and incentives for each independent business operation.

For recycling loops, on the other hand, such a financially-driven transfer mechanism often does not exist. While recycling can extract resources out of the waste stream, their potential market value must then be balanced against the processing costs required. Segregation can be particularly crucial since recyclate quality and market value are determined by the effectiveness of this stage. Balancing the benefits of material segregation against the associated process cost is one important aspect of a recycling infrastructure. The usually commingled post consumer waste needs to overcome large obstacles in order to yield a net recycling profit. In addition, virgin materials usually possess better performance or price characteristics relative to reclaimed post-consumer materials, thereby effectively shutting the latter out of the market place. Without a sustainable infrastructure that continuously provides reliable market signals, there is no incentive for businesses to undertake post-consumer recycling, regardless of its theoretical resource conservation potential.

Another important reason to undertake detailed cost analysis is to test the assumption that recovery technologies can be developed and facilities will be constructed to allow recycling processes' economies-of-scale to drive recyclate prices significantly lower. That is, there is the need to confirm whether the technological change curves of *Figure 3.4* indeed can be driven lower and to the right. This assumption is defensible in instances of *relatively* large fixed costs. The building of a recycling infrastructure surely qualifies as requiring a large fixed cost. However, it is far from obvious how this fixed cost compares with the variable costs (*e.g.* labor and energy required for collecting, sorting, and cleaning wastes) necessary to undertake recycling. Technological developments, while central to meeting the goals of the recycling mandates, are nevertheless often superficially assessed. This disconnection between public policy and technological expectation may have crucial consequences for the legislation's feasibility.

4.2. Assessment of Recycling Initiatives' Impacts On Product Development

The increasing emphasis on post-use management further complicates an already demanding automobile development cycle. A motor vehicle's functional requirements range from cost-effective manufacturing, high quality, high fuel economy, and low exhaust emissions to more qualitative factors such as appealing driving performance and appearance. The resulting design objectives, often mutually contradictory, have lead to an uncertain operating environment for the automotive industry. Producers find commitments to specific component designs and material applications difficult to make for fear of unforeseen future liabilities. Notably, the material selection process has even more cost versus benefit ambiguities. As discussed previously, there is concern that polymer applications designed for lightweighting and/or manufacturing cost reduction may complicate conventional ferrous-based automobile recovery options. Increased use of high strength, stainless, and pre-coated steels, as well as nonferrous alloys also means higher valued materials may become unprofitably trapped in lower value reuse applications.

The ability of post-use issues to affect product development has ramifications far beyond the automakers' design studios and manufacturing facilities. Public policy makers also face conflicting objectives. The automobile is probably the most economically and environmentally conspicuous consumer durable product in today's society. Its manufacturing, achieved through processing technologies spanning numerous industries, is a dominant activity in the economy. The motor vehicle industry in the U.S. accounts for 4.5% of Gross National Product and, along with related industries, provides 1 out of every 7 jobs.[58] The American automobile industry utilizes 20% of all the steel, 12% of the aluminum, 10% of the copper, 5% of the lead, 95% of the nickel, 35% of the zinc, and 6% of the rubber used in this country.[59] Concomitant with this considerable resource consumption profile are the energy intensities and industrial emissions of material processing steps from extraction through refining, forming, assembly, and finishing. In the use stage, the motor vehicle's influence is even more striking. The 190 million existing vehicles in the U.S., traveling more than 2 trillion miles per year, consume approximately 50% of the nation's total annual petroleum consumption.[60,61,62] The combustion of this fuel has the additional detriment of contributing to air pollution. Motor vehicles emissions during use contribute approximately 53% of the carbon monoxide, 30% of the nitrogen oxides, and 27% of the hydrocarbons emissions in the U.S.[63]

Because of its considerable environmental impacts, numerous regulatory measures have been aimed at the automotive industry. Often enacted through contentious government and industry debates, these regulations aim to promote the development of environmentally less burdensome vehicles. The statute that most squarely affects cars is the Corporate Average Fuel Economy (CAFE). Imposed as part of the Energy Policy and Conservation Act of 1973, CAFE and its mandated fuel economy target for an automaker's fleet of vehicles sold went into effect in 1978. Intended to reduce U.S. reliance on imported petroleum, the CAFE standard arguably spurs the development of more fuel efficient automotive technologies. The design trend towards lighter-weight vehicles is strongly driven by the fuel economy regulation as can be seen in the next figure.[64]

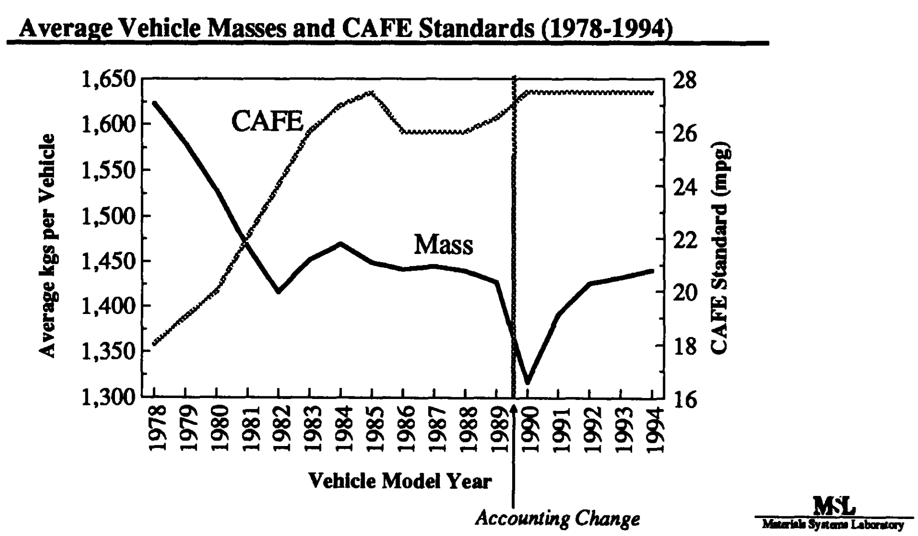

Figure 4.1: Relationship Between CAFE Standard and Average Vehicle Mass

Another mandate that has significant impact on the automobile is the Clean Air Act. Last amended in 1990, some elements of this legislation seek to reduce vehicle tailpipe emissions. Other aspects target manufacturing industries, often automotive related, to reduce stack emissions. Since tailpipe emissions result from fuel combustion, increasing vehicle fuel economy in itself can lead to a lowering of vehicle emissions over a fixed distance driven. A regulation such as CAFE thus can be complementary with certain aspects of Clean Air. Still, the various regulations, intended to stimulate industry to develop products embodying some set of environmental attributes, may at times contradict each other in their objectives. The push towards even lower weight vehicles is likely to continue as legislatory pressure builds to further raise the CAFE standard. Stricter air emission requirements also reinforce this trend. The application of novel material technologies remains an important strategy for meeting this lightweighting challenge.[65,66,67] Traditional product design methodologies may be unsuitable for reconciling these material developments with post-use issues. Typically, a product's functional requirements are established at the concept embodiment stage of a design cycle while specific material selection decisions are relegated to the later detail design stages.[68] Since a product's post-use characteristics are extremely material dependent, explicit considerations of the product's materials content are required much earlier in the design cycle. The need to rationalize vehicle design and material selection decisions, at the concept development stage, to meet the automobile's complex product requirements will become more acute.

4.3. Towards Proactive Environmental Management

Product development is an iterative activity that identifies and balances market needs, regulatory demands, and the producer's capabilities. As environmental concerns increasingly enter a firm's decision making process, the designer demands more comprehensive and flexible analytical tools. Environmental issues traditionally have been trimmed to fit conventional cost accounting methodologies. Economic externalities such as aesthetics, bio-diversity, and resource sustainability are neglected. Instead, the focus has been on market information like pollution abatement costs. These costs, such as those for scrubber, disposal, and permit requirements, allow the straightforward application of monetary trade-off analyses. For example, a paint shop may weigh the potential fines due to volatile organic compound emission non-compliance against the capital required for corrective measures to determine its schedule of equipment upgrades. An automaker may consider CAFE penalties with vehicle models' profit margins to determine its optimal product mix. Such an environmental management paradigm, however convenient, is essentially reactive. Regulatory standards become constraints to product and process designs as industry attempts to meet these standards at the lowest cost.

One way to represent the relationship between government regulation and industry response is with a graph like that shown in *Figure 4.2*. By setting environmental standards, in this case a fuel economy level and a mandated automobile recovery rate, government can dictate a product's acceptable environmental performance (mandated region). For industry, at any given time, a set of technological alternatives exists to achieve a range of vehicle fuel economy and recyclability. These alternatives, whether process or product-based, reside within a feasible region bounded by a technology frontier representing the current state-of-the-art. Industry is compelled to attain at least the minimum compliance levels (*s* and *f*) set by regulators. Thus, the automaker will seek to develop a product, for this simple two attribute example, that lies in the intersection between what it is capable of achieving and what it is required to achieve (mandated and feasible region).

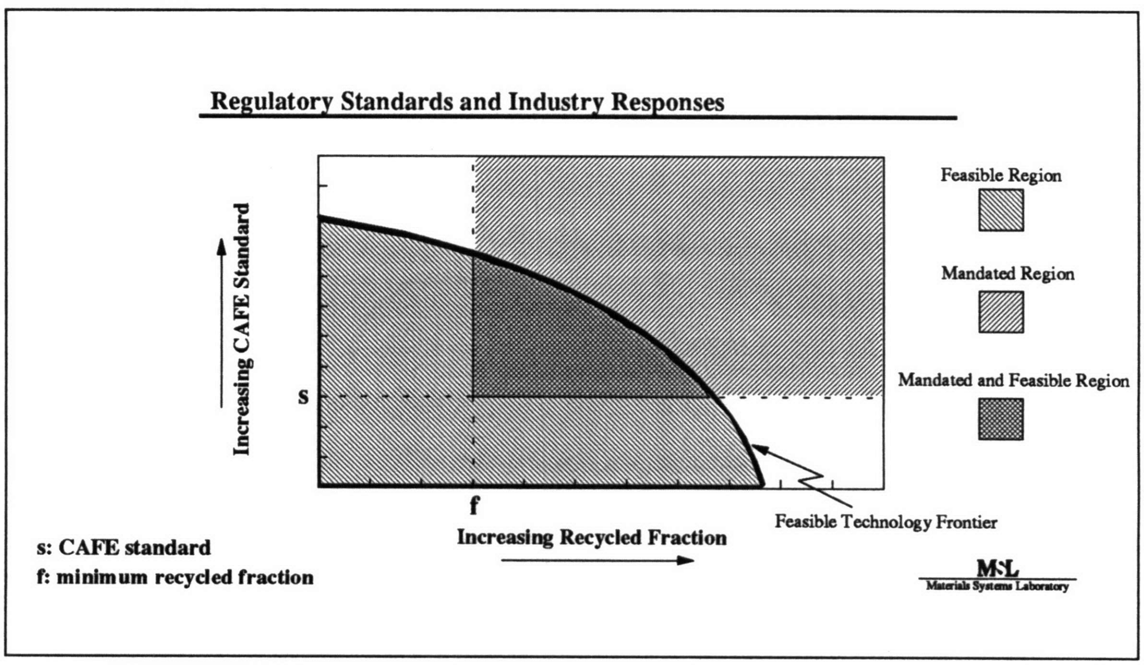

Figure 4.2: Possible Solution Set for Environmental Policy and Management

As increasingly stringent regulations are passed, the mandated region will shift towards the upper right corner as seen in *Figure 4.3*. If the range of technology options available to industry remains static, then the number of complying designs becomes smaller. In reality, the feasible technology frontier can shift. By expanding outward *(e.g.* new developments), the feasible region can encompass more solutions. At the same time the feasible region may contract as previously available options become unrealizable (*e.g.* higher cost, newly classified hazardous material). The crucial scenario is where regulation's mandated solution is out of reach of industry's capabilities. That is, the point of intersection *A* between the standards lies outside of the feasible technology frontier. In this case, environmental objectives are not fulfilled and the cost to industry (and ultimately consumers) becomes unnecessarily high. Proponents of such command-and-control regulations, like the push and pull policy initiatives described previously, argue that imposing more stringent standards represent one method of stimulating the outward expansion of the feasible technology frontier.

This thesis aims to examine this assumption in more detail by assessing the cost and environmental performances of novel automobile recycling technologies.

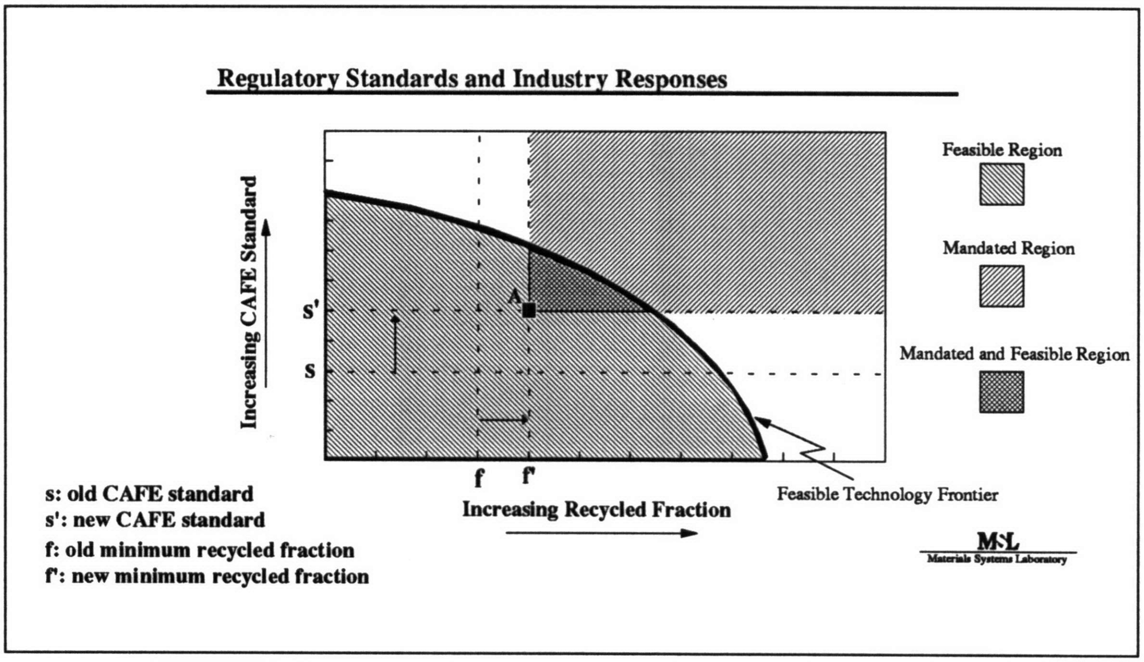

Figure 4.3: Increasing Environmental Standards Under Static Technology Frontier

Industry's traditional response to regulatory mandates has been to achieve compliance at the minimum cost. This mode is essentially a reactive one. The following figure illustrates this reactive approach for a simple example involving meeting the dual challenges of higher CAFE standards and recycling a larger fraction of the post-use automobile. Let *D* represent the current vehicle design with its corresponding fuel economy standard (*s*) and mass fraction recovered through some recycling undertaking (*f*). If new regulations stipulate that higher levels of fuel economy and material recovery are required (*s'* and *f'*, respectively), a firm operating under the reactive mode then will begin to search for alternative to meet these statutes. Traditionally, the design will evolve to address the regulatory demand regarded by the firm to be more pressing (*e.g.* earlier compliance date, greater non-compliance penalty), then further evolve to address the other issue. By reacting to regulations as they occur, a sequential, incremental design pattern emerges. As can be seen in *Figure 4.4*, the vehicle design will move from the current *D* to some intermediate *D** in order to satisfy one regulation (CAFE is chosen arbitrarily in this example). The design then progresses to *D'* in order to satisfy the additional recycling constraint.

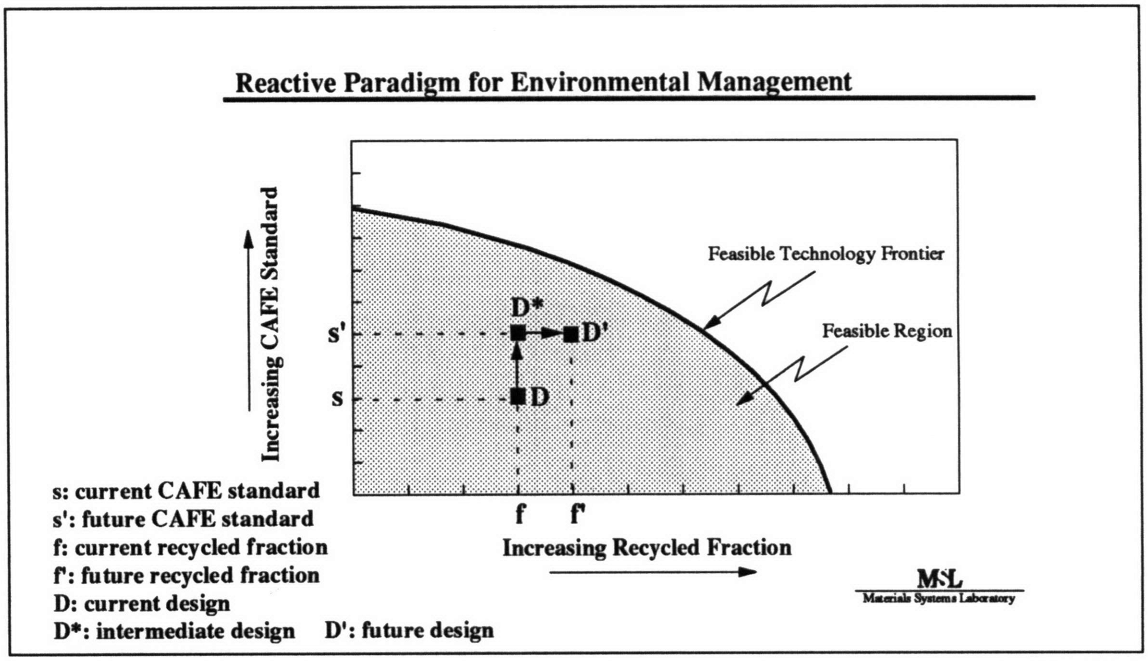

Figure 4.4: Reactive Approach to Managing CAFE and Recycling Regulations

Two major points need to be emphasized. First, the elapsed time from D to D^* and D^* to D' may be several years as a reflection of product cycles and development lead times. Second, the arrows connecting D to D^* and D^* to D' can represent substantial financial investments in terms of research, equipment, and labor. An alternate paradigm is to adopt a proactive stance and incorporate environmental legislations into a firm's design objectives. Rather than responding to each regulation in turn, a proactive stance seeks to better understand the trade-offs involved in meeting diverse environmental regulations and thus offers the opportunity for a more direct design path. Potentially complementary objectives (*e.g.* higher fuel economy and lower CO_2 emission per kilometer) can be exploited. Seemingly opposing objectives (*e.g.* higher fuel economy and more extensive automotive material recycling) should not be resolved through superficial assessments. Instead, the details behind the environmental objectives must be examined. By understanding how specific materials affect fuel economy and behave in vehicle recovery processes, a design more congruous to both objectives can result.

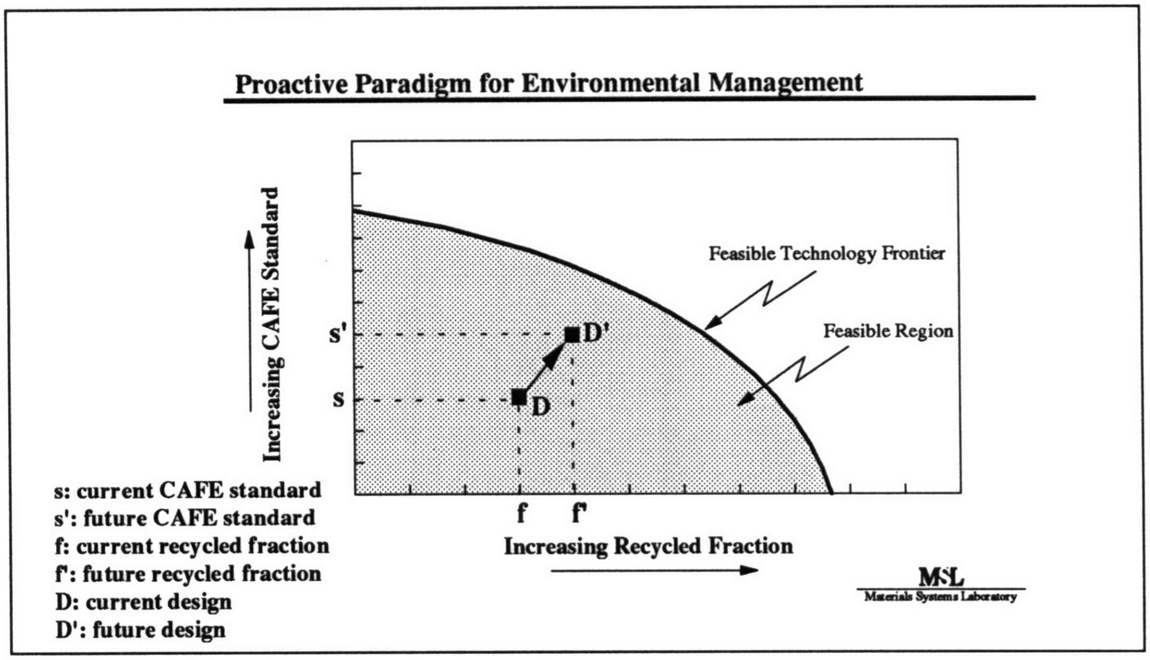

Figure 4.5: Proactive Approach to Managing CAFE and Recycling Regulations

It is important to note that both reactive and proactive approaches can advance to the same ultimate design, as long as both regulators and industry recognize a common environmental objective. While this shared vision is by no means commonplace, there are indications that government and industry alike are seeking to establish a less contentious relationship for environmental management.[69,70,71] The critical point for now is that in accomplishing the same final design objective, a proactive paradigm can be less costly and more timely than a reactive one. With automobile's large number of design requirements, a proactive approach can result in significant competitive advantages.

Another major benefit of a proactive paradigm is that future designs are not dictated in a strictly binary manner. That is, a design alternative is not accepted or rejected based only on a simple test of compliance or noncompliance. The implication is that other solutions will be considered that may potentially be better than *D'*, especially when a third attribute such as cost is accounted. Alternative solutions that push the envelope of know-how (represented by the darker-shaded area) may then be considered.

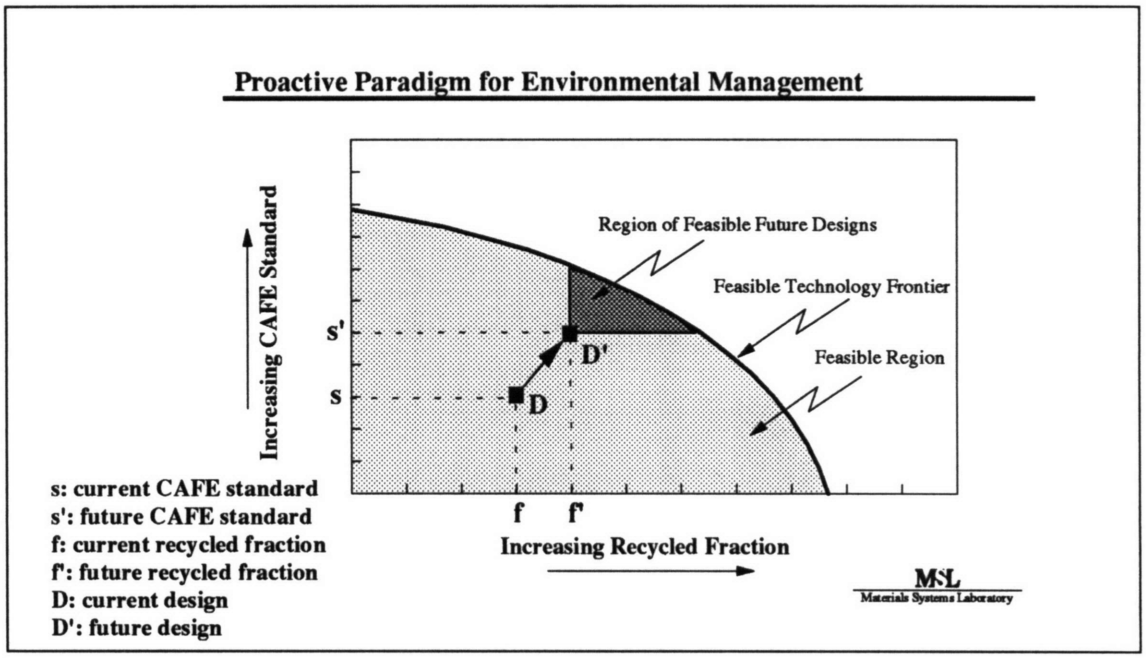

Figure 4.6: Potential of Proactive Paradigm to Uncover More Effective Solutions

There are numerous reasons why a design that exceeds requirements can be attractive. First, such a solution offers a cushion against further tightening of standards. Perhaps more important is the possibility that an alternative may exist within that feasible design region which offers which better performance relative to *D'* without any significant penalty in other desirable product attributes. For example, there may be a solution that offers much better fuel economy with only a slight increase in production cost. While a traditional reactive paradigm simply would have sought the lowest cost acceptable alternative, a more proactive paradigm can better distinguish the nuances among different solutions.

