Reverse Logistics and Large-Scale Material Recovery from Electronics Waste

by

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Abstract

Waste consolidation is a crucial step in the development of cost-effective, nation-wide material reclamation networks. This thesis project investigates typical and conformational tendencies of a hypothetical end-of-life electronics recycling system based in the United States. Optimal waste processor configurations, along with cost drivers and sensitivities are identified using a simple reverse logistics linear programming model. The experimental procedure entails varying the model scenario based on: type of material being recycled, the properties of current recycling and consolidation practices, and an extrapolation of current trends into the future. The transition from a decentralized to a centralized recycling network is shown to be dependent on the balance between transportation costs and facility costs, with the latter being a much more important cost consideration than the former. Additionally, this project sets the stage for a great deal of future work to ensure the profitability of domestic e-waste recycling systems.

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To my parents: thanks for giving me the greatest four years anyone could dream of, on top of 17 dynamite previous ones, of course. Friends, family, fellow course III students, faculty, and staff: you have been an ever-present positive force in my life throughout my time at university and I do not see that changing any time soon. To Will: thank you for your patience and your music. Finally, to Robyn, Anna, Nii, and Bryan: thank you for your unflagging support, excitement, and inspiration.

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Chapter 1

Introduction

Recycling is known to most people as an activity in domestic waste separation with few tangible or financial benefits. Nevertheless, material reclamation flows at many scales play important roles in a number of industries. The development of more, complex systems that can handle both a greater volume and a wider variety of waste materials is a pursuit that is crucial to the establishment of a sustainable society, not to mention a potentially lucrative source of new economic growth.

Dematerialization, or, an "absolute or relative reduction in the quantity of materials required to serve economic functions [6]," is a philosophy central to an emerging generation of engineers, designers, and policy-makers. Similarly, environmental impact as a fourth criterion of design decisions—along with cost, aesthetics, and performance—is advocated in texts such as *Cradle to Cradle* [7] and *Design + Environment* [8]. In the process of minimizing either the total environmental impact or just the bill of materials of some product, issues of material reclamation arise, in a technical sense as well as logistical one.

Effective material recovery is the key to a truly closed-loop industrial ecology. For natural materials (wood pulp, cotton fibers, etc.) this goal can be achieved through the exclusion of all synthetic materials and preservatives; natural material reclamation via biodegradation returns the materials to the Earth system. With technical and synthetic materials, this route is not available (to the defense of humanity, our industrial ecosystem has had less than 300 years to evolve, while nature has had 4.6

billion). Nevertheless, material reclamation is possible at many other scales: tailings and scrap can be recovered from a stamping process and added back into the melt, uniform-composition plastics can be brought back to monomer form, and to a certain extent complex consumer products can be collected and recovered through a series of steps. It is increasing the effectiveness of the final example that is the focus of this thesis project.

1.1 Barriers to Material Reclamation

As promising as the benefits of closed materials loops seem to be, a number of barriers still exist to the development of mature material reclamation systems. Barriers exist at many points in product life cycles, and can be economic, political, technical, social, or a combination. Many of these barriers exist because concerns with product or material end-of-life (EoL) scenarios still play a very small role in overall design and engineering.

Cost Costs of running recycling programs are hotly contested, as standards and tools for analyzing the life-cycle costs of materials and products are still developing. A public recognition of this uncertainty, or more aptly, a belief that all municipal recycling programs operate at a loss, poses a significant stumbling block to the expansion of recycling and material reclamation systems [9]. High costs of inefficient collection schemes combined with the low revenues from the sale of the reprocessed material—if it gets sold at all—offer a great challenge to be overcome. Additionally, a decision about who should shoulder the substantial initial financial burden of recycling and material reclamation has yet to be made on a large scale, in particular by the American market or government. In various countries and regions around the world, waste management strategies such as extended producer responsibility (EPR) have been either voluntarily adopted by or forced upon some manufacturers to incorporate life-cycle costs into their operating costs [4]. In this strategy, now that the producer has to pay for the recycling or disposal of their products, they have the option to share the cost burden with their customers and are financially incentivized to recover as much as they can from their discarded products. From the consumer's perspective this may initially seem undesirable; yet it is actually just shifting expenses currently collected through taxes to each individual product. This strategy also penalizes overly complex and unrecoverable materials while promoting the production of easily disassembled and recycled products. Nevertheless, as private recycling systems begin to expand, system redundancy and unnecessary costs will need to be dealt with.

Policy Policy barriers to widespread, effective recycling and material reclamation exist largely due to economic uncertainty in production, consumption, and waste disposal and a great deal of politicization and ignorance—compounding the uncertainty—to the true environmental costs of different waste disposal techniques [10]. Although there are many different types of public recycling programs around the country, many policies restrict the uses of non-virgin materials to low-risk, low-impact application, such as synthetic lumber and filler material. For example, reclaimed asphalt or concrete is limited to sub-grade filler in the Massachusetts Highway system [11], despite proponents' arguments suggesting beneficial properties from this reclaimed aggregate in surfacings as well [12]. Nevertheless, stringent restrictions on the uses of recycled plastics in food packaging highlights the justifiable mistrust of potential contaminants that may have leached into recycled plastics [13]. This back-end policy effort protecting human health might be less effective than an up-front policy influencing the recyclability of virgin materials or security of material reclamation processes.

Technology Although technical issues are often not the prohibitive element in solutions to large societal problems, recycling technologies aren't proving themselves to be the panacea to humanity's waste problem. Many recycling processes simply do not output material functionally equivalent to their virgin counterparts. For example, recycled plastics often lack the purity, strength, or optical properties desired by consumers [14]. In the case of plastic or glass bottles, this problem stems from poor front-end preparation for recycling—e.g., ineffective labeling, indelible dyes—or poor separation technologies. While metals can often be very effectively removed from a waste stream, the separation and removal of different plastics currently requires a multi-stage process that takes time, energy, and money [15]. This problem is compounded when one attempts to reclaim value from composite or highly engineered materials. The solution to similar problems in the natural world—bacteria that break waste materials down into an undifferentiated form—lacks an analogue in the technosphere [16]. The emergent properties attained by composite materials are incredibly valuable to today's society—new recycling technologies and waste paradigms must be developed to justify continuing to use these materials.

Society A final and often overlooked barrier to widespread material reclamation is the powerful stigma that has been placed on all "waste" materials by modern society. An incomplete understanding of materials science leads the layperson to the erroneous conclusion that a product made from a recycled material is necessarily less functional and less reliable than a virgin material. Although some recycled paper is thicker, coarser and less-white than virgin paper, who is to say that blindingly bright, bleached white paper is the optimal product? For some reason, much more faith is placed in products created from materials found often in low concentrations in natural repositories than in materials already extracted from the Earth and proven to be functional. Of course, much more investment has been put into mining natural resources than mining anthropogenic resources.

This stigma extends to another important barrier: material separation. When clear, green, and brown glass are not separated at home, it saves the consumer an extra few seconds at the garbage can, but eliminates the possibility that that waste flow can be used for clear glass bottles again without manual sorting somewhere else down the line. Co-mingled recyclable bins may have increased the total amount of material recycled, but arguably has limited the utility of those waste flows. Comfort with one's trash is needed for a truly endemic recycling system. Of course, all downstream infrastructures and processes must reflect and capitalize on this initial consumer effort for the change to really happen.

Although barriers to material reclamation can be generally lumped into different categories, they are all highly interrelated and interdependent. The "root" of the problem can be traced to anywhere in the supply-demand cycle. This thesis looks at a small snapshot of what it takes to have a large-scale material reclamation network. Improving the effectiveness of any part of the recycling system can have effects in the larger reverse supply chain (RSC), and may help to bypass some of the barriers discussed above.

1.2 Research Overview

This project attempts to determine the optimal configuration for an EoL RSC infrastructure. It makes use of linear optimization to minimize the total cost of a material reclamation system given a set of hypothetical inputs. Varying these inputs will provide a picture of the cost drivers of the RSC. Additionally, analysis of the changes in economic, logistical, and environmental characteristics of each case highlights the sensitivities of both the RSC and the model itself.

This research was initiated by the Hewlett-Packard Company (HP) asking a simple question of RSC conformation: Is a centralized or decentralized RSC infrastructure a more cost effective system for consolidating EoL electronics? HP, the world's largest computer and information technology corporation, has embarked on a campaign to reduce the considerable environmental impact of its products and supply chains. Its behavior on this front has the potential to be very influential, especially because it is willing to invest in basic research in parallel to its action.

The project focuses on the consolidation step of a RSC; this step is important because it allows for the aggregation and expansion of local material reclamation networks to regional or national scales. The cost optimization of such a small part of the product life-cycle may seem inconsequential in the face of a movement in the design and engineering community that seeks to take a holistic attitude towards life cycles [7]. Vindication comes with the application of scientific methodology to this disaggregation of the product life cycle. This process finds an analogue in the scientific effort expended in the optimization of an individual part of a mechanical system; the analysis provides important specifics to the extant body of knowledge that can be used to understand the whole. Insights travel from the whole to the part as well.

This project deals with electronics waste (e-waste) for a number of reasons, none of which invalidate the results or analysis technique if applied to other waste streams. The main reason e-waste is being investigated is the rapidly growing fraction of the municipal solid waste (MSW) stream that is composed of electronics, much of which have economic value, are easily recyclable, or are toxic. According to the United State Environmental Protection Agency (EPA), electronics make up between 1 and 4 percent of total MSW, or around 2 million tons per year [3]. Other sources estimate e-waste volumes to be upwards of 7 million tons per year, and increasing between 3 and 5 percent per year, faster than the growth of the MSW stream [17]. E-waste is discussed in more detail in the next section.

1.3 Relationship to Prior Work

This project exists at a fascinating intersection of a number of previously well-established research thrusts. Reverse logistics, mathematical programming and modeling, optimization of recycling systems and processes, and the social and environmental problems caused by e-waste are all topics that have significant presences in scholarly publications. Additionally, there have been a few projects or case studies that are very similar to this one.

1.3.1 Reverse Logistics

An RSC is an economic network of people, businesses, and/or governments charged with not the *distribution* of a good or service, as is the case with a traditional supply chain, but the collection and reclamation of some previously distributed material, good, or product. Originally conceived to deal with product recalls—in which products have to be returned to the producer, defective products—which often times would end up in alternative markets, or dedicated service industries—in which products or services are guaranteed for some period of time, this management paradigm has gained popularity in material reclamation industries [18]. To this end, a number of case studies have been performed that highlight the growing popularity of returnable containers [19], waste collection for material reclamation [20, 21], and even e-waste [22, 23]. In fact, an extensive survey of RSCs performed in 2002 [24] reports that more than 25% of all of the case studies performed deal with e-waste. This is disproportionate to the total waste stream, but indicates the high level of interest in either utilizing e-waste as a resource for raw materials or spare parts, or just extending the life-cycle of the complex materials that enable electronics to function.

Despite—or perhaps because of—the large number of RSC case studies, there is a rich vein of research dealing with characterizing reverse logistics [25] and developing new management strategies [26]. RSCs are conflictingly described as either a completely different phenomenon from forward supply chains [18] or an element in a new breed of "green supply chain" that merges forward and reverse supply chains [27]. Finally, the applications of reverse logistics are just as broad as any other econometric paradigm. Purely economic concerns [28] and approaches that embody the entire life-cycle of a product [29] have many instances of overlap.

1.3.2 Material Recovery Optimization

There is a constant battle being fought over the economic viability of recycling. Proponents of recycling and material reclamation have a number of tools at their disposal, including some very sophisticated modeling and mathematical programming. A summary of some examples follows.

Aluminum and vehicle recycling Analyses examine large-scale aluminum recycling through a number of optimization techniques [30] and the specific impacts aluminum-intensive vehicles may have on the recycling industry [31], in particular due to the sensitivity of aluminum to impurities. Another vehicle recycling study [32] uses genetic algorithms to conclude that current focuses on optimizing and expanding the recycling system are misguided; more effort needs to be placed in redesigning the automobile to simplify or tailor the product for material recovery.

Electronics waste E-waste is a popular topic for mathematical modeling. Cost models have been used to support the claim that the cost of policies to manage e-waste outweigh the benefits accrued from properly discarding the waste [33] as well as to explore new ways to ensure the profitability of e-waste recycling [34]. Linear optimization and other mathematical programming are also used to model and optimize the existing electronics recycling industry [35, 36].

RSCs Mathematical programming can be used to optimize the entire life-cycle of a computer, including the configuration of waste processors in Delhi, India [37]. A primary conclusion from this study is the interrelationship between all aspects of the computer's life-cycle, in particular the effect upstream considerations (design, assembly, etc.) have on RSC configuration. Mathematical models have been built to help understand the relationships between sources, recyclers, processors, and consumers in an e-waste RSC [38] and the complexities of vehicle routing and material recovery technologies in general recycling cases [39]. Finally, in what is a ideal industrial ecology case, the inter-industrial symbiotic waste flows that are emerging in Japan are analyzed and modeled with the dual optimization of cost and CO2 production [40].

1.3.3 E-waste

The potential for environmental harm from improperly discarded e-waste is evident in Table 1.1. While the bulk of the composition of a PC is glass, plastic, and common metals, the high concentration of lead is immediately a cause for worry. Lead shows up in many older solders and cathode ray tubes. Nevertheless, a glance at some of the materials that show up at lower concentrations reveals many elements that are carcinogenic or otherwise toxic, e.g., cadmium, mercury, and arsenic [1]. It is this potential for human and environmental damage from improper disposal, along with the high value of other component materials—primarily copper, silver, gold, and platinum—that motivates e-waste material recovery.

Material	% Weight	Material	% Weight
Silica	24.8803	Bismuth	0.0063
Plastics	22.9907	Chromium	0.0063
Iron	20.4712	Mercury	0.0022
Aluminum	14.1723	Germanium	0.0016
Copper	6.9287	Gold	0.0016
Lead	6.2988	Indium	0.0016
Zinc	2.2046	Ruthenium	0.0016
Tin	1.0078	Selenium	0.0016
Nickel	0.8503	Arsenic	0.0013
Barium	0.0315	Gallium	0.0013
Manganese	0.0315	Palladium	0.0003
Silver	0.0189	Europium	0.0002
Beryllium	0.0157	Niobium	0.0002
Cobalt	0.0157	Vanadium	0.0002
Tantalum	0.0157	Yttrium	0.0002
Titanium	0.0157	Platinum	Trace
Antimony	0.0094	Rhodium	Trace
Cadmium	0.0094	Terbium	Trace

Table 1.1: Composition of a generic PC [1].

A highly publicized study co-authored by members of the Basel Action Network and the Silicon Valley Toxics Coalition in 2002 [17] exposed the externality costs associated with the e-waste recycling systems of the time, which would ship 50% - 80% of collected electronics to Asia where they would be disassembled and valuable materials extracted with little or no regard to human and environmental health. Unmanaged incineration, open acid baths, and other processing techniques are causing cancers, poisoning water resources, and destabilizing communities. These claims are echoed in an overview of the environmental impact of e-waste in Africa [41]. In combination with studies that introduce cost-effective and environmentally-sound methods of recycling or disposing of electronics domestically [42, 43, 44, 45, 46], these reports are motivation for the development of large, e-waste material recovery systems.

The European Union (EU) is on the forefront of e-waste regulation with its dual directives on "waste electrical and electronic equipment (WEEE)" [47] and on the "restriction of the use of certain hazardous substances in electrical and electronic equipment" (RoHS) [48]. The WEEE directive, as it is widely known, codifies important definitions of e-waste, encourages green design, and requires that every member country collect and recycle at least 4 kg (8.82 lbs) of WEEE per capita. The RoHS directive, among other things, expressly forbids the use of "lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE)" in new electrical and electronic products. These two directives offer a model for policy-based e-waste management world-wide.

The attention e-waste is receiving in scholarly media is evidenced by a 2005 issue of the *Environmental Impact Assessment Review* focusing entirely on e-waste [49]. Topics covered in that issue include an analysis of the WEEE and RoHS EU directives in a global perspective [50], barriers to e-waste recycling in China [51], and a comparison of the e-waste recycling systems in Switzerland and in India [52], a paper that details optimal e-waste solutions in the context of regional economics, culture, society, values, industrial capabilities, and politics.

Finally, a report from Gallatin County, Montana [53] that documents an extremely successful e-waste collection event offers positive empirical evidence of the ability of communities to deal with e-waste without overwhelming regulatory pressure. This event, which occurred in 2006, ended up collecting 3.08 lbs/capita of e-waste while costing only 0.2 cents/person. Of course, these numbers are not very extensible; shipping costs were waived by the trucking company as this was a one-time event.

1.3.4 Equivalent Studies

There have been a number of studies that occupy an equivalent space as this project does. One of the first, completed at the Georgia Institute of Technology in 1999, examined the optimal geographic configuration of processors for recycling thermoplastic carpet in the state of Georgia [54]. This study, updated in 2004 to include the whole United States [55], introduced a number of the constraints and terminologies used here in this thesis. The same group continued their research with an analysis of e-waste recycling in Georgia [56, 57], effectively communicating the importance of geographic RSC configuration to the viability of using waste electronics as a resource. Another e-waste processor study, performed in 2001, focused on Taiwan [58].

1.3.5 Motivation for this Thesis Project

The location in research space taken up by this project addresses some of the gaps in the studies reviewed above. Primarily, it combines work on RSCs, linear optimization, and the problems of e-waste and presents a nation-wide e-waste facility configuration. The 20,000-foot view taken in this project prioritizes cost factors in the development of this nascent field, giving it more of an applied focus than many of the other studies. In that vein, it presents the beginnings of a solution to some of the problems caused by e-waste and a way for industries to truly start to use e-waste as a viable raw material resource.

1.4 Introduction to Linear Optimization

Linear optimization is a type of mathematical programming that attempts to meet a desired objective given a set of data and constraints. The technique is aptly defined [59] as "a mathematical procedure for determining optimal allocation of scarce resources [59]." This wording belies the tool's utility and ubiquity in business and economics. An example given in [59] describes a hypothetical manufacturing plant with limited labor resources that can create two different products, each unique in its cost, required production time, and available production capacity. The *objective* is to maximize profit, while the *constraints* are the production capacities and labor availability. Examples like this one are pervasive in introductory texts on linear optimization. Needless to say, the utility of the tool is shown by producing a result that is non-intuitive; the ideal mix of expensive—and time intensive—and cheaper products is not the one initially hypothesized.

Linear optimization can also be used to optimize very large systems. While the example given above can easily be solved using simple algebraic or graphical methods, the optimization of a global courier service or a waste disposal network easily includes thousands if not millions of pieces of data. Computer-enabled linear optimization allows for the accurate orientation of extremely large data sets, if one has access to sufficient computing power. Increasingly complex problems are being tackled with linear optimization, many of which utilize higher-level mathematics to even phrase. Limitations of this problem solving method arise when values are required to be integers, when non-linearity is introduced to the problem, and when data sets grow to a size not well handled by modern solving algorithms [59].

1.5 Thesis Outline

The objective of this project is to assess the relative strengths and weaknesses of different types of e-waste RSCs and to make a recommendation as to the optimal configuration. The methodology, alluded to in Section 1.2, utilizes a simple linear optimization model, discussed in Chapter 2. Construction of the model occurred first. This task involved learning the programming language, writing programming code, selecting and collecting raw data, tailoring data sets into the appropriate form, and creating an interface to easily define and run case studies. The experimental procedure was completed next. In this task, described in Chapter 3, initial sensitivity studies were conducted to select an appropriate set of variables and variable ranges followed by the utilization of the model in conjunction with judiciously constructed variable ranges to produce a large set of results. These results come in three types: logistical, economic, and environmental, and are presented in Chapter 4. An emphasis was placed on limiting the experimental scope in light of the condensed, one-semester research window. The remainder of the semester was dedicated to the analysis of the model results (also Chapter 4) and presentation of conclusions, which can be found in the eponymous Chapter 5. Conclusions were drawn with a number of audiences in mind, including the academic, who may be interested in modeling methodology, the business-oriented, who may be thinking about reverse logistics, and the environmentalist, who may be looking for data on the environmental footprint of a particular product. Future work is also presented in Chapter 5.

Chapter 2

Model

The model developed and utilized in this project is a simple linear optimization program, run using LINGO, a computer optimization tool from LINDO Systems, Inc. LINGO, while functionally able to operate using data hard-coded into the programming code, is especially useful due to its ability to interface with Microsoft Excel spreadsheets. Inputs from Excel can be very large, complex, and multidimensional—data known as sets in LINGO lingo—making this a very powerful tool. LINGO can also output selected results to Excel. The model used in this project, while functionally simple, synthesizes a great deal of data. This section will go through the specifics of each part of the model and describe the model design criteria.

2.1 Model Overview

As described in section 1.4, an objective function is optimized with respect to data inputs and a set of constraints. The objective function for this model minimizes the total cost of a recycling network, which in this case is the sum of the transportation costs, operating costs, collection costs, and fixed costs. The data inputs and constraints attempt to give this objective function some physical significance. The text of the model first introduces the data sets and systems to be optimized, follows with a statement of the objective, defines the technical scope with a set of constraints, and closes with instructions about output variables. A transcript can be found in

2.2 Functional Elements

Objective Function The objective function embodies the simplicity of the model and of the technique in general. The function interprets the entire system as the sum of just four terms: transportation cost, collection cost, operating cost, and fixed cost. It guides the selection of the generator-to-processor waste material flows that meet all of the necessary criteria (see below) and minimize total cost.

Constraints There are four constraints. The first three inequalities ensure physical limits are being respected; the fourth constraint is purely clerical, and allows for the selection of individual processor types and locations. Without it, all processor locations and types would be engaged every time, destroying the utility of the model. The first two constraints enable the recycling minima introduced in section 2.3.2. The first constraint makes sure individual regional processing volumes are greater than the minimum required and less than the total amount of waste generated. The second constraint does the same, but on a national scale. The third constraint makes sure that the selected processors have the capacity to handle a sufficient volume of waste.

2.3 Data Inputs

Two types of data are used here: those that define the system, and those that can be varied to optimize the system. The system is defined by the set of waste generation points, the set of potential processor locations, and the range of processor capacities. Additionally, there are characteristics about each of these sets which can be varied to further refine the system definition. Variable data include recycling rate, transportation cost, facility cost, collection cost, and waste volume.

2.3.1 System Definition

A graphical representation of the system within which this model operates can be seen by the map in Figure 2-1. This map displays the 24 equally-populated source regions and designated consolidation points. Each source region was defined using a GIS map of the congressional districts of the contiguous United States as of the 2000 census. Seventeen—sometimes 18—congressional districts are aggregated within each source region. This results in a per-region population of 11,368,000 and a total population of 273,000,000. Attempts were made to minimize the ratio of circumference to area in each of the regions while staying faithful to existing state or economic regional boundaries. One major city within each generation region has been designated as a consolidation point (Table 2.1); in the hypothetical system this city would serve as the hub for all regional collection before any transcontinental transport. When possible, a centrally-located metropolis was selected for this role. In calculating transportation route lengths, measurements were taken to and from these points.

1	Boston, MA	9	Tampa, FL	17	Kansas City, MO
2	Albany, NY	10	Cleveland, OH	18	Boise, ID
3	New York, NY	11	Detroit, MI	19	Dallas, TX
4	Trenton, NJ	12	Indianapolis, IN	20	Houston, TX
5	Baltimore, MD	13	Memphis, TN	21	Las Vegas, NV
6	Richmond, VA	14	New Orleans, LA	22	San Diego, CA
7	Charlotte, NC	15	Chicago, IL	23	Los Angeles, CA
8	Atlanta, GA	16	Minneapolis, MN	24	San Francisco, CA

Table 2.1: A list of consolidation cities for all 24 source regions.

Possible types and locations of processor facilities are also indicated in Figure 2-1. These eight locations all contain major electronics recycling facilities. They are: Atlanta, GA; Dallas, TX; Detroit, MI; Durham, NC; La Vergne, TN; Minneapolis, MN; Newark, NJ; and Sacramento, CA. Sacramento is the only site on the west coast and Dallas is the next location going east. These may seem poorly distributed, however, the allocation of sites roughly follows the American population density.

