Modeling the Economic and Environmental Performance of Recycling Systems

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***Abstract*—A general model for evaluating the economic and environmental performance of electronics recycling systems is developed. This model comprehends the three main functions in a recycling system – collection, processing, and system management – and aims to enable quantification of the impact of context and system architecture on the performance of electronics recycling systems. Different modeling techniques are used, including process-based cost models, to evaluate economic performance, and life cycle assessment tools, to evaluate environmental performance. A case study, based loosely on Maine, is presented to show the utility of such a model in evaluating electronics recycling systems.**

***Index Terms*—electronics recycling systems, electronic waste, process-based cost models, environmental performance**

I. Introduction

As recycling systems for complex goods, and in particular for waste electronics, become more widespread, understanding the economic and environmental performance of such systems becomes critical, both to enable improvement of existing systems and to design and implement new systems. Unfortunately, the variety of system architectural and contextual possibilities makes empirical inference of causality challenging. To address this issue, this paper presents a modeling framework to project the economic and environmental performance of both existing and prospective recycling systems.

The model developed here comprehends the three main functions – collection, processing, and system management – which are common to most recycling systems. Each of these functions is analyzed using different techniques, including logistics models to evaluate collection, end-of-life treatment models to evaluate processing, and process-based cost models to evaluate collection and processing economics. These methods can be used to evaluate the economic performance of a recycling system, whereas other methods, such as life cycle assessment, can be used to evaluate the environmental performance of a recycling system. The models developed here are intentionally meant to be both broad, in order to address entire recycling systems, and general, such that many different systems, both real and hypothetical, can be analyzed.

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II. Background

Some of the critical functions of recycling systems, in particular collection and processing, have been modeled previously on an individual basis. Much attention has been paid to the issue of product collection, sometimes referred to as a reverse logistics or reverse supply chain problem. Reverse logistics models have been developed to analyze how used products can be efficiently collected, thus allowing for future reuse, remanufacturing, or recycling [1-3]. With respect to end-of-life product processing, modeling efforts have focused on a variety of different approaches, from manual disassembly to mechanical separation, examining which processing approaches and related operating parameters should be used [4-6].

Some works have investigated the costs of electronics recycling more comprehensively, focusing on entire facilities or systems operating in a particular geographical or operational context. For example, work by Kang and Schoenung uses a technical cost model to examine the costs and revenues associated with the operation of a materials recovery facility in California [7]. Using scenario-based cost models, Caudill et al. examine an electronics recycling system in the Seattle-Tacoma urban area in Washington State, specifically analyzing the effectiveness of various collection approaches, for example collection at a central drop-off facility versus collection at 20 “big box” stores [8]. In work by Bohr, electronics recycling systems focused on the recovery of waste from electrical and electronic equipment (WEEE) in Europe is modeled, with economic models approximating a central European system [9].

While these previous works provide a solid foundation, the economic and environmental models presented here aim to enable quantification of the impact of context and system architecture on the performance of electronics recycling systems. The flexibility of inputs that the model allows, enables the analysis of a variety of different systems, from the different state systems in the United States to the different country systems in the European Union. In addition, and perhaps more importantly, this flexibility allows for theoretical systems to be modeled and evaluated in a given context. As more states and countries design and implement electronics recycling systems, this ability to evaluate theoretical systems, and the effects of system input choices on these systems, will help to provide insights into critical system design decisions.

The models developed here will take a broad system view, both in terms of the system functions considered, and in terms of the stakeholders considered. Explicitly accounting for the economic and environmental impacts of different stakeholders – from the consumers who generate end-of-life electronics to the consolidators who collect electronic waste to the system managers who oversee the system – provides a level of disaggregation that allows systems to be evaluated with regards to both their overall impacts as well as their impacts on particular stakeholders. A similar disaggregation of functions and stakeholders has been developed in previous work by Gregory and Kirchain [10].

III. Model Development

The system model developed here focuses on three main functions in an electronics recycling system, namely collection, processing, and system management. Fig. 1 shows a basic schematic of the model, with inputs on the left and outputs on the right. For each model, a broad range of inputs are required to comprehend a fully generic case; when modeling more specific scenarios, including existing systems, a smaller set of model inputs may be used, as actual data can replace some modeled values. It is this set of inputs that characterizes the system. The overall approach and implementation of the collection, processing, and system management functions, for the most generic case, are described below.

A. Collection

The collection associated with end-of-life products involves various stakeholders, distances, vehicles, and facilities. The typical first stage in collection involves the transportation of end-of-life products from their point of final use – typically a home or business – to a local collection facility. From there, a product typically travels to a consolidation center, and later to a central processing facility. The modeling of the three major aspects of this collection process, namely transportation, mass collection, and facility operation, are comprehended within the model and detailed next.