4.4. Development of a Lifecycle Analysis Framework

In order to undertake proactive trade-off analyses among the multitude of automobile economic and environmental objectives, a systems perspective is necessary. Not only is a particular product or process design decision's immediate effects relevant, but its upstream prerequisites and downstream consequences must be assessed as well. Furthermore, evaluation of these various impacts is not limited to a single metric but rather extends throughout every environmental and economic attribute that relates to the automobile. Conceptually, this systems approach involves the expansion of the two-dimensional feasibility region in *Figure 4.6* to one in *n*-dimensional space, where *n* is the number of attributes of interest.

One approach for obtaining a systems view of products is through lifecycle analysis. By viewing a product as an amalgam of materials, an automobile's lifecycle can be more fundamentally described as materials lifecycles. The material lifecycle refers to the various physical and chemical transformations a material undergoes from extraction through post-use. Within each stage of the lifecycle, there exists an economically driven infrastructure to carry out that stage's particular processing functions. In the manufacturing stage of an automobile's lifecycle, for example, the infrastructure consists of material suppliers providing inputs, automakers processing these inputs, and vehicle dealers accepting the output products. More detailed views of the infrastructure allow distinctions among specific operations such as casting foundries, stamping plants, molding facilities, tool shops, assembly plants, and paint shops. An attractive feature of the lifecycle perspective is its flexible resolution. That is, one can define each lifecycle stage in as much detail as one wishes. Mass and energy balances can then be performed over as broad and as detailed a control volume as needed. Economic linkages within and among the various lifecycle stages can usually be through market-based transfer prices. As part of a lifecycle framework, market-based costs in conjunction with mass and energy balance data can yield a more complete understanding of a product and its production process. Since it provides a rational framework to analyze resource consumption and conservation, lifecycle is often the focus of environmental arguments.

At a basic level, lifecycle analysis is simply the tracking of every input and output of every process undertaking from raw material through a product's disposal (so called cradle-to-grave analysis). Justifying this type of exhaustive inventory collection is the belief that environmentally-related economic externalities can be incorporated into the product design dialogue. Environmental issues traditionally excluded from financial accounting frameworks may be captured under a lifecycle analysis' expanded metric list. Given parallel sets of environmental information as well as conventional financial data, the designer can begin to ask not merely whether a product or process will be financially feasible, but rather whether it can offer a better combination of financial and environmental consequences. By offering a systems approach, lifecycle analysis acknowledges that an optimal decision in one stage of a material's lifecycle may lead to a suboptimal condition in another part of the same stage or another stage altogether. A classic intra-stage trade-off is the use of a relatively expensive raw material in order to gain lower processing cost advantages. A prime example in the manufacturing stage is a polymer application that may be more expensive than steel on a unit mass of feedstock basis, but less expensive from a press and tool investment perspective. A classic inter-stage trade-off is accepting a higher production cost component in exchange for potential environmental gains. A good example in this case is the use of an aluminum component, more expensive relative to steel, in order to gain weight savings and hence better fuel economy in the use stage.

A lifecycle inventory, while a prerequisite to a more proactive environmental management paradigm, is still only a database of arcane numbers. The impacts on the environment of the various product and process attributes tracked by the inventory (*e.g.* emissions, energy consumption, land use) still need to be determined.[72,73] Furthermore, how these impacts should be evaluated against each other and against the traditional cost metric is unclear.[74] Despite these obstacles, the mere acknowledgment of economic externalities is having a major impact on defining policies. Attempts to incorporate externalities into decision-making models have taken two major forms. The first, typified by Volvo's Environment Priority System (EPS), seeks to formalize externalities through valuation in order to arrive at the familiar cost metric.[75] That is, environmental attributes with no market prices are assigned costs based on some extrapolation from existing data (*e.g.* related health care cost, emission abatement requirements) The second approach, represented by the Society of Environmental Toxicology and Chemistry (SETAC) methodology, aims to track and evaluate each externality separately. Cross-media trade-offs are then made based on this extensive database.[76] Regardless of approach, the inherent assumption is that traditional cost accounting should be expanded to provide more insight into previously cursory issues such as environmental protection.

This thesis proposes an alternative framework to better assess economic and environmental trade-offs in automobile recycling. Recognizing that valuation of environmental attributes is a subjective process, the research instead will focus on ways to better represent inventory information and facilitate trade-off opportunities and consequences.. A major feature of this proposed methodology thus is its transparency. Another distinguishing aspect of this framework is its explicit linkage to product and process variables. This linkage allows iterative analyses when examining the effects of potential design and processing changes on economic and environmental attributes. An important capability of such an approach is its imbedded system perspective. By recognizing and engaging the interrelationships among product design, process design, process control, and their concomitant economic and environmental influences, one can seek solutions that drive towards some global optimum.

The ultimate objective of this thesis then, is to develop a set of tools that can capture environmental issues, articulate them into coherent argument, and facilitate trade-off analyses to arrive at more optimal automobile designs.

A case study driven methodology is used. That is, rather than formulate these analytical tools then search for appropriate test scenarios, this thesis starts by examining the environmental design challenges confronting the automobile industry. Automobile recycling is one such issue that will be analyzed in detail. Tools then are developed and expanded to address specific questions that are raised. For industry, this research can help to reconcile diverse design objectives. For government, this work can help to refine regulations that better motivate environmentally less-stressful products and processes.

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5. Cost Analysis of Recycling Processes

5.1. Technical Cost Modeling

Technical cost modeling (TCM) is the analysis of manufacturing processes using computer spreadsheet-based tools with elements from engineering process analysis, operations research simulation, and financial accounting.[77,78,79] The main attractions of TCM include its ability to highlight the major cost drivers in industrial processes, to compare alternative technologies systematically, and to provide flexibility in simulating market conditions and government regulations. Several studies looking at the cost-effectiveness of alternative automotive manufacturing scenarios have been completed.[80,81,82,83] This thesis applies TCM to the analysis of recycling processes.

The basic structure of a technical cost model can be seen in the next figure.

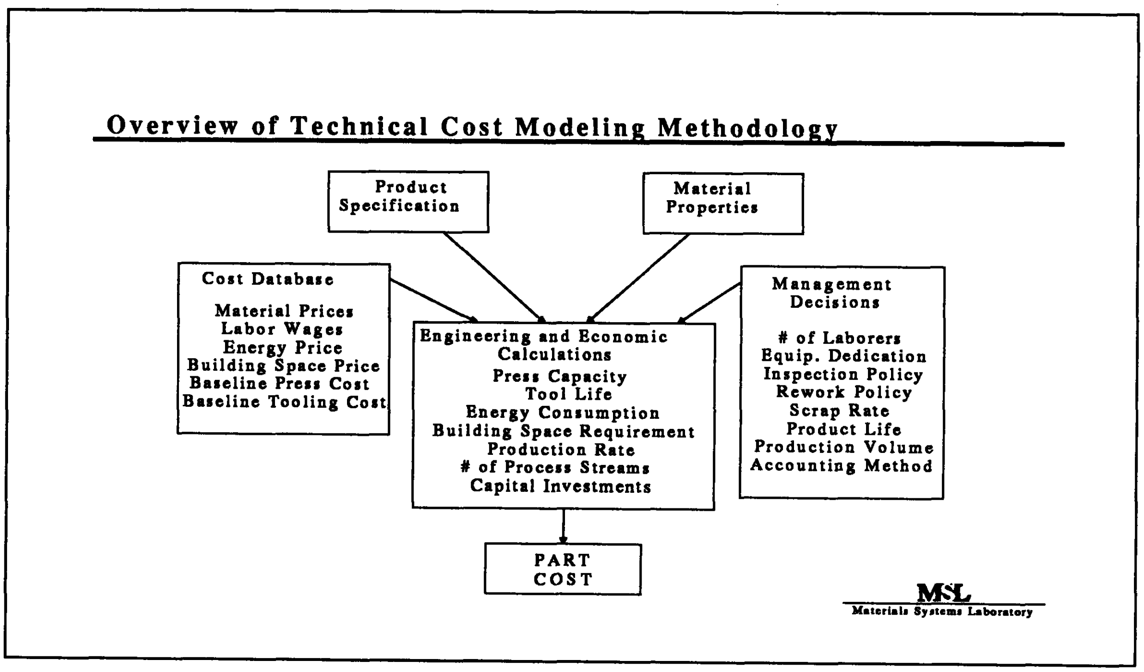


Figure 5.1: Generic Architecture of Technical Cost Modeling

In general, four major types of inputs are required. The model's basic parameters are details regarding the product to be manufactured and the feedstock material to be used. Product specification is information such as the dimension, shape, complexity, and weight of a formed or assembled part. In the case of recycling processes, the product specification is the composition of the recovered material stream. Material properties include density, melting point, and data concerning the material's molding, curing, forming, welding, and bonding characteristics. For recycling process, material properties such as organic content, molecular weight, solubility, and decomposition temperature may also be included.

In addition to the product and feedstock material descriptions, the variable and fixed cost items required by the process must be specified. This price database can contain information such as virgin material price, product sale price, labor wages, utility rates, and building costs. There are also factors used to estimate the costs of machines and tooling based on the particular technology, feedstock material, and output product involved. The final set of inputs involves various management decisions. This information dictates how the various resources (*e.g.* feedstock material, equipment, energy) are to be transformed into the final product. Decisions include the production volume, product lifetime, number of laborers, working hours, and equipment dedication assumptions. Policies regarding quality control, reworking, and scraping also can be defined. Finally, there are the accounting issues of establishing some capital recovery rate and period.

Regulatory mandates can be incorporated in the model by constraining the pertinent material streams. Certain process feedstocks (*e.g.* foams expanded with chloroflurocarbon) may be substituted by other, perhaps more expensive alternatives. In recycling processes, mandated recycling rates can dictate target yields for specific material fractions in specific amounts.

Using these inputs, the model then executes a series of calculations based on engineering and economic principles. Basic mass and energy balances are performed, as well as more involved thermodynamic and mechanical flow equations parameterized by process conditions. These calculations provide information such as process yields and cycle times. With additional process descriptions such as the target output volume and reject rate, the required number of production lines can be calculated. Capital expenditures, estimated from both theoretical principles and empirical industry data, can be allocated over the production volume to derive the cost per part (or more generically per unit mass of output material).

5.2. Baseline Automobile Recycling Scenario

In order to obtain a more realistic representation of the resource-added chain, a detailed process analysis is required. Using *Figure 2.3* as a starting point, each stage of a material's lifecycle can be "exploded" to provide finer cost and resource accounting informations. Such a view for the secondary material stage can be seen in *Figure 5.2*.

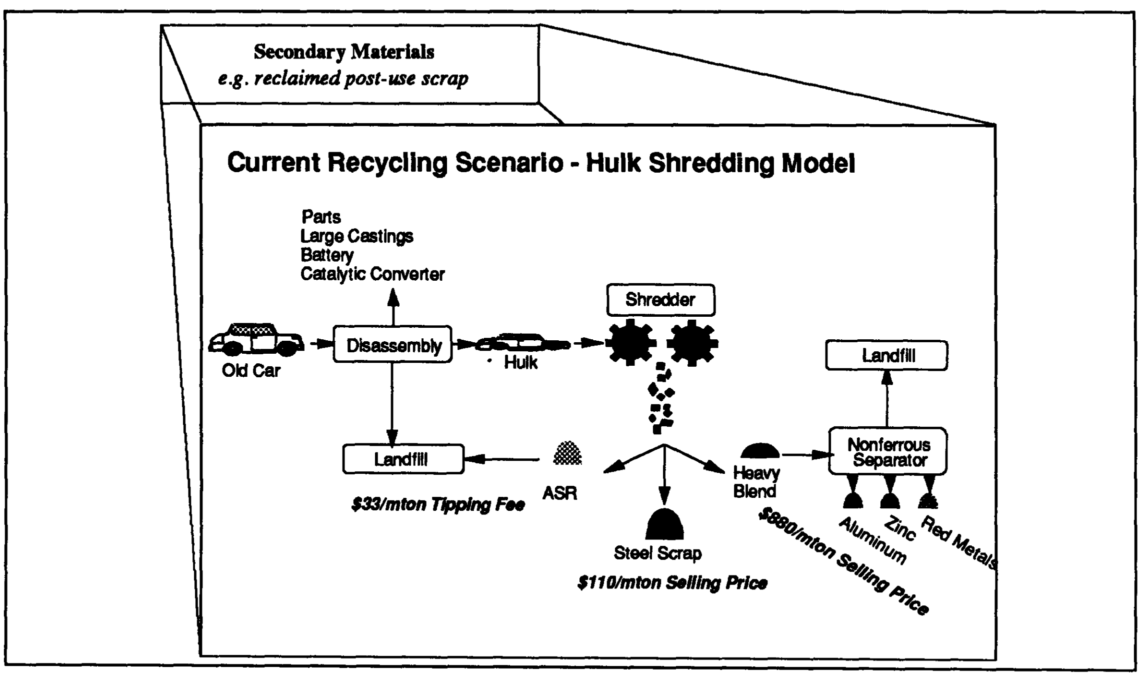


Figure 5.2: Current Automobile Recycling Infrastructure

The above figure illustrates just one possible process scenario for reclaiming post-use consumer scrap. In fact, this hulk shredding scheme is the dominant recycling procedure for today's automobile. Old vehicles typically enter the recycling stream through a dismantler via the last owner (*e.g.* consumer, dealer trade-in, auction). Present market conditions in the United States are such that the dismantler pays the last owner approximately $50 and up per vehicle, depending on the vehicle's condition. Reusable components and particularly valuable material fractions are removed. The specific disassembly targets are largely determined based on their projected saleability. Additional parts such as tires and fluids may be removed not so much for resale but rather to allow the remaining hulk to be accepted by the downstream shredder. Essentially the body and chassis, this hulk is flattened to ease transporting and sent to a hulk shredder. Typically a separate business entity, the shredder buys this hulk from the dismantler for around $50 per hulk.

At the shredding facility, hulks are mechanically reduced into fist-sized chunks. Segregation into the ferrous, nonferrous, and mainly nonmetallic automotive shredder residue fractions can be accomplished using the material streams' magnetic and specific gravity gradients. The ferrous fraction is sold to electric arc furnace mini-mills, the nonferrous fraction is sold to specialized shops where aluminum, zinc, and copper can be segregated and then resold to the respective secondary material markets, and the ASR most commonly is sent to a landfill. It is critical to recognize that for every material transfer, there is a corresponding market transaction. It is these price signals, determined by downstream secondary material and used component markets, that dictate the ebb and flow of materials within the infrastructure. Analysis of the hulk shredding scenario has been undertaken examining the current state and the major economic forces of the industry.[84] Key inputs and outputs for this simulation are presented below. Results have shown the U.S. automobile recycling industry to be quite profitable and robust with net profit for each processed hulk estimated at over $44.

Model Parameter	*Quantity*
Capital Investment	$5,000,000/facility
Hulk Purchase Price	$50/hulk
Ferrous Scrap Price	$110/mton
Nonferrous Scrap Price	$880/mton
Landfill Tipping Fee	$33/mton
Hulk Consumption Rate	95.7 mtons/hour
Ferrous Scrap Output Rate	70.7 mtons/hour
Nonferrous Scrap Output Rate	5.3 mtons/hour
Combustible Fluff Output Rate	12.5 mtons/hour
Noncombustible Fluff Output Rate	6.7 mtons/hour

Table 5.1: Selected Hulk Shredding Model Parameters

From the model's simulation for a 1990 model year vehicle, approximately 0.28 mton of ASR, 0.66 mton of ferrous scrap and 0.05 mton of nonferrous scrap is produced for every shredded hulk. Given the relatively low disposal tipping fees in the U.S., the landfill cost is a relatively small fraction of the total operating cost for this particular case study. The other variable costs (*i.e.* transportation, energy, materials, labor, and capital) are about twice as much as the landfill cost. The high market value of the metallic fraction, accounting for approximately 71% by weight of the hulk, more than compensates for ASR's relatively small cost liability. The major cost contributor is the hulk purchase. A cost breakdown is graphed in the next figure.

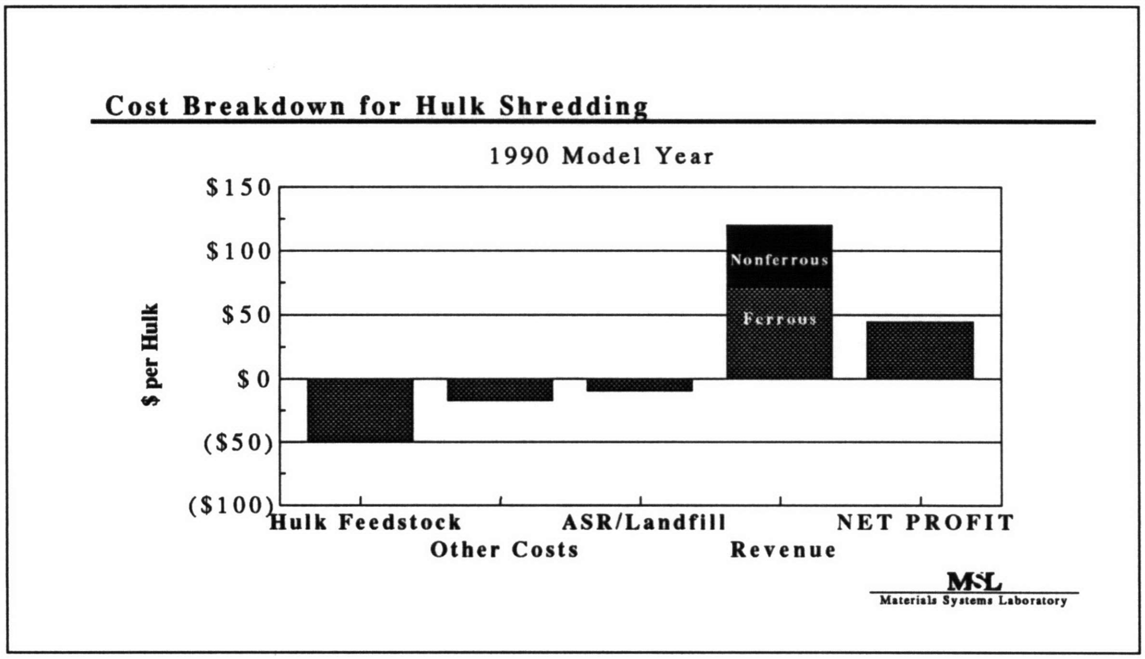


Figure 5.3: Cost Breakdown for Current Automobile Shredding Process

Given the baseline cost scenario, sensitivity analyses can be conducted to see how issues such as changing market conditions, plant capacity, feedstock price, and hulk material content can affect the shredder-based recycling infrastructure. A plot examing the effects of rising landfill tipping fees and increasing polymer content is shown in the next figure.

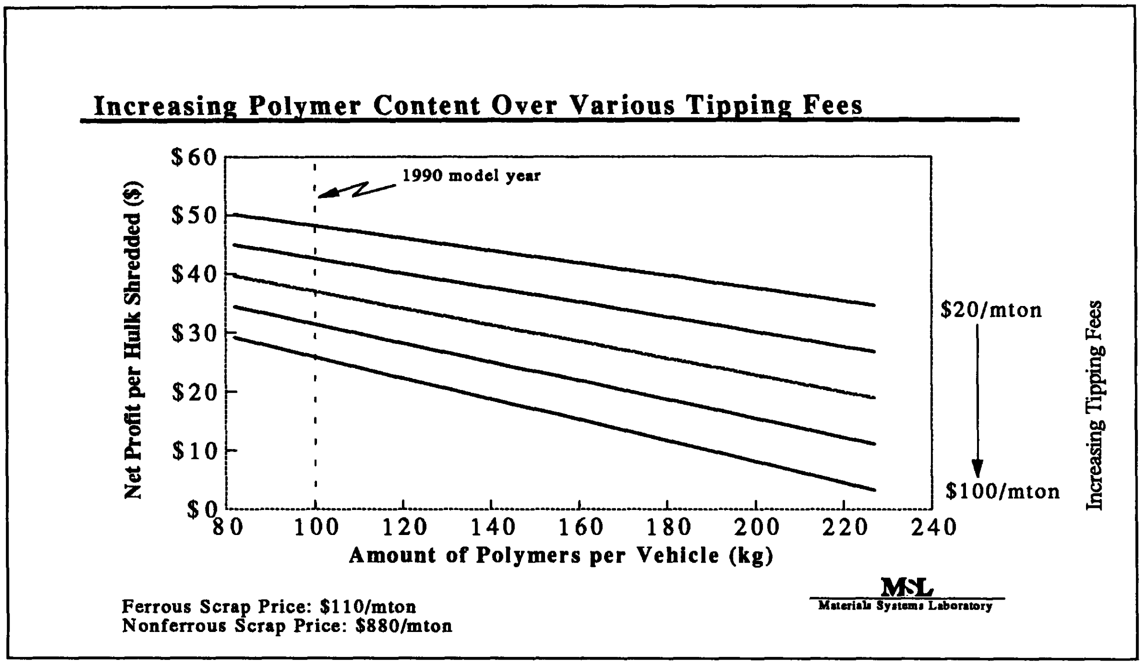


Figure 5.4: Effect of Polymer Content & Landfill Tipping Fee On Profit Per Hulk

As can be seen in *Figure 5.4*, only with extremely high landfill cost and polymeric content will today's shredder-based infrastructure approach collapse. The assumptions behind this plot include those listed in *Table 5.1*. Also, each kilogram of polymer is assumed to replace 1.2 kilograms of steel (*i.e.* 20 percent weight saving). A hulk shredding operation can still achieve profitability at tipping fees as high as $100/mton. In fact, for this set of assumptions (given the 1990 polymer content), net loss for the hulk shredding process will not occur until tipping fees climb to almost $200/mton. While a large sum, this fee is not inconceivable in countries with a land shortage or if ASR becomes classified as a hazardous waste. It should be noted, however, that such long range projections may be misleading. The $200/mton crossover point is for the case where all other variables are held constant. In reality, a dynamic system has multiple changing variables that may drastically alter the economic picture. Nevertheless, carefully planned sensitivity analyses can serve to identify particularly critical issues.

From the dismantler's perspective, the effect of higher polymer content and landfill tipping fee is indirect. Since the dismantler sells parts mainly for its functionality rather than for their material content, the automotive material choice is of little direct consequence. While tires may become a greater liability with higher landfill fees, this component is less subject to materials substitution and thus less pertinent to arguments concerning automobile's changing material content.