Finally, a range of processor facility sizes was selected using existing facility information as a guide. Twelve sizes were selected: 1, 2, 5, 10, 15, 20, 25, 30, 35, 40,

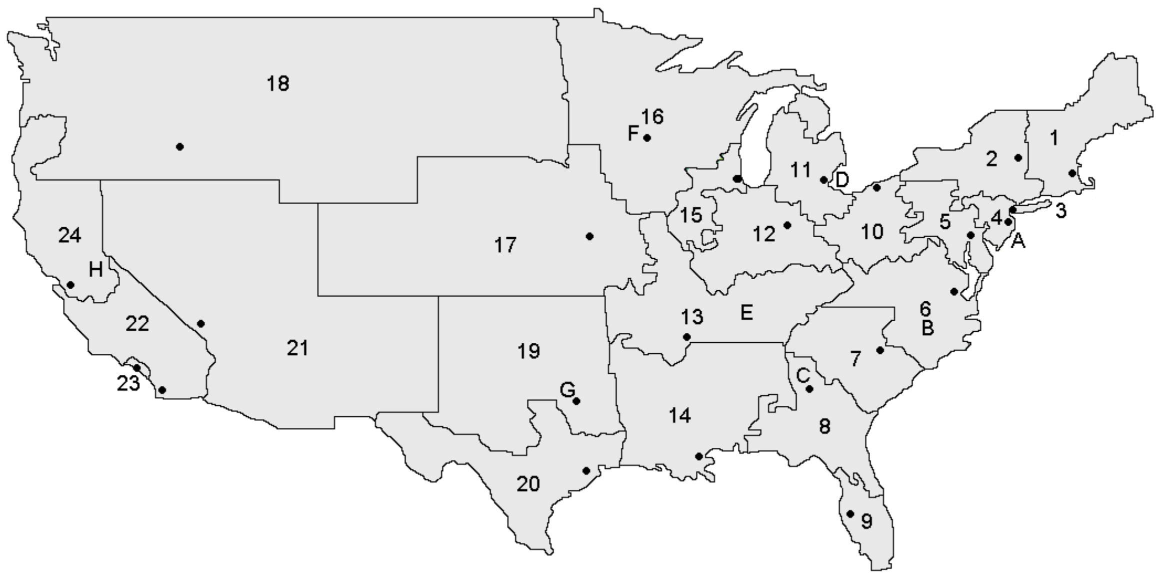


Figure 2-1: Geographical representation of the project scenario. The continental United States is broken up into 24 source regions, each represented by a single consolidation point. The eight processor options are: A) Newark, B) Durham, C) Atlanta, D) Detroit, E) La Vergne, F) Dallas, G) Minneapolis, and H) Sacramento.

45, and 50 million lbs of waste processed per year.

Distances between each generator source point and potential processor location, used for calculating route-length-dependent transportation costs, were calculated using a free on-line service called the Distance Table Calculator [60]. This tool calculates all of the distances between two lists of locations using a Google Maps API. This table of distances can be found in Appendix B.

2.3.2 System Variables

Limiting the range of possible cases served by this project was essential in establishing an accomplish-able research plan. Therefore, five elements were chosen to be independent variables: transportation cost, recycling rate, total waste volume, collection cost, and factory cost

Transportation costs are calculated using a tool provided by Chris Caplice at the MIT Center for Transportation & Logistics that calculates total cost using parameters derived from regression analyses of dry van and full truckload (FTL) costs. Some of these component parameters are source and destination zip codes, distance, volume, and trip frequency. On average, this cost is around $1.20 per mile. For cases in which both generator and processor are located in the same city, a default 10 mile trip is used. To make this value dynamic, a per-mile surcharge can be added in to represent variability in fuel costs or other costs related to shipping waste materials. This model assumes FTL shipping, an industry standard that substantially affects shipping rates. More specifics about the truckload calculator model are omitted with respect to proprietary considerations.

Recycling rate is represented here by processing minima required of each region, of the total system, or of both. In physical terms, this would be affected most likely by regulation. This value is calculated as the quotient of recycled volume and total waste generated.

Waste volume generation is calculated as the product of waste generated per capita and the total population. The per capita volume is input based on average values for for the material under consideration.

Collection cost is related to all of the activities performed before the waste arrives at the consolidation site. Curbside pickup, separation, maintenance of recycling depots, and even publicity encouraging recycling can conceivably be wrapped into this cost. This cost is not dependent on the sizes of the selected facilities, and is input per pound.

Facility cost is the sum of two other costs, each of which is scaled differently across the range of capacities. Fixed cost, which incorporates the physical infrastructure of the facility, increases with increasing volume. The other factory cost component is operating cost. Like collection cost, it is input based on the volume processed, however this rate decreases with increasing facility capacity. Scaling factors were selected to ensure appropriate consistency of costs across the range of facility sizes while taking into account economics of scale. Fixed costs increase to the 0.6^{th} power and operating costs decrease to the 0.9^{th} power with increasing facility capacity.

Operating costs are highly material specific. They incorporate labor, energy, and revenue from the sale of reclaimed material—the latter of course decreasing the total cost. In this model, factory costs are varied uniformly by a linear multiplier. In reality, the variability of factory costs can be attributed to any or all of the component costs—energy spikes, labor shortages, decreased demand for reclaimed material, taxes, new processing technologies, etc.—however to the model, these factors are immaterial, and all that matters is the total cost. Factory costs are calculated using a cost model [61]. This tool incorporates costs and other data about a particular factory—material costs and amounts, labor costs, rate of return, energy costs, equipment lifetime, building size, and processing specifics—and outputs information about the total cost of running the factory.

2.3.3 Case Variables & Other Factors

Other factors can be enabled to vary the functionality of the model. Material-specific elements, such as truck capacity, can be varied to increase the accuracy of cases comparing the recycling systems of different material types. Low density products or materials, like plastic cases, would have a lower truck capacity (in lbs) than high density products, like baled aluminum cans. Regional differences can also be accentuated. Regional cost-of-doing-business (CODB) rankings, adopted from a 2005 Milken Institute study [62], can be used to represent the market forces that favor siting factories in lower-cost areas. In the model, facility and collection costs are adjusted to reflect this variability when CODB is engaged. A table of these values can be seen in Appendix C. Recycling rates can also be switched to reflect average population density in each region. Realistically, one would expect a higher recycling rate on Long Island than in rural Montana just because cities have more mechanisms for waste collection, variations in standards of living notwithstanding.

2.4 Outputs

The LINGO model outputs three pieces of data, which the spreadsheet interface manipulates in a number of ways. As indicated in the final lines of the LINGO transcript (Appendix A), the model outputs an array of all of the flows—including source, sink, and volume—and aggregated calculations of cost and processed volume. Once these values are imported into the spreadsheet, many more important pieces of information can be extracted.

2.4.1 Mass Flows & Processor Selection

High-level answers to the guiding questions of this project are given in the mass flows. Here, the waste generated in each source region is shown to be shipped in entirety or in part to a particular processor, split among two or more processors, or not processed at all. Depending on the constraints, entire regions can conceivably go unserved, as nation-wide recycling minima are met entirely by other regions. It is important to observe the number of under-served and un-served regions when evaluating the ability of a selected infrastructure to withstand changes in either total volume or distribution of waste generated.

Degree of centralization of the recycling infrastructure is indicated by these results as well. A highly centralized infrastructure will see all of the waste to be processed nation-wide shipped to one or two locations served by high capacity processors. A decentralized network will provide a smaller processor at many regionally-distributed sites. Total miles driven is also an indication of centralization—for the same waste volume processed, a higher mileage indicates a centralized network, while lower mileage indicates a decentralized network.

Total mass processed and generated are also retrieved. Although the latter parameter is fixed by the case scenario under investigation, the former parameter is only given a lower bound. Conceivably, total cost minimization could occur with a processing volume higher than the absolute minimum.

2.4.2 Cost Breakdown

Cost contributions from each of the four component costs—transportation, fixed, collection, and operating—along with the total cost of the recycling system, are important pieces of data to be analyzed across a variable range to understand sensitivities as well as overall feasibility. Overall fixed and operating costs are found by adding together the costs of each selected processor. Collection costs come from the total waste value. Transportation costs of each route are determined by volume and shipping distance; the total transportation cost is the summation of all of the flows. The relative contribution of each cost parameter as a percent of total cost can inform sensitivity of the model. For example, high variability of a cost that makes up a large percentage of the total cost will have a higher impact on overall system dynamics than variability of a cost that only contributes a small bit to the total cost. These four costs are also calculated per unit mass to allow for normalization and comparison across different waste volumes.

2.4.3 Environmental Impact

A limited environmental impact assessment is also conducted. Emissions data from transportation are compared with emissions data from the production of component materials in two types of e-waste: CPUs and CRT monitors. The objective of this analysis is to observe the trade-offs between shipping a large mass over a long distance, therefore producing emissions from the combustion of diesel fuel, and the offset emissions from secondary materials processing.

Two types of e-waste are analyzed to represent the large number of materials and compositions in e-waste. The compositions and average masses of CPUs and CRT monitors only include relatively large contributors by mass [2]. The compositions of representative products used here can be seen in Table 2.2.

Emissions analyzed and their dependencies on both mass processed and miles driven are shown in Table 2.3. *Primary* refers to production from raw materials and ores. *Secondary* refers to production from already-refined materials. The difference

Material	CPU Tower	Monitor
Glass (wt. %)	0	44
Steel (wt. %)	67	18
Copper (wt. %)	7	5
Aluminum (wt. %)	5	2
Plastic (wt. %)	19	24
Lead (wt. %)	0.299	3.863
Silver (wt. %)	0.015	0.008
Gold (wt. %)	0.004	0.002
Other (wt. %)	1	0
Total Mass (lbs)	33.95	19.93

Table 2.2: Representative compositions of two types of e-waste [2]

between primary and secondary production is what is offset by utilizing recycled materials. These emissions values were calculated using the tables in Appendix D. Due to inconsistencies between the materials in the composition data and in the emissions data, may simplifications were made. Diesel emissions were calculated assuming a fuel economy of 5.65 miles per gallon (MPG) [63].

Although these are not all of the residues from combustion and manufacturing, the emissions analyzed here provide a picture of the general environmental impact of these industrial activities. Carbon dioxide and methane are well known as contributors to global warming. Carbon monoxide is known to be detrimental to urban air quality. Nitrous oxide is a potent global warming gas in addition to being a contributor to ozone depletion. Nitrogen oxides are smog- and acid rain-forming emissions, a property shared with sulfur oxides. NMVOC refers to non-methane volatile organic compounds, a general term for pollutants that have been shown to be carcinogens, cause respiratory problems, damage the ozone layer, soil, and groundwater.

	Primary		Secondary		Diesel
Emission	CPU (lbs/ton)	CRT (lbs/ton)	CPU (lbs/ton)	CRT (lbs/ton)	lbs/1000 mi
CO_2	145142.36	2661.4	37577.2	7863.27	3503.85
CO	136.27	38.65	10.45	2.18	15.48
CH_4	13.72	9.28	0.86	0.18	0.14
N_2O	1.17	0.59	0.32	0.07	0.09
NO_x	277	105.45	113.64	23.8	12.5
SO_x	1133.17	459.34	498.64	185.06	No Data
NMVOC	No Data	No Data	No Data	No Data	3.05

Table 2.3: Emissions data used in the simplified environmental impact assessment. Primary and secondary processing of CPU and CRT are shown in lbs of pollutant per ton of electronic component. Diesel emissions are shown in lbs of pollutant per 1000 miles driven.

2.5 Model Design Decisions

2.5.1 Integer Values

Although pricing in the model assumes FTL shipping, it required too much computing power to restrict the value (mass flow)/(truck capacity) to integer values. The effects of this assumption will have on the model depends on two main factors: the amount of waste that would actually be shipped in less-than truckload (LTL) conditions and how strict a physical manifestation of this model would keep to the hypothetical rules. If the processed volume is so high that only a little waste spills over each year into a LTL route, then there is no real problem with not using integers. Most likely, an integer constraint would increase the transportation cost slightly and indicate that only very few source regions would experience 100% service. Assuming the model had the ability to apply FTL and LTL pricing, this may be a situation where more waste may be processed than the absolute minimum, depending on the cost of LTL routes. In real life, this problem would probably be avoided through short term on-site stockpiling or other similar strategies.

2.5.2 Frequency-Dependent Transportation Costs

The MIT CTL trucking cost model, when used dynamically, takes into account surcharges added to infrequent routes. Because the matrix of source points and processor options is fixed, and because LINGO does not interface with MS Excel during optimization, the cost model was used only once, to identify all of the possible route costs. The addition of a number of "if" statements to the objective function, each one representing a route frequency, resulted in a prodigious slowdown in the model solve time. Because the surcharge values range from about \$50 to \$150 and the cases being examined in this project are upwards of \$50,000,000, a decision was made to eliminate the frequency surcharge from the calculation.

2.5.3 Facility Redundancy

The way the model is built, only one facility of each size can be assigned to any given processor city. This has obvious limitations when the waste volume is such that a city needs to process more than twice the capacity of the largest processor option. However, in real life, the logical solution would not be to build multiple processors, but one, larger facility. For consistency, the same range of facility capacities was used for almost all of the cases—further discussion of this decision can be found in section 5.2.

2.5.4 Environmental Impact Optimization

Especially when compared with full life-cycle assessments (ISO 14040 series), the environmental analysis described in section 2.4.3 is lacking. Due to inconsistencies in analytical boundaries and input inventory, the calculations are not meant to provide an overwhelmingly accurate representation of the environmental impact of recycling. Instead, they are meant to serve as an order-of-magnitude estimation for use in comparisons. Performing even a single environmental impact assessment on e-waste is a viable topic for a Ph.D. thesis. In ideal circumstances, a full environmental impact assessment would be added to the objective function, forcing the model to report a recycling infrastructure that minimizes the entire life-cycle cost as well as life-cycle environmental impact. However, that step is outside the scope of this project.

Chapter 3

Experimental Procedure

The main scenarios evaluated can be illustrated by a 3x5 array (Table 3.1), with an experimental run corresponding to each cell in the array. On one of the axes, one finds the five variables selected for this project: transportation cost, facility cost, collection cost, waste volume generated, and recycling rate. In each case, only the specified variable is varied—all other parameters are fixed. On the other axis lie three different system scenarios: one that assumes uniform waste collection and variable CODB, one that keeps both collection and CODB constant, and one that has both factors regionally variable. In addition to these 15 main experimental runs, four specialized cases were examined: one that greatly elevates the e-waste generation volume, one that engages and varies a regional recycling minimum in addition to the nation-wide constraint, and two that observe the applicability of this model to other materials: PET bottles and aluminum cans.

	Scenario 1 CODB Varied Coll. Constant	Scenario 2 CODB Constant Coll. Constant	Scenario 3 CODB Varied Coll. Varied
Transportation Cost			
Facility Cost			
Collection Cost		**Cases**	
Waste Generated			
Recycling Rate			

Table 3.1: Array illustrating the experimental procedure

3.1 Selection of the Base Case

A base case was selected that represented a slightly ambitious but physically relevant recycling situation. Illustrated in Table 3.2, the base case provides not just a starting point for this analysis, but also a constant for comparison during analysis. From this base case, each of the five variables are varied independently one by one to see the individual effect of each factor on the otherwise unchanged system.

CODB	Varied
Collection Type	Constant
Transportation Surcharge	\$0/mi.
Facility Cost Multiplier	1x
Collection Cost	\$0.05/lb.
Waste Generated	0.5 lb./capita
Recycling Rate	90 %

Table 3.2: Base Case Parameters

Physical analogues for each of these variables are given in the next section.

3.2 Description of the Five Variables

While ranges for each of the five variables can be selected simply to observe behavior of the model, a more effective approach is to select variable ranges with physical significance. For uniformity, 20 values, along with a sometimes-invoked 0^{th} value, make up each variable range. All utilized variable ranges and, if available, their associated physical analogues can be seen in the tables below along with paragraphs to explain the ranges and calculation of the analogues. Full explanations of the variables can be found in section 2.3.2. Tables 3.3 and 3.4 display the ranges and any relevant physical data for each of the variables.

3.2.1 Facility Cost

The facility cost multiplier operates on a core pair of values calculated for a 15 million lb/year facility. Using [61], fixed costs were found to be \$1.5 million in total

	Facility Cost				Collection Cost
	Cost Multiplier	Fixed Cost ($/yr)	Operating Cost ($/lb)	Material (Revenue) Cost ($/lb)	($/lb)
0	0	0	0	(0.052)	0
1	.1	150,000	0.004	(0.048)	0.005
2	.2	300,000	0.008	(0.044)	0.01
3	.3	450,000	0.012	(0.040)	0.015
4	.4	600,000	0.016	(0.036)	0.02
5	.5	750,000	0.020	(0.032)	0.025
6	.6	900,000	0.024	(0.028)	0.03
7	.7	1,050,000	0.028	(0.024)	0.035
8	.8	1,200,000	0.032	(0.020)	0.04
9	.9	1,350,000	0.036	(0.016)	0.045
10	1	1,500,000	0.040	(0.012)	0.05
11	1.1	1,650,000	0.044	(0.008)	0.055
12	1.2	1,800,000	0.048	(0.004)	0.06
13	1.3	1,950,000	0.052	0.000	0.065
14	1.4	2,100,000	0.056	0.004	0.07
15	1.5	2,250,000	0.060	0.008	0.075
16	1.6	2,400,000	0.064	0.012	0.08
17	1.7	2,550,000	0.068	0.016	0.085
18	1.8	2,700,000	0.072	0.020	0.09
19	1.9	2,850,000	0.076	0.024	0.095
20	2	3,000,000	0.080	0.028	0.10

Table 3.3: Variable Ranges, pt. 1

	Transport Cost ($/mi)	Transport Cost ($/gal)	Waste Generated (lbs/capita)	Recycling Rate (%)
0	0	0	0	0
1	0.05	0.28	0.05	5
2	0.10	0.56	0.1	10
3	0.15	0.85	0.15	15
4	0.20	1.13	0.2	20
5	0.25	1.41	0.25	25
6	0.30	1.69	0.3	30
7	0.35	1.98	0.35	35
8	0.40	2.26	0.4	40
9	0.45	2.54	0.45	45
10	0.50	2.82	0.5	50
11	0.55	3.10	0.55	55
12	0.60	3.39	0.6	60
13	0.65	3.67	0.65	65
14	0.70	3.95	0.7	70
15	0.75	4.23	0.75	75
16	0.80	4.52	0.8	80
17	0.85	4.80	0.85	85
18	0.90	5.08	0.9	90
19	0.95	5.36	0.95	95
20	1.00	5.65	1	100

Table 3.4: Variable Ranges, pt. 2

and operating costs 4 cents/lb, or \$600,000. These values are then mapped to the other facility sizes using regressions discussed in Section 2.3.2. A total list of values across the range of facility capacities can be seen in Appendix E. The facility cost range multiplies these two base values by the cost multiplier, which ranges from 0 to 2. Many factors contribute to both the fixed and operating costs; only one—recycled material cost or revenue—was selected to illustrate the meaning of the cost multiplier here. Recycled material can be either a cost or a source of revenue for a recycler. The market value of a recycled material greatly influences the cost effectiveness of a recycling system. Revenues seen here illustrate a conservative yet realistic range of prices for recycled mixed electronics. Although material cost contributes only to the operating cost, its variability shows how certain factors can change to justify the cost multiplier.

3.2.2 Collection Cost

Although the range of collection costs used in this project could refer to the variability of cost of fuel in trucks, labor costs, or even entirely different types of collection paradigms, one would need an additional collection cost model to understand how these factors interact, something not included in this model. Furthermore, the understanding of the real costs of collecting e-waste is difficult to characterize, as the space is shared by private firms and public organizations. Collection costs in this project range from 0 to 10 cents per lb, calculated in a similar manner to facility cost.

3.2.3 Transportation Cost

Assuming the average diesel tractor trailer in the US gets 5.65 MPG [63], a fuel cost in \$/gallon can be calculated from the transportation surcharge values, which range from 0 \$/mi to 1 \$/mi, by multiplying the surcharge value by the fuel economy value. As of August 13, 2007, diesel prices averaged \$2.85/gallon in the US [64]. With recent fuel price volatility expected to continue into the future, the range investigated here is appropriate.

Contributing to total transportation cost, yet not utilized as a variable in this study, is truckload mass. The conservative assumption used in this model is that 25,000 lbs of e-waste can be shipped at once. Given that the maximum weight allowance for these trucks is 40,000 lbs, this represents a significant source of inefficiency in shipping.

3.2.4 Waste Volume Generated

The last two variables are not directly tied to recycling cost, instead focusing on the size of the recycling network. First is waste volume generated. Using a per capita mass, this value can be related to types of materials being disposed. E-waste here has a limited definition—only high tech products like computers and televisions, not washing machines. The base case of 0.5 lb per person could refer to one in every 50 people throwing out a 25 lb CRT monitor annually (a realistic estimation in some places) or every person disposing 1 and 2/3 4.8 ounce iPhones yearly (not so realistic) [65]. Turnover of laptops (3-8 lbs) and desktops (upwards of 100 lbs) is so high that the range used in this project: 0 to 1 lbs/capita, might actually be on the low end. On the other hand, with increased miniaturization, even if waste generation in terms of numbers of devices keeps increasing into the future, overall waste mass could conceivably stay constant.

3.2.5 Recycle Rate

In even the best waste disposal systems, not all of the waste generated gets recycled. The selection of 90% as the base case was an optimistic one—90% recycling may allow us to avoid significant future environmental degradation and use waste electronics as a viable resource for raw materials. This value can refer to a percent of the total waste stream diverted to recycling in units of whole products—9 out of 10 computers getting recycled. This variable is run from 0% to 100%, although both extremes are not realistic.

3.3 Scenario Descriptions

Adding another dimension to the project, both CODB and collection rate have the ability to be constant or varied by region. In real life, population density, economic vitality, and other factors greatly influence waste disposal decisions, including those governing recycling. Varying characteristics of the background system on which a network of facilities will be placed gives insights not only into the important qualities to consider when actually creating a reverse supply chain but also the sensitivity of this model to changes in the system setup. All five of the previously described parameter variations are performed in each of the three following scenarios.

3.3.1 Scenario 1: Varied CODB & Constant Collection Rate

The first scenario, and the one in which the base-case scenario was envisioned, uses the state-by-state CODB ranking system developed by the Milken Institute [62]. The other variable, collection rate, is kept constant. The CODB index is used just to influence the facility and collection costs. It is normalized by setting the CODB of the state with the mean ranking to 100.

3.3.2 Scenario 2: Constant CODB & Constant Collection Rate

The second scenario keeps both variables constant. This is the least realistic of the possibilities, but gives insight into the behavior of the model, as it eliminates as many exogenous variables as possible. In this scenario, the cost of building a facility in Alabama is the same as building one in Illinois.

3.3.3 Scenario 3: Varied CODB & Varied Collection Rate

The final scenario varies both CODB and Collection Rate. The latter variable is varied by linking a source region's recycling rate to its population density. Using as a normalization factor the mean population density, the total waste collected stays the same as in the previous two scenarios, but the breakdown favors the big cities significantly. The regional population densities can be found in Appendix B.

3.4 Additional Cases

The next step is to select specialized cases of particular interest to investigate. The cases selected here involve all five of the variable parameters.

3.4.1 WEEE Volume

One element in the WEEE directive passed by the EU in 2003 mandates that member states collect 4 kg (8.82 lbs) of e-waste per person. Although this directive includes electrical equipment (i.e. any product with a cord) in addition to electronic equipment, it is a useful analysis to see the results of this model when evaluating a system with such elevated waste volumes. If the model is robust enough to consider such a waste flow, then this analysis may give insights into the ability of nascent material reclamation infrastructures to scale up to meaningful volumes.

3.4.2 Regional Recycling Minima

For all 15 cases run in the body of the research, source regions have no individual recycling minima. This case adds an additional constraint onto the base case defined in section 3.1 to observe a result of regional waste collection requirements that are beginning to be enacted nationwide. In all three system scenarios (the three permutations of variability in CODB and collection rate), a regional recycling rate minimum is introduced, ranging from 0% to 100%.