1) Transportation

In many cases, the first collection step involves an individual consumer driving a product or products to a collection center. In order to model this first step, population distribution models, which create a series of customer locations given an initial location and probability distribution, are used [11]. Typically, such a population distribution model

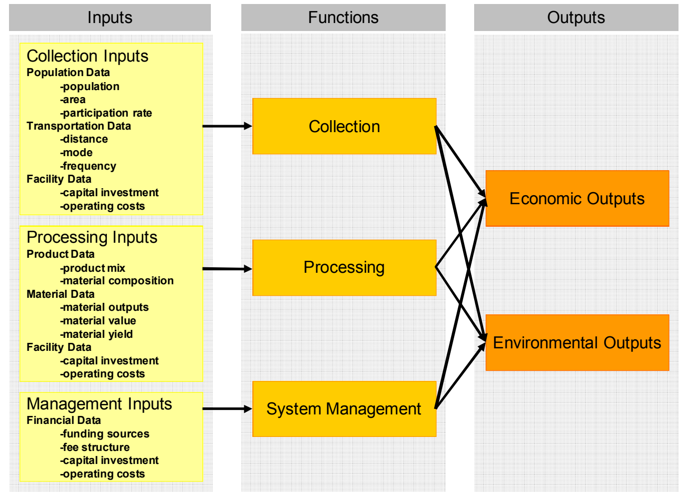

Fig. 1. A rough schematic of the model, including some of the basic inputs, shown on the left, and the primary outputs, namely economic and environmental impact, on the right.

is used to represent a city or town, although other, less-clustered populations, can also be represented. By combining a few different population distributions, population data for a larger area, with multiple population centers, can be created. With a population in place, facility location models are used to determine the optimal siting for collection facilities and processing facilities. Alternatively, locations can be determined based on other criteria, including proximity to other end-of-life product collection sites, or other local concerns.

With locations for the population, and locations for collection sites, distances between the two must be calculated. In the generalized case, straight-line distances between the population location and collection location are calculated, then multiplied by a road factor to account for the additional distance added due to infrastructure constraints.

Once products are collected at a collection facility, they must then travel to a processing facility, either directly or via a consolidation facility. These legs of the collection function are typically completed using a truck, as opposed to the first leg of the journey, which in the case of home electronics, typically involves the use of private automobiles. Processing facilities are sited in much the same way as collection facilities were sited earlier, drawing on an existing body of literature around facility siting. With a known processing facility location, and known collection facility locations, straight-line distances are calculated, and again multiplied by a road factor to yield actual distances travelled. Combining the distance from the collection facility to the processing facility with the distances from the point of final product use to the collection point, yields the total distance travelled. It is important to point out that these different legs are completed using different vehicles and different loading factors, meaning that they have different economic and environmental impacts. Furthermore, the costs of these legs are borne by different stakeholders in the system.

2) *Mass Collection*

In addition to distance calculations, the amount of mass collected and the mix of products collected, must also be characterized. In the population distributions generated above, not all members of the population will have electronic waste to recycle and, of those who do, not all will choose to dispose of their waste within the system of interest. Modeling the percentage among the population that will travel to a collection center involves the consideration of many factors, including the saturation of electronic products, the availability of other end-of-life disposal options, customer awareness of collection centers, and the distance to a collection center, among other factors. While estimating such values can be difficult, there is empirical data about such participation rates in the literature, both for end-of-life recycling facilities as well as for other related collection facilities [12, 13].

One critical factor in participation rate, the distance a consumer must travel to reach a collection facility, is incorporated into the models developed here by including an effect known as distance decay. In this context, distance decay refers to the often pronounced decrease in participation rate as a customer's distance to a collection center increases. This behavior is exhibited in a number of related scenarios, from travel to shopping centers to the utilization of park-and-ride facilities [14, 15]. Distance decay can take various functional forms, but is often modeled as either a power function or an exponential function [16, 17]. In either case, the decay from high participation rates close to the collection facility, to lower participation rates farther away from the facility, can have a profound impact on collection amounts, and thus on the economic and environmental performance of a recycling system.

With population and participation rates, the last piece of information necessary to characterize mass collection is the amount and type of electronic waste deposited at the collection site per trip. These values, much like the participation percentage described above, can depend on a host of different factors, including the saturation of electronic products, the socio-economic status of the area, and the types of electronics products included in the collection system, among other factors. While the effects of these factors can be hard to determine individually, empirical evidence from existing systems again provide reasonable estimates of collection amounts per visit.