The dynamics of the hulk transfer price hold interesting implications for the shredder, dismantler, and the entire recycling infrastructure. If metal scrap prices drop, revenue from the sales of reclaimed metals will decrease and the shredder's financial viability may become jeopardized. A likely consequence is that the shredder will pay the dismantler less money for hulks. A scenario where the shredder begins to charge the dismantler for accepting the hulks also may be possible. This charge will depend on the cost of alternative disposal routes available to the dismantler (*e.g.* landfilling entire hulks). Another mitigating factor is that the shredder, being a capital intensive operation, will be anxious to keep its machines working. The dismantler, driven more by variable costs like labor, is less sensitive to capacity constraints and thus more tolerant of fluctuating throughput levels. Nevertheless, with sufficient financial pressure, the dismantler may also seek relief by passing on its costs to the last user. If the vehicle's last owner balks at the prospect of paying for disposing old automobiles, indiscriminate vehicle dumping may occur. This scenario represents the most severe consequence of an infrastructure collapse. A privately organized automobile recycling scheme degrades into a public disposal problem.

Despite the current infrastructure's profitability and robustness, increasing attention is being focused on looking for alternative recycling schemes. One reason for the concern is that the preconditions for collapse (*i.e.* landfill cost overwhelming revenue from scrap material resale) may be realized. As mentioned before, landfill charges have been on an upward trend for the past several years. In relatively land-scarce countries like Germany and Japan, landfill charges are already more than twice the U.S. average. Disposal policy differences among nations may also lead to nontariff trade barriers by presenting foreign automakers with a higher cost of doing business in a particular market relative to domestic automakers. The foreign firm may perhaps be required to invest heavily in local post-use management facilities or even to ship post-use vehicles back to the overseas production source. Globalization of the automotive industry implies that local solutions for local conditions may not satisfy overall corporate needs. Therefore, even if the current American automobile recycling infrastructure is robust, U.S. automakers still need to be concerned about alternative recycling issues in the world market. The more intriguing reason for developing alternative automobile recycling schemes goes back to the theory of economic externalities. The basic idea that economic activities often have unaccounted consequences such as environmental damage implies that even if the current automobile recycling scenario is cost-effective, there may be alternative solutions that offer more desirable balances between economics and the environment.

5.3. Alternative Automobile Recycling Scenarios - Vehicle Dismantling

Automobile disassembly is a highly labor intensive undertaking. Traditionally, automotive components with current or anticipated market values greater than the effort required for the dismantling process are removed. These parts are generally resold for their functional capabilities rather than their material content. Notable exceptions are the lead in batteries and platinum group metals in catalytic converters. Regulatory and public pressures for product recycling now are forcing the dismantling industry to consider directly a part's material content and more thoroughly capture an automobile's post-use value. One proposed recycling procedure is the extensive dismantling of an automobile in order to obtain homogeneous material streams.

Disassembly of the post-use vehicle, and the associated attempt at design for disassembly, is a major research focus of automakers. All the major European automakers, among them BMW, Volvo, Fiat, Renault, and Volkswagen, have established pilot disassembly plants.[85,86,87] In the U.S., the Vehicle Recycling Partnership (VRP), consisting of General Motors, Ford, and Chrysler, also has established a research program examining the feasibility of disassembly. Automakers' keen interest in vehicle dismantling lies in the recognition that careful segregation of a vehicle's material fractions is necessary to avoid material contamination and thus achieve quality (and market price) comparable to that of virgin materials. Whether driven by the traditional ideal of closed-loop recycling or simply the desire to capture more of a material's embodied resource value, vehicle disassembly offers a way to secure clean scrap. Once segregated scraps streams are obtained, they typically undergo mechanical size reduction and cleaning before reprocessing into products.

Of course, dismantling also offers the potential for more thorough vehicle component reuse. Not only can the resources required to produce materials be recovered, but those resources used to convert materials into parts also can be saved. A schematic illustrating the various process flows can be seen in the next figure.

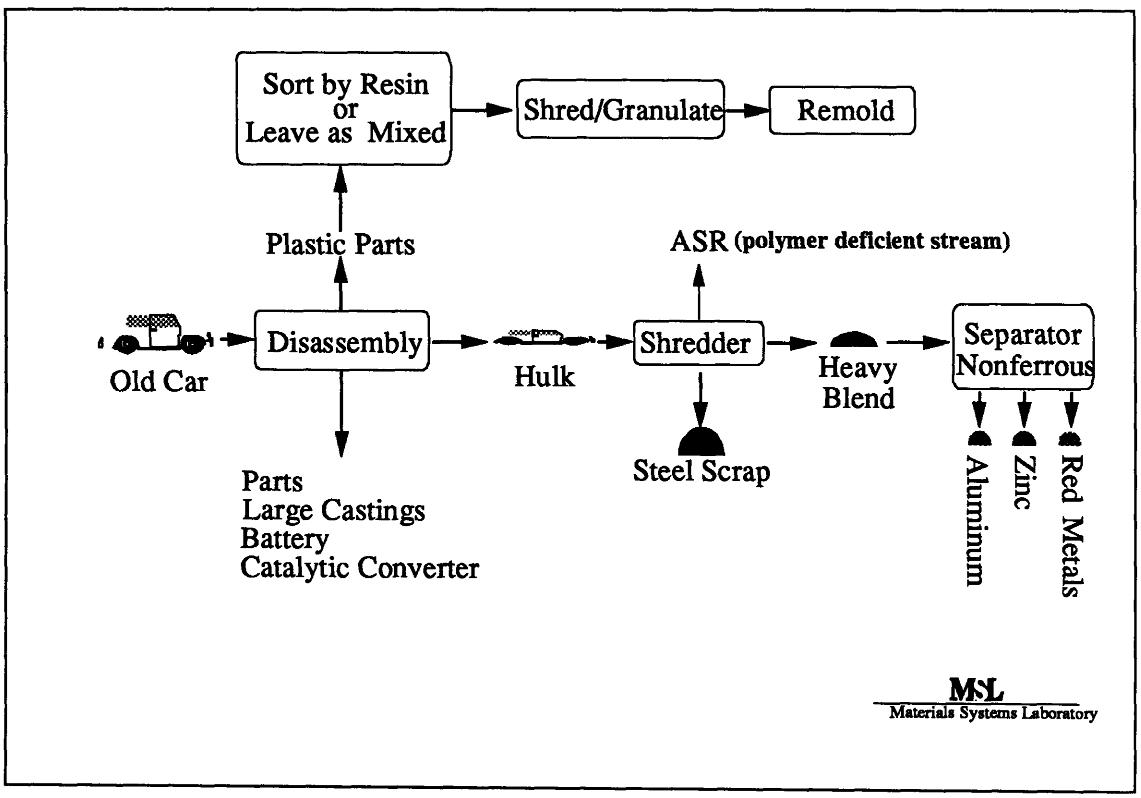


Figure 5.5: Vehicle Dismantling Based Recycling - Polymer Components Case Study

A disassembly cost model has been developed to provide better estimates of the economic consequences for different extents of automobile dismantling. The immediate goal is to calculate systematically the cost involved in such undertakings. Furthermore, such a tool can function as a material balance node between a vehicle's production and post-use stages. By tracking the material types and masses removed, feedstocks for downstream recycling processes can be accurately and consistently characterized. In the long term, the information derived from the disassembly model provides feedback into the design of the next generation automobile. A useful feature of this model is its ability to simulate various removal criteria. Among the choices available is disassembly of specific material types, masses, and location within the vehicle. An explanation of this model's construction can be found in Appendix A. One useful output from this model can be seen in the next figure. All simulations are bases on a specific compact-sized vehicle model's interior (composed mostly of plastics). The dismantling time, mass, and material data have been supplied by VRP.

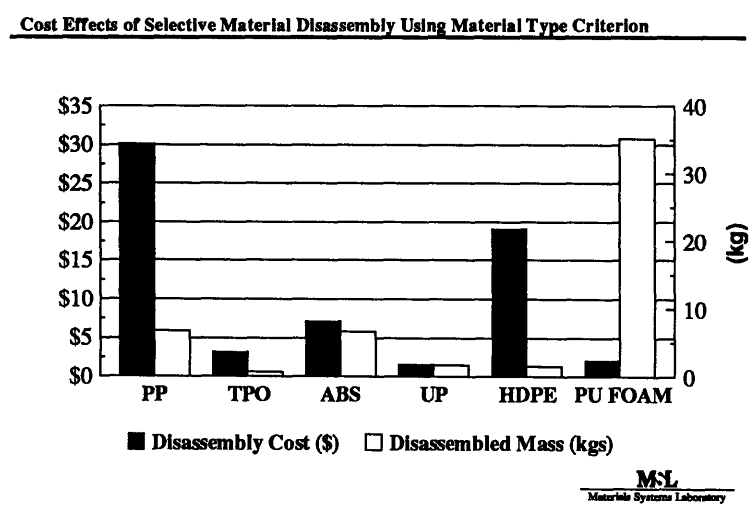


Figure 5.6: Disassembly Costs for Specific Polymer Resins

The above figure presents the cost of removing particular resin types. The figure shows that there is a wide range of mass-to-cost ratios among the different materials. In terms of removing as much mass from the vehicle as possible (in order to minimize landfill liability), polyurethane foam offers by far the best combination of low cost and large mass. By linking the above cost and mass outputs to a recyclate material price database, a net profit can be easily calculated.

The next graph shows the effect on cost of removing different sized parts by using a mass criterion for disassembly. That is, the cost model can be modified to yield the cost of removing parts with specific masses. For this graph, a continuously decreasing range has been entered. The simulation begins by assuming all parts with masses between 0 and x_1 are removed (where x_1 is the mass of the heaviest part). Then, those parts with masses between 0 and x_2 are removed (where $x_2 < x_1$,). This iteration ends when the cost model attempts to find those parts with masses between 0 and 0. The cost of removing all the interior parts in this particular case, for a total mass of 63 kilograms, is approximately $80 per vehicle.

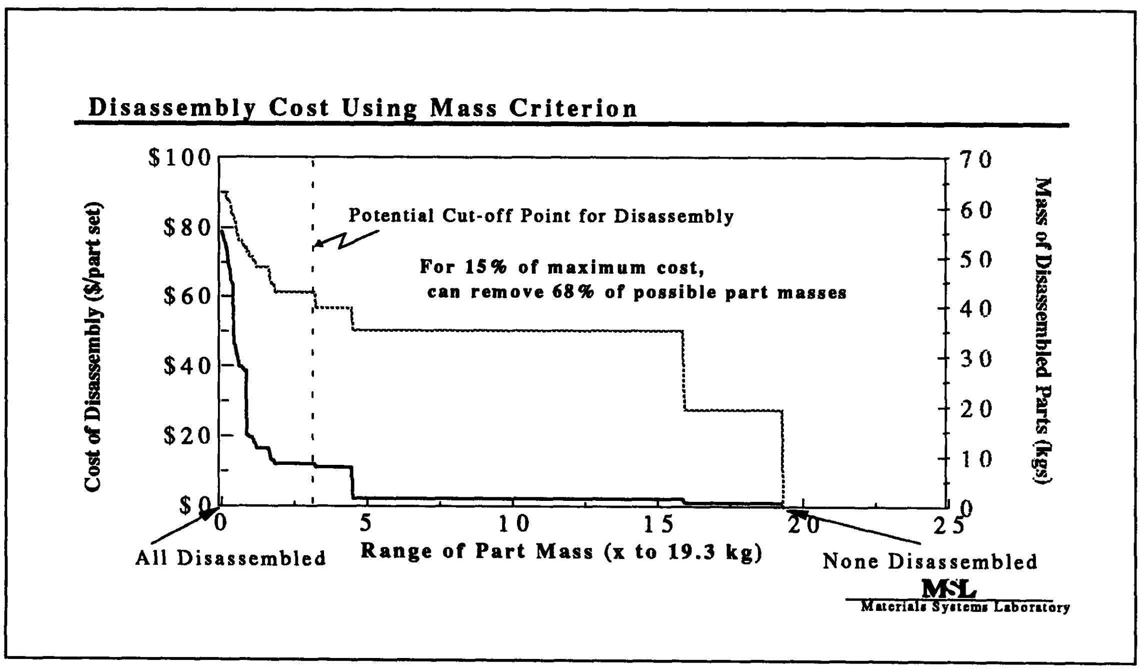


Figure 5.7: Disassembly Costs for Mass-based Parts Removal

Figure 5.7 leads to an important conclusion. There is clearly a strategic dimension to vehicle dismantling. Complete vehicle disassembly is foolhardy given its rapidly diminishing return. Instead, there may be some intermediate point at which disassembly should stop. In the above example, one possible point is indicated by the vertical dotted line. At this degree of disassembly, 68% by mass of the interior parts can be removed at only 15% of the cost of complete removal. Together with up to date component and secondary material prices, potential dismantling profits can be calculated. A confluence of analyses balancing removal cost with resale prices, landfill savings, and regulatory requirements will lead to some optimal level of vehicle dismantling.

While greater demand and more stable pricing have occurred even in polymer secondary material markets, extracting material value from post-use vehicles through disassembly is likely to be of dubious value to recycling businesses in the short term. Dismantling efficiency and segregation accuracy are usually low.[88,89] Other material sources, such as plastic bottles, can be more easily obtained and processed to yield homogeneous material streams. As an alternative post-use management route, dismantling is under severe cost pressure. Using the case study's $80 cost per 63 kilograms of removed parts as a base number, a simple linear extrapolation yields a dissassembly cost of $1270 for each metric ton of removed parts. Put another way, the recovered material must average a resale price of $1.27/kg, a very high number for most automotive secondary material, just to break even. Once the costs of cleaning, grinding, and compounding in preparation for reuse is included, the breakeven point becomes even more difficult to attain. With the average U.S. landfill cost at only $33/mton of waste, vehicle dismantling as a recycling approach appears insupportable on a for-profit basis. Nonetheless, dismantling remains an important element of a long term vehicle post-use strategy. Component reuse, fluid draining, and selective material removal (*e.g.* very valuable or hazardous materials), all contribute to a more effective and efficient automobile recycling infrastructure.

5.4. Alternative Automobile Recycling Scenarios - ASR Treatment

Another area of research interest has been recycling of the shredder residue.[90,91,92,93,94,95,96] The leading reason for this attention is the implicit compatibility of these processes with today's shredder-based recycling infrastructure. By choosing recycling procedures with a relatively high tolerance for mixed wastes, the polymer-containing ASR stream as generated by the shredder can be suitable feedstocks. The ability to process unsegregated wastes is crucial given the potentially enormous costs, cited earlier and in work elsewhere, required in dismantling and segregating automotive components.[97]

The existence of the recycling infrastructure is a consequence of the value inherent in a post-use vehicle. As seen *Figure 5.3*, even if one only extracts the ferrous scrap value, a typical automobile can yield approximately $70 in revenue. With 9 million vehicles entering the U.S. waste stream each year, this translates to a potential annual revenue base of $630 million. While the corresponding ASR portion may currently represent an $81 million landfill liability, there is also significant residual value within that fraction. Information supplied by Argonne National Laboratory, which has done much work in the field of ASR treatment, is used for this study. The typical ASR composition, based on a fluff sample received by Argonne from one particular shredder, is seen in the next figure. Assuming a 1400 kg vehicle, the composition weight percentages can be converted to a mass and value on a per vehicle basis.[98] Recyclate prices are actual market numbers where available. Conversations with industry experts supplied the remaining figures. Notably, thermoset resins are conservatively recovered and priced for low value filler applications.

Material	*Weight % of ASR*	*Weight % of Vehicle*	*Potential Resale $/kg*	*Potential Value ($)/Vehicle*
Moisture	10.0%	2.5%	$0	$0.00
Magnetic Fines	19.0%	4.8%	$0.06	$3.99
Nonmagnetic Fines	19.0%	4.8%	$0.02	$1.33
Oils	5.2%	1.3%	$0.07	$1.27
PU Foam	4.8%	1.2%	$0.55	$9.24
PP	1.8%	0.5%	$0.50	$3.15
PE	1.8%	0.5%	$0.60	$3.78
ABS	2.7%	0.7%	$0.80	$7.56
PVC	2.7%	0.7%	$0.40	$3.78
Thermoset Polyester	5.5%	1.4%	$0.02	$0.39
Phenolic	1.3%	0.3%	$0.02	$0.09
Other Plastics	2.2%	0.6%	$0.02	$0.15
Other Inorganics	24.0%	6.0%	$0.02	$1.68

Table 5.2: ASR Composition & Its Potential Reclaim Value for 1400 kg Vehicle

Based on the above reclaim value assumptions, ASR has an inherent market value of over $36 per vehicle. This figure may seem surprisingly high given that this shredder fluff is commonly viewed as a worthless nuisance. After the cost of recovery and the reusability of the reclaimed plastics are considered, however, the difficulties of finding alternative ASR management options become clear. The fluff is a highly commingled material mixture. The processing implication is that segregating and sorting the various constituents may be time consuming and costly. The recyclate quality implication is that contaminated recyclates may not perform as well as the virgin counterparts and thus not command a high market price. Developing an efficient and effective reclaiming process has been the major obstacle in achieving ASR recycling and therefore more complete automobile recycling. Identifying technologies that can offer this required combination, whether they are process-based or product design-based, is one of the industry's primary concerns.

Two processes that have been modeled are pyrolysis and selective precipitation. These two recycling schemes are chosen for analyses since they offer distinctly different resource and value saving opportunities. Referring back to *Figure 2.3*, pyrolysis brings the recyclate back to the feedstock stage as petroleum products. Selective precipitation, on the other hand, brings the recyclate back to the intermediate product stage as polymer resins. Brief discussions of these two recycling processes are presented below.

Pyrolysis is the thermal decomposition of organic materials in an oxygen-free environment. The feedstock is heated to between 550-1200 degrees Celsius. The resulting extracted products can be categorized into three major streams; oil, gas, and solid residue. Energy is required to start the reaction while the product gas typically can be used to sustain the reaction. The oil can be sold while the residue is either landfilled or sold for its fillers and metal scrap potential. A schematic of the ASR pyrolysis process can be seen in *Figure 5.8*.

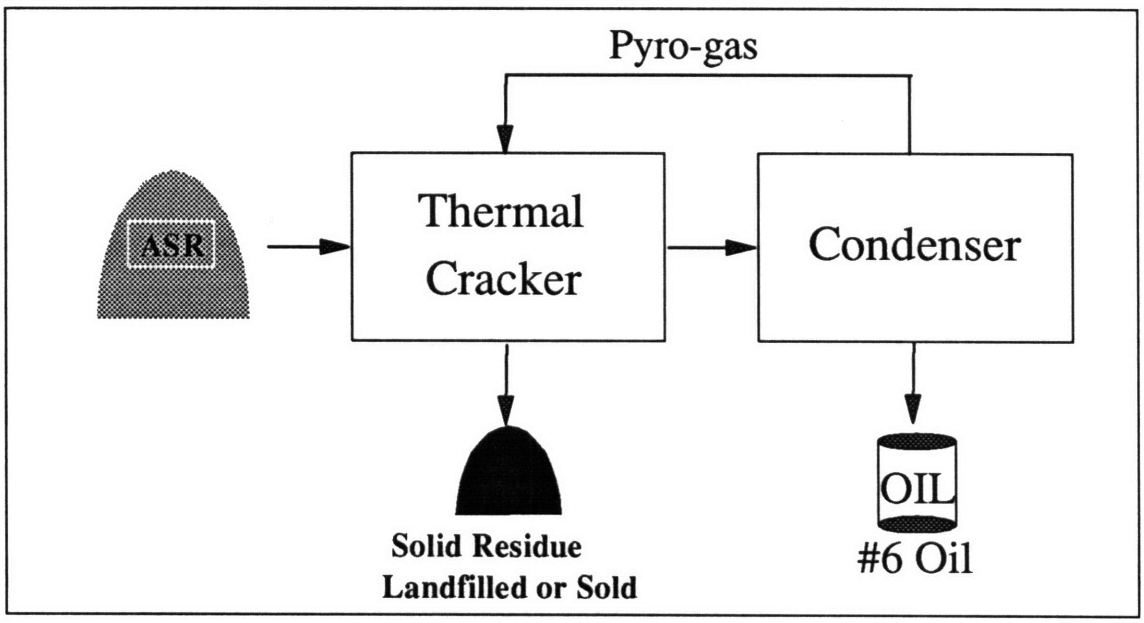


Figure 5.8: Schematic Diagram of ASR Pyrolysis Process

The second recovery process, consisting of mechanical separation and selective precipitation stages developed at Argonne National Laboratory, seeks to reclaim higher-valued recyclates. *Figure 5.9* shows a schematic diagram of the Argonne process. The ASR is first dried. It then enters a stage where polyurethane foam (PUF) is segregated via a mechanical trommel/air classification process. This dirty foam is then washed, dried, and sold. A portion of the outlet stream from this wash cycle consists of automotive fluids that may require further treatment before disposal. Another fraction that is recovered by the mechanical separation set-up is termed "fines". These fines, less than 0.6 cm in diameter, are rich in iron oxide and silica. This stream can, after some pretreatment, be used as a feedstock for cement making. The foam and the fines constitute almost 50% by weight of the incoming ASR. The remaining portion of the ASR, termed the polymer rich stream (PRS), is then sent to the selective precipitation stage where a circulating hot solvent extracts nearly all of the thermoplastics. By carefully selecting extracting solvent(s) and precipitating anti-solvents, specific thermoplastic polymers are selectively extracted through precipitation. For this particular study, acrilonitrile butadiene styrene (ABS), polyvinyl chloride (PVC), and a polyolefin mix of polyethylene (PE) and polypropylene (PP) are the recovered fractions.

By recovering polymer resins instead of pyro-oil, the products of this process retain more economic and resource value. Partially offsetting these advantages is the fact that the Argonne process requires a large amount of steam and electricity to recycle the working solvents. The initial investment in solvents and the subsequent recycling of these solvents may lead to substantial monetary and resource outlays. A schematic flow diagram for the Argonne process can be seen in the next figure.

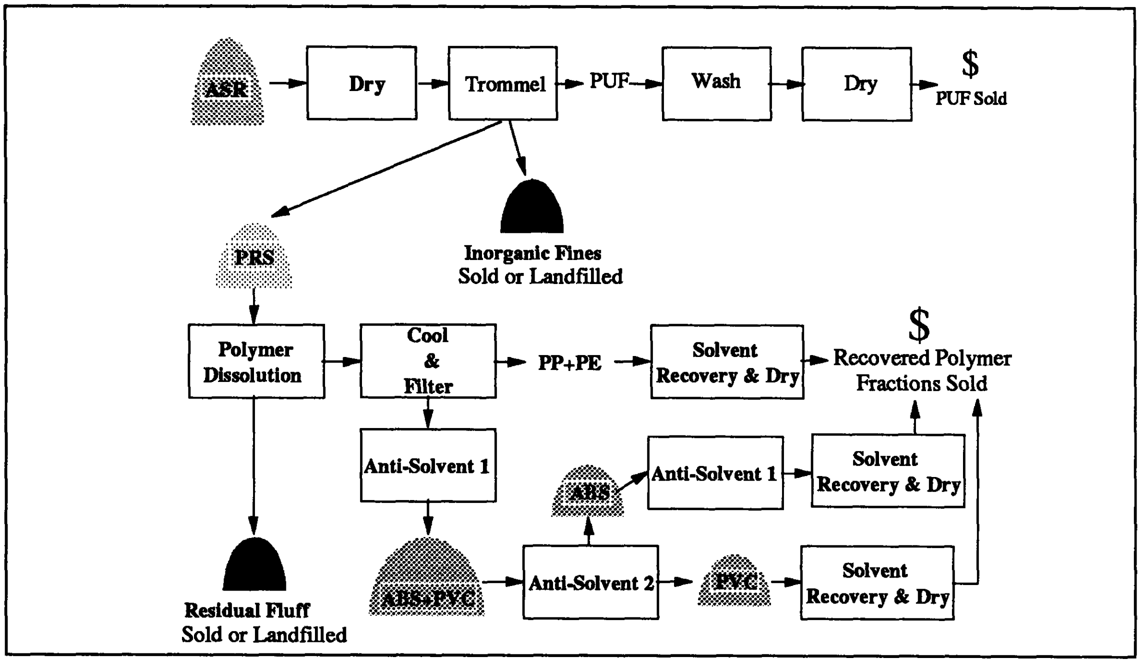


Figure 5.9: Flow Diagram of ASR Mechanical Separation/Selective Precipitation

One major factor affecting the operation and economic feasibility of ASR treatment processes designed for polymer recovery is obviously the fluff stream's polymer content. For both the pyrolysis and mechanical separation/selective precipitation processes, the derived products are directly a function of ASR's organic composition. Available data on ASR's makeup varies widely depending on whether the fluff was pre-dried and cleaned before the analysis. The specific products that enter the shredder (vehicle model, amount of white goods, *etc.*) also have major impacts on ASR composition. Again, for the cost simulations in this study, the ASR composition presented in *Table 5.2* is used.