3.4.3 Other Materials

Material reclamation is a larger problem than just with electronics waste. Movement towards a design and engineering philosophy that approaches used products and materials as viable sources of raw materials requires not only new design processes but also effective RSCs. A useful metric for gauging the effectiveness of this investigation can be attained through comparison with existing, more mature recycling systems. Two materials that have established domestic recycling flows are observed. Material price data were gathered from public sources of prices in materials markets.

In Table 3.5, system parameters for both materials are displayed [3, 4]. Assumptions were made regarding facility costs for each of these materials, and due to the total waste volumes under consideration, larger facilities were added to the model. Another main difference from e-waste is the truck capacity for each of these materials. In this hypothetical arrangement, waste products do not arrive at the recycling facility in the same state as when thrown away; physical consolidation—in addition to the waste flow consolidation discussed in this project—is often employed to allow for a better use of available shipping weight, exceeding the e-waste shipping mass of 25,000 lbs.

PET Bottles Polyethylene terephthalate (PET) is a ubiquitous material in packaging; soda and water bottles made of PET are often marked with the number 1 recycling code. According to the EPA, 850,000 tons of PET was discarded in 2005 by Americans, equaling 5.67 lbs per capita [3]. Used often in homogeneous, discrete products (bottles), curbside pickup is possible, something that doesn't explain the material's mediocre recycling rate, 34.1% [3]. The value of baled, mixed PET bottles is 21 cents/pound.

Aluminum Cans Aluminum is one of the most effectively recycled materials; processing secondary aluminum requires less than 10% of the energy required to processes primary aluminum. 1.45 million tons of aluminum cans are thrown away every year, and despite the cost savings, only 44.8% of this valuable waste is reclaimed [3]. After collection and sorting, aluminum cans are often densified. Densified Al cans can be sold for upwards of $2000 per ton, or almost a dollar per pound.

Material	Baled PET Bottles	Densified Al Cans
Secondary Price ($/lb)	0.21	0.96
Generation (lb/capita)	6	9.7
Truck Capacity (lbs)	35,000	39,000
Recycling Rate	34.1%	44.8%
Base Fixed Cost ($/lb)	0.09	0.07
Base Operating Cost ($/lb)	0.05	0.05
Collection Cost ($/lb)	0.54	0.29

Table 3.5: Additional Materials Input Data [3, 4].

Chapter 4

Results & Analysis

This chapter presents and discusses the results from the experimental cases described in the last chapter. Beginning with the base case to establish a point of comparison, major results are presented in a way that hopefully highlights trends and patterns in model behavior, preceding a discussion section that synthesizes these results into suggestions for creating a real reverse supply chain. Other data presented here are the environmental impact analysis and the results from the additional cases described in Chapter 3.

4.1 Base Case

The base case results illustrate a configuration neither highly centralized nor decentralized. Shown in Figure 4-1 is the configuration of waste processors selected by the model as the optimal configuration superimposed on the scenario map. The three processor facilities selected are located in Durham, NC, La Vergne, TN, and Dallas, TX. Although these three sites are all centrally located, they effectively break the country into three distinct zones, each serving the shaded region in which they are located. Most of the source regions are fully served. Two regions—10 and 18—send waste to two different processors each. One region—22—is only 60% served, and two—23 and 24—are not served at all. Notice that the three under- or un-served regions are all on the west coast, farthest away from the three selected processor sites, removed from other regions of high population density, and in a state with a high CODB. As set forth in the case constraints, 90% of all waste is recycled—to meet this goal the model selected two 50 million lb processors (Durham and LaVergne) and one 25 million lb processor (Dallas).

The cost breakdown (Figure 4-2) among the four constituent costs—transportation, collection, operating and fixed—has facility costs dominating with 56%, transportation cost contributing the least at 17%, and collection cost making up the remainder.

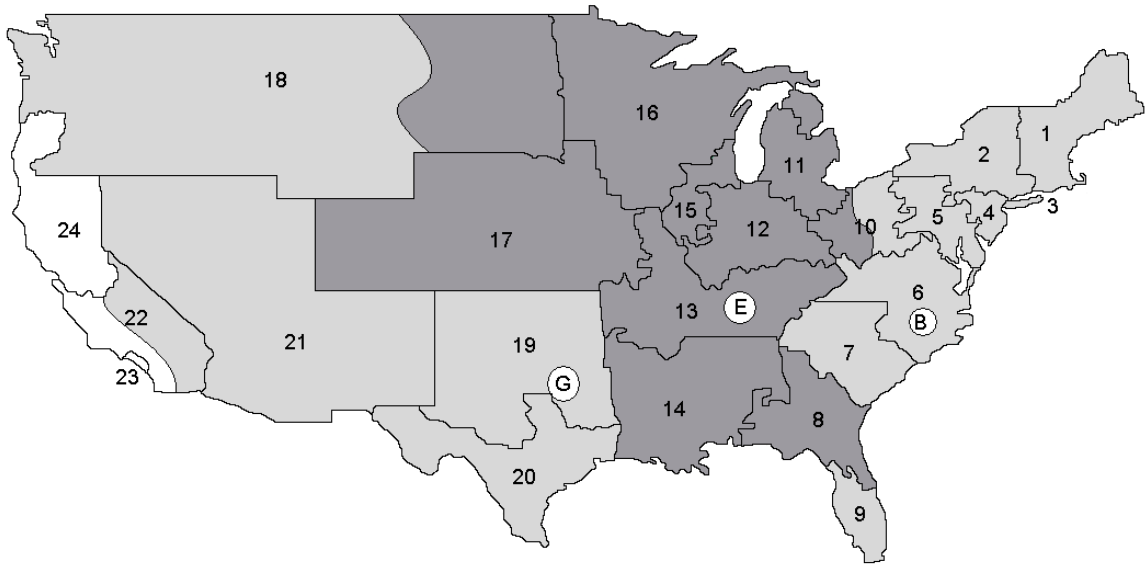


Figure 4-1: Geographical representation of base case results

4.2 Sensitivity Analysis Results

Table 4.1 displays five different solution characteristics from experimental permutations of five variables in all three scenarios: (1) the base case scenario, (2) constant CODB, and (3) varied CODB with collection rate tied to population density. In each of the 75 cells, one of three symbols has been placed, indicating the effect each variable has on the particular solution characteristic. The letter **H** indicates the variable has a large effect across the whole variable range; the change can either be continuous or discrete. The letter **L** means that although change in the variable causes a change,

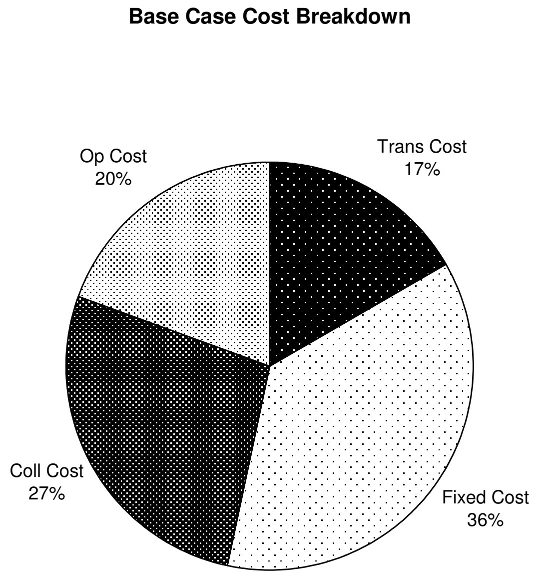


Figure 4-2: Cost breakdown of base case

it is just a small change or effects solely at the extremes of the variable range. The symbol **0** indicates the variable has no discernible effect on the behavior of the metric.

4.2.1 Significant Solution Characteristics

Examination of Table 4.1 can give high-level insight to the sensitivities of each type of solution characteristic to changes in each variable, which then leads the way to more investigation. This discussion focuses on results from scenario 1, in which the base case was carried out. In this and subsequent sections, representative figures are displayed in the body of this paper to illustrate trends. For a full display of graphical results, see Appendix F.

Total Cost

The total system cost is very sensitive to all of the variables except for transportation cost. As seen in Figure 4-3, the relatively small increase in transportation cost is not enough to restructure the system and therefore cause changes in the other three costs as well. The small change from just over \$20 million to \$23 million is in contrast with

Scenario	Variable	Total Cost	Cost Breakdown	Unit Cost	Source Regions	Central-ization
1	Fac. Cost	H	H	H	L	H
	Coll. Cost	H	H	H	0	0
	Trans. Cost	L	L	L	L	L
	Volume	H	L	L	0	H
	Rec. Rate	H	L	L	H	H
2	Fac. Cost	H	H	H	L	H
	Coll. Cost	H	H	H	0	0
	Trans. Cost	L	L	L	L	L
	Volume	H	L	L	L	H
	Rec. Rate	H	L	L	H	H
3	Fac. Cost	H	H	H	L	H
	Coll. Cost	H	H	H	L	L
	Trans. Cost	L	L	L	H	L
	Volume	H	L	L	L	H
	Rec. Rate	H	L	L	H	H

Table 4.1: Qualitative summary of main results. Key: H–big effect, L–small effect, 0–no effect. Scenario 1–varied CODB, constant coll. rate; Scenario 2–constant CODB, constant coll. rate; Scenario 3–varied CODB, varied coll. rate.

the change in total cost that can be seen from the waste volume variable (Figure 4-4), which results in a total cost ranging from a mere $2.5 million all the way up to almost $40 million. It is evident that the variability in total cost is very sensitive to changes in processed volume—changed here by both volume and recycle rate—and by changes in dominant cost elements.

Cost Breakdown

If the change in total cost is driven mostly by the changes in one or two cost categories, then the cost breakdown will also change significantly. This can be seen well in Figure 4-5, which at the low end of facility costs sees transportation cost and collection cost making up all of the cost but receding to less than 40% of the total at the maximum facility cost. Interestingly, most of the change comes from collection cost and the transportation cost component changes little. Although waste volume and recycling rate both cause large changes in total cost, Figure 4-6 indicates that the

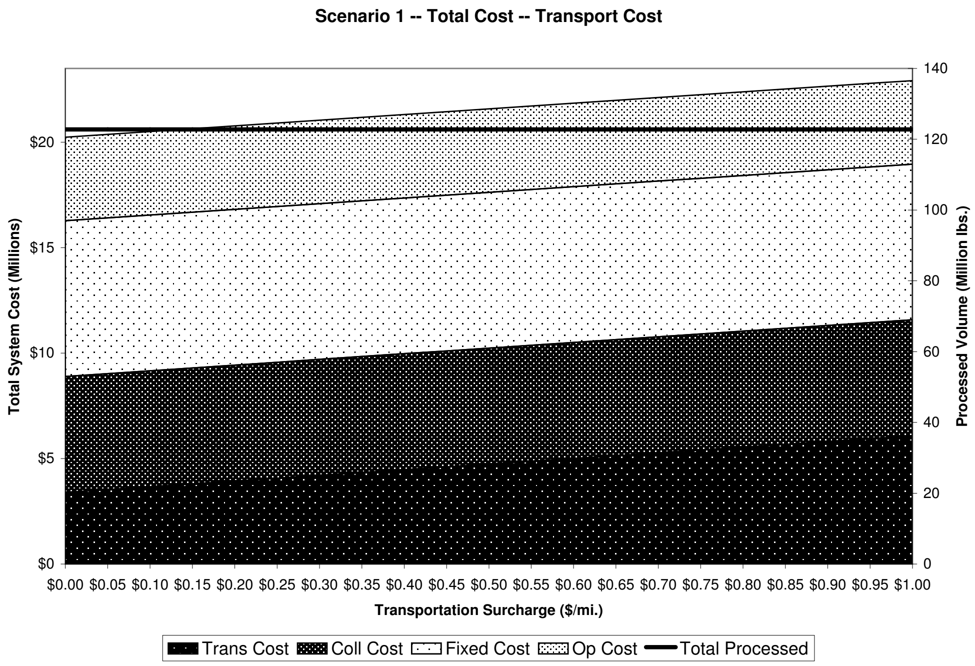


Figure 4-3: Total cost as a function of transportation cost

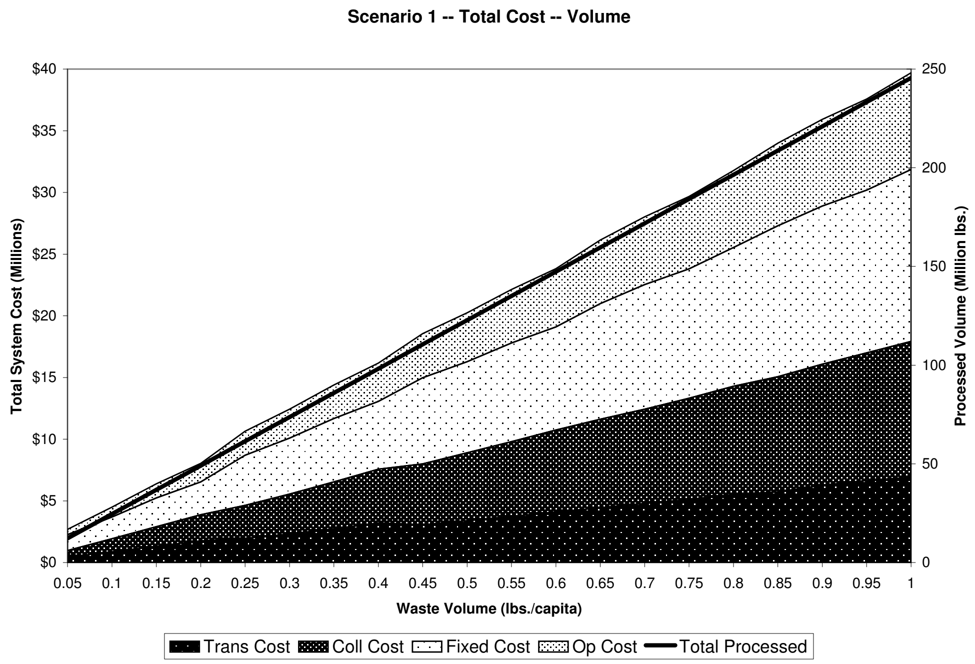


Figure 4-4: Total cost as a function of waste volume generated

ratios between the cost components change very little across the variable ranges. The lumpiness of the sections, particularly transportation cost, can be attributed to reconfigurations of the system as volume increases.

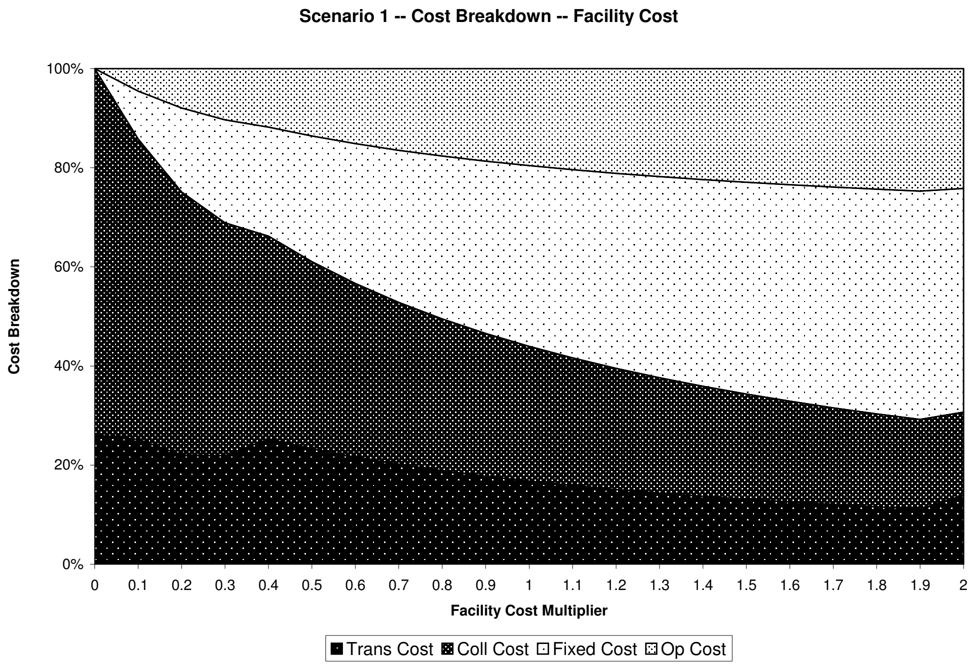


Figure 4-5: Cost breakdown as a function of facility cost

Unit Cost

Unit cost of the RSC is calculated by dividing total cost by weight processed at every point. The cost parameters (facility, collection, and transportation), have unit cost results that are redundancies of their total cost results because total processed volume does not change over the ranges of these variables. This phenomenon can be seen in Figures 4-7 and 4-8, in which the constant processed volume is represented by a horizontal line across both graphs. On the other hand, variables that affect the waste streams rather than directly affecting the cost have unit cost results that differ significantly from the total cost results. A comparison between Figures 4-9 and 4-4 shows the small effect volume actually has on the unit cost, despite its influence in total cost. The correlation between processed volume and total cost is not totally

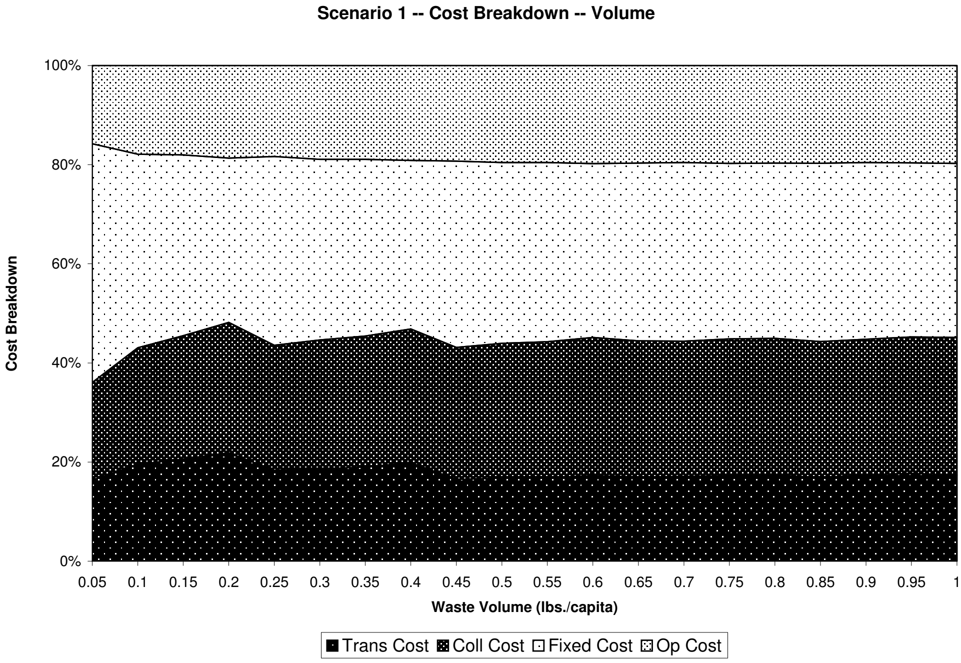


Figure 4-6: Cost breakdown as a function of waste volume generated

linear, however, as the unit cost graph displays an elevated unit cost at low volumes. This can be attributed to the benefits from economies of scale at high volumes.

Source Regions

The final two solution characteristics describe configurational characteristics of the systems designed by the model. Source region service refers to how well every region is served by the system. Overall, this value stays unchanged throughout the ranges of most of the variables. The glaring exception is recycling rate. In Figure 4-10 it is demonstrated that as recycling rate increases, so does the ratio of fully-served regions to un-served regions. Nevertheless, similar to those results that are constant, the model tends to minimize the number of regions that are neither fully nor totally un-served. An example of this can be seen in Figure 4-11. This bar graph shows no variation; across the range, 21 of the regions are fully served, three regions are totally unserved, and only one region gets partially served.