3) *Facilities*

In modeling collection, the cost of collection facilities must also be included. These facility costs include capital costs, such as buildings, equipment, and other infrastructure, as well as operating costs, such as labor, electricity, and packaging material; all of these costs can vary with context. Another critical factor is whether or not the facility is dedicated for electronics recycling. When collection facilities are used exclusively for electronics recycling, costs for a facility can be substantial. However, when facilities are non-dedicated, meaning that they are also used for other functions, allocated facility costs for electronics recycling are reduced.

B. *Processing*

During processing, electronic waste that has been collected and consolidated is broken down into resalable components and material streams. Models of processing facilities thus focus primarily on the operations within the facility itself, as well as on material flows into and out of the facility. Processing facility cost categories are similar to those described above for collection facilities, namely capital costs, covering buildings, equipment, and other infrastructure, and operating costs, covering labor, electricity, and other costs. The magnitude and distribution of these costs is again highly dependent on geographic context, as building costs, labor rates, and other financial data can vary greatly depending on location. The distribution of costs between equipment and labor can also vary significantly from one processing facility to another, depending on the means of material separation and sorting. For more-automated facilities, capital costs for equipment can represent a significant cost; for less-automated facilities, which rely more on manual labor, labor costs can be significant. The ability of the processing cost model to comprehend various processing scenarios, allows for different operational approaches to be tested, and decisions regarding such approaches to be made.

Processing facilities can also realize revenue streams from the sale of reusable components and recyclable materials. The mix of components and materials recovered, and in turn the value recovered from end-of-life electronic waste, depends heavily on both the mix of products received at the processing facility, as well as the means of sorting and separating these products. The mix of products received comes from the mass collection part of the collection model, as described earlier. The operational information, regarding sorting and separating, is determined in the processing model, and is based on a variety of factors, including product volumes, product mix, labor rates, capital costs, and others.

C. *System Management*

The system management component of the model accounts for the management and oversight of the entire system. These costs are largely administrative, and are heavily dependent on the fee structures and oversight mechanisms that are put in place; as fee structures become more complex, and as oversight increases, system management costs increase. In general, these costs can be modeled using simple cost models, in which labor and related expenses are often the dominant costs.

IV. Case Study

To explore the usefulness and sensitivities of the model outlined above, a case study of an electronics recycling system was executed. The contextual and architectural data used as a baseline for this case, are based loosely on both the demography of Maine and on the system currently operating there. Collection models, processing models, and system management models are all used to arrive at economic and environmental measures of system performance. In this example, the primary focus will be on analyzing the effect of one aspect of system architecture – the number of collection sites – on the economic and environmental performance of the system.

The electronics recycling system analyzed here focuses primarily on the collection of end-of-life monitors and televisions from residential consumers. The total population covered by this system is approximately 1.3 million people, distributed over an area of roughly 80,000 square kilometers (~31,000 square miles). For this study, the overall population was distributed in actual cities and towns in Maine, according to recent census data for the state [18]. The location of collection facilities, consolidation facilities, and processing facilities was also based on actual data from the Maine Department of Environmental Protection, Bureau of Remediation and Waste Management, and from electronic waste consolidators operating in the state [19]. Actual road distances between different locations, including the distance from towns to collection centers, and from collection centers to processing facilities, were calculated using commercially available mapping software.

In modeling the effect of the number of collection sites on system behavior, it was necessary to increase and decrease the number of collection sites from the current number of approximately 130 sites. To reduce the number of collection sites, sites with the lowest mass collection totals were removed. To increase the number of collection sites, collection facilities that currently exist, but that do not currently take electronic waste, were included.

Participation rates for this system were modeled using an exponential distance decay function, as the exponential form is generally more appropriate for modeling distance decay over distances on the scale of those considered here [17]. The parameters of this function were set using total collection amounts in Maine, as well as data from drop-off collection activities in other jurisdictions [12, 20]. Average collection amount per trip was set at 25 lbs – representing the approximate weight of a monitor – and was established to calibrate total collection amounts to those found within the current system.

The inclusion of distance decay in the formulation of participation rate has a profound effect on the amount of mass collected versus the number of collection sites available. Fig. 2 plots the total amount of mass collected versus the number of collection sites. The steady increase in total mass collection is perhaps obvious; with more collection sites, consumers are more likely to live closer to a collection facility, thus increasing their participation rate.