For the pyrolysis process model, the required feedstock input information is the aggregate polymer content. The cost model uses 28% in its calculation of pyro-product yields. The mechanical separation and selective precipitation process models, on the other hand, require a more detailed breakdown. The weight fractions for PU Foam, ABS, PVC, and the PP + PE mixture as listed in the table above are inputs into the model. Besides ASR composition, there are other model inputs common to both recycling processes. Note that the process tipping fee, *i.e.* money paid to the recycler by the waste generator, is assumed to be $33/mton for both pyrolysis and mechanical separation/selective precipitation. Absent a significant number of commercial scale tertiary recycling operations, no actual fee can be cited. Nonetheless, for the purpose of comparing alternative technologies, a recycling process tipping fee equal to the landfill charge is a reasonable assumption

Process Parameter	*Model Input*
Direct Wages (with benefits)	$20/hour
Working Uptime	7,884 hours/year
Capital Recovery Rate	12%
Capital Recovery Period	10 years
Process Tipping Fee	$33/mton
Landfill Tipping Fee	$33/mton

Table 5.3: Major Model Inputs For Pyrolysis & Mech. Sep./Selective Precipitation

Process parameters specific to each recycling scheme are listed in the following two tables.

Process Parameter	*Model Input*
Main Equipment Investment	$960,000
Plant Capacity	13,635 mtons/year
Number of Direct Workers	2/line
ASR Processing Rate	1.8 mtons/hour
Oil Recovery Rate	40 wgt % of organic content
Oil Market Value	$0.07/liter
Resaleable Solids Recovery Rate	14 wgt % of incoming ASR
Solids Market Value	$0.022/kg
Scrap Metal Recovery Rate	10 wgt % of incoming ASR
Scrap Metal Value	$0.066/kg

Table 5.4: Major Model Inputs for ASR Pyrolysis

Process Parameter	*Model Input*
Overall Process Capacity	74,765 mtons/year
Mechanical Separation Main Equip Invst.	$558,000
Selective Precipitation Main Equip. Invst.	$5,600,000
Number of Direct Workers	6/line
ASR Separation Rate	9.33 mtons/hour
PRS Dissolution Rate	10 mtons/hour
PU Foam Recovery Rate	4.8 wgt % of incoming ASR
ABS Recovery Rate	2.74 wgt % of incoming ASR
PVC Recovery Rate	2.74 wgt % of incoming ASR
PP + PE Mixture Recovery Rate	3.64 wgt % of incoming ASR
PU Foam Recyclate Price	$0.55/kg
ABS Recyclate Price	$0.88/kg
PVC Recyclate Price	$0.55/kg
PP + PE Mixture Price	$0.11/kg

Table 5.5: Major Inputs for ASR Mechanical Separation & Selective Precipitation

The cost modeling results, expressed as net profit or loss for each metric ton of automobile residue processed, are presented in the next two figures.

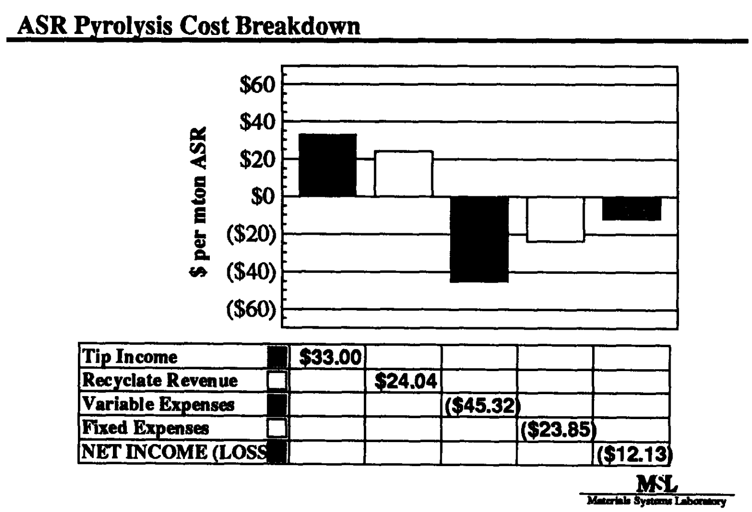
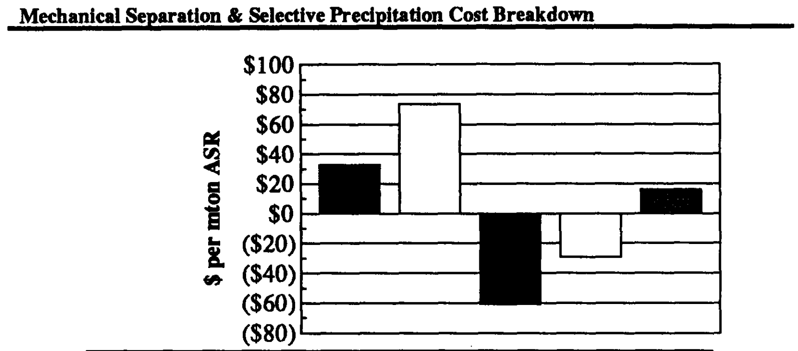


Figure 5.10: ASR Pyrolysis Cost Breakdown



Tip Income	$33.00				
Recyclate Revenue		$73.63			
Variable Expenses			($60.84)		
Fixed Expenses				($29.40)	
NET INCOME (LOSS					$16.39

MSL
Materials Systems Laboratory

Figure 5.11: ASR Mechanical Separation/Selective Precipitation Cost Breakdown

Mechanical separation followed by selective precipitation's has a potential profit of approximately $16 for each mton of processed ASR. Pyrolysis, on the other hand, has a projected loss of $12 for each mton of processed ASR. This dramatic difference in economic feasibilities indicates the economic consequence of reclaiming higher-valued products. Higher labor and capital investments of the mechanical separation/selective precipitation processes are offset by the greater throughput and recyclate values. Nonetheless, both of the above cost figures represent upper bounds since fluff transportation and handling costs between the shredder and ASR processor have been neglected.

Both of the above two cost projections assume a near 100% process capacity utilization. As can be seen, there is a limit to how greater recycling economies-of-scale can lead to lower recyclate costs. While greater plant utilization certainly leads to a lower per unit fixed cost, the processes modeled still cannot independently achieve profitability. The tipping fee remains the critical revenue source for either process. Variable costs such as energy and labor, together with fundamental physical and chemical constraints of materials processing, ultimately impose a financial asymptote.

Sensitivity analyses again can yield valuable insights. The effects of process parameters such as cycle time, pyrolysis temperature, and solvent usage on overall yields and costs can be examined. These analyses can help to identify the more influential cost drivers and thus indicate potential areas warranting additional technical developments. The process economics' sensitivity to fluctuating ASR composition can also be assessed to better establish process robustness. Cost modeling simulations have indicated that tipping fees and recyclates' resale values are by far the most crucial variables in determining the process' economic feasibility.

The cost models can also be used to address strategic issues in automobile recycling. One particularly important analysis, shown in the next figure, suggests the logistical implications of recycling undertakings.

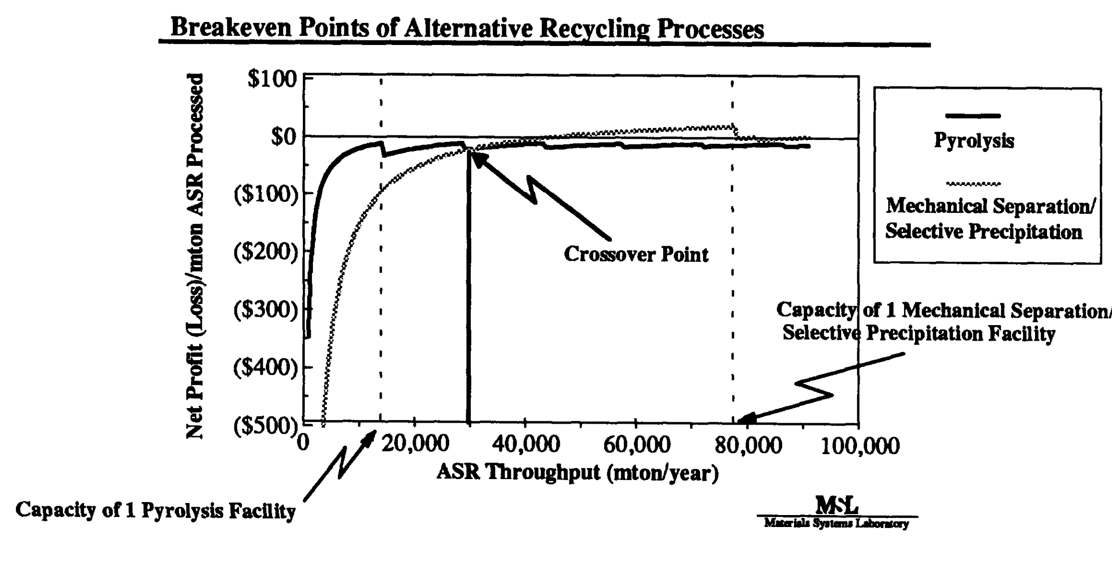


Figure 5.12: Logistical Implications in Alternative Recycling Processes

As the above graph indicates (as well as the cost breakdowns of *Figures 5.10* and *5.11*), the pyrolysis undertaking results in net loss while mechanical separation/selective precipitation can result in a net profit. Both facilities are assumed to be operating at near capacity and their projected costs are indicated by the dotted lines. A more interesting way of viewing *Figure 5.12* is to assume a given amount of available fluff. That is, within a certain geographical area, only a finite amount of ASR can be cost-effectively collected. Since the net profit versus throughput volume curves of different recycling undertakings follow different trajectories, technology choice becomes critically dependent on the amount of available ASR. From the above graph, if less than 30,000 mtons of ASR (*i.e.* from ~100,000 to 110,000 shredded hulks) can be collected each year at one location, then pyrolysis may be the preferred recycling alternative (assuming only the above two choices were available). A net loss is still realized but pyrolysis offers a smaller loss relative to mechanical separation/selective precipitation. If more than 30,000 mtons can be centralized, then the latter approach is preferable. At precisely the crossover point, a recycler would be indifferent to these two choices. Recycling clearly deals with not just material science and process technology challenges but encompasses a broader set of strategic financial issues as well. Technical cost models can identify these issues and analyze their impacts on recycling process economics.

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6. Cost Analysis of the Recycling Infrastructure

6.1. Infrastructure Modeling - Distributional Aspects of Recycling

Technical cost modeling quantifies technological promises and converts vague perceptions into tangible information. For automobile recycling, TCM has confronted allegations pronouncing the hulk shredding infrastructure's imminent collapse by parameterizing perceived material substitution, secondary material pricing, and landfill cost trends into workable variables. These variables are process-based, thus allowing ill-defined intuitions to be correlated with explicit numbers. By simulating a range of scenarios, the models can establish the boundary conditions in the automobile recycling issue. That is, extreme conditions can be explored to test the economic robustness of the hulk shredder.

While the tracking of process costs and recyclate market values in order to calculate a recycling scheme's net profit or loss is an essential financial analysis, a deeper understanding of the underlying cash flows also is required. TCM can provide information on the present recycling situation and broadly outline future outcomes, but it is not capable of explicating the mechanism by which one recycling scenario may evolve into the next. In effect, technical cost models can identify those situations where a particular recycling undertaking can become financially feasible or infeasible. However, the specific economic interactions required to achieve this transformation are unclear. Even for the existing dismantler-hulk shredder infrastructure, the failure mechanism through which it may fail is not obvious. An analytical framework that tracks cash flows should offer some insights into this question. For regulators trying to shift the materials flows of automobile recycling and for businesses operating in this changing environment, clear knowledge of the concomitant cash flows is crucial. This information not only can help avoid an inadvertent infrastructure collapse, but also can allow recyclers to react better to the price signals within their industry. Finally, this knowledge facilitates comparisons of alternative recycling schemes.

When comparing alternative recycling routes, a common method is through net income statements such as the bar graph below. The profits and losses of the recycling undertakings within an infrastructure simply are summed. As can be seen, all three automobile recycling alternatives have higher aggregate revenues than costs and thus lead to overall profits. These positive results may give the impression that all three infrastructure are financially desirable. Such a conclusion would be premature.

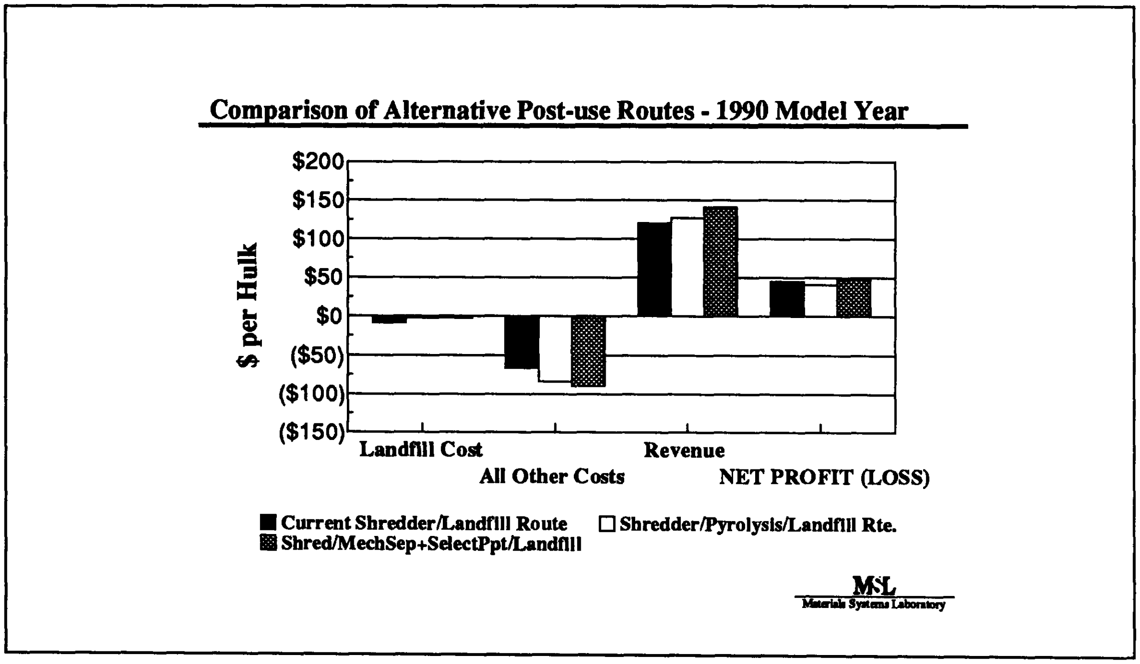


Figure 6.1: Comparison of Hulk Shredding With Alternative Recycling Routes

To analyze the feasibility of alternative recycling infrastructures, one needs to look beyond the infrastructure's bottom line sum and focus on how this sum is distributed along the infrastructure. Since recycling is a business based on playing the margins among feedstock, virgin material, and recyclate spot prices, understanding the sensitivity of fluctuating cash flows on overall process profitability is essential. Unlike the existing recycling infrastructure, which spontaneously organized itself due to market signals, novel recycling processes often originate from regulatory nuances and risky market forecasts. Infrastructure stability can be quite precarious.

An analytical tool has been developed to track the cash flows and the cost distributions within an industrial infrastructure. This framework is applied to the hulk shredding/ASR pyrolysis and hulk shredder/mechanical separation/selective precipitation schemes. These cost distributions, estimated through technical cost models, can be seen in the following two figures.

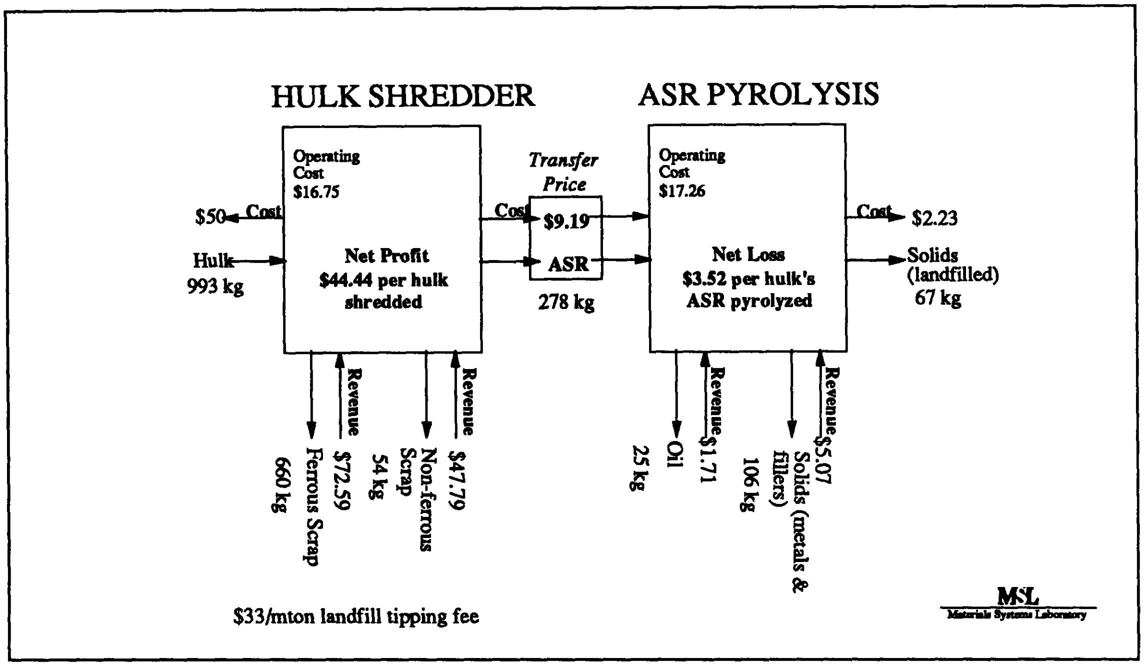


Figure 6.2: Schematic Flow Diagram of Hulk Shredding Followed by ASR Pyrolysis

Viewed as a flow sheet diagram similar to that found in chemical engineering, the above graph clearly shows the inputs and outputs of each process stage within an infrastructure. Such a cost distribution analysis is able to provide a more accurate and useful economic representation. The above figure indicates the material and cash flows for the hulk shredder and the ASR pyrolyzer based on recent feasibility studies. Note that certain material streams (*e.g.* pyro-gas, steam) are not explicitly shown since they are consumed or lost during the process undertaking. Embedded in each process box is a technical cost model capable of simulating process changes such as equipment improvements, plant capacity utilization, and feedstock material changes. Econometric modules predicting, for example, the price elasticity of the secondary scrap market, can also be attached to provide a more dynamic representation of market conditions.

The link between the two stages of this alternative recycling infrastructure lies in the transfer price. Given an average 1990 model year vehicle, an estimated 278 kg of ASR will be generated for each hulk shredded. At a landfill charge of $0.033/kg, each hulk will thus have approximately $9 of ASR landfill liability. Assuming the hulk shredder is indifferent to who fulfills its ASR disposal needs, this $9 can be redirected as a tipping fee to the pyrolysis operator. In fact, given the current public enthusiasm for landfill conservation, the hulk shredder will certainly welcome the opportunity to divert ASR to a recycling alternative as long as there is no increase in its cost. With this $9 transferred to the pyrolysis process, a net loss of more than $3 for each 278 kg of ASR processed (*i.e.* the amount of ASR from 1 hulk) still exists. Despite this net loss, some proponents of recycling may argue that this $3-4 loss is a small price to pay for the potential decrease in landfill consumption. Alternatively one may then argue that landfill charges should be raised, thereby increasing the transfer price, until this $3-4 loss is covered. If one simply sums across both the hulk shredding and ASR pyrolysis stages like in *Figure 6.1*, the overall infrastructure appears to still yield a positive cash flow. This positive cash flow for the entire infrastructure, however, is irrelevant. The fact that the ASR pyrolysis stage faces a net loss for every hulk processed, even with the tipping fee, means this particular infrastructure in unsustainable. No one will be willing or able to run this money losing operation. Unless there is some outside financial force (*e.g.* cash subsidy, landfill restrictions, recycling mandates), the hulk shredding/ASR pyrolysis infrastructure outlined above can not exist.

Due to its two stage configuration and multiple product feature, the recycling infrastructure involving ASR mechanical separation and selective precipitation has a more complex distribution profile than that for pyrolysis.

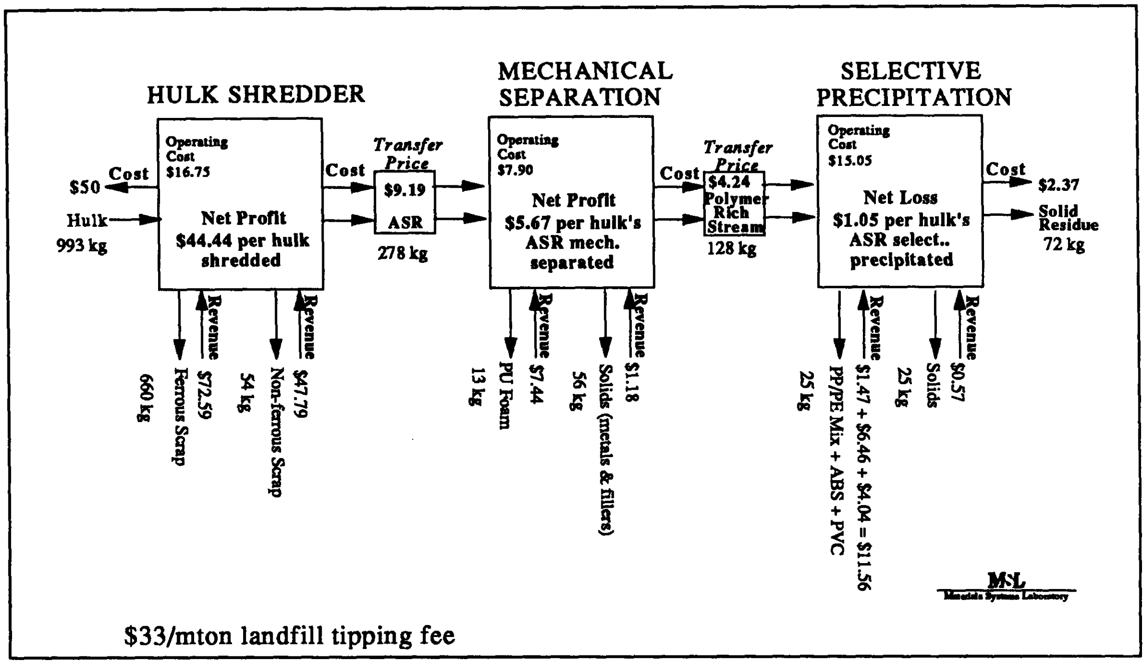


Figure 6.3: Hulk Shredding Followed by Mech. Separation & Selective Precipitation

As before, given an average 1990 model year vehicle, approximately 278 kgs of ASR will be generated for each hulk shredded. The resulting ASR landfill liability of about $9 can then be treated as a process tipping fee to the immediate downstream recycling operation, in this case the mechanical separation stage. Together with the potential income from the sale of recovered polyurethane foam, metallic fines and non-metallic fines, these sources of revenue contribute to a net profit of over $5 for each hulk's ASR fraction mechanically separated. In addition to the operating expense, the costs at the mechanical separation step include the landfill liability of those fluff fractions not reclaimed by this undertaking. Equivalent to 128 kilograms of fluff at $33/mton landfill charge, this $4.24 charge can in turn be viewed as a transfer from mechanical separation to selective precipitation. Essentially, part of the original $9.19 tipping fee from the hulk shredder is passed through to the selective precipitation step. Even with this transferred charge, the selective precipitation stage is not a profitable undertaking. The revenues from recovered material fractions are not sufficient to overcome the large operating expenses. It is important to note that this vehicle recycling alternative, like pyrolysis, does not lead to a complete avoidance of landfill use. There are still residual fluff fractions that need to be landfilled.