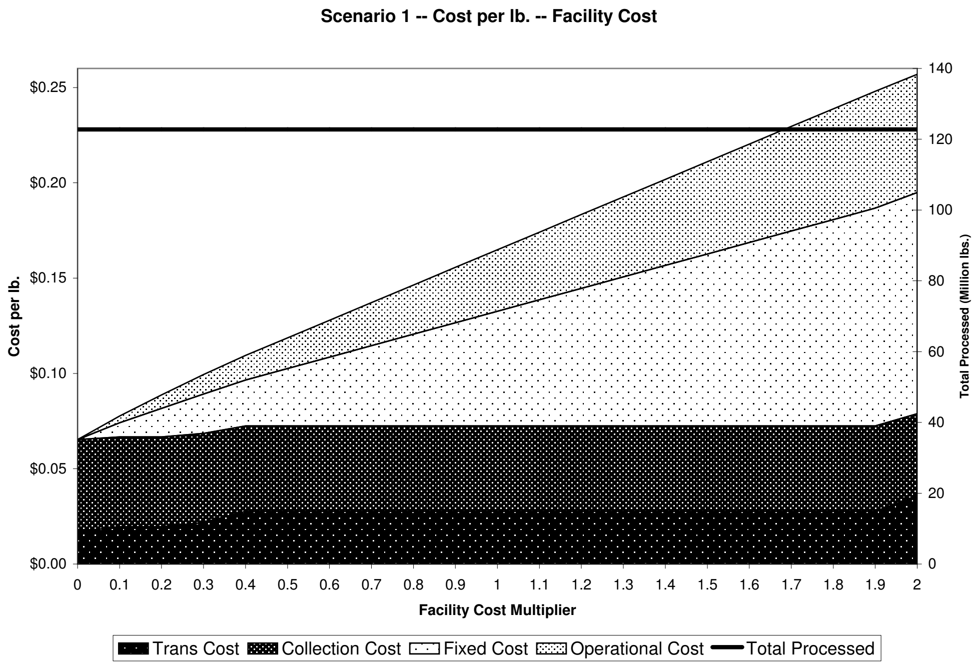


Figure 4-7: Unit cost as a function of facility cost

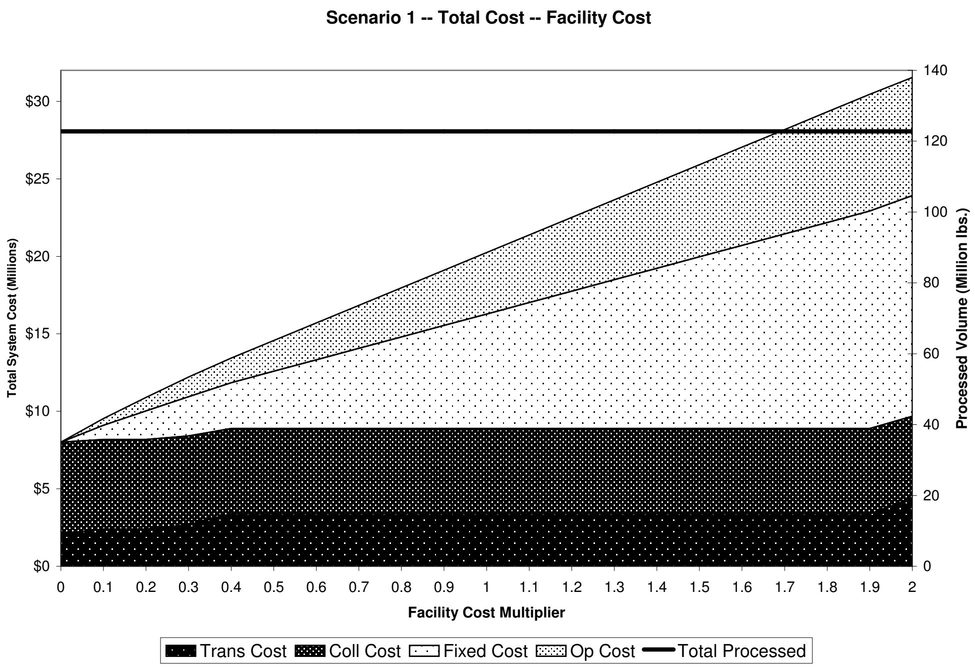


Figure 4-8: Total cost as a function of facility cost

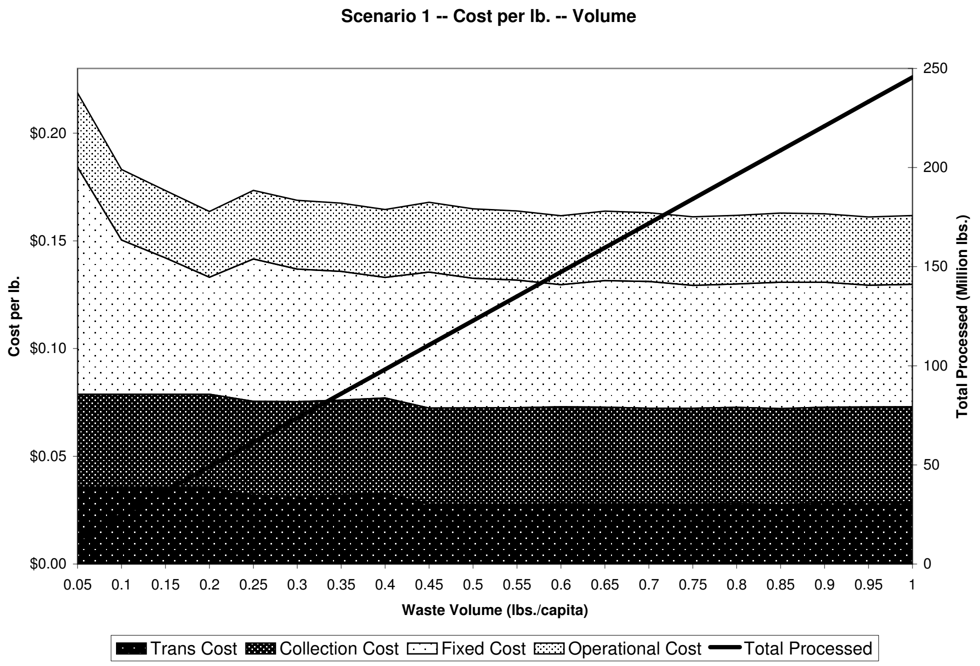


Figure 4-9: Unit cost as a function of waste volume generated

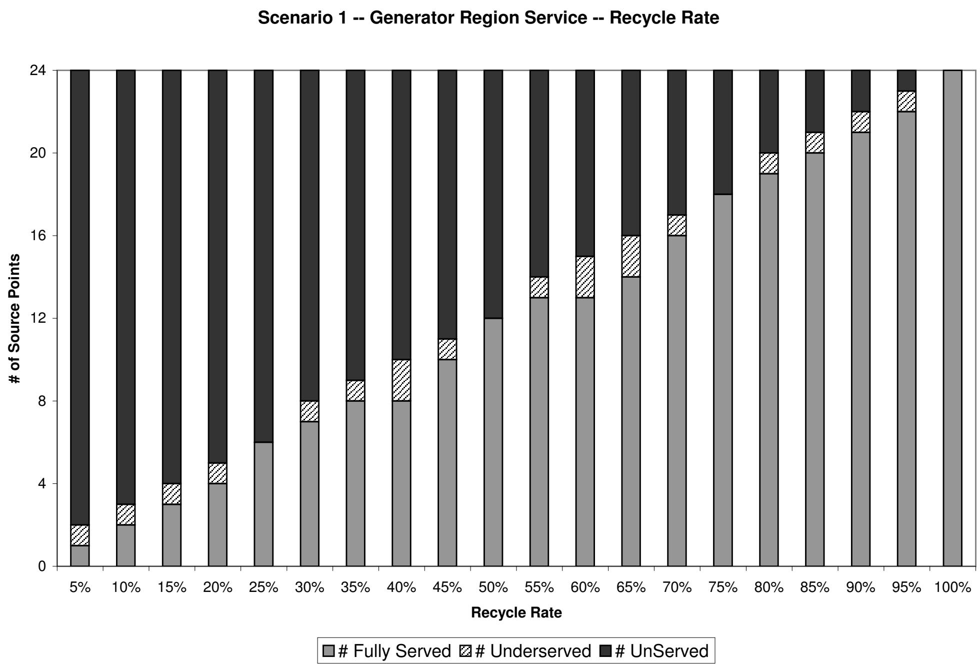


Figure 4-10: Source region service as a function of recycle rate

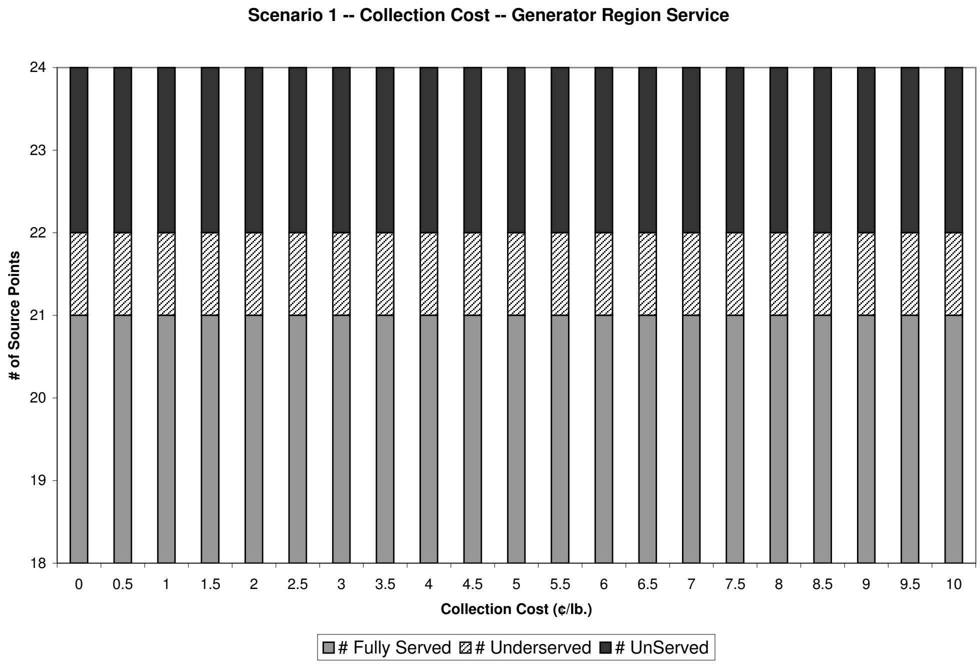


Figure 4-11: Source region service as a function of collection cost

Degree of Centralizaton

The degree of centralization of the RSC is demonstrated by the juxtaposition of a bar graph indicating both the total number of facilities assigned by the model and the number of cities in which those facilities were placed with a line indicating the total mileage driven on the shipping routes. Results from the facility cost experimental run are shown in Figure 4-12, and demonstrate a range from extreme decentralization at the minimum facility cost and total centralization at the maximum facility cost. In the decentralized case, seven of the eight possible processor sites are engaged, often with many facilities at each site. Total mileage is low because waste does not have to travel far to get from source region to the local processor. As facility costs increase, so does the total distance traveled, eventually stabilizing just over 2.5 million miles for most of the experimental range. At this distance, the entire system is served by just three processors in three different cities, just like the base case. As facility costs continue to increase to double that of the base case, all the waste gets sent to just one city: La Vergne, TN, and transportation cost must increase to serve this single city.

Because the total volume of waste has not decreased at all, three processors must be engaged in this city to handle the processing load.

While the other two cost variables, (collection and transportation), do not affect system centralization significantly, the two waste volume-based variables present interesting results. In Figure 4-13, total mileage increases with the number of cities and processors. In contrast to the trend towards centralization seen in Figure 4-12 that occurs as total mileage increases, here, a medium degree of centralization persists or even lessens throughout the entire experimental range. At the low end, only a small amount of waste is generated, and so requires the services of only one processor. However, this processor is serving regions nation-wide. As volume increases, the waste flows become too great for just one or two sites, and three sites are engaged to handle the recycling, although towards the high end of the run even multiple facilities per site is not a sufficient solution and a fourth city is selected. The very large mileage number at the high end of the experiment is not necessarily from a great deal of centralization; it is a manifestation of the elevated number of shipments that must be made to handle the high waste volume.

4.2.2 Variable Influence on Solution Characteristics

Another important consideration is the influence of the variables on solution characteristics. An initial impression of the relative influence of each of the variables can be attained by observing the number of H's, L's and 0's in Table 4.1. By this reckoning, the variables can be ranked, from most influential to least (scenario 1 only): Facility cost, Recycle rate, Collection cost, Volume, Transport cost. Differences that come about from the removal of CODB variation or the addition of a population density-based collection rate are discussed in section 4.2.3.

Facility Cost The facility cost significantly influences the behavior of the model solution. Because it is a significant part of the base case cost breakdown, facility cost variability has a large impact on the cost of the system. Changes in facility cost elicit configurational changes, something illustrated by small bumps in the

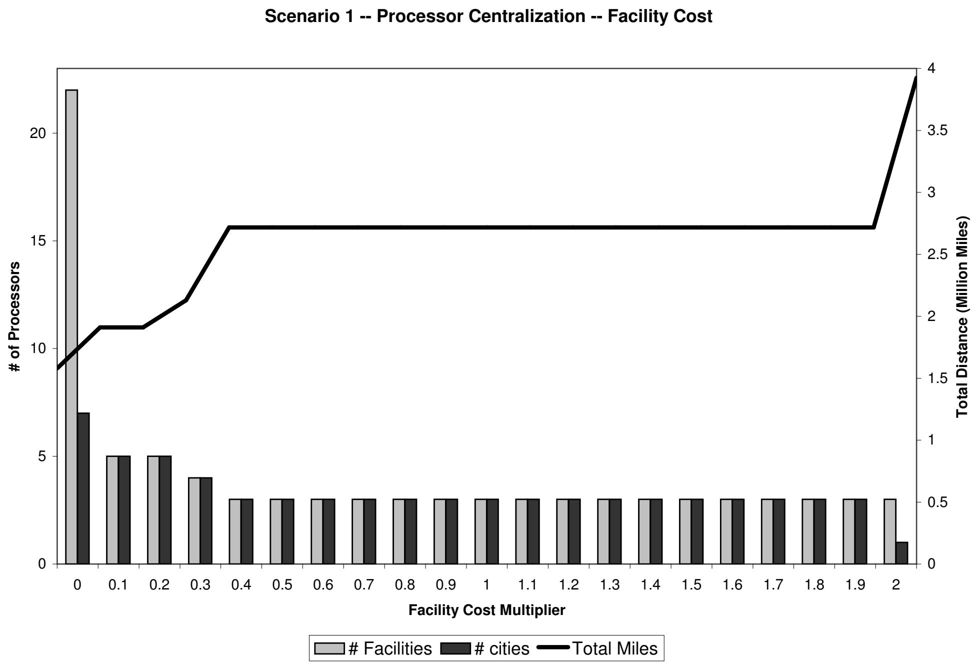


Figure 4-12: Degree of centralization as a function of facility cost

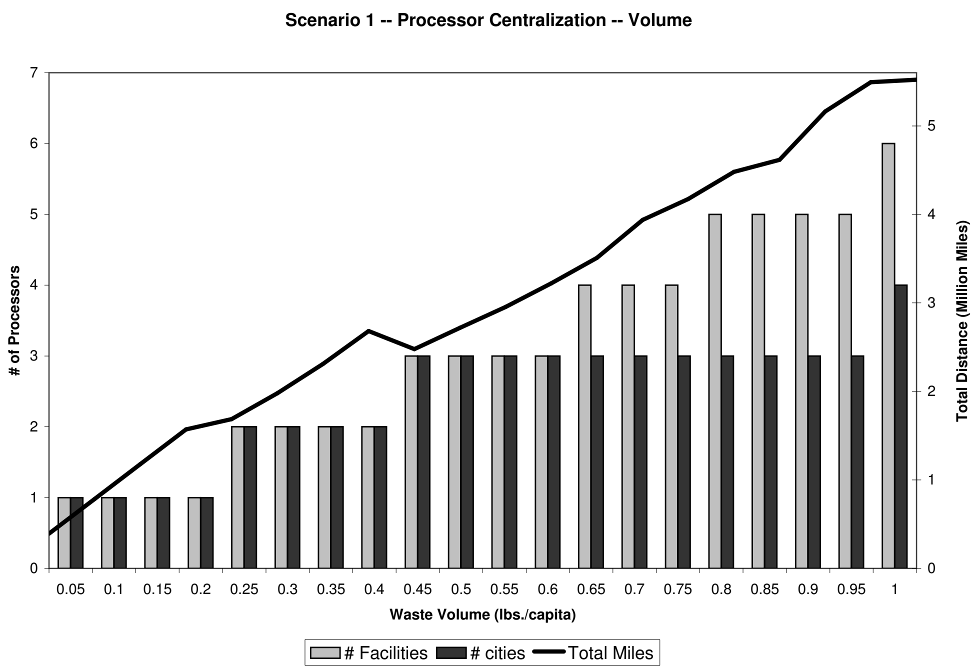


Figure 4-13: Degree of centralization as a function of waste volume generated

cost figures, such as in Figure 4-8 at 0.3x and at 1.9x facility cost multiplier. However, these changes have little impact on cost. Although varying the facility cost has little effect on service to source regions, it does have a large effect on the processor centralization. Nevertheless, around the base case there is a buffer allowing some variation in facility cost without any change in processor configuration.

Recycle Rate Recycle rate has the second largest effect on cost and configuration of the RSC. Although total cost increases with processed volume, the relationship is not directly proportional. At low recycling rates, facility cost makes up a larger component of the total cost than the other cost elements and creates high unit costs. As expected, a low recycling rate results in only small numbers of source regions being tapped for e-waste. Interestingly, as recycling rate increases, the model moves from region to region, exhausting the supply of e-waste from the already-served regions before opening up another region. This is most likely a result of the facility cost being greater than transportation cost—instead of opening another facility to manage the e-waste from another region, existing routes are utilized, again echoed by processor centralization results, shown in Figure 4-14. Here, transportation costs are seen increasing until facilities are maxed out, at which time another city is given a facility. But again, around the base case—90%—there is an allowance for variation.

Collection Cost Collection cost is treated very similar to facility cost, and therefore has a similar, yet smaller, impact on the behavior of the model. The main difference is that the collection cost has no impact on the configuration or degree of centralization of the system. The way it is modeled in this project has collection cost not directly linked to facility cost or transportation cost, so at least in the range investigated here it serves as just an additional cost.

Waste Generated Waste volume variation behaves like the recycle rate in cost results, but displays independent configurational results. Volume-related variables result in cost increasing with total processed volume, and although the

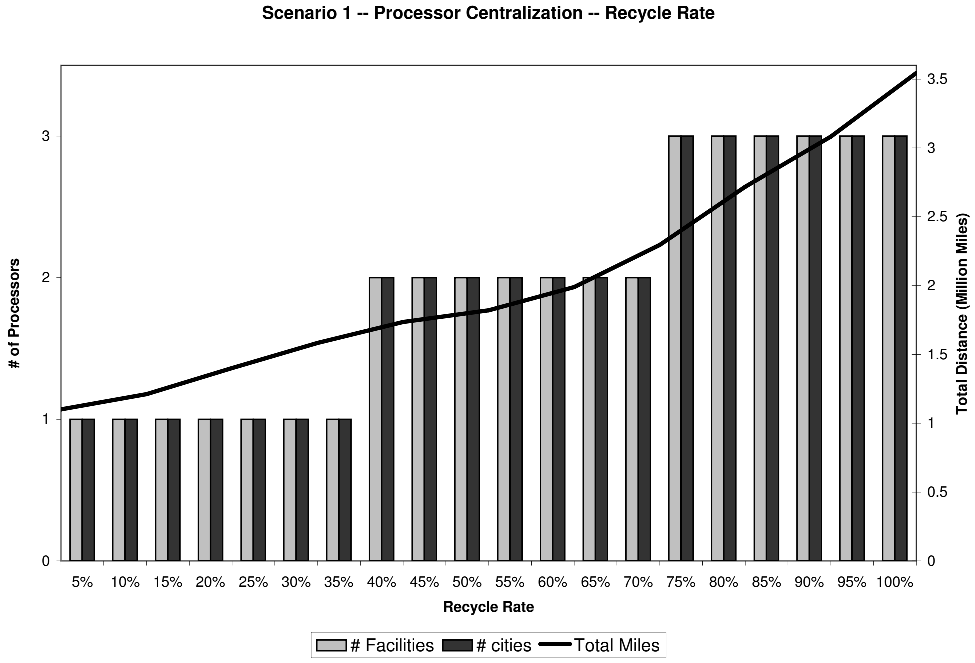


Figure 4-14: Degree of centralization as a function of recycle rate

cost breakdown and unit cost are similar to that of recycle rate, the effect is smaller. Because in this analysis there is a constant 90% recycle rate of everything generated, there is no change in service to the source regions. On the other hand, the significant variance in total waste processed leads to a significant change in processor configuration. At volumes greater that 0.6 lbs/capita, the model places multiple facilities in the selected processor cities, indicating that the volume is getting larger than the model can deal with reliably. Nevertheless, at even larger volumes, the system becomes more decentralized with more cities, more facilities, and more shipping routes. Total mileage seems to be very susceptible to waste volume, as it undergoes a correction just before every reconfiguration.

Transport Cost The smallest of the constituent costs, transportation cost has a similar behavior to that of collection and facility costs, but even less influential. A small impact on total cost, cost breakdown, and unit cost, the only sign that transportation cost is actually having an effect on model configuration is a small decrease in total mileage to keep transportation costs down that is facilitated by the adjustment of source region service arrangements. At high transportation costs, more regions are partially served, and fewer are totally unserved.

4.2.3 The Effects of CODB & Collection Rate

Table 4.1 gives a high-level indication of the effect of CODB and collection rate calculations on the model. An in-depth analysis reveals specifics about the effects of regional variance in establishing a RSC and also the effects of adding additional complexity to the model.

CODB

The elimination of the regional CODB occurs in scenario 2. Apart from an overall increase in the total cost of recycling, the elimination of CODB values increases configurational variability. CODB values give geographic locations intrinsic values. Regions with low CODB will attract processors—it is the equivalent of having local energy minima in a thermodynamic system. The system must exceed some minimum activation energy—here represented by either a low facility cost or high transportation cost—in order to escape the influence of these sites. Without the lower CODB that exists in middle-America, flows between certain source regions and processors sites are not only different from those in scenario 1, they are also more variable within a single experimental run.

In Figure 4-15, which shows the distribution of selected processors in all of the experimental cases, notice the broader distribution of processor locations selected by the model when CODB is constant. In particular, centrally-located sites like Dallas and Durham, which are used heavily when CODB is engaged, are sacrificed for Sacramento and Detroit, indicating a trend towards decentralization. The big exception, of course, is La Vergne, TN, which is utilized irrespective of scenario. The lines extending from the top of each bar on the graph give the number of processors assigned to each site. From this data, it can be seen that Durham and La Vergne are sites of very heavy centralization—exceeding the capacity of even the largest available processor multiple times. Other sites, like Minneapolis and even Sacramento, seem to be much more incidental or appropriately sized.

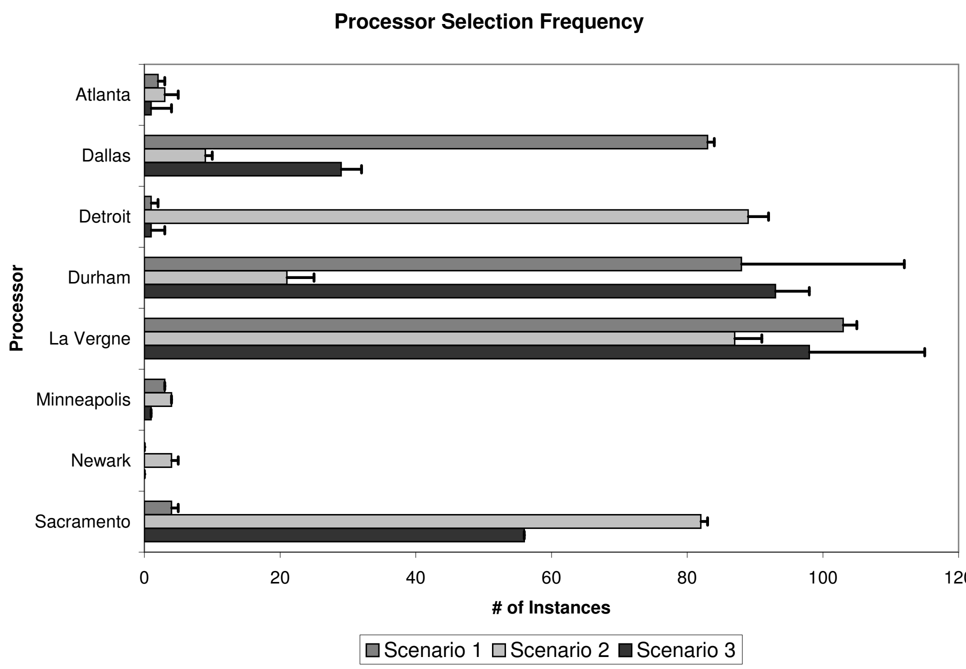


Figure 4-15: Selection frequency of each processor site. Scenario 1–varied CODB, constant coll. rate; Scenario 2–constant CODB, constant coll. rate; Scenario 3–varied CODB, varied coll. rate.

Collection Rate

The addition of another region-discriminating variable adds another layer of physicality to this model. Linking collection rate to population density segregates source regions into, essentially, cities and everything else (discussed in Section 3.3.3). Los Angeles, New York City, and to a much smaller extent the regions represented by Trenton and Chicago significantly outweigh the remainder of the regions, which consist of many miles of rural landscape. With the ability to make small changes in source region service that will result in large changes in the waste flows, this added layer of complexity introduces a great deal of variability in waste sourcing. The significantly higher waste volumes in Los Angeles and New York lead to greater activity particularly on the west coast, as seen in Figure 4-16.

Figure 4-16 displays the number of instances in each of the three scenarios that each source region is fully, under-, or un-served by the model. This takes into account every experimental case, including recycle rate, which increases the concentration of un-served regions. The graph shows only minor variability in the first 15 regions, but the latter nine contain some interesting information. First of all, it shows that in scenario 1, although the west coast is pretty much avoided, the rest of the country is very well served. Not so with scenario 2. Without CODB values, the model selects odd regions to ignore: Minneapolis, Houston, and San Diego. Combined with data from Figure 4-15, it still seems quite arbitrary. With both CODB and collection now regionally varied, many of the results resemble those from scenario 1, except that this scenario seems to vary service the very dense Los Angeles region over most others as the main mechanism for achieving optimum conditions. Finally, similar to the scenario 2 results, Minneapolis is again not well served.

4.3 Environmental Impact

Results from the limited environmental impact assessment show that energy and environmental benefits from offsetting primary electronics manufacturing outweigh the costs from the substantial transportation necessary to facilitate that offset. A representation of this relationship can be seen in Figure 4-17, in which the base case environmental impact is portrayed (note the logarithmic scale on the y-axis). This figure shows just how significant the environmental gains stand to be with the success of an e-waste RSC. The two emissions on the right, SO_x and NMVOC, are included just as points of comparison, even though they are not complete data sets.

Because emissions from transportation are linearly dependent on total mileage and emissions from both CRT and CPU manufacturing are linearly dependent on total processed volume, results from each variable range are not distinct from those described in the previous sections.