In addition to modeling participation rates and transportation distances, cost models for other collection activites, as well as for the processing and system management functions, were developed. Collection facilities were modeled using process-based cost models, and were

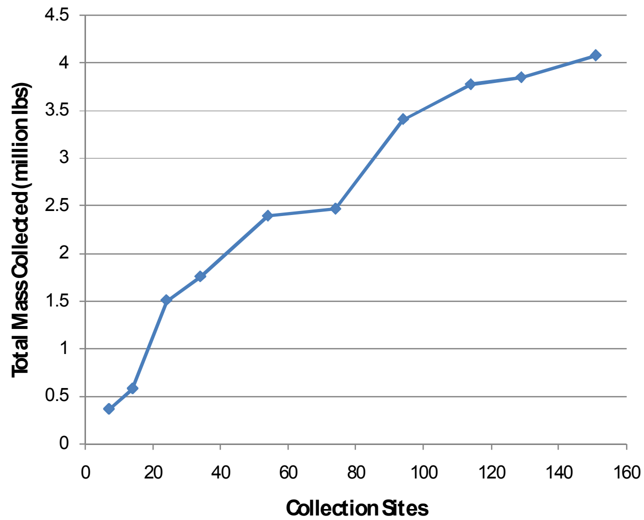

Fig. 2. Total mass collected as a function of the number of collection sites.

assumed to be non-dedicated, meaning that the costs associated with these facilities scaled quite closely with the amount of mass handled by each facility.

Processing facilities, based around primarily manual sorting and separation, were also modeled using process-based cost models; the inputs to these models reflected the operational context being examined. Included in the processing facility model was a materials flow model, which tracked the inflow of materials in the form of products, and the outflow of separated materials in the form of reuseable components or recyclable materials. These outgoing material streams were priced using market data for recycled materials, and represented a revenue stream for the processor [21]. The cost figures for processing shown here represent a net cost; revenue from outgoing material streams was deducted from the total processing cost. Like the models of the collection facility, the processing facility was also considered to be non-dedicated.

System management costs were represented by a fixed cost, and did not scale with the amount of mass collected or with the number of collection sites available in this analysis. The total cost for system management came from previous literature on Maine recycling system costs [10].

With each of the three functions – collection, processing, and system management – modeled, overall costs were examined. Fig. 3 shows the total recycling system cost per pound collected versus the number of collection sites. Costs to consumers, consolidators, processors, and system managers are all included in these total costs. Overall, the total cost per pound collected is relatively stable through a broad number of collection sites. From approximately 20 collection sites through approximately 120 collection sites, total system costs vary by less than 5%. While this variation equates to a cost difference of only about \$0.02/lb, when multiplied over millions of pounds of electronic waste, this difference can represent tens of thousands of dollars. The lowest total

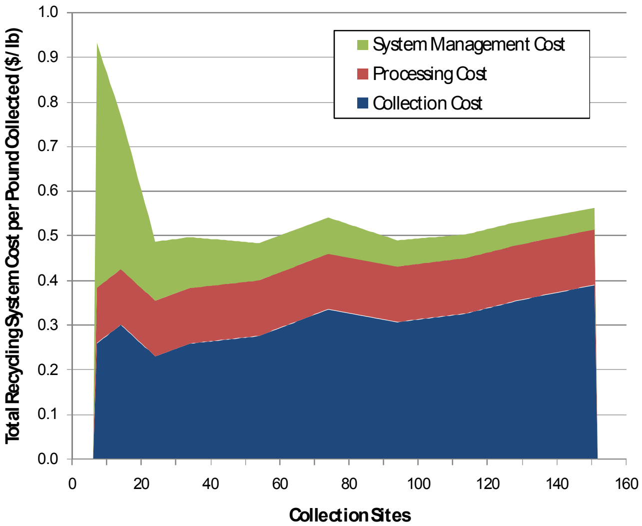

Fig. 3. Total recycling system cost per pound collected ($/lb) as a function of the number of collection sites.

system costs occur at around 25 to 55 collection sites in total. At lower numbers of collection sites, system management costs begin to dominate; at higher numbers of collection sites, collection costs begin to dominate.

Using the models developed here, specific aspects of the recycling system can also be examined. For example, transportation can be examined both in terms of the distance travelled by individual consumers, as well as the distance travelled by consolidators. Fig. 4 shows the total distance travelled and the distance travelled per pound collected across different numbers of collection sites. The total distance travelled increases as the number of collection sites increase, reflecting the increase in participation rate. Clearly, in terms of total distance travelled, the burden of transportation weighs more heavily on consumers, assuming that their trips are completely allocated to the task of electronics recycling. This contribution by consumers is an often-overlooked aspect of recycling systems, and one that is made apparent in this model through the identification and disaggregation of different stakeholders. Although the contribution, in terms of distance travelled, is relatively small for consolidators, their equipment, namely their trucks, are more heavily burdened with regards to environmental impact and cost.