Figure 6.3 again emphasizes the importance of assessing recycling alternatives as business undertakings. Like the pyrolysis case study in *Figure 6.2*, a net profit obtained by summing across all three stages is irrelevant. A loss in any single step, in this case the selective precipitation process, can lead to this particular infrastructure's collapse. For regulators, identifying such potential points of infrastructure breakdown can help in formulating more attainable and cost-effective public policies.

Another major implication for establishing alternative recycling schemes also emerges. The various recycling activities (*e.g.* hulk shredding, mechanical separation, selective precipitation) can be strategically grouped. That is, new business opportunities and hence operating units can evolve to sustain recycling initiatives. *Figure 6.3* is a prime illustration of these opportunities. From a purely technical perspective, the mechanical separation and selective precipitation processes are designed to extract the inherent value within the ASR waste stream. Mechanical separation, in addition to recovering certain material fractions, also prepares ASR for the selective precipitation step by concentrating the feedstock's polymer content. As a result, these two steps are typically regarded by technology developers as undertakings by a single ASR treatment business entity. A combined net profit of $4.62 (*i.e.* $5.67 -$1.05) is then possible. With this grouping of activity centers, a sustainable infrastructure exists.

Some interesting issues are raised if other grouping possibilities are considered. From the perspective of a recycler entering the ASR treatment business, there is the financial incentive to undertake mechanical separation for the PU foam content, but to forego selective precipitation in favor of simply landfilling the remaining polymer rich stream. The hulk shredder, recognizing PU foam's value, may take the initiative to perform mechanical separation on site (thereby increasing its net profit/hulk to about $50) before sending the remaining fluff fraction to the landfill or other downstream recycling activity. Which of the above groupings becomes the established infrastructure depends on a wide range of regulatory and economic variables. The hulk shredder's ability to finance and operate a facility to mechanically extract PU foam is certainly a critical factor. A firm seeking to establish an independent foam separating facility needs to evaluate the transportation costs involved in bringing ASR on-site and shipping reclaimed foam and residual fluff off-site. Perhaps the overriding concerns in ASR treatment schemes are the pertinent environmental regulations. If reclaiming automotive polymers is somehow required (*e.g.* material recovery targets, landfill ban), then a mechanical separation business may be forced to tolerate the loss incurred in operating the additional selective precipitation process or perhaps be able to command a higher process tipping fee to offset this loss. As regulations and market conditions such as recyclate prices and landfill fees change, the recycler needs to continually assess its operation's driving forces and position itself advantageously. With the infrastructure cash flow modeling tool shown above, businesses can make such strategic decisions.

6.2. Recycling Policies' Effects On Infrastructure Distribution

Earlier in this thesis, recycling policies were described as supply and demand curve manipulating instruments. The introduction of infrastructure distributional analysis allows a more refined and prescriptive examination of recycling initiatives. The pushing and pulling of recyclate markets can be clarified as the influencing of specific cash flows within the recycling infrastructure. A relatively straightforward example is the raising of landfilling cost. By setting higher landfill charges, alternative recycling processes and infrastructures may become feasible. For ASR pyrolysis, this process break-even point occurs at a landfill charge of approximately $50/mton of waste. The cash flow behind this move towards profitability can be broken into two components. First, the higher landfill cost results in the shredder operator willing to offer a larger process tip to the pyrolysis operator, thereby increasing the latter's revenue. At the same time, the higher landfill charge raises the pyrolysis operator's by-product disposal costs. Since the tip income rises at a faster rate than the landfill liability, the pyrolysis process moves towards profitability and the infrastructure becomes financially stable. The pyrolysis technical cost model outputs in the next figure graphically demonstrate this scenario. The plot on the left indicates the process' net profit as a function of increasing tipping fee. The plot on the right isolates the contributing cash flows.

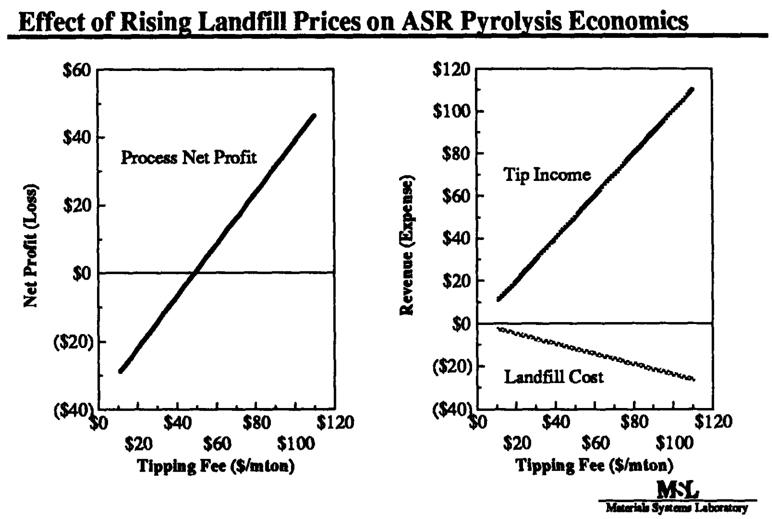


Figure 6.4: Effect of Higher Landfill Charges on Profitability of ASR Pyrolysis

With infrastructure distribution analysis, ASR pyrolysis' move towards profitability is better documented. It is important to realize that as the pyrolysis stage enjoys a higher process tip, the hulk shredding stage incurs a higher ASR disposal expense. *Figure 6.2* can be recalculated to reflect these cash flows and cost distribution shift. This new infrastructure distribution can be seen in *Figure 6.5*. For more complicated scenarios with more price transfer opportunities, such as that for mechanical separation/selective precipitation, a distribution analysis like that below can be especially helpful in clarifying infrastructure dynamics and recycling opportunities.

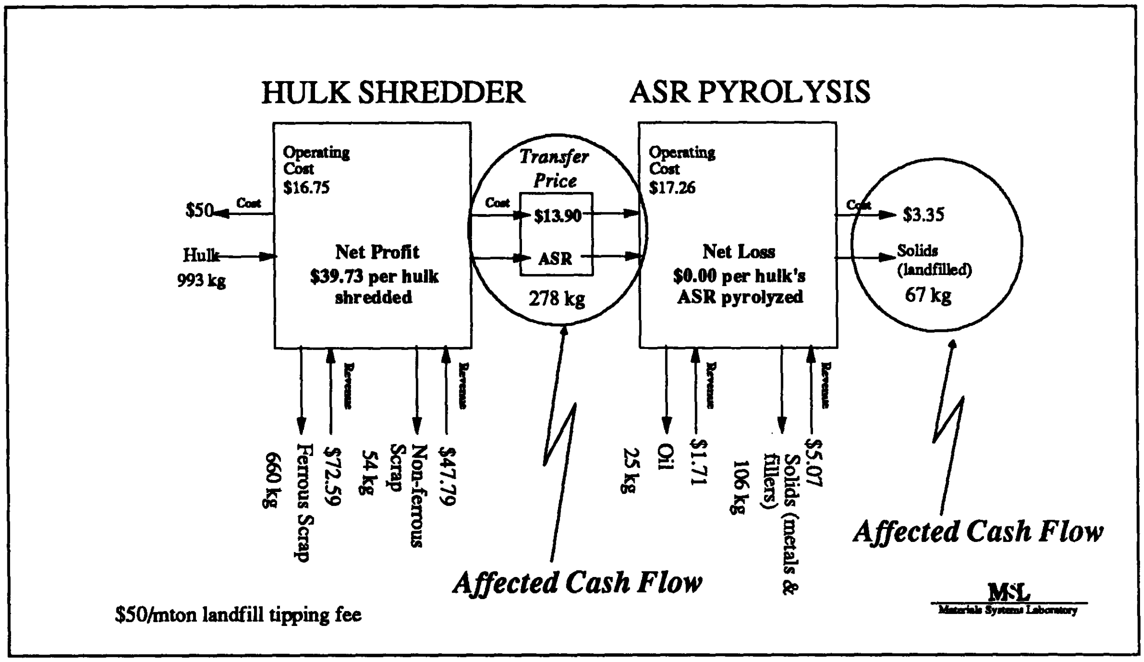


Figure 6.5: Cost Redistribution Due To Higher Landfill Charge - ASR Pyrolysis

The landfilling cost paid by the pyrolysis operator as well as the transfer price between the hulk shredder and the pyrolysis operator should be affected by a rise in the landfill tipping fee. The hulk shredder may pass on its increasing ASR liability by demanding hulk price concessions from the dismantler. Assessing the likelihood and extent of this occurrence requires additional analysis of the economic interactions between the dismantler and the shredder.

The capabilities of infrastructure distribution analysis become even more apparent when used to analyze more complex recycling policy initiatives. For example, a policy like that proposed for the German automobile industry can be analyzed. Similar to that already instituted for packaging materials, this "push" proposal requires each automobile manufacturer to take back its own products upon the end of their use life. Ideally, this return occurs free of charge to the last user. Each major material category within the automobile then has a target recycling (*i.e.* primary or secondary recycling) rate. By imposing recycling from outside the market, this environmental regulation is essentially manipulating the naturally occurring cost distribution. One way such policy mandates can be satisfied technically is through a process like mechanical separation/selective precipitation. Compliance with recycling target rates can be easily verified since the mass of each material stream is tracked. By specifying a no-charge vehicle take-back scheme, the possibility of a consumer subsidized automobile recycling scheme (at least a directly-funded one) can be ruled out. Faced with these two constraints, the automaker is then faced with the task of balancing the various cost and revenue streams within an infrastructure like that shown in *Figure 6.3*. Industry may, for example, choose to directly subsidize the selective precipitation stage.

For this thesis, the primary goal is not to identify the "better" recycling alternative, but to provide a framework within which this decision can be made. Undoubtedly, there are technologies not considered during the course of this research that may offer more extensive material recovery and/or superior economics. More importantly, the preferred alternative will depend on the conditions of a particular geographical area, industry composition, and corporate viewpoint. The infrastructure distribution analysis framework is able to distill these informations into a cohesive and coherent articulation of the relevant issues. While this framework can facilitate financial manipulations and comparisons among alternative recycling infrastructures, it does not address recycling's environmental driving force. That is, it does not provide quantifiable justification that the current profitable recycling infrastructure should be replaced with an alternative. In order to address this issue, an expanded technical cost modeling methodology that explicitly considers recycling's environmental attributes, needs to be developed.

7. Multi-attribute Technical Cost Modeling

7.1. Environmental Attributes of Recycling Processes

When comparing alternative recycling scenarios using a traditional cost modeling paradigm, the problem of rationalizing environmental issues becomes evident. One processing scheme can have a higher cost structure than another but may still be considered to offer more net benefit from a broader perspective that encompasses environmental issues. By explicitly valuing environmental effects individually instead of as some aggregated remediation cost, drastically different decisions may be reached. For example, the value of keeping water clean becomes the focus of debate as opposed to the cost of cleaning up polluted water. The present technical cost modeling methodology is unable to capture this subtlety. Specifically developed to examine process cost structures, TCM relies on market prices. By utilizing market prices, TCM better reflects actual technological and process scenarios faced by businesses. This practicable simulation approach comes at the expense of completeness since the present methodology ignores those consequences which can not be valued. Thus, environmental impacts are not considered beyond a simple remediation cost.

Even though traditional cost analysis has shortcomings when depicting environmental issues, it can serve as a foundation upon which an expanded accounting system can be constructed. Financial feasibility certainly remains a primary concern when considering whether or not to undertake a particular recycling process. An additional explicit accounting of environmental attributes, however, can offer a more comprehensive decision making perspective. A recycling scheme undoubtedly can be externally compelled to become a preferred post-use management route. For example, regulators can cite economic externality arguments and redefine land scarcity. One way to push up artificially the value of land and thus increase landfill prices is by requiring extensive licensing and inspection requirements. Recycling processes and infrastructures then may become financially attractive and stable alternatives to landfill disposal. The resulting environmental benefits, however, are not undeniable. Recycling schemes are complex market-driven undertakings that may not exhibit the win-win characteristics some proponents expect. A case study result, for a 1990 vehicle model year hulk, is shown in the graph below (reprise of *Figure 6.1*). The solid bars represent the traditional hulk shredding followed by ASR landfilling. The empty bars represent hulk shredding followed by ASR pyrolysis and the gray bars represent hulk shredding followed by mechanical separation and selective precipitation. The cost structure corresponds to those in the previous section.

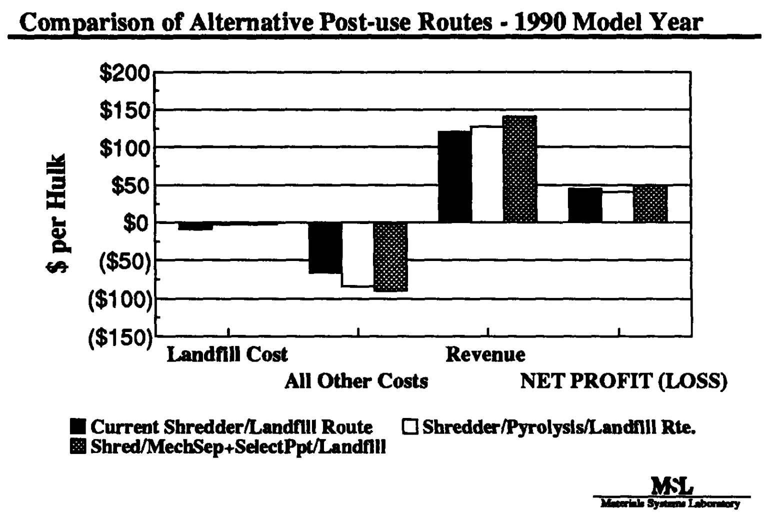


Figure 7.1: Comparison of Hulk Shredding With Alternative Recycling Routes

As the above graph shows, recycling may conserve and recover resources but nevertheless have negative financial results. Given a strictly financial interpretation of the above graph, together with the earlier infrastructure distribution analysis, the existing hulk shredding/ASR landfilling recycling infrastructure should not be replaced by shredder/pyrolysis. However, the above statement is based on the assumption that market prices capture the full cost of industrial undertakings. From the perspective of economic externalities, one can argue that the market price for, say landfill usage, is not actually a true reflection of the landfill's value. Therefore, while current market prices may indicate that landfill conservation is an infeasible business undertaking, a framework that explicitly accounts for environmental aspects may overturn this conclusion. The question to be asked then is not whether recycling can be financially advantageous but rather whether recycling can offer a better combination of financial and environmental consequences when compared to virgin material usage and landfilling. Likewise, a financially more appealing scenario, like mechanical separation followed by selective precipitation, may become unattractive under a broader accounting perspective. It is important to remember that an accounting framework, expanded or not, simply provides a decision making process with information. Corporate strategies and policy objectives ultimately determine how this information is applied.

This thesis proposes an expanded accounting framework better to assess economic and environmental trade-offs in automobile recycling. Multi-attribute technical cost modeling methodology is based on the traditional cost modeling methodology but explicitly tracks environmental attributes as well as the cost metric. This broader information set allows both recycling's process cost structures and environmental consequences to be better analyzed. The two specific processes described earlier, pyrolysis and mechanical separation/selective precipitation, are examined in this manner to *1)* test the methodology's usefulness, *2)* quantify the economic and environmental impacts, and *3)* identify relative strengths and weaknesses of different recycling schemes.

7.2. Energy Metric

The main objective of multi-attribute technical cost modeling, for this study, is to determine whether recycling may allow a more "equitable" balance between the traditional concept of market-priced costs and the currently uncosted aspects of environmental impacts. The first iteration in developing multi-attribute cost modeling focuses on recycling's energy balances as the additional attribute to traditional market price costs. There are several reasons for choosing energy. First, as discussed in Chapter 2, recycling's potential as an energy saving material production route is a primary appeal. Another reason is energy's commonality among recycling processes. While other environmental attributes such as emissions can differ drastically from one process to another, energy intensity is relatively transferable. Given a particular energy source and other process variables (*e.g.* yield, quality) being equal, lower energy consumption is no doubt preferred. Since different energy sources can have drastically varying environmental consequences, power generation issues can be further explored through sensitivity analyses.

Finally, the energy metric can serve as a proxy for a myriad of environmental emissions. Air emissions in particular are often a direct function of the amount of energy consumed. Carbon dioxide, a primary concern in the Clean Air Act for its role in global warming theory, is a by-product of carbon fuel combustion. The emission of carbon dioxide occurs for any of the alkane fuels including gasoline used to power automobiles and industrial fuels to power manufacturing processes. Similarly, fuel containing sulfur will evolve sulfur dioxide, the precursor to acid rain. Hydrocarbons and oxides of nitrogen also are directly linked to fuel consumption. Using the multi-attribute technical cost modeling methodology, environmental attributes such as energy are tracked alongside cost. Like for cost, the energy metric is also sensitive to the product design and process parameters inputs used in the model. Thus, a wide range of components and manufacturing scenarios can be studied.

For energy tracking, several heat content figures are required and can be seen in *Table 7.1*. The combustion heat content (column *C*) refers to the energy evolved if the material itself is burned. The feedstock heat content (column *A*) refers to the energy evolved if the feedstocks that goes into making the material are burned. The process heat content (column *B*) refers to the energy required to transform these feedstocks into the material. A material's "embodied" energy can be then defined as the sum (*A*+*B*) of the starting feedstock's heat of combustion and the processing energy to convert the feedstock to the final material. This concept of embodied energy can be used to characterize the input feedstock for any material recycling process. Together with the product heat of combustion *C*, these energy numbers can define the upper and lower bounds of a material's recoverable energy. Energy content information for ASR and the recovered products is presented in the following table.[99]

	A	B	C
Material	*Feedstock Heat of Combust. (MJ/kg)*	*Process Energy (MJ/kg)*	*Product Heat of Combust. (MJ/kg)*
ASR	13	8	9
#6 Heating Oil	35	---	35
Natural Gas	21	---	21
PU Foam	51	17	37
ABS	57	19	42
PVC	29	30	18
PP + PE Mixture	65	14	46

Table 7.1: Material Energy Content Assumptions

For the pyrolysis process, the potentially recoverable energy is simply the combustion values of the reclaimed gas and oil. For mechanical separation/selective precipitation, the materials' embodied energies can be recovered since polymer resins are reclaimed. Using the ASR composition data in *Table 5.2* and the energy content information in *Table 7.1*, the potentially recoverable energies for the two recycling processes can be calculated and are presented in the following figure.

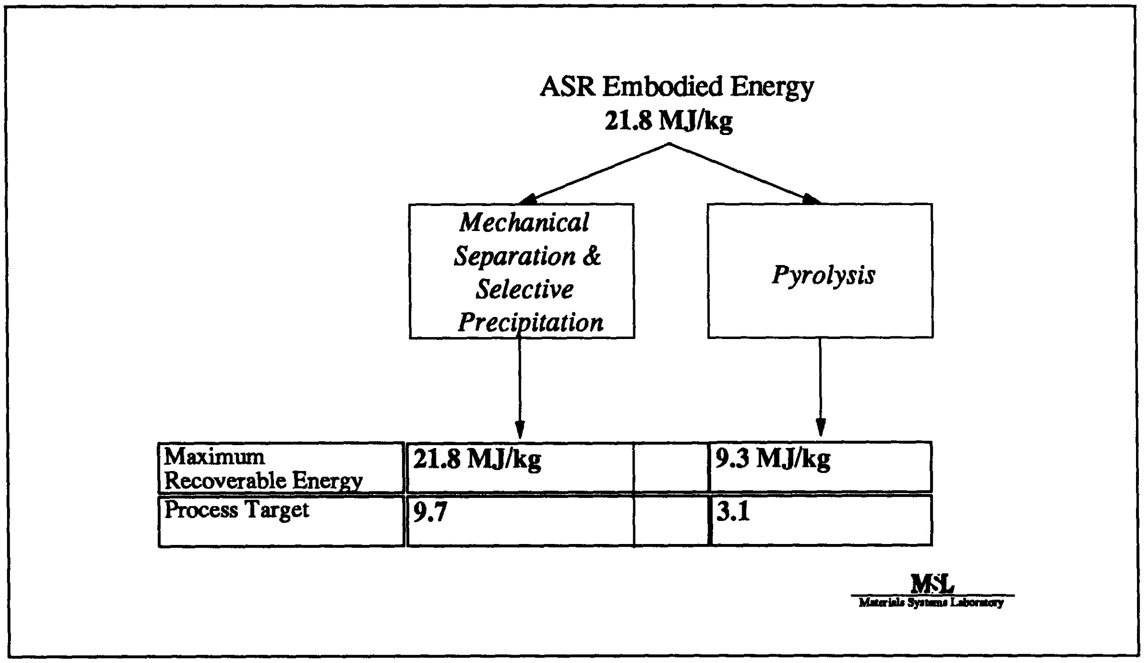


Figure 7.2: Potential Levels of Energy Recovery

The maximum recoverable energy represents a theoretical upper bound for potential energy recovery. The process target is defined as the amount of energy the recycling scheme is designed to retrieve. As can be seen, selective precipitation possesses an overwhelming advantage over the pyrolysis from a maximum recoverable energy perspective. This advantage derives directly from selective precipitation's smaller return loop up the material's energy chain (refer to *Figure 2.3*). However enticing this potential energy recovery, a complete analysis encompassing technological and market constraints yields a more sobering outlook. Although there are some efforts to reuse thermoset resins as fillers or construction shapes, the ability to re-utilize polymer resins through primary or secondary recycling is typically limited to thermoplastic resins. Thus, a large fraction of automobile polymeric wastes consisting of thermosets such as the reaction injection molded polyurethanes (RIM PU), unsaturated polyester (UPE), and rubber, usually continues to be landfilled. For the mechanical separation/selective precipitation process, the process target reflects the extraction of polyurethane foam, polypropylene, polyethylene, acrylonitrile butadiene styrene, and polyvinyl chloride. Of the polymeric materials commonly found in automobile shredder residue, only these five resins are present in large enough quantities and have a relatively established secondary market to interest recyclers. For pyrolysis, the process target represents the heat of combustion value for the recovered oil. The evolved gas fractions are used to sustain the pyrolytic reaction.

In addition to the energy content of these materials, the recycling processes' externally supplied energies are included in the analyses. In particular, electricity and steam consumption is tracked and expressed in terms of MJ/mton of processed ASR to allow additivity. One kilogram of steam is assumed to equal 2.2 MJ. The energy consumption is presented in the next table.

Process	*Electricity* (MJ/mton)	*Steam* (MJ/mton)	Total (MJ/mton)
ASR Pyrolysis	693	0	693
ASR Mechanical Precipitation	57	317	374
PRS Selective Precipitation	225	1,182	1,407

Table 7.2: Recycling Process Energies (per mton of ASR)

Even with only two tracked attributes, the expanded analytical framework presents a more meaningful depiction of environmental and economic trade-off possibilities. A graphical representation of the combined multiattribute modeling results is presented in the next figure.