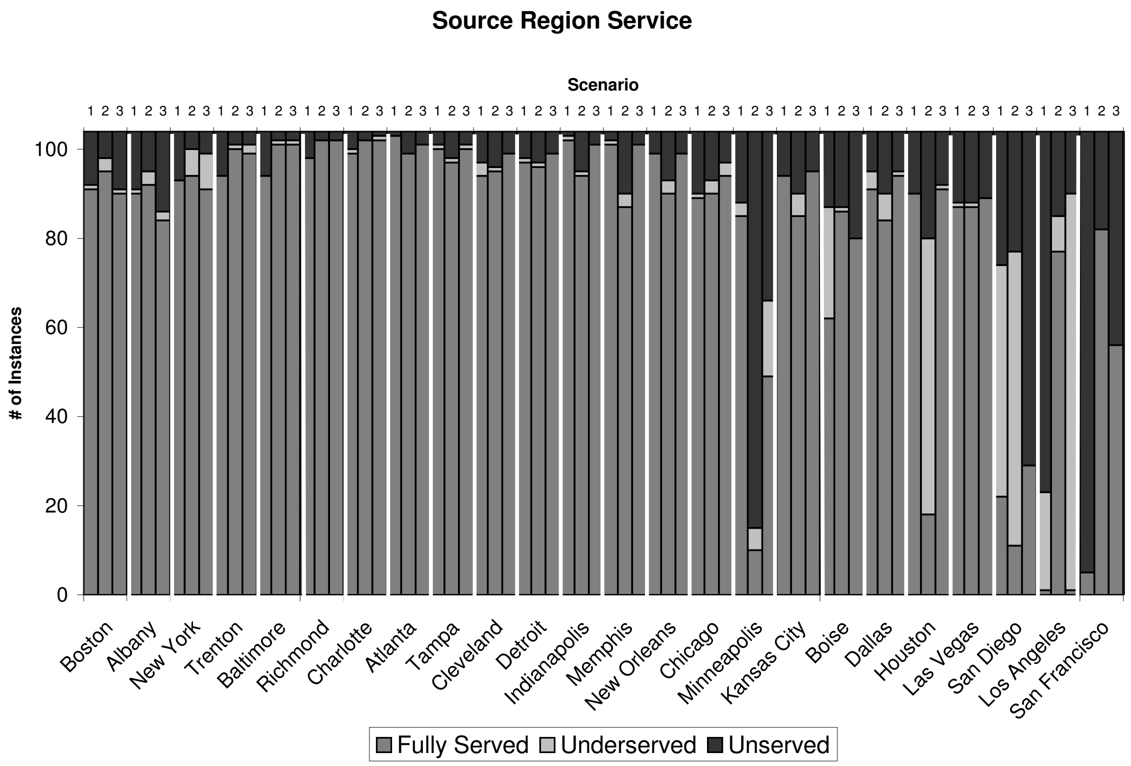


Figure 4-16: Variability of service to each source region. Scenario 1–varied CODB, constant coll. rate; Scenario 2–constant CODB, constant coll. rate; Scenario 3–varied CODB, varied coll. rate.

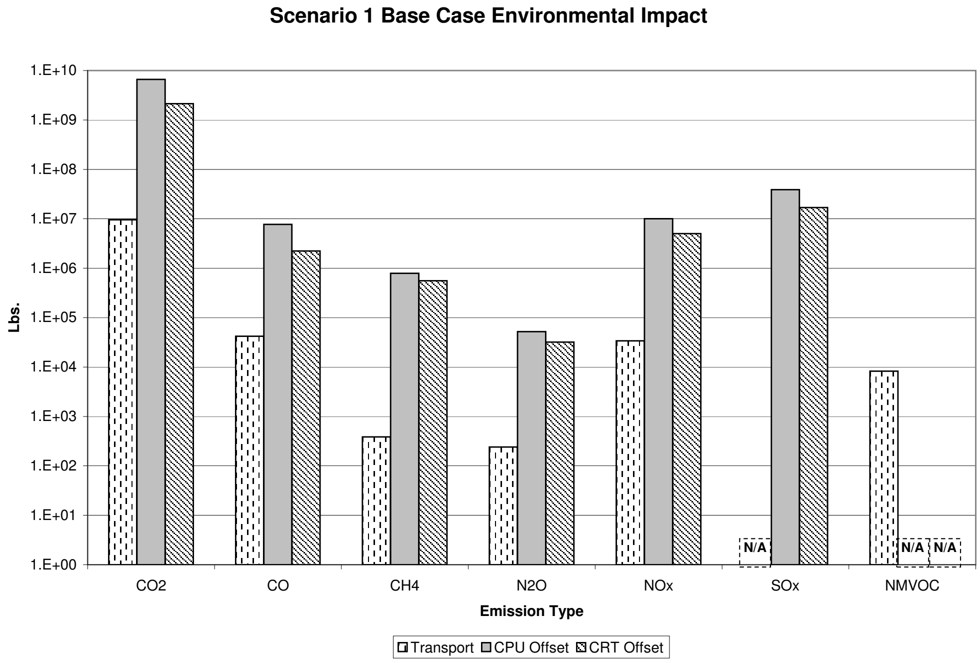


Figure 4-17: Base case environmental impact

4.4 Additional Cases

4.4.1 WEEE Directive Volume

The short description of the behavior of the model when faced with the 4 kg per capita e-waste element in the EU WEEE directive is that it broke. The massive amount of waste introduced to the system—more than 17 times the base case value—highlight many of the failings of this model, primarily that it has a finite number of facility capacity options. This configuration engages 75 facilities in all 8 processing location options, a wholly unrealistic result. Of course this would not be as big of a problem if multiple identical facilities were able to be assigned to any given site. With a total cost exceeding $390 million, this result does not take advantage of the economies of scale the system would be sure to enjoy at such immense processing volumes. At this level, it is possible, however, that transportation costs would play a larger part in dictating infrastructure configuration. Nevertheless, the failure of this model to output meaningful data does bring attention to the fact that the transition from waste volumes being considered by HP and others to waste volumes that the EU directive claim are environmentally meaningful is not insignificant.

4.4.2 Regional Recycling Minima

As more and more states adopt their own e-waste policies, nation-wide reclamation networks will have to take into account local recycling minima. The uniform regional recycling minimum constraint is unrealistic because it treats waste from every region equally, an assumption that is fallacious. The addition of this constraint causes some change in total cost because the facilities now have to serve every source region. This causes either an inflated transportation cost as regions on the coasts ship their wastes to locations on the interior, or new facilities get built to serve the coasts. In the cases that were run, the former occurred in the scenario 1 model (variable CODB), but when CODB was constant and when both CODB and collection rate were varied a facility was built in Sacramento, although east cost regions were still served by mid-west facilities.

No other significant changes occurred due to the addition of a regional recycling constraint. A future step is to give this recycling rate geographical variability, that is, link regional recycling rates with real data.

4.4.3 Other Materials

The objectives of running experimental cases with cost and volume data from other recycled materials were to see a) if the model developed with e-waste in mind is extensible to other materials, and b) if these much more mature recycling flows give any more insight to the sensitivities of centralized or decentralized recycling systems. When possible, results are displayed on maps.

PET Bottles

Results from the plastic bottle recycling case differ only slightly from the original base case, with the major exception that larger facilities are used. The model selected

La Vergne, Durham, and Dallas as the processor sites, placing two 100 million lb. facilities in Durham and Dallas and a total of 360 million lbs of capacity in La Vergne. Figure 4-18 and Table 4.2 show the effect the 34% recycling rate has on the model.

While the total recycled volume is much greater than the e-waste volumes, this recycling system only serves the southern and eastern parts of the country. Unsurprisingly, the selected processor sites correspond to some of the lowest CODBs.

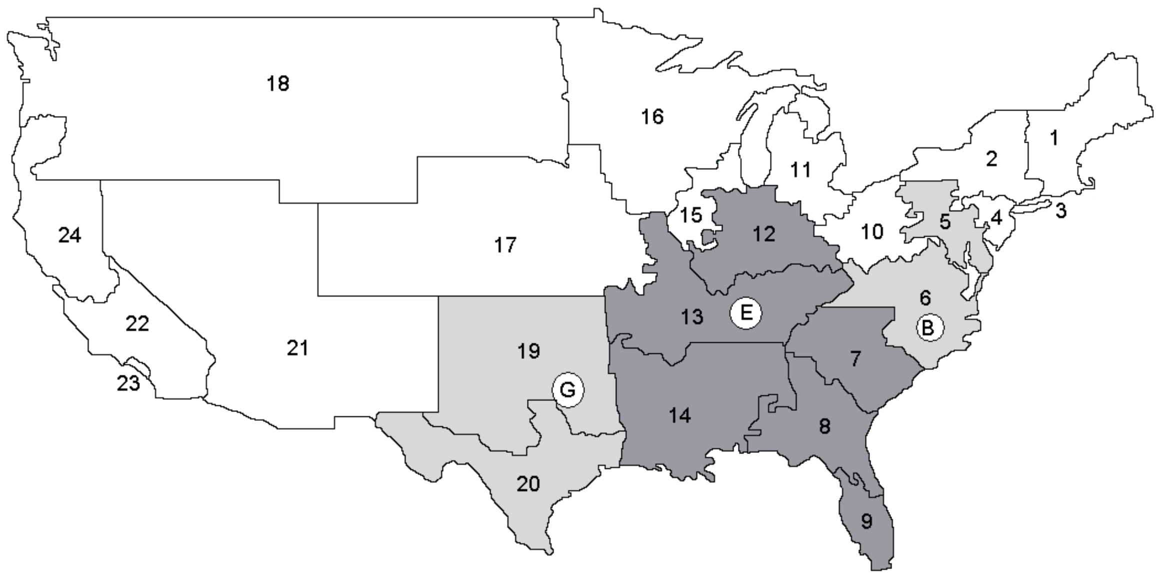


Figure 4-18: Geographical representation of processor configuration for recycling PET bottles

Aluminum Cans

Aluminum can recycling as modeled by this program produces a result similar to that from the PET bottles. In Figure 4-19 and Table 4.3, it is shown that, due to an increased volume, a fourth processing site has been added in the south-east. However, this could be due more to the inability of the model to continue adding larger facilities than an actual cost savings.

Service	Source	F—Dallas 100 Mlbs	B—Durham 100 Mlbs	E—La Vergne 360 Mlbs
0%	1-Boston	0	0	0
0%	2-Albany	0	0	0
0%	3-New York	0	0	0
0%	4-Trenton	0	0	0
47%	5-Baltimore	0	31,794,922	0
100%	6-Richmond	0	68,205,078	0
100%	7-Charlotte	0	0	68,205,078
100%	8-Atlanta	0	0	68,205,078
100%	9-Tampa	0	0	68,205,078
0%	10-Cleveland	0	0	0
0%	11-Detroit	0	0	0
100%	12-Indianapolis	0	0	68,205,078
100%	13-Memphis	0	0	68,205,078
28%	14-New Orleans	0	0	18,974,610
0%	15-Chicago	0	0	0
0%	16-Minneapolis	0	0	0
0%	17-Kansas City	0	0	0
0%	18-Boise	0	0	0
100%	19-Dallas	68,205,078	0	0
44%	20-Houston	29,985,280	0	0
0%	21-Las Vegas	0	0	0
0%	22-San Diego	0	0	0
0%	23-Los Angeles	0	0	0
0%	24-San Francisco	0	0	0

Table 4.2: Waste flows for PET bottle recycling

Service	Source	C—Atlanta 270 Mlbs	F—Dallas 225 Mlbs	B—Durham 270 Mlbs	E—La Vergne 421 Mlbs
0%	1-Boston	0	0	0	0
0%	2-Albany	0	0	0	0
0%	3-New York	0	0	0	0
15%	4-Trenton	0	0	49,470,248	0
100%	5-Baltimore	0	0	110,264,876	0
100%	6-Richmond	0	0	110,264,876	0
100%	7-Charlotte	49,470,248	0	0	60,794,628
100%	8-Atlanta	110,264,876	0	0	0
100%	9-Tampa	110,264,876	0	0	0
0%	10-Cleveland	0	0	0	0
27%	11-Detroit	0	0	0	29,410,743
100%	12-Indianapolis	0	0	0	110,264,876
100%	13-Memphis	0	0	0	110,264,876
100%	14-New Orleans	0	0	0	110,264,876
0%	15-Chicago	0	0	0	0
0%	16-Minneapolis	0	0	0	0
4%	17-Kansas City	0	4,038,196	0	0
0%	18-Boise	0	0	0	0
100%	19-Dallas	0	110,264,876	0	0
100%	20-Houston	0	110,264,876	0	0
0%	21-Las Vegas	0	0	0	0
0%	22-San Diego	0	0	0	0
0%	23-Los Angeles	0	0	0	0
0%	24-San Francisco	0	0	0	0

Table 4.3: Waste flows for aluminum can recycling

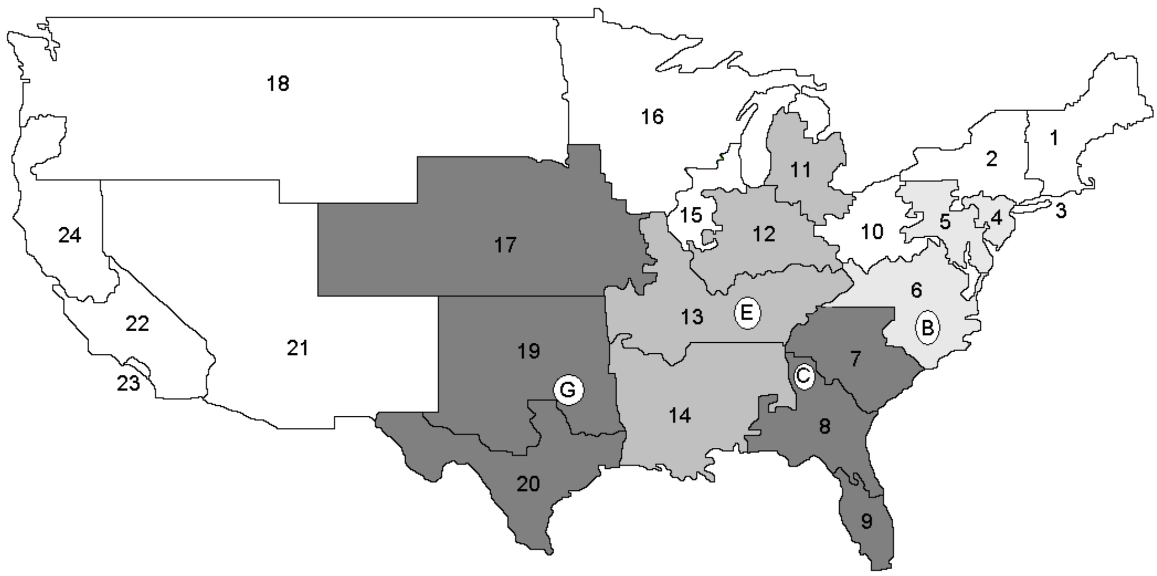


Figure 4-19: Geographical representation of processor configuration for recycling aluminum cans

4.5 Discussion

Data have been presented here with the intention of developing a preliminary set of guidelines for setting up an RSC for material recovery. Transferring the assumptions inherent in the model from the virtual world, in which these experiments were run, to the physical world, however, might actually turn out to be only relevant in highly specialized cases. Nevertheless, the results from the 15 main cases and four secondary cases can be used to start codifying rules about the behavior and sensitivities of e-waste RSCs.

The input values chosen for the base case resulted in a solution that is resilient to fluctuations in costs and volumes. This three-facility, regionally-centralized setup could potentially be the most cost effective configuration. It is a compromise between a decentralized setup, in which there are savings in transportation, and a centralized setup, which can take advantage of economies of scale at the very high facility capacities. The exact locations of these facilities cannot be suggested with any great certainty, as the physical susceptibility such a facility might have to local concerns are not confidently included in the model.

Assuming reasonable model inputs, the main barrier to long-term cost effectiveness of such an RSC is the high cost of the actual processing. Facility cost, which includes both operating and fixed costs, is not only consistently higher than the cost of collection and transportation, but it also seems to be the deciding factor in a discussion about degree of centralization. This is the most likely reason that some processors choose to send e-waste to Asia for further processing. In the United States, high labor and property costs make it challenging for some recycling facility to make much of a profit. E-waste is no different. Non-standardized products in a still-evolving waste stream make it difficult for processors to justify investing in anything but the most generalized equipment.

Uncertainty is also a big barrier to adoption. Uncertainty in waste composition, as mentioned above, can drive down revenues; uncertainty in the degree to which total costs are susceptible to regional variations are also dangerous. In the model, regional CODB, collection rate, and recycling minima are all investigated, and while some conclusions can be drawn as to the impact these parameters have on the model behavior, there is uncertainty in the degree to which the model reflects reality. After all, although elevated CODB costs might cause the model to place processors away from the coasts, transitional RSCs might require facilities located in densely populated cities on the coasts in order to find a large enough waste stream.

The environmental elements of this project as described in Section 4.3 are questionable. Although the analysis was preluded by a caveat to take the results as purely illustrative of the kind of results one might get in a real environmental impact assessment, one may wonder how results would change if minimizing environmental impact were a second objective, like it is in [37]. This objective would require a way of comparing environmental impacts, i.e. weighting one type of damage, like eutrophication, over another, like global warming potential; even so, the energy advantage secondary metals processing has over primary processing is significant. However, an accurate assessment of displaced energy consumption requires information about where the recovered material goes. Does it, like plastics, become some low quality filler material, or like steel in cars, does it get put back into the very role it had been playing?

Although it seemed like the other materials chosen for the additional cases were appropriate—after all, plastic and aluminum are both heavily recycled consumer goods, something that one may claim e-waste should be—it is possible that these types of materials are not ideal points of reference. Plastic and aluminum containers are very simple, ubiquitous, cheap, and homogeneous products. The most complicated step in recycling these materials can be argued to be the initial separation from the rest of the co-mingled waste stream. Electronics, on the other hand, are phenomenally complex devices, engineered at the atomic level in some cases. Although this study treats e-waste processing as a black box, represented by a set of cost figures, perhaps a better model for comparison is another highly complex, common product that is already heavily recycled: the automobile.

Cars are very common products that define our society (the same can be said for electronics). They are highly complex, with many different parts, complicated, international supply chains, and have a mature recycling industry. Also, the environmental impact not of car disposal, but of car use, is a common worry. The situations are very similar, so instead of looking to external producers, consumers, and other market forces to manage e-waste, electronics OEMs should develop a way to a) make their products easily recyclable or repairable, b) figure out a way to utilize a much higher concentration of secondary materials than are being used today, and c) start making the symbiotic relationships that naturally exist between two organisms that subsist off of the other's outputs.

Chapter 5

Conclusions & Future Work

5.1 Summary & Lessons Learned

E-waste has recently become a topic of great interest. Rapidly increasing e-waste volumes due to a combination of higher electronics production, lower costs, and shorter product lifespans have opened up many investigations into the harmful effects of improper disposal of e-waste. Additionally, there has been a realization that many electronic components have significant value as scrap. HP, among other large corporations, is looking to reduce the impact its activities and products have on the environment, probably in a large part as a way to increase the company's moral capital, but also because they realize our society is not so slowly destroying the environment. To that end, reverse logistics tools are being used to try to develop guidelines for the development of the most cost-effective e-waste material reclamation system possible. This project uses linear optimization to gain a high-level understanding of the driving costs of this RSC and to make a recommendation as to the degree of centralization of the optimal configuration.

Results from the main experimental cases supplemented with information from the limited additional cases, can be synthesized into a few guidelines or conclusions regarding characteristics of a cost effective e-waste RSC.

- Facility cost is the most influential of all the cost elements. It is the largest cost component, and, depending on the composition of the waste stream, has the potential to be highly variable.

- A regionally centralized system appears to be the most cost-effective, at least in the general sense. It serves as a compromise between the transportation cost-effectiveness of a decentralized configuration and the economies of scale of a centralized configuration. Of course, as facility costs are greater than transportation costs, the system will likely be more centralized than not.

- Sensitivity of the three- or four-facility configuration to input parameter variation seems to be low. This indicates that even if the base case was inaccurate, many of the results would have been the same as reported here.

- The ease of transition from a small-volume recycling system to a large one, as illustrated by the two volume-related parameters, is not certain. Although small variations in waste volume are not disruptive to the selected processor configuration, the results from this project do not necessarily predict the trend continues to much larger waste streams. In other words, it is as yet inconclusive if the degree of centralization observed in low-volume RSCs is the same as in high-volume RSCs.

- From either a cost or technical point of view, it looks like an e-waste RSC only has high-level elements in common with other MSW recycling systems. The current black-box approach taken by this and other studies that allows e-waste to be evaluated like MSW may be limiting in the long run. Aspects of design and production that hinder material recovery will likely be uncovered only at EoL. Communication of these specific design issues may be muted by black-box treatment, even though product redesign would likely lead to improved economic and environmental performance.

- Results from the addition of regionally variable parameters, like CODB and collection rate, reinforce the regional differences in this country. From purely a cost perspective, population densities and costs of living lead to a somewhat rigid RSC configuration. However, once other factors begin to be introduced, such as state regulations, the definition of "optimal" configuration is less clear.

Many of the other results from this project give insight into how to improve the linear optimization model. These include:

- The WEEE volume case highlighted the inability of this model to handle very high volumes. It also made suspect some of the results from the main experimental group that had high volumes. The solution to this issue is to simply provide a larger selection of processor capacities.

- The environmental results alluded to the increased value this model would have if environmental impact were added to the objective function.

- Uncertainty is discussed many times in this thesis project, although always qualitatively. The broad assumptions made in the model lend themselves to the inclusion of a quantitative uncertainty factor, similar to that in [57].

All in all, some of the best lessons from this project may be found in the next section, Future Work. So many questions arose during the experimentation that could not be answered due to the time constraints that this project could almost be best used for as a jumping off point for the next studies.

5.2 Future Work

The problem of large-scale e-waste consolidation and material recovery is not solved. In fact, at the completion of this work, there are more questions about the topic than there were before. Attaining a fully closed-loop industrial ecosystem will require a gradual evolution, especially because of society's current paradigm of cradle-to-grave material consumption. Also, it seems that there is a trend in new classes of problems. At the beginning there are few answers but also few questions. For the first few years, as interest builds, real answers still come very infrequently, but the volume of questions and even confusion grows rapidly because of the better understanding the scientific community is getting of the actual problem. Finally, there is the break-even point, when the rate of new question generation slows and solutions begin emerging, something that continues until the mainstream moves on to a new topic, declaring the old topic well-enough solved. Reverse logistics is very much in its nascence, and its application to recycling is even newer. This study opens many doors with regards to next steps, both directly and indirectly.

In the process of completing this project, a number of limitations were identified: in the model, in the initial assumptions, and in the experimental choices. A productive next step would be to select new variable ranges, a modified set of starting assumptions, a different base case, and a more robust model, and continue to investigate the conformational tendencies of e-waste RSCs. Some of the trends discussed in section 4.5 may hold fast, indicating some physical significance of those results.

A second realm for future investigation stems from the results from the additional cases as described in section 4.4. Just touching upon other related factors in this project gave the main experimental procedure a bit more dimension, but only to the extent that these initial forays—regulatory pressures on recycling, regional variability, and comparisons between e-waste and other waste streams—be investigated further. All three topics, among many others, are ripe for investigation.

A more indirect next step has to do with the role this topic can play in a broader sense. These may be the beginnings of a large paradigm shift in which anthropogenic resources are utilized to fuller and fuller extents. To assist with this transition, research should be conducted on the effects the composition of the e-waste stream has on the e-waste RSC. Predictions as to the ability of material recovery technology to keep up with increased miniaturization and ubiquitous computing, all framed in terms of total cost and environmental impact, would be valuable to technology companies, policymakers, consumers, and academics.

Finally, as a research project with a direct application (i.e. HP's e-waste policy) this thesis is well poised to spawn other projects that straddle the border between industry and scholarship. Achieving closed loops in industry is not something that can be done solely in an academic setting; market players are important partners. A longer-term research initiative coming out of this project would be to work with the major players in an existing e-waste RSC and study how concerns that may not be easily communicated through cost information but are important in the larger picture, e.g., how recyclers can influence OEMs to produce products easier to recycle without requiring regulation. As e-waste volumes grow in the short term, it will be imperative that mechanisms be in place to one day mitigate the looming environmental crisis.