In terms of total distance travelled per pound of electronic waste collected, more collection sites corresponds to lower distances travelled per pound, as depicted in Fig. 4. There is a plateau in the distances travelled per pound collected at higher numbers of collection sites, as increases in total distance travelled are offset by increases in mass collected.

Using outputs from the logistics model in life cycle assessment tools allows the environmental impact of transportation to be examined. Fig. 5 shows total transportation energy and transportation energy per pound collected across different numbers of collection sites. Total transportation energy increases as the number of collection sites increases; given the transportation data shown in Fig. 4, this result is not unexpected. However, the transportation energy per pound collected appears to reach a minimum at around 115 collection sites. At higher numbers of collection sites, the increase in distance travelled, and in particular, the increase in truck distance travelled, with its larger energy impact than automobiles, leads to larger per pound energy inputs.

The results shown here for Maine demonstrate just some of the capabilities of this model. Given the complex implications of changing the number of collection sites, and the many ways in which this can in turn affect the overall system, the economic and environmental ramifications of such a change can be difficult, if not impossible, to decipher through

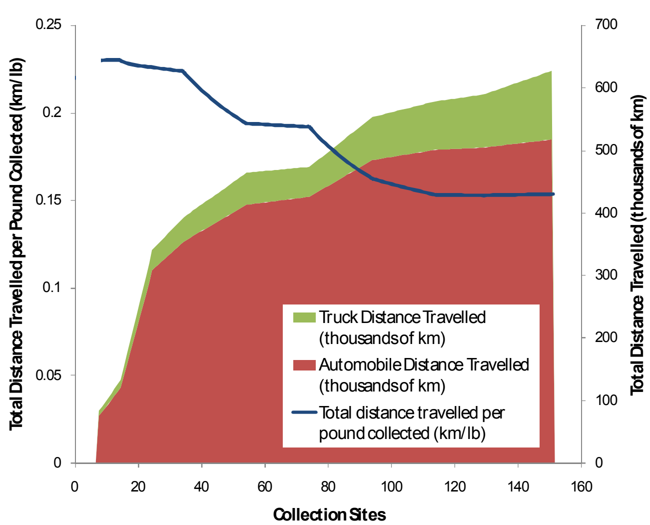

Fig. 4. Total distance travelled and the distance travelled per pound collected as a function of the number of collection sites.

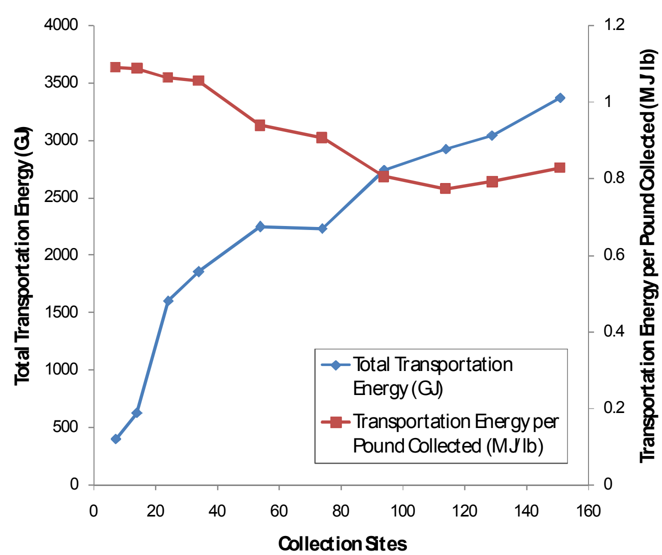

Fig. 5. Total transportation energy and transportation energy per pound of electronic waste collected as a function of the number of collection sites.

intuition. However, the ability to explore changes in system parameters through the use of a model, allows interesting and sometimes non-intuitive results, such as the relative stability of the total per pound recycling system cost over a broad number of collection sites, to come to light.

V. Conclusion

The model presented here provides a tool for analyzing the performance, both economic and environmental, of a range of architectural and contextual options for electronics recycling systems. By incorporating an ability to analyze either parametric or actual demographics, the model is broadly applicable to both hypothetical systems and specific systems operating in real contexts, such as the case study presented here for Maine. Given the complexity and interdependence of factors in electronics recycling systems, modeling provides a powerful tool for system evaluation. In the future, this model, along with data from ongoing system evaluation work, can be used to evaluate the performance of existing systems across a range of different contexts [22].

Acknowledgment

The active participation of Edgar Blanco from the MIT Center for Transportation and Logistics in the development of the collection model is greatly appreciated.

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