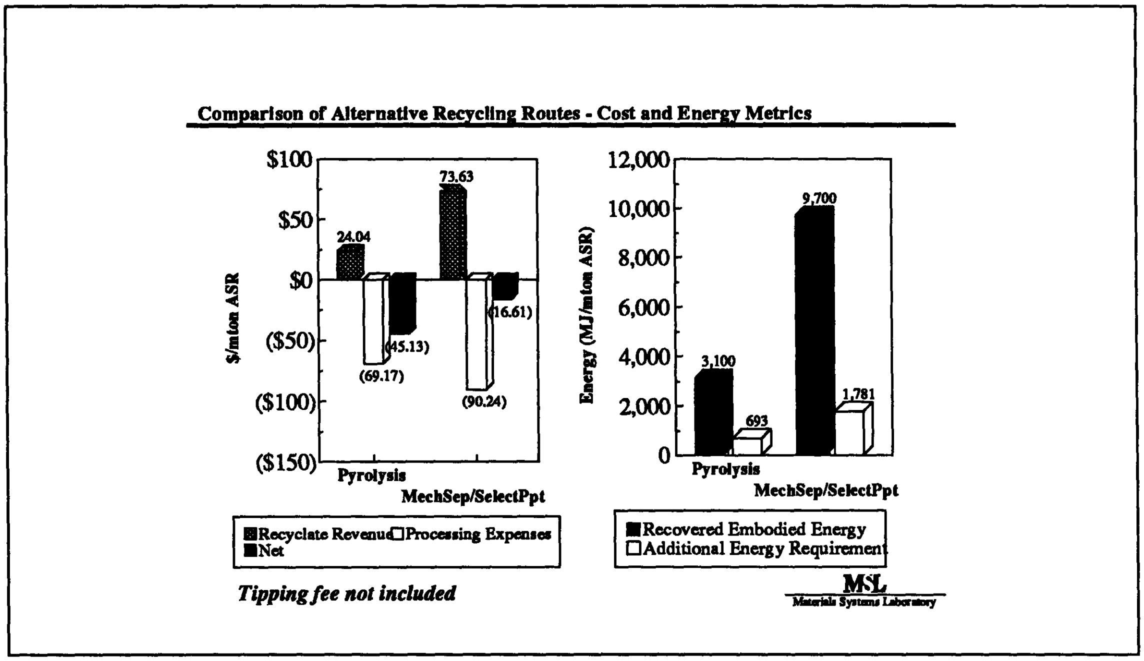


Figure 7.3: Multi-attribute View of Alternative Recycling Processes

As can be seen in the above figure, recovering a greater portion of ASR's embodied energy content leads to a greater revenue. This finding is in keeping with the original premise of *Figure 2.3* that recycling is based on exploiting the energy/value chain. The more interesting finding is the amount of process energy involved in extracting the embodied energy. While this process energy had been represented as variable costs with the traditional cost modeling methodology, its environmental implications are now more fully exposed using the multiattribute framework. In the above case study, mechanical separation/selective precipitation appears to be better from economic and recovered energy perspectives. If minimizing additional process energy is the important factor, then pyrolysis is preferable. While the recovered energy may benefit the material production stage in the next product lifecycle, the additional process energy is borne by the current post-use stage. Therefore, the choice between these two alternatives, and ultimately versus the existing landfill option, requires inter-lifecycle stage trade-offs.

As the cost analyses in this thesis have shown, the various recycling schemes can have dramatically different cost structures. By expanding the modeling framework to encompass environmental metrics, the recycling alternatives also demonstrate diverse environmental load structures. The multi-attribute models still do not, and should not, identify clear environmental winners among competing processing alternatives. The primary objective, instead, is to clarify the multivariate and multistage structure of industrial processes. Within the post-use stage (*i.e.* intrastage), there are thus potential trade-offs among these different metrics to find some better balance of economic and environmental welfare. As seen above, interstage trade-offs also exist. Thus, even with a multi-attribute modeling approach, the thinking that recycling may offer broader resource conservation benefits can be difficult to validate. Reconciling the diverse economic and environmental objectives, in order to incorporate recycling into the broader environmental management and product design setting, requires a better representation of the complex relationship between a material's lifecycle and a material's processing infrastructure.

99 Curlee, T. Randall and Sujit Das, "Plastics Recycling in the Industrial Sector: An Assessment of the Opportunities and Constraints," *ORNL/TM-11258*, Oak Ridge National Laboratory, 1989.

8. Broader Environmental Policy Implications

8.1. Economic-Environment Attributes Mapping

While recycling's first order function is as a landfill management alternative, advocates increasingly emphasize broader resource conservation issues. Arguably, resource chains such as the energy example in *Figure 2.3* may be exploited to recapture natural resources and/or economic value. A multi-stage mapping framework, using outputs from cost models, can better articulate the relevant interstage and intrastage trade-offs. The following figure, using this mapping methodology, illustrates the basic rationale behind the resource conservation thinking for a hypothetical automobile. Tracking the vehicle through the four major lifecycle stages of virgin material extraction (*A*), vehicle production (*B*), vehicle usage (*C*), and vehicle post-use (*D*), two aspects of each stage are plotted. The cumulative cost of each undertaking (*i.e.* before accounting for revenue) reflects the total capital expenditure over the product lifecycle. The net resource consumed (*i.e.* resource used minus resource recovered), reflects some aggregate impact on the environment. While the graph will shift depending on the particular resource that is tracked, resource as a generic term is sufficient at this point to illustrate the varying consumption characteristics of different lifecycle stages. The implicit assumption is that minimizing resource consumption leads to less environmental damage.

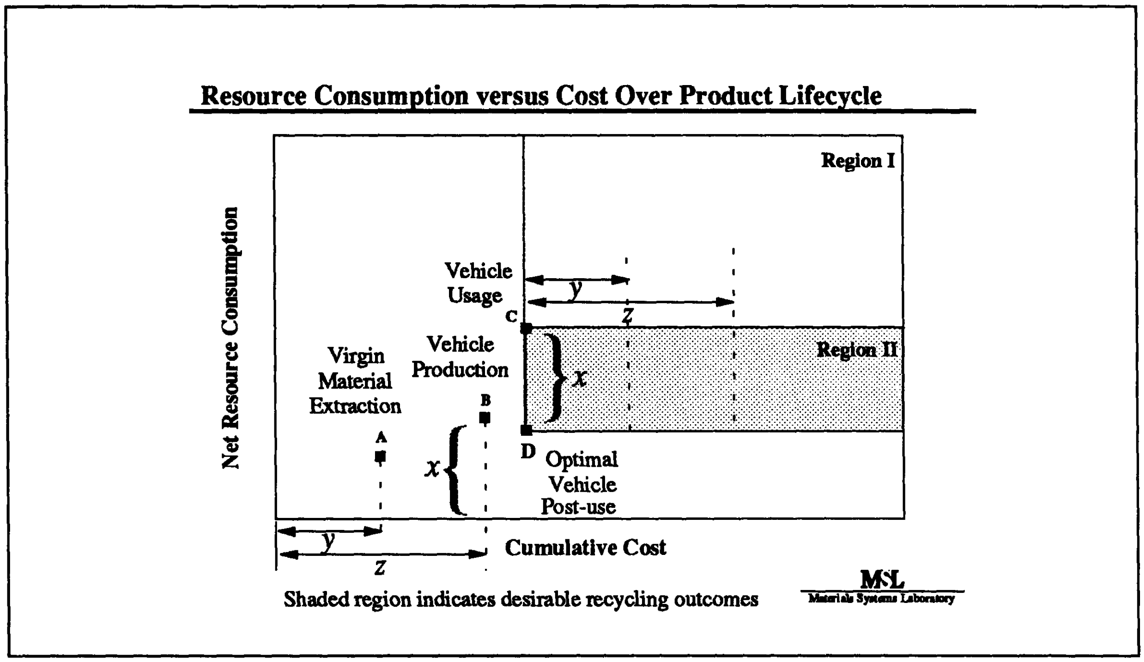


Figure 8.1: Net Resource Consumption & Cumulative Cost In Vehicle Lifecycle

The above plot summarizes the resource and cost outlays through the vehicle's use stage. The post-use stage, however, may either result in a net increase or decrease in resource use. Therefore, post-use can lie anywhere in *Regions I* or *II*, inclusive of the borders. The area to the left of these two regions is unattainable since the post-use stage cannot have a negative cost (recall that the abscissa represents cost, not net profit or loss). *Region I* is not desirable since the particular post-use option will result in further net resource consumption. An example of this scenario is landfilling post-use vehicles without any attempt at material extraction or simply the abandoning of vehicles. The primary additional resource consumed in these cases is land.

Region II encompasses post-use solutions that more effectively pursue resource conservation objectives. The current vehicle recycling route arguably lies in this region by aggressively reclaiming components and materials with only the residual, roughly 25% of the vehicle weight, ultimately landfilled. By being principally a ferrous scrap extraction process, the current scenario allows the next generation product to avoid the ore extraction and some refining stages. In terms of resource accounting, this implies a credit and thus a move towards the lower area of *Region II*. Theoretically, the maximum amount of recoverable resource (point *D*) is that which is embodied in not only the vehicle's material, but more broadly in its product functionality. For example, if the entire vehicle is reused, then all the resource and cost consumptions (quantities *x, y, z,* respectively) from raw material extraction through the automaker various value-added manufacturing steps can be avoided. The cost and resource consumption associated with the use stage (*e.g.* fuel, maintenance, insurance) is obviously not recoverable. If the post-use stage is more costly to undertake than the virgin material route (> *y* or even worse > *z*,) then there is no financial incentive to seek alternative automobile disposal options. Rather, the cost of producing virgin materials, new components, or new vehicles will be lower.

Despite the current scenario's unobjectionable position on the cost-resource map, recycling policies are nonetheless proposed either as a defensive measure due to the automobile's changing material content or perhaps as an ambitious move towards a better cost-resource combination. Essentially, there is a wish to drive a product's post-use stage ever closer to its theoretical optimum. It is important to appreciate the fact that, once resources have been consumed, they are not retrievable *per se*. Rather, through recycling, the next generation product may avoid all or part of the virgin resource consumption cycle by reusing all or part of the preceding generation's remnants. Thus, a post-use option that allows the vehicle to retain its function as much as possible leads to lower resource consumption over multiple lifecycles. Through more extensive material recovery or component reuse, more resources may be conserved. The desire to apply recycling as a broad resource conservation initiative may be one reason why tertiary and quaternary recycling processes (*i.e.* the recovery of chemical components and thermal energy, respectively) usually are not favored in recycling mandates. Such processes (pyrolysis and incineration are the most commonly identified) neither aggressively exploit a resource chain such as seen *Figure 2.3* nor recover any resource that can be specifically reused in the original application. Nevertheless, these technologies may offer a compromise between an intensive resource recovery and a bearable processing cost.

The cost-resource map approach conveniently segregates a product's lifecycle into distinct stages. Although the stages from raw material extraction through use have clear private economic stakeholder associated with them, post-use is in the public domain. The major consequence of this dissimilarity is that, if the post-use stage degrades to a "do-nothing" vehicle dumping scenario, the impact will be huge at the society level but relatively weak at the individual level. Absent strong personal stakes, environmental goals such as resource conservation may be difficult to motivate. Interestingly, while reduced operating intensities in the raw material extraction, vehicle manufacturing, or use stage arguably can be environmentally beneficial, a reduction in post-use management is probably undesirable.

The next figure, based on the cost-resource map of *Figure 8.1*, is a schematic plot of energy consumption versus cost for the two specific recycling technologies highlighted in this paper. The current recycling scenario of hulk shredding followed by ASR landfilling is also plotted for reference. While the *x* and *y* scales remain arbitrary, the points' relative ordering is realistic. The post-use stage, which is the principal topic of this thesis, is based on the multi-attribute technical cost models' outputs.

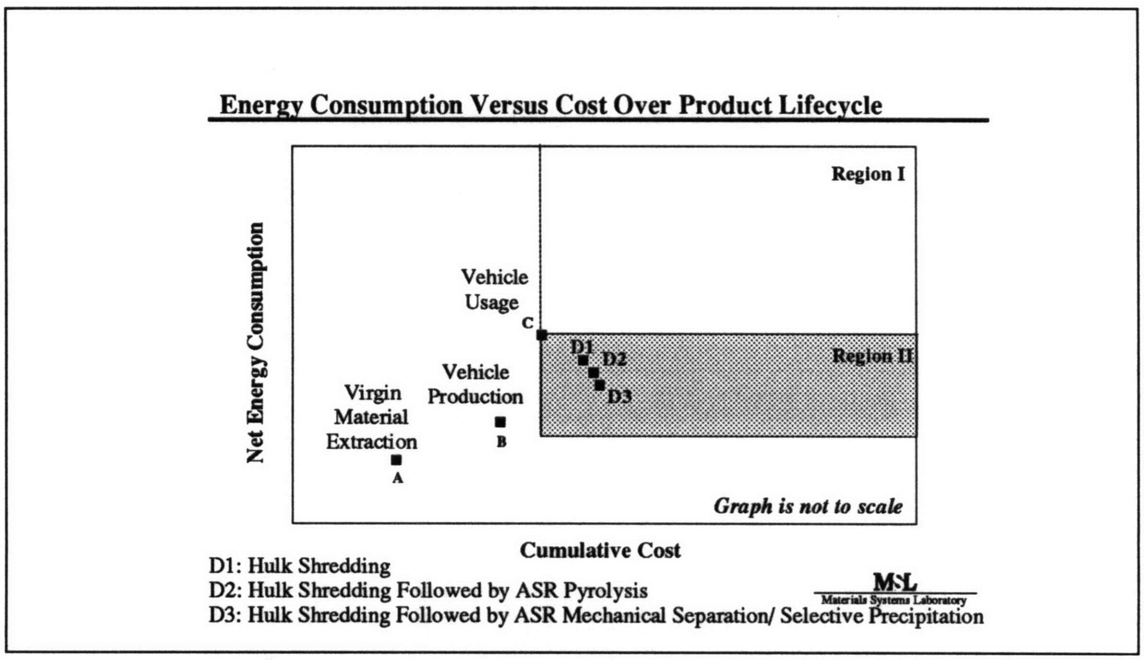


Figure 8.2: Mapping of Recycling Alternatives - Energy Perspective

All three post-use alternatives are in the desirable *Region II* (*i.e.* net recovery of energy content). Mechanical separation/selective precipitation, while offering a greater amount of recovered energy, requires a greater cost outlay. Of course, as the economic analyses show, the greater cost can be offset by higher value recyclates. In the next figure, landfill consumption is tracked and a different picture emerges.

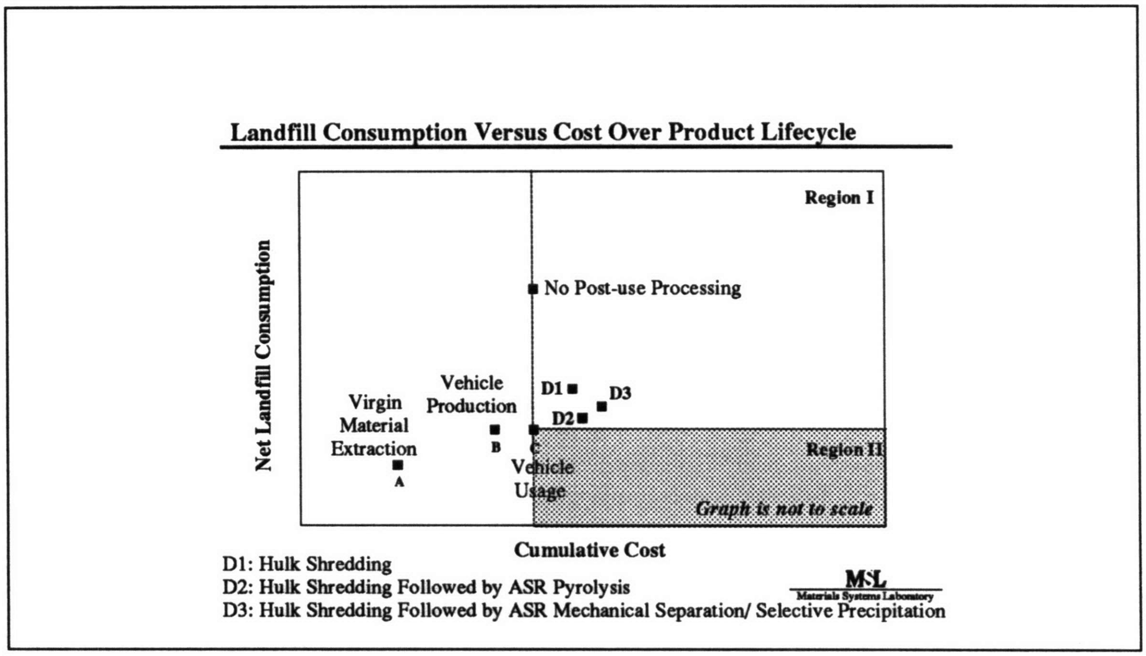


Figure 8.3: Mapping of Recycling Alternatives - Landfill Perspective

From the landfill conservation perspective, all three post-use options are in *Region I*. That is, some additional consumption of landfill is always necessary. Nonetheless, when compared to a do-nothing scenario of vehicle dumping, all three alternatives are vastly superior. The theoretically optimal environmental scenario, in this case, is the border between *Regions I* and *II*. Both of the ASR recycling options analyzed in this study do move towards this line, thus validating recycling's original objective of landfill conservation. Perhaps surprisingly, the more aggressive landfill conservation process does not demand higher operating expenses. Pyrolysis, in this case, appears to be the more efficient landfill user.

Trade-offs between cost and environmental metrics are long recognized. As *Figure 8.2* indicates, the relationship between cost and an environmental attribute can be monotonic (*i.e.* more cost leads to more energy recovery). *Figure 8.3*, on the other hand, shows that the trade-off can also exhibit non-monotonic behavior. Thus, a simple statement that equates more environmental benefit with a more costly undertaking would be wrong. Perhaps the more important use of cost-resource mapping is its ability to demonstrate environmental policies' attribute specificity. A superior technology from one environmental perspective may be inferior from another. In the figures above, the choice of recycling alternatives clearly depends on whether landfill or energy is considered. This idea is further clarified if the cost-resource maps are converted to net profit-resource maps like those in *Figure 8.4*. Alternative *D3* (*i.e.* hulk shredding followed by ASR mechanical separation and selective precipitation), may be the most profitable undertaking but may not be the least environmentally burdensome.

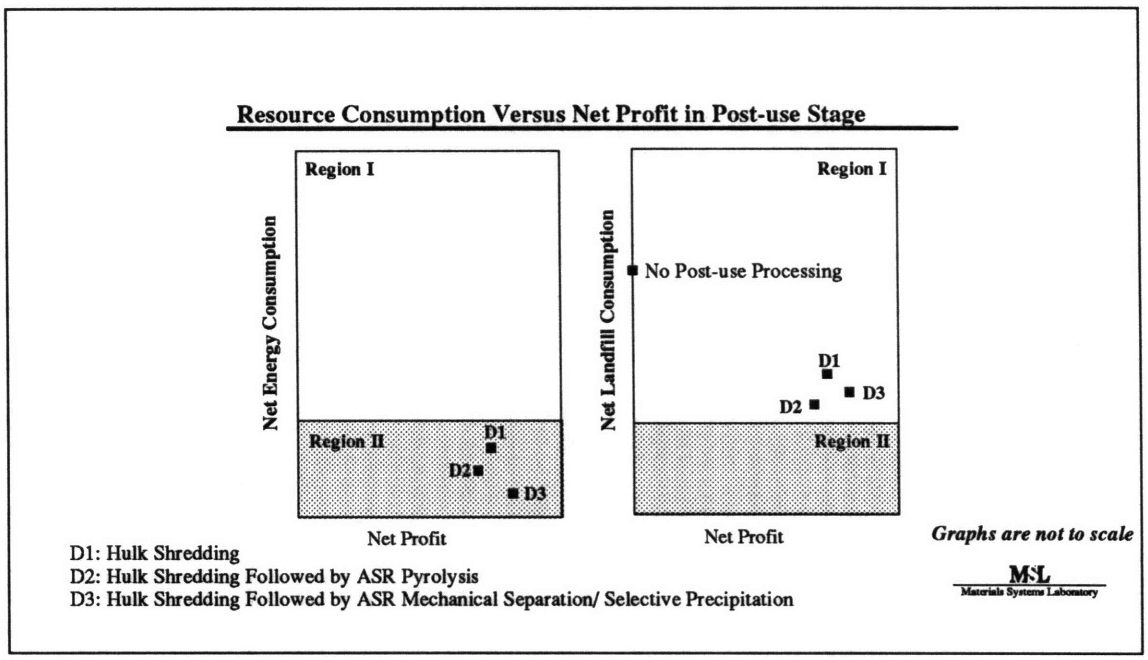


Figure 8.4: Schematic Net Profit Representation of Recycling Alternatives

The major assumption in the above plots is that alternative recycling infrastructures can be described by a single net profit number. In reality, as shown by infrastructure distribution analysis, such a concept can be misleading and is usually unsound. Nevertheless, if a single economic entity is responsible for the entire automobile recycling infrastructure (perhaps under a manufacturer take-back program), a simple profit summation may be used. For now, *Figure 8.4.* is constructed only to better illustrate the dependency of recycling choice upon the particular resource perspective. As environmental attributes in addition to energy and landfill space are considered, the complexity of comparing alternative recycling schemes increases. Adopting a systems approach is thus necessary. Policies that pontifically promise specific environmental benefits may have unforeseen outcomes in other attributes. Instead, policy arguments need to be elevated to ones based on environmental trade-offs. While cost-resource maps can demonstrate explicitly the environmental and economic consequences of technological alternatives, balancing the underlying environmental objectives (*e.g.* landfill versus energy conservations) is the critical task.

8.2. Interdependence Between Post-use Stage and Other Lifecycle Stages

The cost-resource map can be used to examine issues within a specific lifecycle stage. In the above examples, different recycling schemes are compared within the post-use stage. The mapping methodology also can suggest some relative significance of environmental impacts among the different lifecycle stages. A cost-resource map can be plotted to scale and thus illustrate the relative consumption levels of a specific resource throughout an automobile's lifecycle. This refinement nevertheless results in a snapshot representation of the product's cost and environmental attributes. In order to allow product and process designs to progress towards some more desirable end (however this is defined), a dynamic and more interactive analytical tool is required. Evolving product design and manufacturing decisions' impacts on the post-use stage need to be demonstrated. Conversely, such a tool should also address questions regarding how post-use policies and management options may affect other lifecycle stages. For example, material specific taxes, deposit fees, recovery rates, and product's recyclate content levels, all can influence vehicle design and material selection decisions. Choices that may enhance post-use recovery (*e.g.* avoiding non-ferrous applications) will certainly have implications on manufacturing costs. Very likely, the vehicle's use stage environmental impacts will be affected as well.

This interdependence among the lifecycle stages implies that environmental policies' aimed specifically at a single lifecycle stage (*e.g.* recycling initiatives), may achieve only locally optimal design solutions. A product policy cutting across all lifecycle stages, on the other hand, may yield a more globally optimal solution.[100] An iterative evaluation framework, capturing cost and environmental implications of a vehicle's design and material content, has been developed to allow such interdependencies to be represented. Multi-attribute technical cost modeling is the principal component of such a framework. As previously described, these models incorporate economic and environmental metrics of industrial processes. The thesis so far has focused on the post-use stage and only presented modeling efforts for recycling processes. In order to expand the scope of this thesis beyond post-use and encompass the upstream lifecycle stages as well, production and use stage modelings have also been undertaken.

100 Ehrenfeld, John R., "Industrial Ecology: A Strategic Framework for Product Policy and Other Sustainable Practices," *Green Goods: The Second International Conference and Workshop on Product Oriented Policy*, Stockholm, September, 1994.

9. Lifecycle Profiles

9.1. Vehicle Design and Manufacturing: Cost Estimation Methodology

In expanding the scope of this study to reflect a product's lifecycle, a fundamental modeling issue is encountered. Each stage of the lifecycle depicts a different aspect of the automobile. In the production stages, the vehicle is represented by materials, components, and subassemblies. In the use stage, the finished vehicle is considered. In the post-use stage, analyzed in the previous chapters, the vehicle is described by its materials composition and the mass of each material. This variation in vehicle descriptions means care must be taken when transferring or comparing information among stages. One way to ensure interstage equivalence is to model the complete automobile manufacturing sequence from raw material extraction through disposal. This approach, although theoretically possible, is impractical since it would entail simulating the production of hundreds of components through dozens of processes across several industries. While a gross and static estimation of the automobile's economic and environmental impacts can be made (*e.g.* using aggregated industry and government data on capacity utilization, capital investments, employment level, productivity, toxic release inventory), this type of assessment offers little in the way of proactive environmental management. Such macroscopic views sacrifice detail for completeness and do not possess the subtlety to explore specific product design and material selection options. This thesis thus prefers applying multi-attribute technical cost modeling's process-based approach even if an entire automobile is not depicted. The research objective is not to assess the lifecycle impacts of automobiles *per se*, but to understand the lifecycle consequences of using alternative materials in the automobile. That is, relative costs and benefits are sought rather than some absolute figure.