Appendix A

LINGO Transcript

```
MODEL:
!Capacitated Plant Location Problem;

SETS:
GENERATORS: eWGen;
  !Every generator location has a characteristic amount of e-waste generated;
PROCESS_LOC: CODB;
  !Every processor location has a characteristic cost of doing business;
FACILITIES: Capacity, bFIX_COST, bCollect_Cost, bOp_Cost;
  !Each different type of facility has a capacity, fixed cost, collection
   cost, and operating cost;
ROUTES (GENERATORS, PROCESS_LOC): SHIPPING_RATE;
  !Each route (generator/process loc. combination) has a particular distance
   and shipping rate;
PROCESSORS (PROCESS_LOC, FACILITIES): FIX_COST, Collect_Cost, Op_Cost, OPEN;
  !Each possible processor is defined as a combination of all possible sites
   and all possible processor types;
ARCS(PROCESS_LOC, FACILITIES, GENERATORS) : COST, VOL;
  !Every combination of start- and end-points and facility types;
ENDSETS
```

```
DATA:
!General parameters;
ProcessedTotal = @OLE('thesis_model_HP_RUN.xls','ProcMinTotal');
  !as % of total waste generated;
ProcessedPerCity = @OLE('thesis_model_HP_RUN.xls','ProcMinPerCity');
  !as % of total waste generated;
Truck_Capacity = @OLE('thesis_model_HP_RUN.xls','Truck_cap');
  !lbs  per truckload;
CODB_INDEX = @OLE('thesis_model_HP_RUN.xls','Index_Basis');
  !CODB index normalization factor;

!Table data;
GENERATORS, eWGen =
     @OLE('thesis_model_HP_RUN.xls','Generators', 'eWGen');
PROCESS_LOC, CODB =
     @OLE('thesis_model_HP_RUN.xls', 'proc_locations', 'CODB');
FACILITIES =
     @OLE('thesis_model_HP_RUN.xls', 'Facility_Types');
Capacity, bFIX_COST, bCollect_Cost, bOp_Cost =
     @OLE('thesis_model_HP_RUN.xls', 'baseFacData');
SHIPPING_RATE =
     @OLE('thesis_model_HP_RUN.xls','Shipping_Rates');
ENDDATA

@FOR( PROCESSORS(L, F): [assignlocalcost]
      FIX_COST (L, F) = bFIX_COST(F) * CODB(L)/CODB_INDEX;
      Collect_Cost(L, F) = bCollect_Cost(F) * CODB(L)/CODB_INDEX;
      Op_Cost(L, F) = bOp_Cost(F) * CODB(L)/CODB_INDEX;
      );

!The objective -- minimize total cost;
[TTL_COST] MIN = @SUM( ARCS(L,F,G):
```

```
    SHIPPING_RATE(G,L)*VOL(L,F,G)/Truck_Capacity
  + VOL(L,F,G)*(Collect_Cost(L,F)
  + Op_Cost(L,F)))
  + @SUM( PROCESSORS: FIX_COST * OPEN);

!The individual city processed meets generation goal per city;
@FOR( GENERATORS(G): [GenSatpCty]
  @SUM( ARCS(L,F,G): VOL(L,F,G)) >= ProcessedPerCity * eWGen(G));
@FOR( GENERATORS(G): [Availability]
  @SUM( ARCS(L,F,G): VOL(L,F,G)) <= eWGen(G));

!Total processed meets goal;
Total_Processed = @SUM(ARCS:VOL);
[TTLGENSAT] Total_Processed >= ProcessedTotal * @SUM(GENERATORS:eWGen);

!The supply constraints;
@FOR( PROCESSORS(L,F): [SUPPLY]
  @SUM( ARCS(L,F,G): VOL(L,F,G)) <= Capacity(F) * OPEN(L,F));

!Make OPEN binary(0/1);
@FOR( PROCESSORS: @BIN( OPEN));

DATA:
@OLE('thesis_model_HP_RUN.xls','flows') = VOL;
@OLE('thesis_model_HP_RUN.xls','Total_Cost','Total_Processed') =
TTL_COST, Total_Processed;
ENDDATA

END
```

Appendix B

Distance Table (miles)

Generators	Processors								Pop. Density
	Atlanta	Dallas	Detroit	Durham	La Vergne	Minneapolis	Newark	Sacramento	(people/sq. mi.)
Boston	1103.2	1833.8	724	705.2	1101	1399.6	225.6	3023.1	189
Albany	1006.2	1669.6	559.7	647.2	1079.5	1233.9	151.1	2858.9	206
New York	889.2	1597.1	613	491.2	877.6	1195	10	2815.7	6927
Trenton	836.3	1558.8	615.9	438.1	834.1	1207	52.1	2830.5	937
Baltimore	701.3	1434.2	525.7	303.2	701.1	1107.8	181	2728.5	315
Richmond	539.8	1274.2	620.8	152.7	610.3	1202.9	322.2	2836.3	139
Charlotte	243.6	1025.5	677.1	144	430.4	1257.6	641.9	2786.8	159
Atlanta	10	781.2	721.8	383.3	233.7	1158.7	881.5	2527.1	148
Tampa	456.4	1155.1	1183.4	675.4	689.9	1659.9	1132.7	2911.2	384
Cleveland	713.6	1216.4	168.3	548.3	542	750.4	452.8	2371.4	243
Detroit	720	1216.5	10	711.1	553	696.7	604.2	2308.6	242
Indianapolis	532.9	898.9	312.9	656.1	304.7	610.9	697.7	2181.9	150
Memphis	387.4	452.5	802.5	742.5	230	949	1136.6	2094.2	83
New Orleans	467.4	519.9	1063	853.4	540.3	1348.7	1304.1	2285.1	75
Chicago	751.1	921.7	302.6	866.2	522.9	409	777.7	2043.6	400
Minneapolis	1158.3	940.7	696.1	1289.2	930.2	10	1191.6	1959.6	59
Kansas City	800.5	500.4	793.2	1050	572.3	436.3	1183.7	1773.5	37
Boise	2174.3	1621.9	1957.6	2506.9	1941.9	1467.2	2456.2	552.8	18
Dallas	780.9	10	1255.1	1194.5	681.9	940.9	1588.5	1733.9	56
Houston	809.9	239	1374.9	1195.1	859.4	1231	1614.4	1932.3	90
Las Vegas	2151.1	1214.4	2010.7	2323.8	1810.2	1656.5	2509.4	575	27
San Diego	2137.5	1357	2346.1	2562.1	2048.5	1991.8	2857.6	503.8	134
Los Angeles	2215.8	1435.4	2279.3	2580.4	2024	1999.4	2890.7	383.9	5237
San Francisco	2594.4	1728.2	2406.7	2837.6	2324	2040.9	2905.2	87.1	132

Appendix C

Cost of Doing Business Index

	State	Index		State	Index
	Hawaii	143.1		Ohio	93.3
	New York	130.7	*	Texas	92.8
	Massachusetts	125.5		Oregon	92.6
*	California	124.2		Colorado	92.6
	Connecticut	122.7	*	North Carolina	91.6
	Alaska	120.8	*	Georgia	91.6
*	New Jersey	120.7		Louisiana	89.1
	Delaware	109.6		Kansas	88.9
*	Minnesota	107.9		Indiana	88.8
*	Michigan	106.1		Kentucky	87
	Vermont	106		Missouri	86.8
	Nevada	103.8		Utah	86.8
	Illinois	103.7		Nebraska	86.5
	Washington	103.5	*	Tennessee	86.2
	Rhode Island	103		Alabama	86.2
	New Hampshire	101.9		West Virginia	86.1
	Maryland	101.8		Arkansas	85.3
	Pennsylvania	100.2		Oklahoma	84.8
	Maine	96		South Carolina	84.2
	New Mexico	95.6		Mississippi	84.1
	Wisconsin	95.4		Idaho	83.3
	Florida	95.1		Montana	80.6
	Wyoming	94.7		Iowa	80.2
	Virginia	94.7		North Dakota	76.9
	Arizona	94		South Dakota	71.9

Entries marked with a "*" are used in this study [62].

Appendix D

Environmental Analysis Data

Materal	CO_2	CO	CH_4	N_2O	NO_x	SO_x
Ferrous Metals	7.6553	0.0008	0.0001	0.0000	0.0074	0.0069
Aluminum	35.8535	0.1436	0.0007	0.0003	0.1049	0.1247
Copper	13.9942	0.0038	0.0003	0.0001	0.0425	0.8366
Lead	4.6684	0.0015	0.0001	0.0001	0.0155	0.0250
Plastics	8.0185	0.0044	0.0041	0.0002	0.0255	0.0218
Glass	2.7780	0.0009	0.0000	0.0000	0.0155	0.0044
Rubber	5.1800	0.0008	0.0002	0.0000	0.0043	0.0330
Nickel	4.9200	0.0088	0.0002	0.0004	0.0161	0.3562

Table D.1: Emissions from primary materials production (lbs/ton) [2]

Materal	CO_2	CO	CH_4	N_2O	NO_x	SO_x
Ferrous Metals	2.7812	0.0008	0.0001	0.0000	0.0084	0.0087
Aluminum	2.7174	0.0009	0.0001	0.0000	0.0082	0.0043
Copper	6.2974	0.0017	0.0002	0.0001	0.0191	0.3765
Lead	0.7611	0.0002	0.0000	0.0000	0.0021	0.0104

Table D.2: Emissions from secondary materials production (lbs/ton) [2]

Coal	45.55%
Fuel oil	4%
Natural gas	16.97%
Nuclear	18.5%
Hydro	12.66%
Biomass	1.64%
Other Renewables	0.67%

Table D.3: 2000 U.S. grid mix [5]

Appendix E

Facility Costs

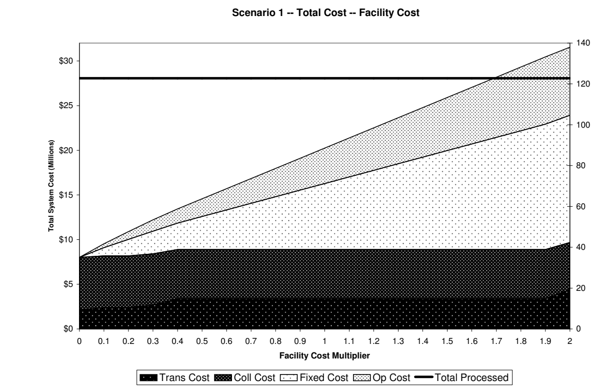
Capacity	Fixed	Operating ($/lb)
01Mlbs	$295,418	$0.0524
02Mlbs	$447,769	$0.0489
05Mlbs	$775,923	$0.0446
10Mlbs	$1,176,079	$0.0417
15Mlbs	$1,500,000	$0.0400
20Mlbs	$1,782,602	$0.0389
25Mlbs	$2,037,983	$0.0380
30Mlbs	$2,273,575	$0.0373
35Mlbs	$2,493,890	$0.0368
40Mlbs	$2,701,920	$0.0363
45Mlbs	$2,899,773	$0.0358
50Mlbs	$3,089,004	$0.0355

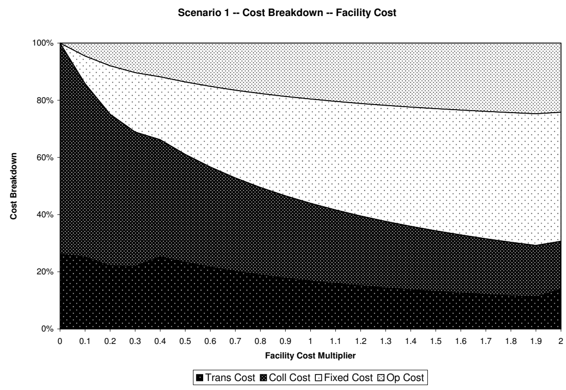
Appendix F

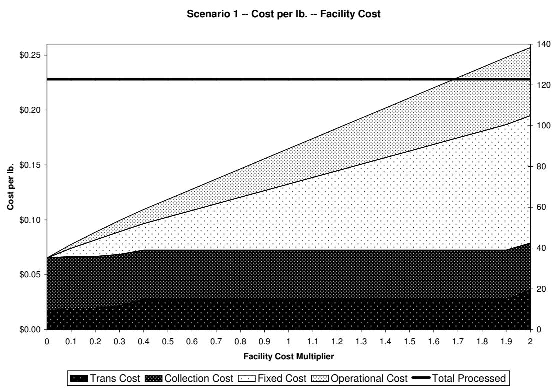
Graphical Results

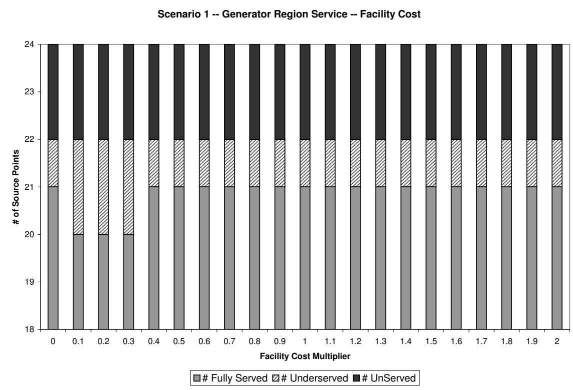
Below are all 75 graphs from the main experimental procedure.

Scenario 1	
CODB	Varied
Collection	Constant

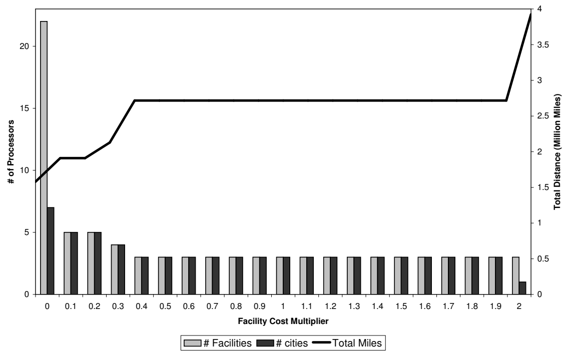




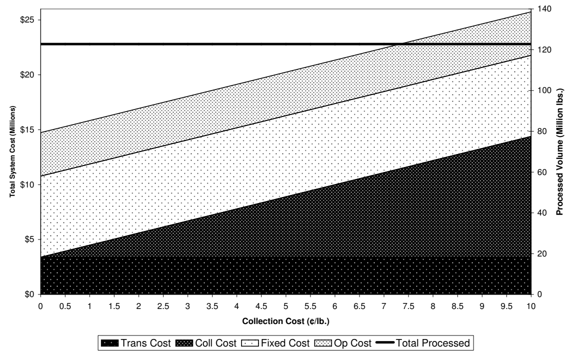




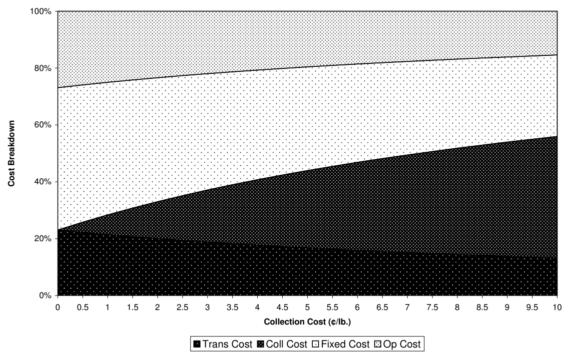
Scenario 1 -- Processor Centralization -- Facility Cost



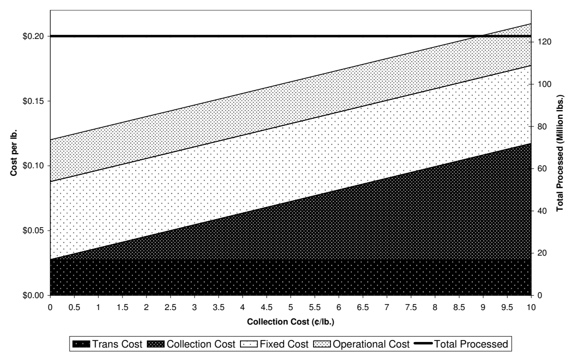
Scenario 1 -- Total Cost -- Collection Cost



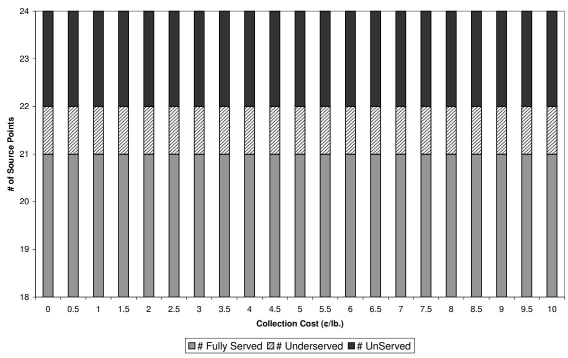
Scenario 1 -- Cost Breakdown -- Collection Cost



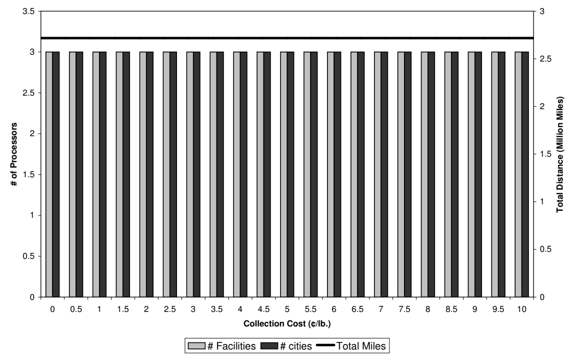
Scenario 1 -- Cost per lb. -- Collection Cost



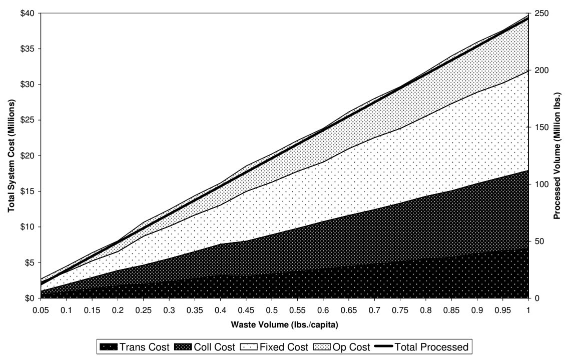
Scenario 1 -- Collection Cost -- Generator Region Service



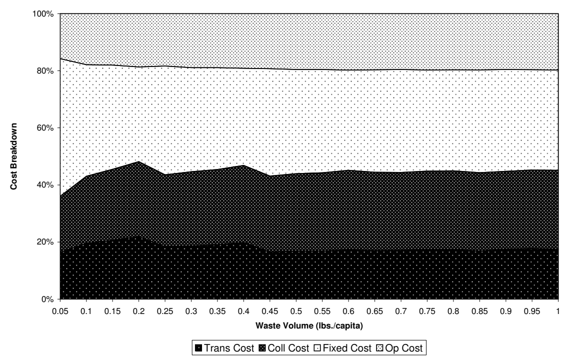
Scenario 1 -- Processor Centralization -- Collection Cost

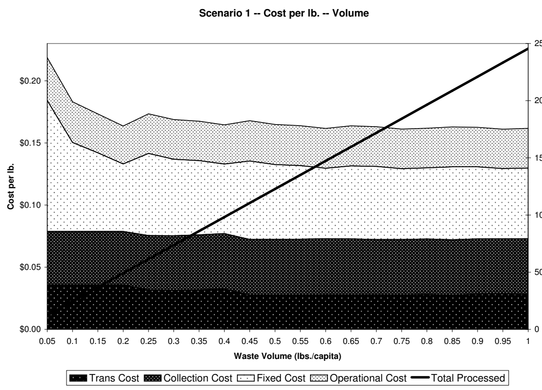


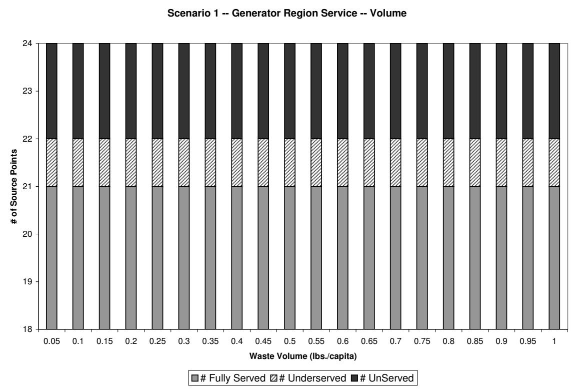
Scenario 1 -- Total Cost -- Volume

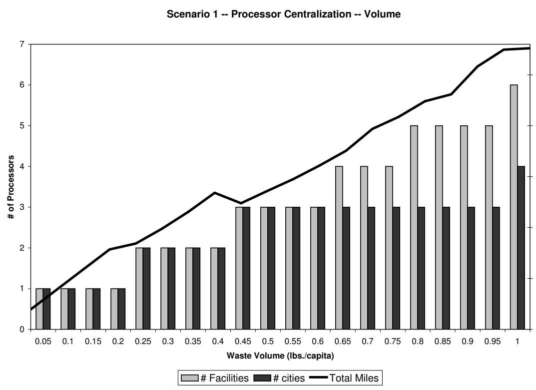


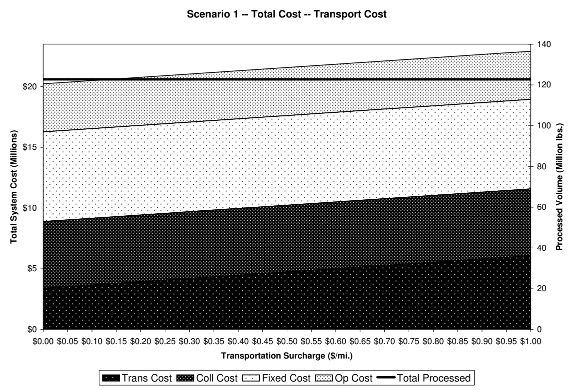
Scenario 1 -- Cost Breakdown -- Volume

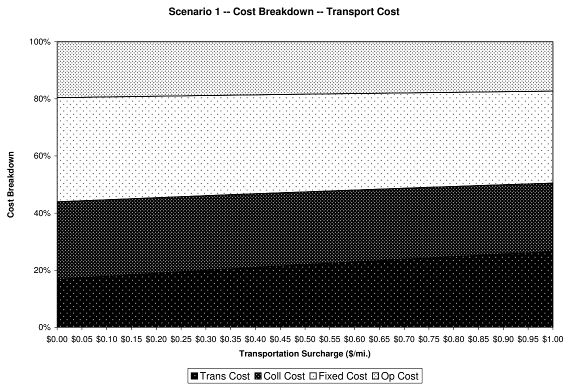


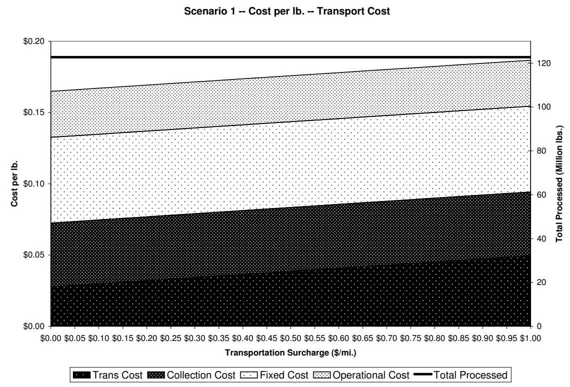

Scenario 1 -- Cost per lb. -- Volume
Cost per lb.
Total Processed (Million lbs.)
Waste Volume (lbs./capita)
Trans Cost
Collection Cost
Fixed Cost
Operational Cost
Total Processed

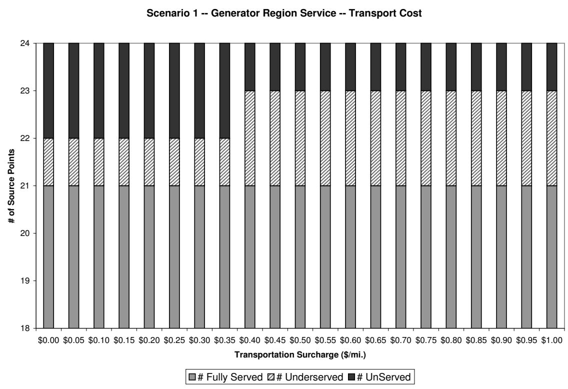

Scenario 1 -- Generator Region Service -- Volume
# of Source Points
Waste Volume (lbs./capita)
Fully Served
Underserved
UnServed