The Materials Systems Laboratory at MIT has undertaken a project comparing the manufacturing economics of alternative vehicle body designs. Generated with material choice as the principal consideration, these designs are intended to demonstrate the consequences of using different materials in the automobile body-in-white (BIW). Non-structural and semi-structural components (*e.g.* deck lids, fenders) have already seen large scale commercial application.[101,102,103] Structural parts, like those found in BIW, are relatively undemonstrated and represent the next area of materials competition.[104,105,106] Accounting for approximately 25% of a vehicle's curb weight, the BIW can represent a significant portion of a vehicle's lifecycle impacts. The component forming step of the body-in-white in itself requires considerable resource consumption and cost outlay. It also has far reaching influence on the finishing requirements in the painting and final assembly steps. Driven by vehicle lightweighting initiatives, materials substitution in the BIW directly influences the vehicle's use stage operating cost and fuel consumption. In the post-use stage, the BIW affects the shredded hulk's output material streams. Being both an area of growing materials competition and a subassembly requiring significant cost and resource consumptions, the body-in-white represents a conceptually ideal opportunity to examine the relationship between alternative product designs and their lifecycle impacts. Information from the various lifecycle stages are related through the body-in-white. Therefore, in the production stages, the BIW manufacturing sequence is modeled. Although it is unrealistic to consider the fuel efficiency alternative BIWs in the use stage, it is possible to consider the fuel efficiency of vehicles containing alternative BIWs. In the post-use stage, again it is not realistic to discuss the post-use processing (*e.g.* shredding) of alternative BIWs. However, it is possible to analyze the post-use processing of hulks containing alternative BIWs.

This thesis, focusing on the economic and environmental consequences of automotive polymers, examines a polymer-intensive BIW in detail. In order to aggressively utilize polymeric composites (and perhaps aluminum as well), a spaceframe technology is probably required to achieve sufficient vehicle stiffness with the least material outlay. A more conservative material substitution approach, and the subject of this first iteration, is to retain the basic steel unibody design with certain components replaced by polymers. While perhaps not as potentially effective a weight reduction strategy as a spaceframe approach, retaining the unibody concept allows an incremental incorporation of structural polymeric composites. At every level of polymer composite "intensity", there is a trade-off between the benefits of working with the familiar unibody design and the increasing incompatibility of polymers in a steel manufacturing setting. At some point, rationalizing the polymer-intensive unibody concept will become a series of hollow assumptions.

The polymer-intensive BIW will be compared with a traditional steel unibody. The moldings of the polymer body-in-white components, assuming the use of an unsaturated polyester/glass fiber/calcium carbonate compound, have been simulated using technical cost models. For this study, the body-in-white is defined as those parts of an automobile body that are the primary providers of structural stiffness. These parts include the floorpan, roof, door frame, quarterpanel, dash support, and radiator support. Closure panels (*e.g.* doors, fenders, hoods, deck lids) are non- or semi-structural and thus are excluded from this study. It is important to note that the vehicle designs modeled are chosen *a priori* not necessarily for their cost effectiveness or superior performance, but rather for their simulation feasibility. In fact, it is undoubtedly inappropriate to assume that the unibody construction evolved to take advantage of stamped steel's properties is equally suitable for polymer-intensive vehicles. Instead, the study's objective is to examine the relationship between the vehicle's material composition and manufacturing requirements. Through the process simulation tool of technical cost modeling, this relationship can be represented by a changing cost number. Using this type of analysis, a more realistic vehicle design offering hybrid materials technology can then emerge.

As a first estimate, the polymer-intensive unibody will consist of polymeric floorpan, roof, dash support, and radiator support assemblies. All other parts will remain in steel. A combination of adhesive bonding, welding, and mechanical fastening is used in the subassembly and assembly processes. A flowsheet of the manufacturing process is shown in the next figure.

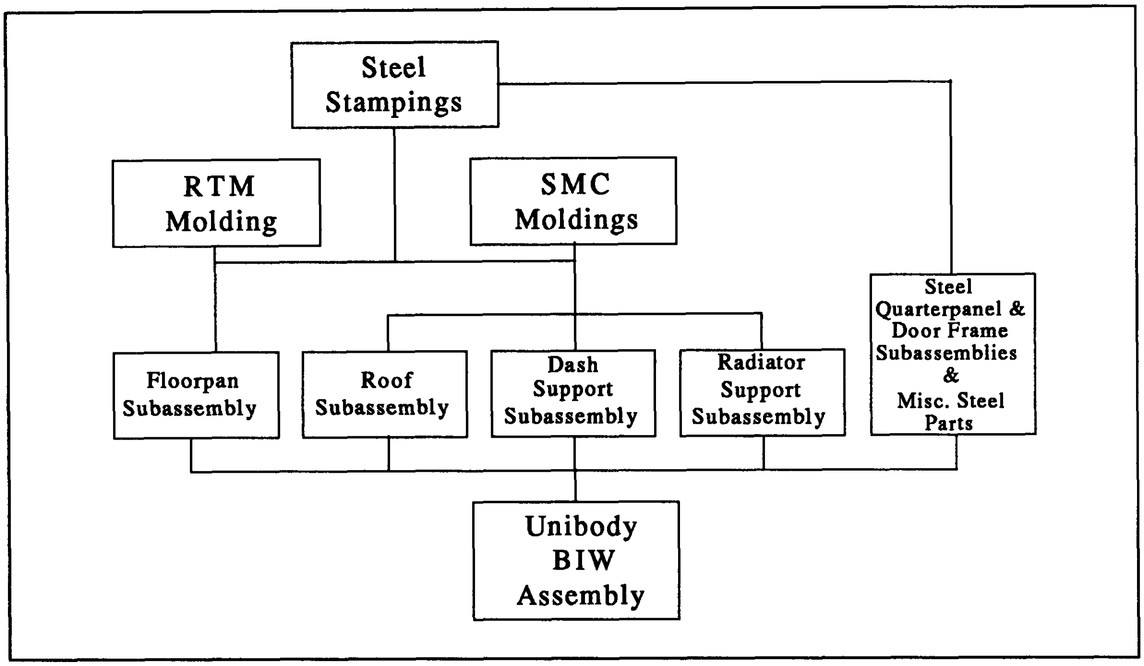
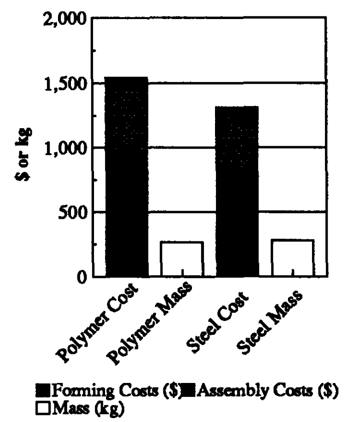


Figure 9.1: Schematic Flow Diagram of Polymer-Intensive Unibody Manufacturing

The major inputs and outputs of each polymer component manufacturing and assembly step are discussed in Appendix B. Since a complete model print-out will run to over a hundred pages with several thousand variables, only major cost drivers have been itemized. All costs are estimated for a mid-sized four door vehicle (*e.g.* Taurus, LH, Cutlass) at an annual production volume of 500,000. This high production volume is chosen to establish polymeric materials' potential beyond niche vehicle applications. Further analyses on production volume sensitivity can determine the crossover point among different vehicle/material designs. Design and fabrication assumptions are based on interviews with members of the automobile industry and on a large database of technical papers.[107,108,109,110,111,112,113,114,115] Optimistic assumptions regarding resin prices and cure times are used. The goal of the costing exercise is not to establish the polymer-intensive unibody's current production feasibility (given that no such design has been commercialized, it is probably not an obviously feasible project), but rather to recognize the scenario at which such a design may become a realistic undertaking. Cost numbers for the steel unibody, as well as those for the steel stampings used in the polymer-intensive BIW, are from an earlier study comparing steel and aluminum bodies.[116]

The cost summary for the two alternative body-in-whites is presented in the next figure. The steel unibody at $1311 is $231 or approximately 15% less expensive than the polymer alternative at $1542. On the other hand, the polymer-intensive BIW at 265 kgs is 15 kgs or about 5% lower in mass compared to the traditional steel design at 280 kgs. In other words, the polymer alternative has a $15/kg cost premium. Other high production volume polymer for steel substitutions (*e.g.* automobile hood) potentially require only a $1 cost penalty per kilogram weight saving.[117] Based on the much higher cost premium estimated in this study, a polymer-intensive unibody design most likely is economically infeasible. Furthermore, this design's small weight savings may indicate its limited influence on fuel savings in the use stage. The unimpressive figures projected by the models are not surprising given that polymer components are simply grafted onto an unibody design evolved to take advantage of steel's high modulus. In order to yield equivalent part stiffness, the polymer components need to be substantially thicker than the steel ones which they replace. With the larger cross-sections, these polymer parts become heavier and more costly to manufacture.

Summary of BIW Modeling Results - 500,000 vehicles/year



	Polymer BIW	Steel BIW
Forming Cost	$971	$832
Assembly Cost	$571	$479
Mass	265 kg	280 kg

Figure 9.2: Cost and Mass Summary of Alternative Body-in-White Designs

Nevertheless, the polymer-intensive unibody BIW is a suitable case study for this thesis. While cost and weight are important product attributes, there are a wide range of environmental issues currently not considered during the product design cycle. The steel and polymer alternatives presented in this study offer enough divergences throughout the production, use, and post-use stages to illustrate the lifecycle impacts of design and material choices.

The primary design variables in generating a vehicle body's lifecycle profile are its mass and material content. For the raw material production through BIW manufacturing stage, environmental data provided by the Institute for Polymer Testing and Polymer Science (IKP) at the University of Stuttgart is applied. The BIW manufacturing cost is estimated using the cost modeling methodology described in the previous chapter. For the post-use stage, cost and environmental results are those presented throughout this thesis. The existing hulk shredding/ASR landfill scenario is considered.

9.2. Raw Material Production and Body-in-White Manufacturing

The energy requirements and selected emissions to produce each kilogram of polymer composite and galvanized steel sheet component (*i.e.* raw material production through part forming and assembly) are presented in *Table 9.1*. Obviously, a complex set of assumptions regarding production routes, energy sources, and remediation technology are behind these numbers. The IKP software, from which these figures are derived, allows a wide range of scenarios to be modeled. For the purpose of this thesis, the primary goal is to demonstrate the compatibility of cost modeling with environmental modeling and the decision support capabilities of such a framework. Thus, the validity of the underlying processing assumptions will not be critically verified. Instead, the focus will be on examining the interrelationships between the BIW's post-use stage with its upstream precursors.

Environmental Attributes	*Quantity per kg Polymer*	*Quantity per kg Steel*
Energy Requirements	MJ/kg	MJ/kg
	6.35E+01	3.62E+01
Air Emissions	kg/kg	kg/kg
CO_2	2.77E+00	2.51E+00
SO_2	1.62E-02	4.13E-03
NO_x	1.13E-02	4.00E-03
NM VOC	8.03E-03	3.57E-05
CO	1.95E-03	2.43E-02
CH	5.84E-03	1.32E-02
N_2O	5.31E-04	3.04E-05
Dust	2.63E-03	6.18E-03
Solid Emissions	kg/kg	kg/kg
Ore Waste and Tailings	2.15E+00	3.55E+00
Waste	1.77E-01	2.46E-01
Hazard Waste	1.77E-02	NA
Water Emissions	kg/kg	kg/kg
CSB	2.15E-03	3.57E-05
HC into Water	9.07E-04	7.14E-07
Organic Solute	6.64E-05	NA
Inorganic Solute	5.24E-03	5.36E-05

Table 9.1: Polymer and Steel - Material Production and Component Manufacture

Given the BIW design information, summarized in *Table 9.2*, the environmental burden for the alternative BIWs can be calculated.

	Polymer-Intensive BIW	*Steel BIW*
Mass of PolymerUsed (kgs)	54	0
Mass of Steel Used (kgs)	211	280
Total Mass of BIW (kgs)	265	280

Table 9.2: Material Composition of Polymer-Intensive and Steel Body-in-Whites

Each design's material content is multiplied through the data array in *Table 9.1.* using the following calculation. The masses of polymer and steel components in a particular design is denoted by M_p and M_s, respectively. The environmental attributes associated with polymer and steel are denoted by p_i and s_i, respectively. The body-in-white's environmental profile (BIW_i), from raw material production through body manufacture, is presented in its disaggregated form.

$$M_p \begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ \cdot \\ \cdot \\ \cdot \end{bmatrix} + M_s \begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ \cdot \\ \cdot \\ \cdot \end{bmatrix} = \begin{bmatrix} BIW_1 \\ BIW_2 \\ BIW_3 \\ \cdot \\ \cdot \\ \cdot \end{bmatrix}$$

The environmental profiles, on a per BIW basis, for the polymer-intensive and steel alternatives considered in this thesis are presented in *Table 9.3*.

Environmental Attributes	*Quantity/Polymer-Intensive BIW*	*Relative Magni-tude*	*Quantity/Steel BIW*
Energy Requirements	MJ/BIW		MJ/BIW
	1.11E+04	>	1.01E+04
Air Emissions	kg/BIW		kg/BIW
CO_2	6.79E+02	<	7.03E+02
SO_2	1.75E+00	>	1.16E+00
NO_x	1.45E+00	>	1.12E+00
NM VOC	4.41E-01	>	1.00E-02
CO	5.24E+00	<	6.81E+00
CH	3.09E+00	<	3.69E+00
N_2O	3.51E-02	>	8.50E-03
Dust	1.45E+00	<	1.73E+00
Solid Emissions	kg/BIW		kg/BIW
Ore Waste and Tailings	8.66E+02	<	9.95E+02
Waste	6.16E+01	<	6.90E+01
Hazard Waste	9.56E-01	>	NA
Water Emissions	kg/BIW		kg/BIW
CSB	1.23E-01	>	1.00E-02
HC into Water	4.91E-02	>	2.00E-04
Organic Solute	3.58E-03	>	NA
Inorganic Solute	2.94E-01	>	1.50E-02

Table 9.3: Environmental Attributes - Material Production Through BIW Assembly

9.3. Use Stage Environmental Profile

For the use stage, the BIW's environmental impacts are assumed to depend solely on the vehicle's fuel consumption. Repair, maintenance, and accidental spillage thus are ignored. In turn, fuel economy is affected by the masses of the alternative BIW designs. For the steel case, a baseline set of vehicle curb weight and fuel economy rating approximating a mid-sized automobile is used. Assuming that a 10% reduction in vehicle mass can lead to a 4.5% reduction in fuel consumption, the fuel economy of a vehicle containing a polymer intensive BIW can be derived. While a lighter BIW potentially can lead to further weight savings in engine and chassis sizes (*i.e.* secondary weight savings), while maintaining equivalent driving performance, this additional calculation is avoided. The interrelationships among vehicle mass, performance, and fuel economy are complex. A simple assumption regarding secondary weight savings will only detract from the thesis' primary objective of establishing an environmental management methodology.

Use Stage Parameters	*Vehicle Containing Polymer BIW*	*Vehicle Containing Steel BIW*
Curb Weight of Vehicle	1,399 kgs	1,414 kgs
BIW Portion	265 kgs	280 kgs
Non BIW Portion	1,134 kgs	1,134 kgs
Fuel Economy	9.69 liters/100 km	9.74 liters/100 km

Table 9.4: Fuel Economy of Vehicle Alternative Body-in-White Designs

Knowing the vehicle's fuel economy and assuming a lifetime distance traveled of 150,000 kilometers, total use stage fuel consumption can then be calculated for a particular vehicle. By dividing the lifetime fuel consumptions by the alternative designs' respective curb weights, a number representing fuel consumption per mass of vehicle, can be obtained.

Use Stage Parameters	*Vehicle Containing Polymer BIW*	*Vehicle Containing Steel BIW*
Curb Weight of Vehicle	1,399 kgs	1,414 kgs
Lifetime Fuel Consumption	14,534 liters	14,604 liters
Fuel Consumption /Unit	10.39 liters/kg of vehicle	10.33 liters/kg of vehicle

Table 9.5: Fuel Consumption of Vehicles With Alternative Body-in-White Designs

By reducing a vehicle's fuel consumption characteristic to a generic liters/kg number, a BIW's fuel consumption can be established. This number is a theoretical construct since a BIW is not a self-propelling object. Nevertheless, a BIW fuel consumption figure serves as an agent for comparative analyses among different designs. By assuming that 1 liter of gasoline equal to 32.2 MJ of combustion energy, the use stage's energy metric can be made compatible with those in the other stages. Furthermore, each MJ of energy derived through fuel combustion has a concomitant emission. For example, 1 MJ of energy obtained through gasoline combustion is assumed to release 0.0723 kgs of carbon dioxide. Other equivalent emission conversion factors for each MJ of gasoline derived energy are shown in the next table.

Air Emission	*Quantity per MJ Gasoline Derived Energy* (kg)
CO_2	7.23E-02
SO_2	1.75E-05
NO_x	1.15E-05
NM VOC	9.19E-06
CO	1.03E-06
Methane	1.43E-05
N_2O	1.94E-08
Dust	5.81E-07

Table 9.6: Air Emission Quantity for Each MJ of Gasoline Derived Energy

As an additional refinement, the energy consumption and emissions associated with gasoline refining can be included.

Environmental Parameter	*Quantity per liter of Gasoline Produced*
Energy Consumption	3.97E+00 MJ
CO_2	2.35E-01 kg
SO_2	1.20E-03
NO_x	8.18E-04
NM VOC	6.50E-04
CO	7.45E-05
Methane	9.49E-04
Dust	4.09E-05

Table 9.7: Environmental Profile of Gasoline Production

With the above conversion factors, alternative designs' environmental profiles (air emissions and energy consumption) in the use stage (including gasoline refining) can be calculated on a per BIW basis. These numbers, shown in *Table 9.8*, demonstrate how the polymer alternative's lighter weight translates into a superior environmental profile during the use stage relative to that of the heavier steel body.

Use Stage Parameters	*Polymer-intensive BIW*	*Rel Mag*	*Steel BIW*
Energy Consumption	99,711 MJ/BIW	<	104,737 MJ/BIW
CO_2	7.07E+03 kg/BIW	<	7.42E+03 kg/BIW
SO_2	4.85E+00	<	5.09E+00
NO_x	3.27E+00	<	3.44E+00
NM VOC	2.60E+00	<	2.74E+00
CO	2.96E-01	<	3.11E-01
Methane	3.89E+00	<	4.08E+00
N_2O	1.72E-03	<	1.80E-03
Dust	1.64E-01	<	1.72E-01

Table 9.8: Environmental Profile for Alternative BIWs During Use Stage

9.4. Post-use Stage Environmental Profile

In the post-use stage, the principal effect of alternative BIW designs is the amount of ASR generated. Since the BIW constitutes a relatively small portion of a shredded hulk, the energy required to shred either the polymer or steel design is assumed to be the same (~69 MJ). With an additional assumption about the energy source (*e.g.* natural gas, fuel oil), the emissions attributable to hulk shredding can be accounted as well. Using the hulk shredding cost model, the economic as well as the landfill consumption associated with a particular vehicle design can be simulated. While the economic consequence is fairly small, the polymer-intensive body does yields a larger amount of shredder residue.

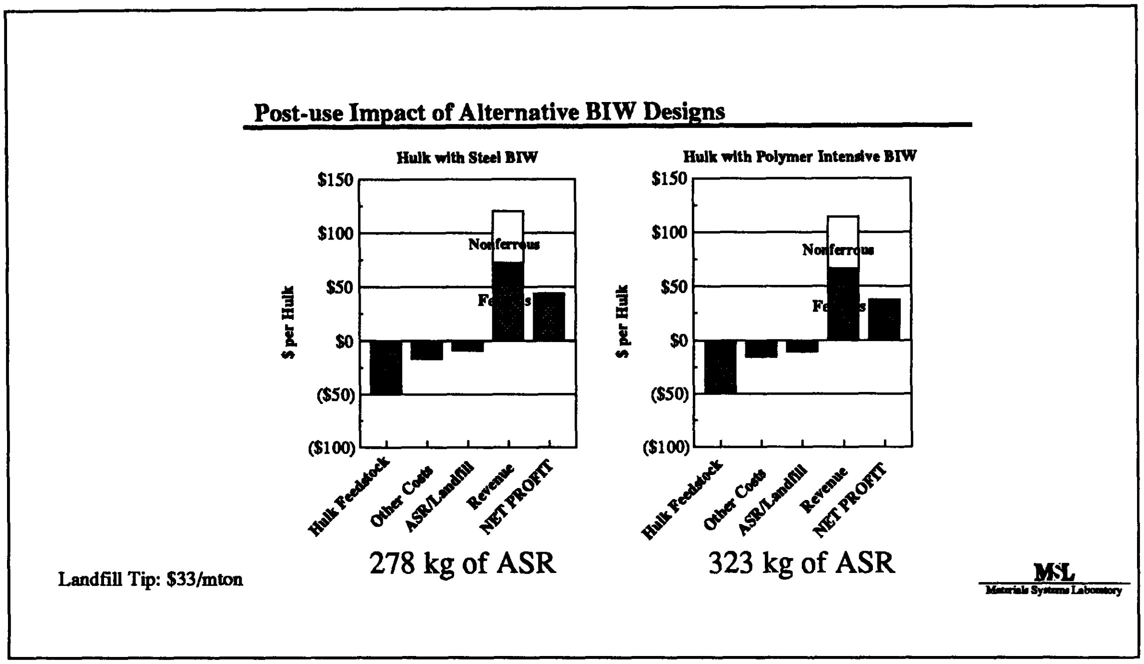


Figure 9.3: Post-use Stage Environmental Profile for Alternative BIWs

9.5. Lifecycle Profiles As a Strategic Framework for Environmental Analysis

As can be seen in the above environmental profiles, there is no clearly preferable design. Each material system has its particular impacts on the environment. Depending on the resource, emission, or lifecycle stage considered, a design will appear to be better than another. The critical task of a lifecycle framework then, is not to choose optimum routes but to facilitate the reaching of a mutually acceptable set of environmental values. It is important to acknowledge that choices need to be made based on an individual's, a firm's, an industry's, or a society's valuations and priorities.

The foremost task of a lifecycle methodology then, is organizing environmental data in a form that is both transparent to and interactive with the user. Transparency is accomplished by maintaining a product's environmental and economic attributes in their disaggregated and unvaluated forms. Especially important is avoiding a simple summation of a particular attribute across the various lifecycle stages. Since each lifecycle stage is represented by different stakeholders, a totalled cost, resource consumption, or emission is misleading. From the perspective of each stakeholder, such a number offers little usable information in their activities. For example, condensing the CO_2 emission data set for a particular product throughout its various lifecycle stages certainly is a doable undertaking. Arguably, a product (*e.g.* automobile) with a lower overall CO_2 emission total is preferable to one with a higher emission. This simplistic approach, however convenient, overlooks the fact that CO_2 emission assumes different roles in different lifecycle stages. In the use stage, carbon dioxide is a mobile emission while in the other stages this gas is a stationary source emission. Furthermore, geographical conditions dictate whether a particular level of emission is critical. The different stakeholders also may have varying degrees of control and abatement cost structures for a particular emission. Multiple stage emission summations lack the subtlety to allow such issues to emerge.

For traditional financial data, where cost minimization has been the standard practice, the applicability of a summed figure through the various lifecycle stages also is obscure. A vehicle with the lowest overall lifecycle economic cost is by no means the most financially viable. The product that will ultimately survive in the marketplace must prove feasible within each one of its lifecycle stages. Again, each lifecycle stage contains its own group of economic entities. Those costs directly affecting a particular business have priority consideration in its decision making process. Thus, for example, the raw material supplier may pay little notice to how post-use management costs are rising and the automaker may not care about its buyers' usage costs (*i.e.* post-vehicle-purchase costs). Of course, market interactions among the various businesses eventually make such indirect costs from other stages more pressing. A prime example is car buyers' sensitivity to vehicle quality. While the initial purchase price is still a critical selling point, maintenance costs have also become a competitive issue for the automakers. In addition to fluctuating market signals, environmental regulations often step in to supplant such signals. For example, CAFE has raised automakers' awareness of their products' fuel consumption costs. Recycling regulations potentially can also force producers (raw material suppliers and/or original equipment manufacturers) to account for post-use management costs. The point is that a simple cost summation precludes these market dynamics from being represented. It is not the absolute magnitude of the costs that is important, but rather the distribution of these costs.

Interactivity with the user is the other critical feature of an environmental analysis framework. A static "snap shot" lifecycle description of a product, while useful for benchmarking activities, is basically just a detailed inventory. To qualify as a design support tool, a lifecycle methodology must be capable of sensitivity queries. A convenient representation of the disaggregated and unvaluated data set is through plots like that in *Figure 9.4*. By plotting multiple product attributes for alternative designs (ordered by increasing degree of polymer-for-steel substitution), a more engaging lifecycle framework is evolved. Trade-offs among the different attributes from the various lifecycle stages can be represented. From the sample plot below, the trade-off between higher manufacturing cost and lower vehicle mass (and thus lower use stage energy consumption), is clear. Production stage energy consumption, on the other hand, rises with increasing polymer content.

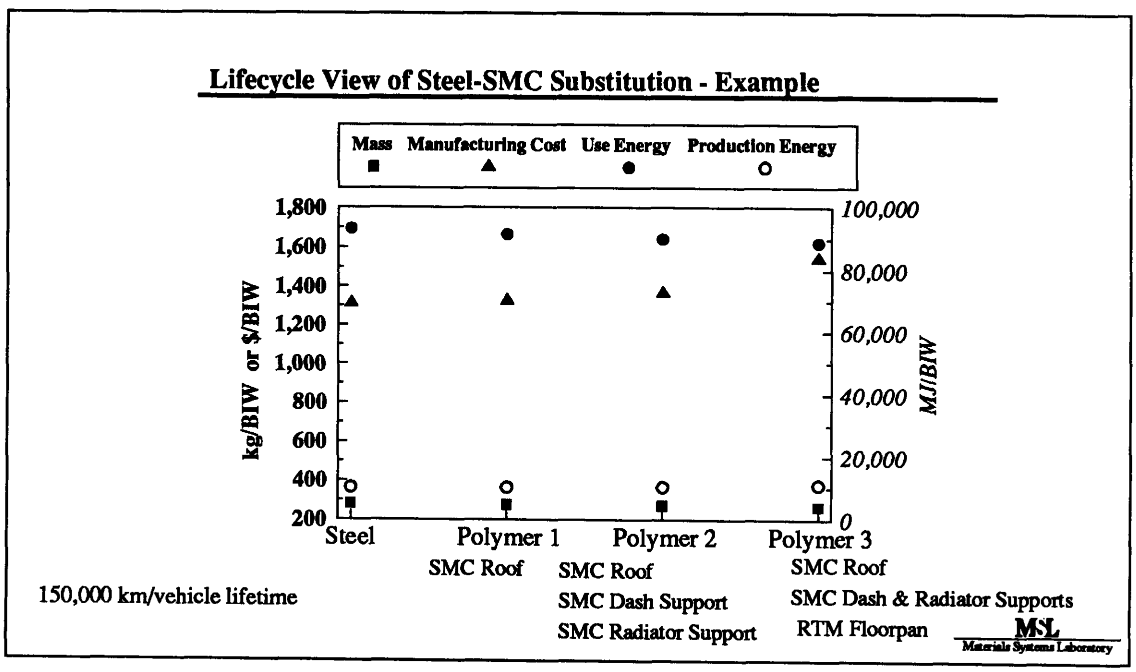


Figure 9.4: Lifecycle Comparison Among Alternative BIW Designs

Two additional characteristics of the lifecycle framework proposed in this thesis further promote its user interactivity and distinguish it from other methodologies. First, this thesis' approach is built upon process simulation tools. Behind the graphical representations of *Figure 9.4* are technical cost models capable of providing tenable representations of alternative product and process designs. Such computer simulating tools can analyze relatively quickly a large portfolio of lifecycle scenarios. The models' modular constructions allow alternative infrastructures to be simulated as well. By manipulating process-based design variables to arrive at projections, rather than simple extrapolation from existing products, more realistic and robust estimates can be obtained.

The second distinguishing characteristic of the lifecycle framework proposed by this thesis is the integration of cost in the methodology. Environmental optimizations performed in isolation to financial considerations offer little information upon which businesses can act. By understanding the cost implications of environmentally driven design changes, one can operationalize environmental issues by rationalizing such changes within the familiar context of financial calculations. In particular, the concept of return on investment can be applied to environmental improvements. As seen in *Figure 9.4* and clarified in *Table 9.9* for use energy, there clearly are different degrees of betterment and costs associated with the different designs.

	Steel	Polymer 1	Polymer 2	Polymer 3
Use Energy (excl. fuel refining)	93,253	91,469	89,976	88,778
BIW Manufacturing Cost	$1,311	$1,325	$1,366	$1,542

Table 9.9: Use Energies and Manufacturing Costs for Alternative BIW Designs

For each step of polymer substitution (*i.e.* steel to polymer 1, polymer 1 to polymer 2, polymer 2 to polymer 3), the ratio of change in environmental performance over the corresponding change in cost can be calculated. This ratio can be interpreted as the marginal environmental improvement. As can be seen in *Figure 9.5* (graphically represented by *Figure 9.6*), there is decreasing return for the various BIW designs considered.

	Steel →	Polymer1 →	Polymer2 →	Polymer3
$\frac{\Delta \text{ Use Energy}}{\Delta \text{ Manufacturing Cost}}$	127.43	36.41	6.81	

Figure 9.5: Ratio of Use Energy Change to Manufacturing Cost for Alternative BIW

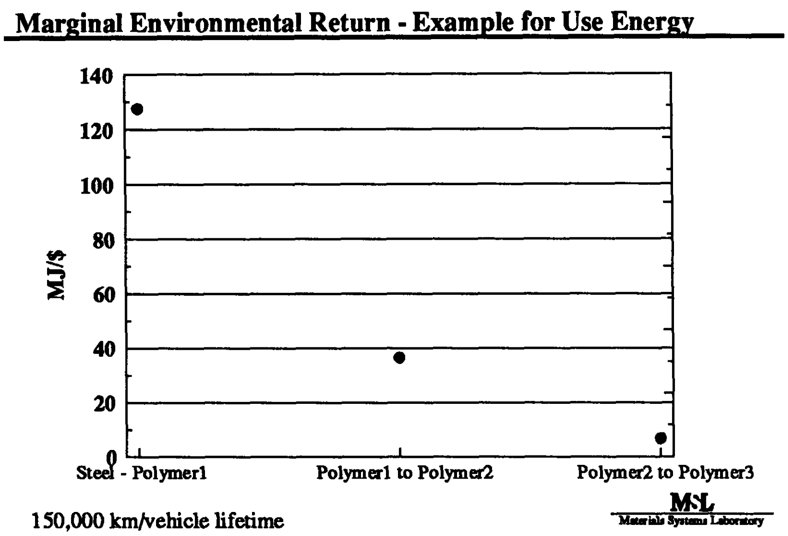


Figure 9.6: Decreasing Marginal Return for Environmental Improvement

There clearly is a strategic dimension to design for the environment. Rather than focus on attaining a specific and perhaps arbitrary target, a cost driven approach allows scarce financial resources to be put to most effective use.

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10. Summary

10.1. Recycling and the Environment

By developing and employing a process-based analytical methodology, this thesis has demonstrated product recycling not to offer the unequivocal environmental improvements with which it is often associated. Far from being simply a resource recovery and conservation undertaking, recycling is a materials processing operation that consumes resources and emits wastes like any industrial process. Recycling policies often exhibit short-sighted environmental planning by overlooking these characteristics and instead narrowly focusing on landfill conservation. Analyses in this thesis have shown that while various alternatives can more aggressively recover post-use automotive materials and ostensibly reduce landfill consumption, other environmental goals may be compromised. Notably for the automobile industry, recycling mandates can be counter-productive to vehicle lightweighting strategies to increase fuel efficiency and reduce tailpipe emissions.

In addition to providing a more rigorous assessment of recycling's environmental attributes, this thesis has also established an economic framework for analyzing alternative recycling infrastructures. Recycling's usefulness and applicability lie in its ability to redirect and transform waste material streams to higher-value applications. Arguments for recycling emphasize this potential to extract value from waste but often fail to adequately account for the expense involved in this undertaking. By developing and applying process simulation models that provide dynamic assessments of technological capabilities, this thesis has demonstrated some recycling schemes to have costs far greater than the potential revenue from recyclate resale. If this market reality is ignored and such post-use alternatives are mandated into existence, the sustainability of the existing automobile recycling infrastructure may be jeopardized. By adamantly pursuing narrowly defined environmental objectives, greater economic and environmental problems may result.

10.2. Shift to Product Policy

This thesis has addressed issues in recycling policy, resource conservation, and lifecycle design. Essentially offering different perspectives on products' environmental impacts, these diverse topics indicate a shift away from the traditional paradigm of regulating industrial processes to one that focuses instead on rationalizing product designs. By embracing product policy, a much broader perspective on environmental policy and management is adopted. This regulatory transition has dramatic effects on environmental management concepts. It is no longer sufficient for firms to consider emissions and resource consumptions at specific industrial sites. The boundary of analysis now extends to the entire firm. Not only are the physical and tangible aspects of manufacturing under scrutiny, the more intangible issues regarding a product's functionality are being debated as well. That is, the discussion has transcended from one of asking why a particular substance or process is used to one of asking the more fundamental question of why a product should exist in a certain way in the first place. Industrial process design and control are still addressed, albeit implicitly, under a product policy paradigm.

While the product-based policy arguably has become a pivotal part of environmental debates and can powerfully alter industrial practices, it is still an ill-defined and often misunderstood concept. This thesis has sought to better define the product policy concept by analyzing actual scenarios. The various recycling initiatives are one variant of product policy in that they usually stipulate recycling targets in terms of mass fraction per product rather than some portion of processing throughput. For example, many of the current recycling legislation mandate that new products contain some specific amount of recyclates rather than directly require the production process to be capable of incorporating recyclate feedstock streams. This thesis has shown that the product policy concept is much more than simply the addressing of environmental issues on a product basis. While the various recycling policies mentioned in this paper may force industry to better rationalize product designs, they are narrowly focused on specific aspects of a product's environmental impacts. If landfill conservation in the post-use stage is the overriding environmental concern, then such regulatory approaches to promote recycling may be valid. Analyses from this thesis, in particular infrastructure distribution and economic-environment attributes mapping, have shown that there are consequential and often unexpected trade-offs among various economic and environmental resource conservation objectives. These trade-offs occur not only within each stage of a product's lifecycle, but also across the different lifecycle stages.

Product policy then, must be formulated and applied from a systems perspective such as the product lifecycle. Such a system encompasses not only the original equipment manufacturers and their immediate component suppliers, but also those indirect suppliers further upstream stretching back to raw material extraction. Downstream consuming entities, such as product buyers, repair shops, and post-use processor, are contained in the system as well. The rationale behind such exhaustive inclusion is that product design changes have reverberations throughout this system. Process selection, use requirements, and post-use possibilities are all functions of product design. By capturing such dependencies through a lifecycle framework, policymakers can better avoid undesirable regulatory consequences such as non-attainment and conflicts among the various mandates. For industry, lifecycle-based analyses can articulate the multiple objectives encountered in product development cycles and thus better find cost-effective environmental strategies. Ultimately, a lifecycle framework strives to provide a common discussion platform among the various environmental stakeholders and to make transparent the issues and potential solution set. Environmental policymaking and management can then move from undertakings based on adversarial standard-setting debates to ones based on cooperative efforts.

10.3. Design Tools

To support the shift to product policy, this research project has developed and introduced a set of analytical tools for environmental management and policy formulation. These tools, consisting of multi-attribute cost modeling, infrastructure distribution analysis, economic-environment attributes mapping, and lifecycle profiling, all contribute to establishing a systems perspective for analyzing environmental issues. Binding the various economic and environmental entities throughout the various lifecycle stages is the cost metric. Prices, whether established by the market or externally imposed through regulations, provide the basic inputs for decision making and are the informations most easily transferred among the different stakeholders in the system. Allowing the cost implications of environmentally-driven activities to be better demonstrated is thus a common characteristic shared by the analytical tools presented in this thesis. The tracking of environmental attributes further supports the decision making process by explicitly evidencing those attributes which may escape a simple monetary representation.

A major idea that is promoted through this thesis is that environmental issues are too complex and subjective to be resolved through an expert system. A self-contained decision making tool capable of distilling vast amounts of diverse information into actionable recommendations is certainly appealing. However, such an approach will require dubious assumptions that may seriously compromise its validity. Throughout this thesis, the observation that there is no absolutely better design has been repeatedly emphasized. Instead, explicit considerations of the various economic and environmental attributes are required. Subsequent trade-offs among these attributes, based on the individual stakeholders' utility functions and capabilities such as technology know-how and financial position, can then converge towards a satisfactory solution. Expert systems inherently contain valuations based on the opinion of a relatively narrow, albeit expert, group of individuals. Furthermore, these valuations may not be obvious to outsiders. While such a focused valuation may streamline the decision making process, it may not reflect public demands. Many environmental issues have attained prominence based on vociferous outcries not necessarily based on scientific or even environmental facts. Landfill conservation, for example, is frequently based on the public's NIMBY (not in my backyard) attitude. The CAFE standard, while arguably have been effective in increasing automobile fuel efficiency, has skirted the more fundamental issue of petroleum conservation. Total fuel consumption has continued to increase each year as individual vehicles are driven greater distances and the overall vehicle fleet size expands.

This dichotomy between expert opinions and public wants can only be resolved through political debate. As public sentiment and regulatory emphasis shift, industry must be flexible enough to respond. A decision system, expert or not, that is based on outdated valuations will lead to unsuitable conclusions. Continual changes in technological developments and market conditions further underline the need to avoid inflexibly imposing a specific set of assumptions. The analytical tools presented in this thesis offer an alternative. Environmental management becomes a strategic undertaking. Rather than pontifically synthesizing equivocal recommendations, specific environmental issues are analyzed in detail and the results are transparently presented with no hidden subjective valuations. Environmental improvement, however it is defined, can be integrated into businesses' familiar profit-maximizing objectives by closely relating various environmental consequences with their economic implications. Instead of reactively viewing environmental issues as arbitrary external constraints, a proactive application of these same issues as business undertakings can lead to a more robust environmental solution.

Appendix A. Input Variables in the Disassembly Model

In constructing the disassembly cost model, input requirements are kept to a minimum. Detailed design data, while useful, are not required. Instead, a group of basic and relatively obtainable information for each part of interest is used.

Material

The material type is of paramount importance. For polymers, and for metals as specialized alloys are increasingly prevalent, meticulous material segregation is needed for effective secondary material applications. Depending on the desired degree of segregation, the material type inputs can be broad resin categories or detailed grade specifications.

Mass

The mass input allows the model to perform a mass balance on incoming vehicle and outgoing hulk. This mass balance is especially important in determining a particular post-use vehicles landfill liability and scrap value for the shredder.

Surface area (and/or part thickness)

While landfill liabilities are usually quoted in terms of $/unit mass, there is an interest in the corresponding $/unit volume. Especially for relatively low density materials such as polymers, volume may be a better indication of environmental progress. Information on surface area or simply the thickness can allow volume information to be derived.

Time

Disassembly is currently, and for the foreseeable future, a labor intensive process. The time requirement for part removal is therefore the critical parameter in determining process cost.

The above four input parameters allow the model to simulate current disassembly practices. Furthermore, crucial information regarding an automobile's material mix, downstream recycling possibilities, and landfill liabilities can be extracted. In order to extend the methodology beyond descriptive to predictive capabilities, more detailed part information is required. Quantitative linkages among automotive manufacturing and design choices and disassembly effort need to be established. Such relationships, derived from existing vehicles designs and tear-down analyses, can then offer insights into new designs for easier disassembly.

Perimeter

The part perimeter is an approximation of the attachment area. That is, information such as weld and bond lengths for each part may be represented by the perimeter. While not a perfect representation, the perimeter number is relatively easy to characterize.

Sequence

The removal sequence is another piece of useful design information. Automobile parts are often assembled in layers. In terms of disassembly, this layered configuration often leads to the situation where many parts need to be removed before exposing the target part. Sequence information allows the model to estimate disassembly costs for parts at different layers of the automobile. More importantly, this information may allow future vehicles designs to incorporate easier to remove part/material combinations.

Difficulty

This qualitative measure of disassembly difficulty is useful when actual disassembly time information is not available. For example, vehicles that are still under development often will not have the luxury of undergoing a complete tear-down analysis. As a rough substitute, qualitative measures of difficulty can be correlated with disassembly data from actual vehicles to arrive at some idea of time.

Attachment Method

Information on the attachment method used for each part provides insight into how different assembly techniques translate into different degrees of disassembly difficulty (or time). This information may prove to be the most useful in design for disassembly since changing the attachment technique is often a feasible undertaking. Together with an existing assembly cost model, trade-offs among manufacturing and disassembly costs can be examined.

Appendix B. Polymer Intensive BIW Cost Modeling

RTM Floorpan

The floorpan consists of the front and rear pan together with 3 cross members molded via a resin transfer process. The description for this part is presented below. Various side members, seat tracks, and supports are stamped steel.

RTM Floorpan Molding Parameter	**Input** *or* Output
Mass	**31.8 kg**
Surface Area	**54,825 cm^2**
Thickness	**0.30 cm**
Cycle Time	45 min
Part Cost	$246

RTM Floorpan Subassembly Parameter	**Input** *or* Output
Mass of RTM Floorpan	**31.8 kg**
RTM Part Cost	**$246**
Mass of Steel Parts	**52.3 kg**
Steel Parts Cost	**$88**
Adhesive Bond Length	**1,422 cm per assembly**
Cure Time to Attain Green Strength	**90 sec**
Adhesive Cost	$20/floorpan
Subassembly Cost	$393

SMC Roof

The roof structure consists of an outer panel formed through a sheet molding compound process with a steel support structure.

SMC Roof Outer Panel Molding Parameter	**Input** *or* Output
Mass	**7.3 kg**
Surface Area	**17,806 cm²**
Thickness	**0.23 cm**
Cycle Time	1.7 min
Part Cost	$23

SMC Roof Subassembly Parameter	**Input** *or* Output
Mass of SMC Outer Panel	**7.3 kg**
SMC Panel Cost	**$23**
Mass of Steel Parts	**6.4 kg**
Steel Parts Cost	**$11**
Adhesive Bond Length	**1,270 cm per assembly**
Cure Time to Attain Green Strength	**90 sec**
Adhesive Cost	$18/roof structure
Subassembly Cost	$59

Dash Support

The polymer dash support consists of a SMC molded panel dash and a front cross member. Another front cross member and reinforcing panel remain in steel.

SMC Dash Support Molding Parameter	**Input** *or* Output
Mass of SMC Panel Dash	**5.5 kg**
Surface Area of Panel Dash	**13,550 cm^2**
Panel Dash Thickness	**0.23 cm**
Panel Dash Cycle Time	1.2 min
Panel Dash Cost	$15
Mass of SMC Front Cross Member	**4.5 kg**
Surface Area of Front Cross Member	**4,190 cm^2**
Front Cross Member Thickness	**0.64 cm**
Front Cross Member Cycle Time	1.4 min
Front Cross Member Cost	$14

SMC Dash Support Subassembly Parameter	**Input** *or* Output
Mass of SMC Parts	**10 kg**
SMC Part Costs	**$29**
Mass of Steel Parts	**3.2 kg**
Steel Parts Cost	**$5**
Adhesive Bond Length	**1,016 cm per assembly**
Cure Time to Attain Green Strength	**90 sec**
Adhesive Cost	$14/dash support
Subassembly Cost	$55

Radiator Support

The polymer radiator support consists of three SMC moldings - support with hood latch, reinforced support upper, and reinforced support lower. Various brackets remain in steel.

SMC Radiator Support Molding Parameter	**Input** *or* Output
Mass of SMC Support Radiator	**2.3 kg**
Surface Area of Support Radiator	**4,968 cm^2**
Support Radiator Thickness	**0.23 cm**
Support Radiator Cycle Time	1.2 min
Support Radiator Cost	$8
Mass of SMC Reinforced Support Upper	**0.91 kg**
Surface Area of Reinf. Support Upper	**2,000 cm^2**
Reinf. Support Upper Thickness	**0.23 cm**
Reinf. Support Upper Cycle Time	1.2 min
Reinf. Support Upper Cost	$5
Mass of SMC Reinforced Support Lower	**1.1 kg**
Surface Area of Reinf. Support Lower	**2,000 cm^2**
Reinf. Support Lower Thickness	**0.23 cm**
Reinf. Support Lower Cycle Time	1.2 min
Reinf. Support Lower Cost	$6

SMC Radiator Supt Subassembly Parameter	**Input** *or* Output
Mass of SMC Parts	**4.3 kg**
SMC Part Costs	**$19**
Mass of Steel Parts	**1.4 kg**
Steel Parts Cost	**$2**
Adhesive Bond Length	**1,016 cm per assembly**
Cure Time to Attain Green Strength	**90 sec**
Adhesive Cost	$14/dash support
Subassembly Cost	$42

Polymer-Intensive Body-in-White Assembly

In the assembly stage, the various subassemblies are joined. Specifically, the RTM floorpan, SMC roof, SMC dash and radiator supports, 2 steel quarterpanels, and 2 door frames are brought together. Various steel components (*e.g.* brackets, reinforcing members, mounts, etc.) are also attached. For the sake of modeling ease, these latter parts all are assumed to be attached directly to the BIW rather than via intermediate subassemblies. The part list for the assembly model is as follows.

Polymer-Intensive BIW Assembly Part List	*Mass (kgs)*	*Input Cost*
Roof	**13.7**	**$59**
Floorpan	**84.1**	**$393**
Dash Support	**13.2**	**$55**
Radiator Support	**5.7**	**$42**
Quarterpanels (left and right)	**24.1**	**$263**
Door Frames (left and right)	**40.9**	**$285**
Miscellaneous Steel Parts	**83.2**	**$159**
Total	*265*	*$1256*

Polymer BIW Assembly Parameters	**Input** *or* Output
Mass of Input Parts	**265 kg**
Cost of Input Subassemblies & Parts	**$1,256**
Adhesive Bond Length	**4,262 cm per BIW assembly**
Adhesive Bead Size	**0.0028 kg/cm**
Cure Time	**5 sec**
Adhesive Cost	$117/BIW
Mechanical Fastening Length	**4,262 cm per BIW assembly**
Number of Fasteners	**200 per BIW assembly**
Weld Length	**2,725 cm per BIW assembly**
Number of Welds	**1700 welds**
Assembled BIW Cost	$1542

Steel Unibody Body-in-White

The following outputs are updated cost estimates of a steel unibody design first modeled by Prof. Helen Han in her 1994 MIT Ph.D. thesis titled "The Competitive Position of Alternative Automotive Materials".

Steel Unibody BIW Baseline Information	*Mass (lbs)*	*Input Cost*
Roof Subassembly	**16.4**	**$62**
Floorpan Subassembly	**88.6**	**$248**
Quarterpanel Subassemblies (left and right)	**24.1**	**$263**
Door Frame Subassemblies (left and right)	**40.9**	**$285**
Dash and Radiator Support Parts	**24.5**	**$85**
Miscellaneous Steel Parts	**85.5**	**$159**
Total	*280*	*$1102*

Steel Unibody BIW Assembly Parameters	**Input** *or* Output
Mass of Input Parts	**280 kg**
Cost of Input Subassemblies & Parts	**$1102**
Weld Length	**3,493 cm per BIW assembly**
Number of Welds	**2200 welds per BIW assembly**
Adhesive Bond Length	**3,493 cm per BIW assembly**
Adhesive Bead Size	**0.0014 kg/cm**
Cure Time	**5 sec**
Adhesive Cost	$48/BIW
Assembled BIW Cost	$1311