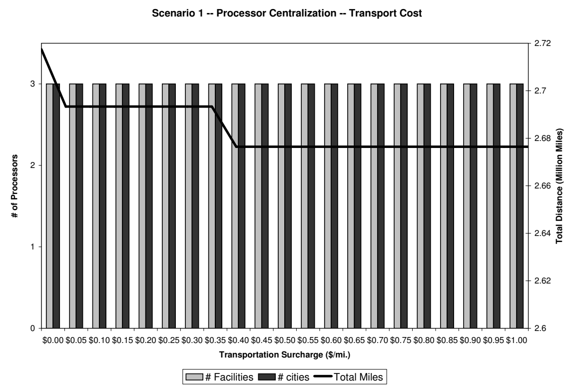

Scenario 1 -- Processor Centralization -- Volume
# of Processors
Total Distance (Million Miles)
Waste Volume (lbs./capita)
Facilities
cities
Total Miles

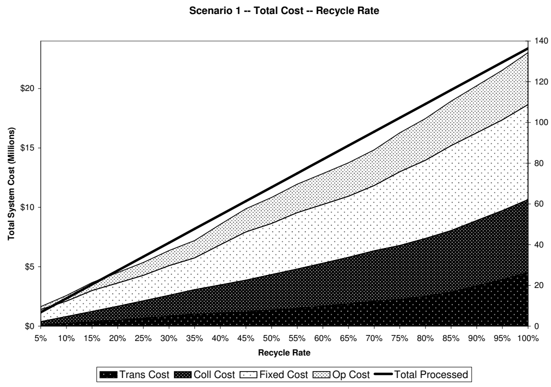

Scenario 1 -- Total Cost -- Transport Cost
Total System Cost (Millions)
Processed Volume (Million lbs.)
Transportation Surcharge ($/mi.)
Trans Cost
Coll Cost
Fixed Cost
Op Cost
Total Processed

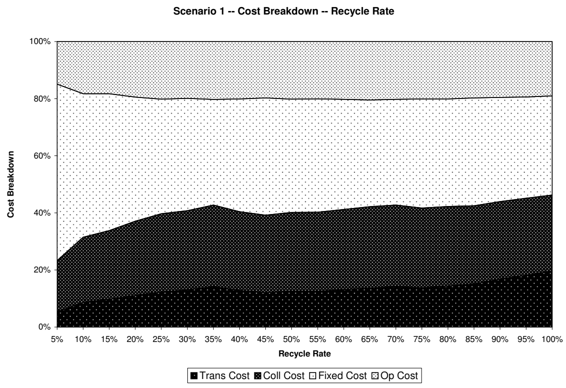

Scenario 1 -- Cost Breakdown -- Transport Cost
Cost Breakdown
Transportation Surcharge ($/mi.)
Trans Cost
Coll Cost
Fixed Cost
Op Cost

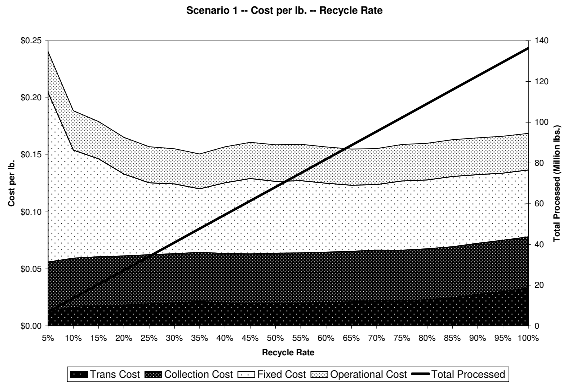

Scenario 1 -- Cost per lb. -- Transport Cost
Cost per lb.
Total Processed (Million lbs.)
Transportation Surcharge ($/mi.)
Trans Cost
Collection Cost
Fixed Cost
Operational Cost
Total Processed

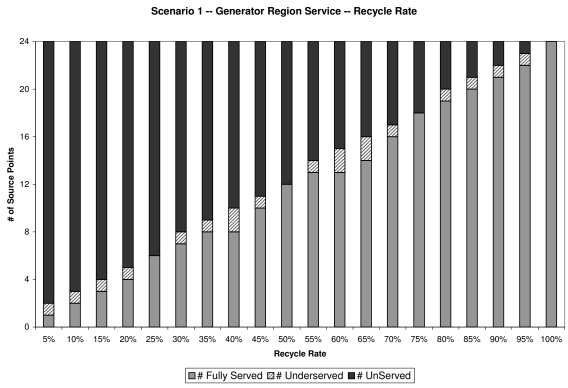

Scenario 1 -- Generator Region Service -- Transport Cost
# of Source Points
Transportation Surcharge ($/mi.)
Fully Served
Underserved
UnServed

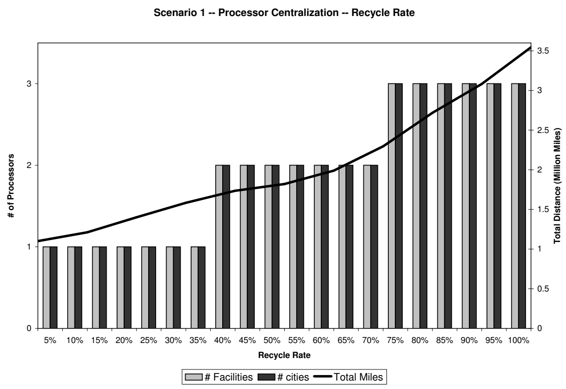

Scenario 1 -- Processor Centralization -- Transport Cost
# of Processors
Total Distance (Million Miles)
Transportation Surcharge ($/mi.)
Facilities
cities
Total Miles


Scenario 1 -- Total Cost -- Recycle Rate
Total System Cost (Millions)
Processed Value (Million lbs.)
Recycle Rate
Trans Cost
Coll Cost
Fixed Cost
Op Cost
Total Processed

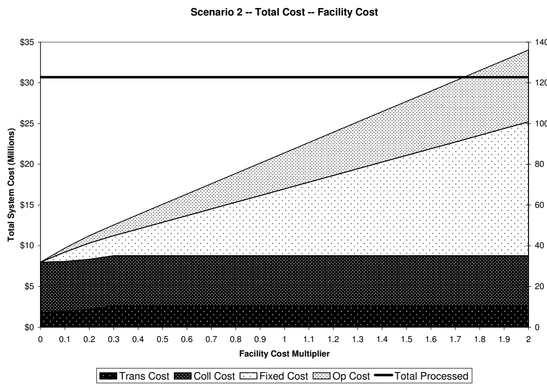

Scenario 1 -- Cost Breakdown -- Recycle Rate
Cost Breakdown
Recycle Rate
Trans Cost
Coll Cost
Fixed Cost
Op Cost

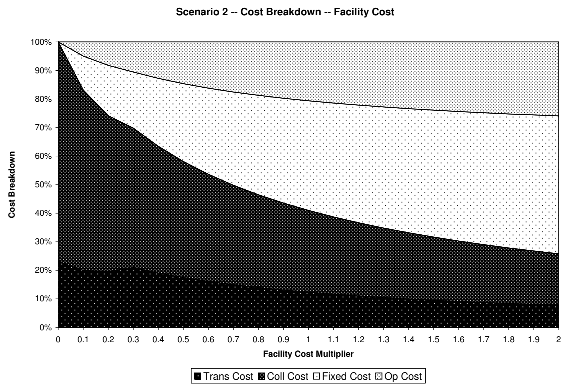

Scenario 1 -- Cost per lb. -- Recycle Rate
Cost per lb.
Total Processed (Million lbs.)
Recycle Rate
Trans Cost
Collection Cost
Fixed Cost
Operational Cost
Total Processed

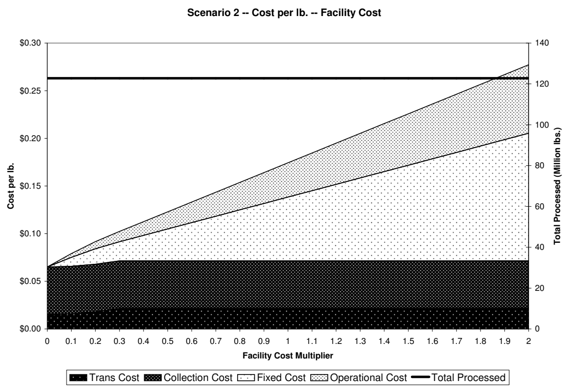

Scenario 1 -- Generator Region Service -- Recycle Rate
# of Source Points
Recycle Rate
Fully Served
Underserved
UnServed

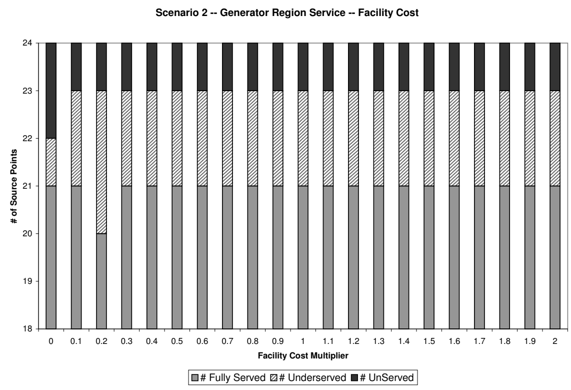

Scenario 1 -- Processor Centralization -- Recycle Rate
# of Processors
Total Distance (Million Miles)
Recycle Rate
Facilities
cities
Total Miles

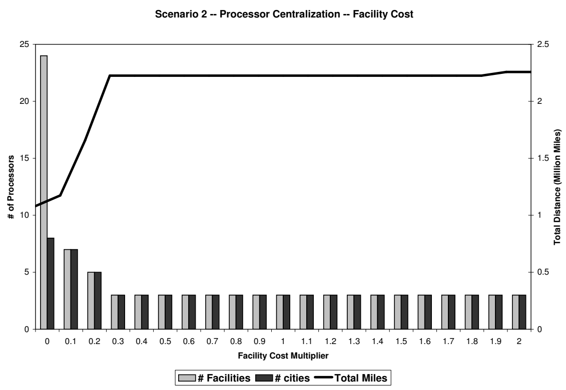
Scenario 2	
CODB	Constant
Collection	Constant

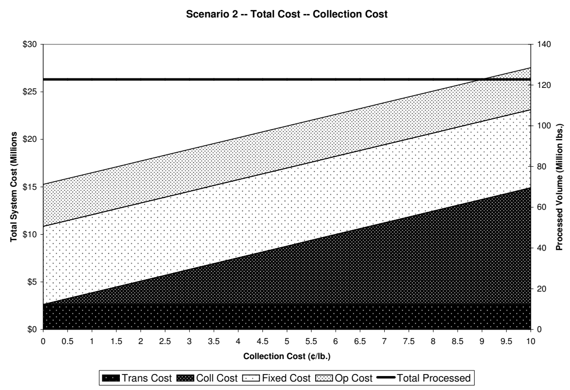


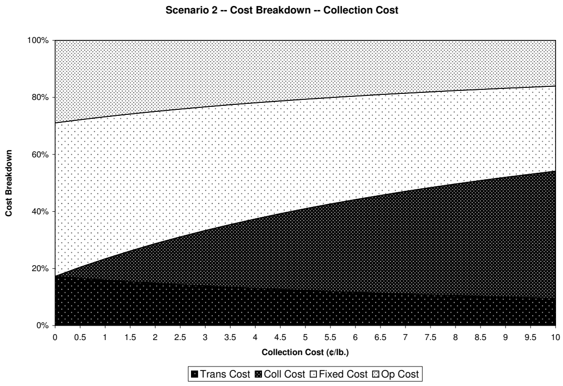


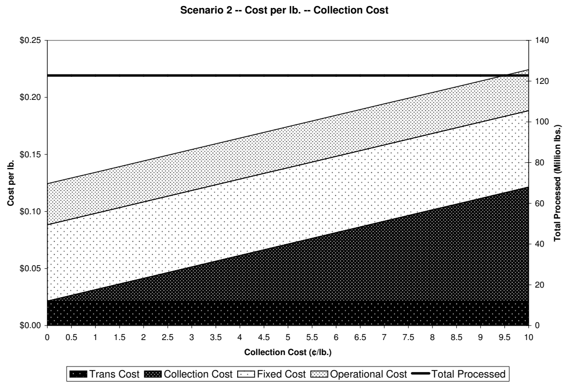


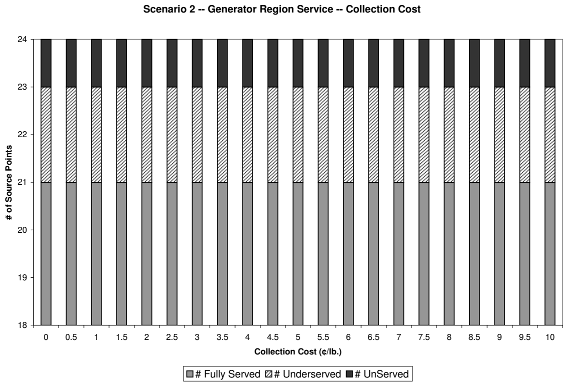


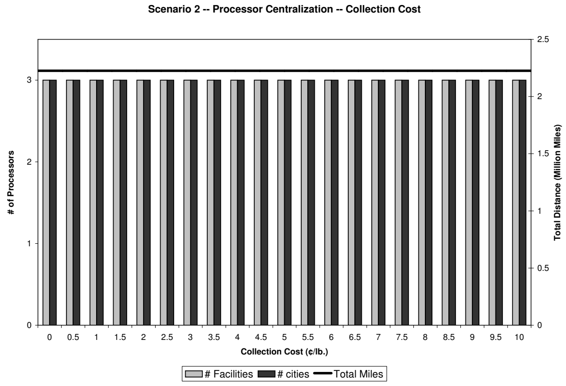


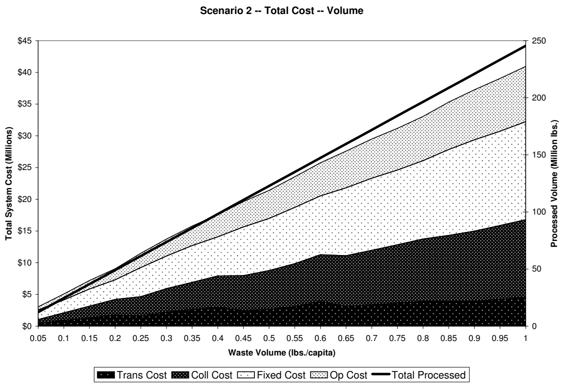


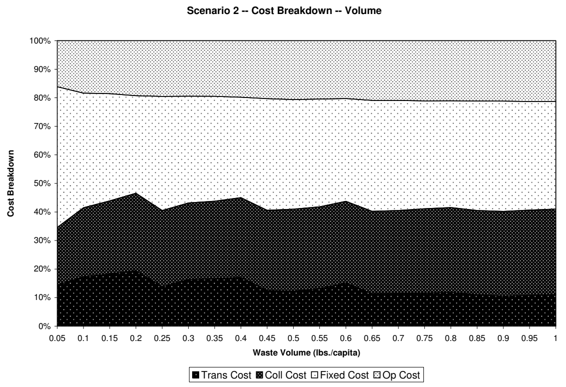

Scenario 2 -- Cost Breakdown -- Collection Cost
Cost Breakdown
Collection Cost (c/lb.)
Trans Cost
Coll Cost
Fixed Cost
Op Cost


Scenario 2 -- Cost per lb. -- Collection Cost
Cost per lb.
Total Processed (Million lbs.)
Collection Cost (c/lb.)
Trans Cost
Collection Cost
Fixed Cost
Operational Cost
Total Processed


Scenario 2 -- Generator Region Service -- Collection Cost
# of Source Points
Collection Cost (c/lb.)
Fully Served
Underserved
UnServed


Scenario 2 -- Processor Centralization -- Collection Cost
# of Processors
Total Distance (Million Miles)
Collection Cost (c/lb.)
Facilities
cities
Total Miles


Scenario 2 -- Total Cost -- Volume
Total System Cost (Millions)
Processed Volume (Million lbs.)
Waste Volume (lbs./capita)
Trans Cost
Coll Cost
Fixed Cost
Op Cost
Total Processed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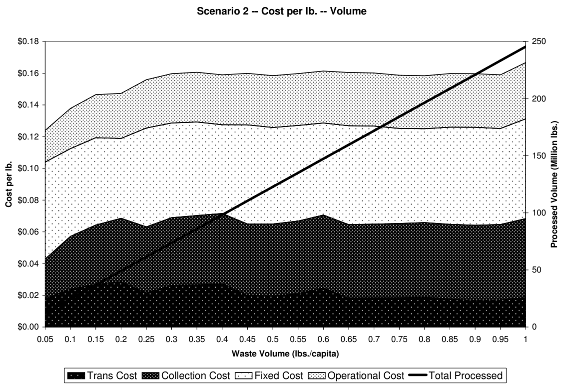
Cost Breakdown
Waste Volume (lbs./capita)
Trans Cost
Coll Cost
Fixed Cost
Op Cost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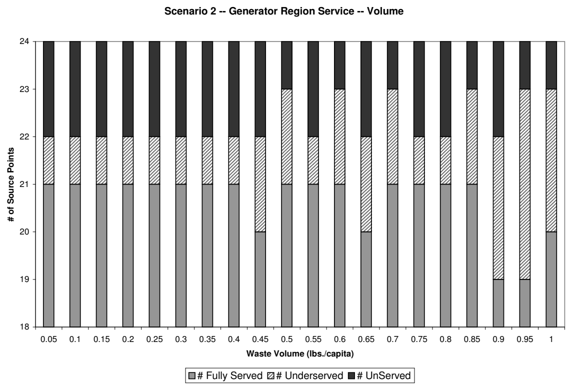
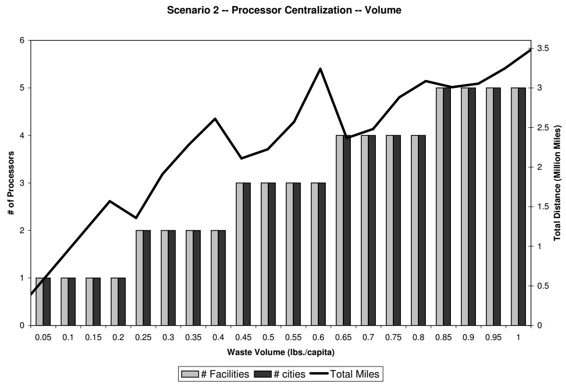
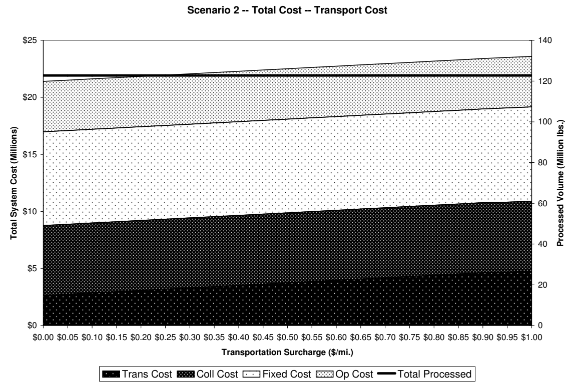
Cost per lb.
Processed Volume (Million lbs.)
Waste Volume (lbs./capita)
Trans Cost
Collection Cost
Fixed Cost
Operational Cost
Total Processed


Scenario 2 -- Generator Region Service -- Volume
# of Source Points
Waste Volume (lbs./capita)
Fully Served
Underserved
UnServed


Scenario 2 -- Processor Centralization -- Volume
# of Processors
Total Distance (Million Miles)
Waste Volume (lbs./capita)
Facilities
cities
Total Miles


Scenario 2 -- Total Cost -- Transport Cost
Total System Cost (Millions)
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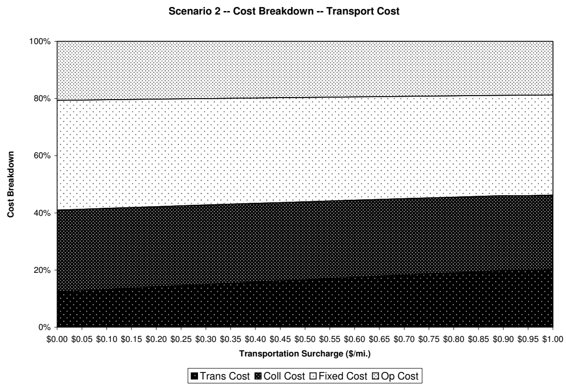
Transportation Surcharge ($/mi.)
Trans Cost
Coll Cost
Fixed Cost
Op Cost
Total Processed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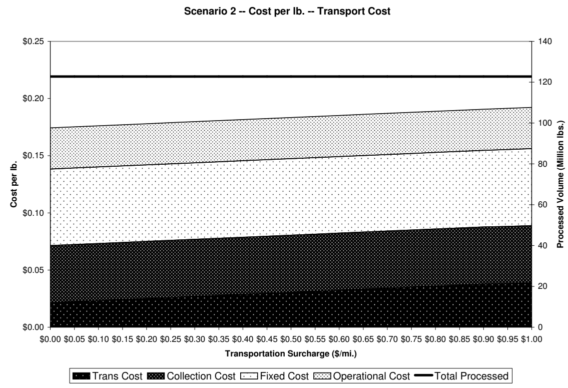
Cost Breakdown
Transportation Surcharge ($/mi.)
Trans Cost
Coll Cost
Fixed Cost
Op Cost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Cost per lb.
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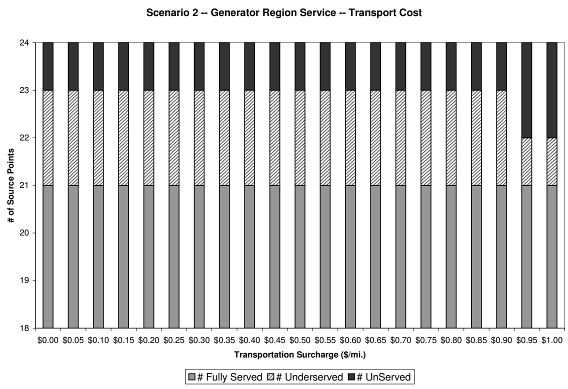
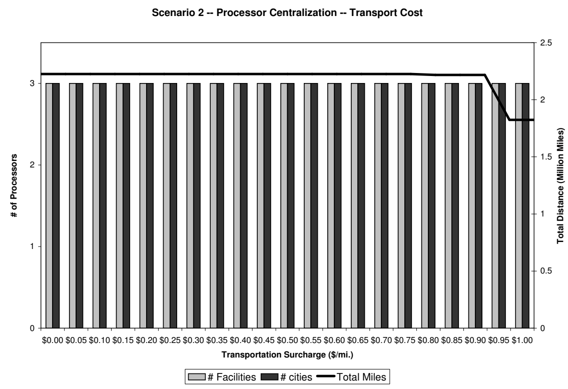
Trans Cost
Collection Cost
Fixed Cost
Operational Cost
Total Processed


Scenario 2 -- Generator Region Service -- Transport Cost
# of Source Points
Transportation Surcharge ($/mi.)
Fully Served
Underserved
UnServed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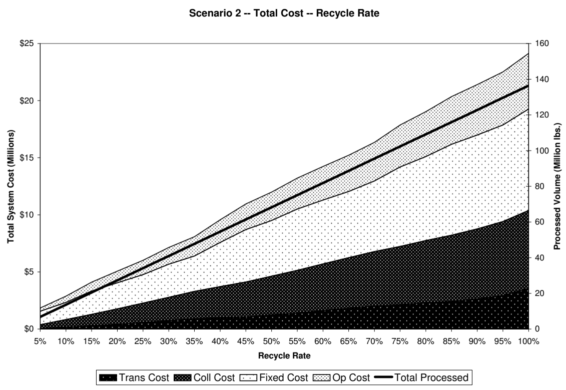
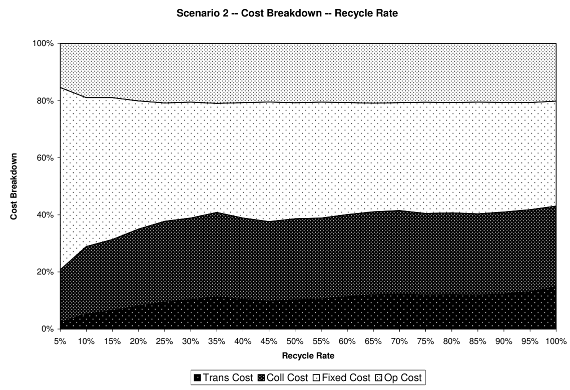
# of Processors
Total Distance (Million Miles)
Transportation Surcharge ($/mi.)
Facilities
cities
Total Miles


Scenario 2 -- Total Cost -- Recycle Rate
Total System Cost (Millions)
Processed Volume (Million lbs.)
Recycle Rate
Trans Cost
Coll Cost
Fixed Cost
Op Cost
Total Processed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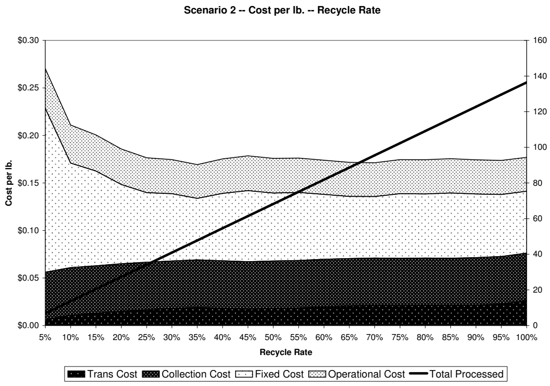
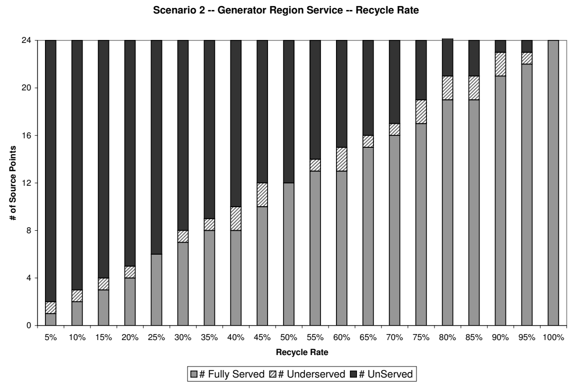
Cost Breakdown
Recycle Rate
Trans Cost
Coll Cost
Fixed Cost
Op Cost


Scenario 2 -- Cost per lb. -- Recycle Rate
Cost per lb.
Processed Volume (Million lbs.)
Recycle Rate
Trans Cost
Collection Cost
Fixed Cost
Operational Cost
Total Processed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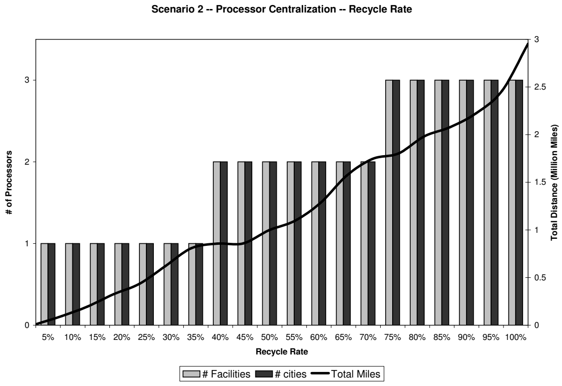
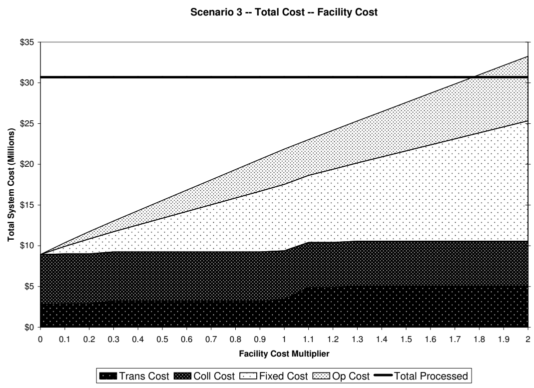
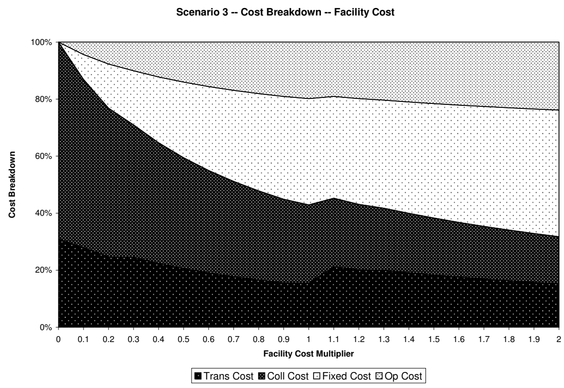
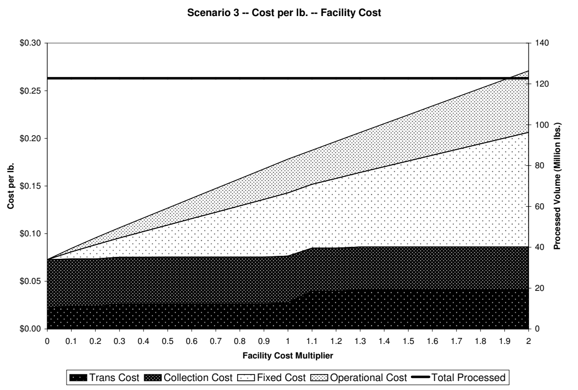
# of Source Points
Recycle Rate
Fully Served
Underserved
UnServed

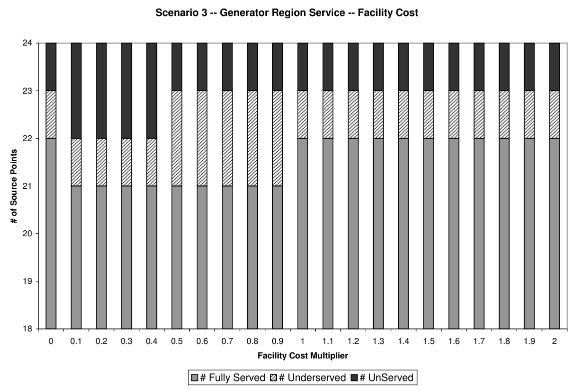

Scenario 2 -- Processor Centralization -- Recycle Rate
# of Processors
Total Distance (Million Miles)
Recycle Rate
Facilities
cities
Total Miles

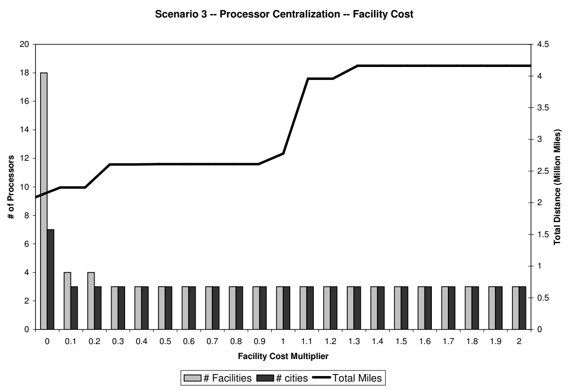
Scenario 3	
CODB	Varied
Collection	Varied

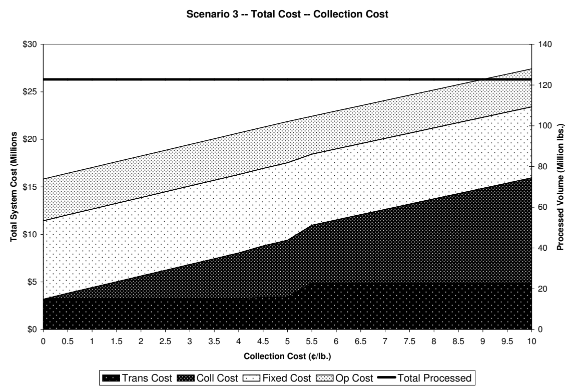


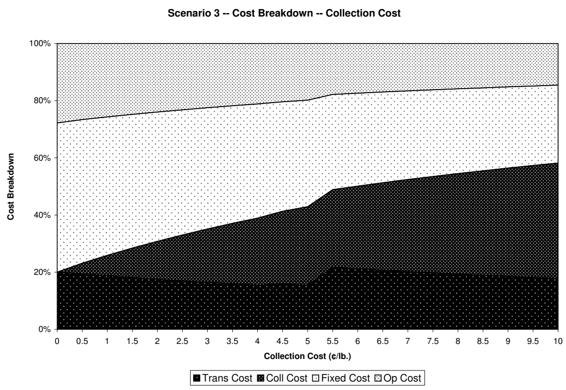








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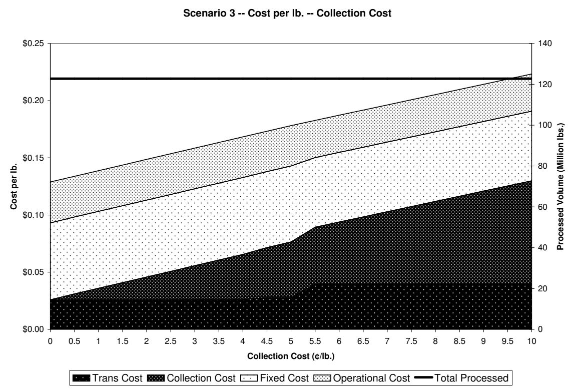
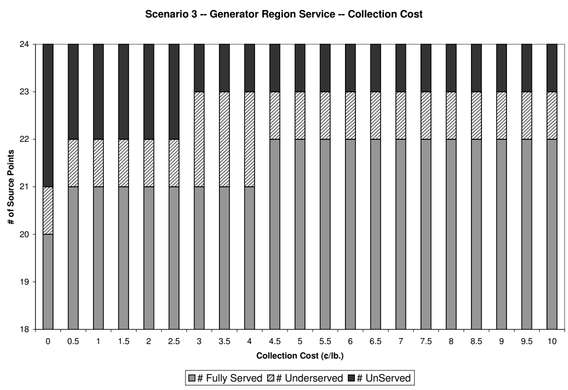
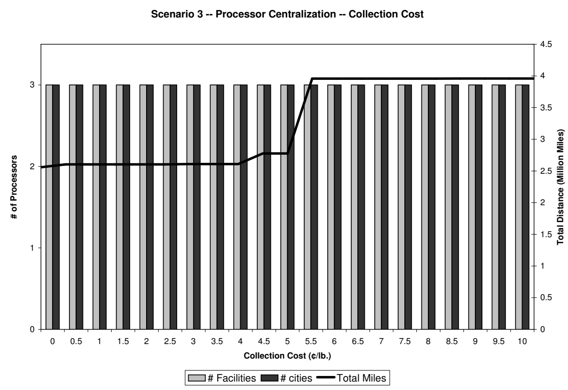
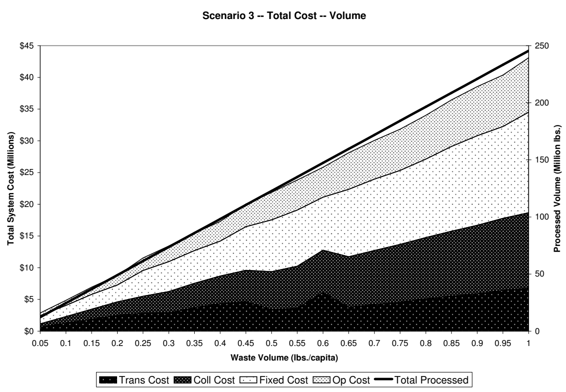
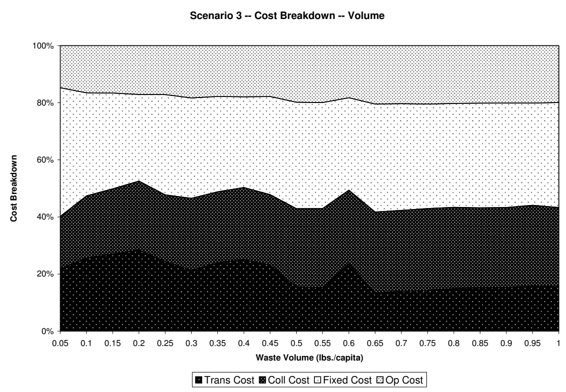
Cost Breakdown
Collection Cost (c/lb.)
Trans Cost
Coll Cost
Fixed Cost
Op Cost

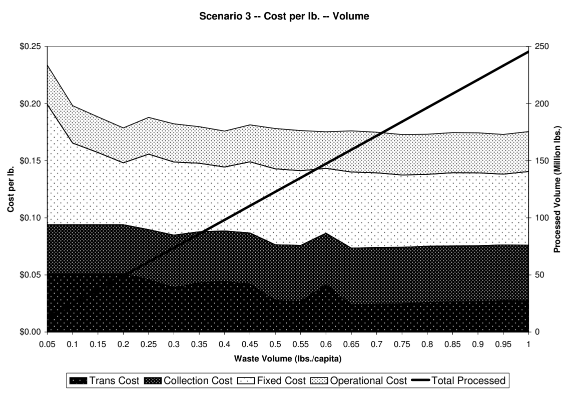

Scenario 3 -- Cost per lb. -- Collection Cost
Cost per lb.
Processed Volume (Million lbs.)
Collection Cost (c/lb.)
Trans Cost
Collection Cost
Fixed Cost
Operational Cost
Total Processed

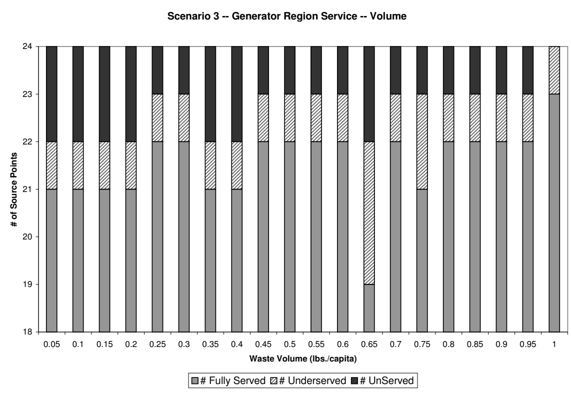

Scenario 3 -- Generator Region Service -- Collection Cost
# of Source Points
Collection Cost (c/lb.)
Fully Served
Underserved
UnServed


Scenario 3 -- Processor Centralization -- Collection Cost
# of Processors
Total Distance (Million Miles)
Collection Cost (c/lb.)
Facilities
cities
Total Miles


Scenario 3 -- Total Cost -- Volume
Total System Cost (Millions)
Processed Volume (Million lbs.)
Waste Volume (lbs./capita)
Trans Cost
Coll Cost
Fixed Cost
Op Cost
Total Processed


Scenario 3 -- Cost Breakdown -- Volume
Cost Breakdown
Waste Volume (lbs./capita)
Trans Cost
Coll Cost
Fixed Cost
Op Cost


Scenario 3 -- Cost per lb. -- Volume
Cost per lb.
Processed Volume (Million lbs.)
Waste Volume (lbs./capita)
Trans Cost
Collection Cost
Fixed Cost
Operational Cost
Total Processed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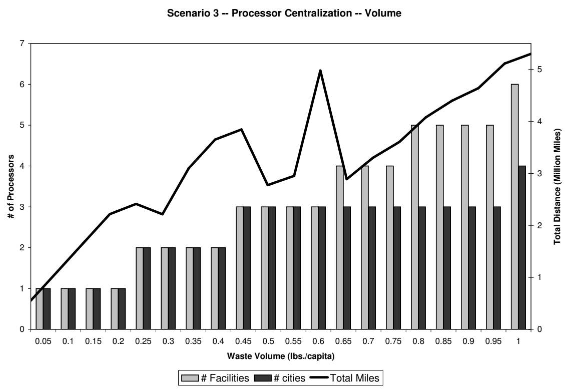
# of Source Points
Waste Volume (lbs./capita)
Fully Served
Underserved
UnServed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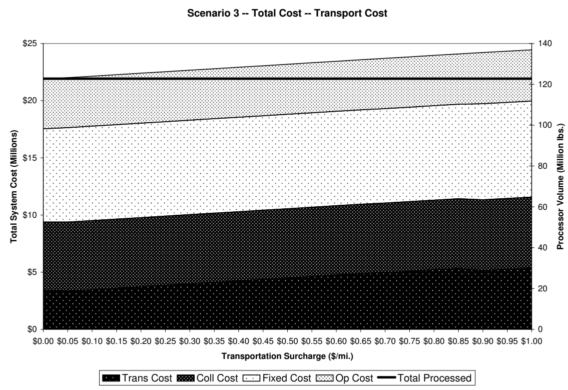
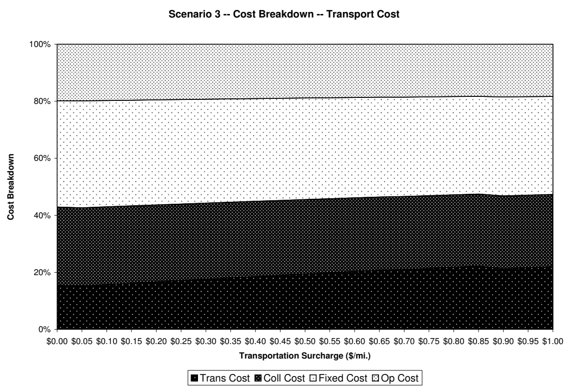
# of Processors
Total Distance (Million Miles)
Waste Volume (lbs./capita)
Facilities
cities
Total Miles


Scenario 3 -- Total Cost -- Transport Cost
Total System Cost (Millions)
Processor Volume (Million lbs.)
Transportation Surcharge ($/mi.)
Trans Cost
Coll Cost
Fixed Cost
Op Cost
Total Processed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Cost Breakdown
Transportation Surcharge ($/mi.)
Trans Cost
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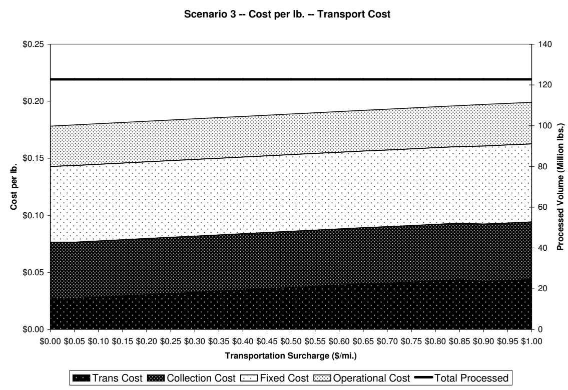
Fixed Cost
Op Cost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Cost per lb.
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Transportation Surcharge ($/mi.)
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Collection Cost
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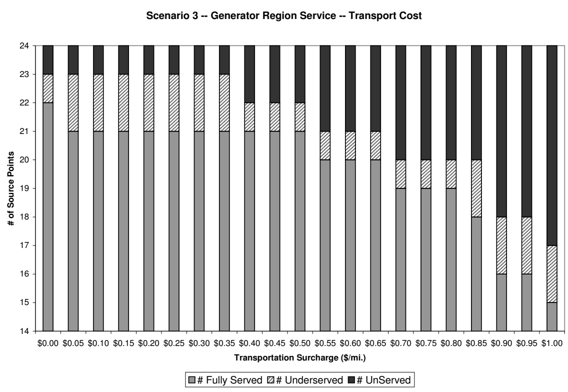
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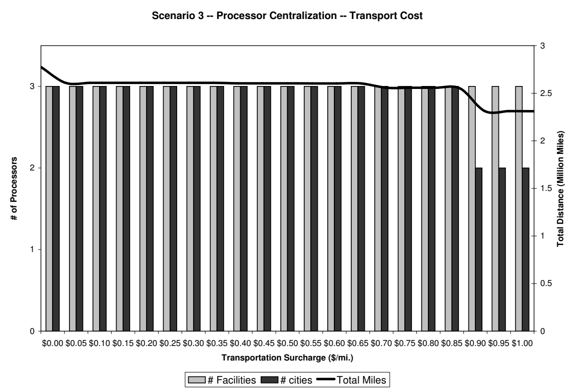
# of Source Points
Transportation Surcharge ($/mi.)
Fully Served
Underserved
UnServed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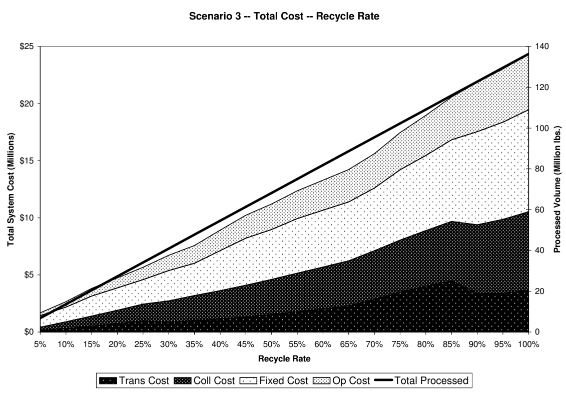
# of Processors
Total Distance (Million Miles)
Transportation Surcharge ($/mi.)
Facilities
cities
Total Miles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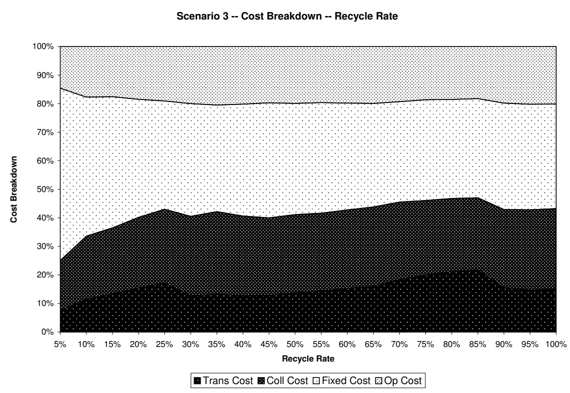
Total System Cost (Millions)
Processed Volume (Million lbs.)
Recycle Rate
Trans Cost
Coll Cost
Fixed Cost
Op Cost
Total Processed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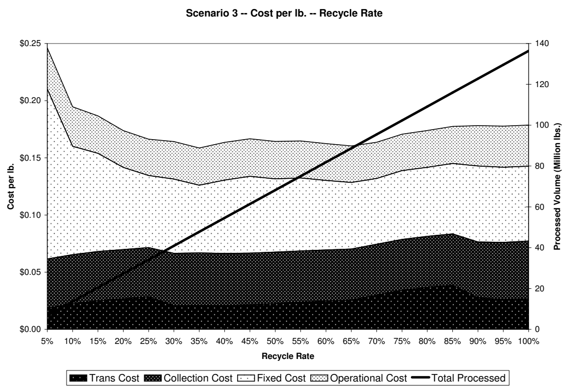
Cost Breakdown
Recycle Rate
Trans Cost
Coll Cost
Fixed Cost
Op Cost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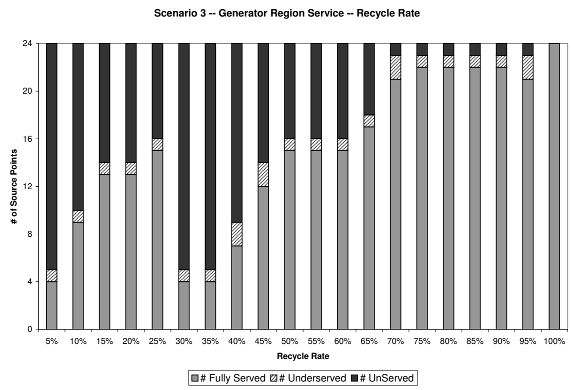
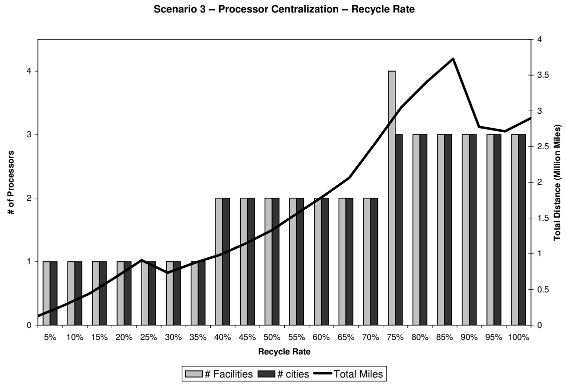

Scenario 3 -- Generator Region Service -- Recycle Rate
# of Source Points
Recycle Rate
Fully Served
Underserved
UnServed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Total Distance (Million Miles)
Recycle Rate
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