A Process-Based Model of End-of-Life Electronics Recycling

Driving Eco-Efficiency-Informed Decisions

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***Abstract*—This paper describes a model of end-of-life electronics recycling that uses process-based cost modeling and value-based metrics to determine the economic and value-recovery effectiveness of a processing operation. The process-based cost models combine engineering process models, operational models, and an economic framework to map from details of product and process to operating costs. The value-weighted mass recovery assessments, when compared against simple mass recovered, provide a better estimate of both environmental impact and retained quality. The combination of these two aspects offer several advantages over existing modeling methodologies: they consider the variety of products a recycler processes, are driven by data that a recycler collects, and can respond to rapidly changing conditions. Background on these aspects is provided, followed by a description of the modeling framework. An example case involving cathode ray tubes is presented to depict the type of analyses possible using the model.**

Keywords - Recycling; electronics; economics; modeling; cathode ray tubes.

I. Introduction

Maryland's recently enacted statewide computer recycling program that places financial responsibility on manufacturers for the recycling of waste computers represents only the latest in a set legislation emerging globally that extends responsibility for life-cycle impacts to producers. The goal of these extended producer responsibility (EPR) policies is to effect positive changes in a material/product system by creating economic signals that drive more sustainable decisions. Many discussions of EPR efficacy focus on how such policies drive better product design at the manufacturer or improved consumer participation through increased recycling rates. However, EPR policies should also alter the decisions of another group of stakeholders – the processors within the material recovery system – whose strategic and operational decisions are critical to determining the effectiveness of that system. These decisions include the configuration of the take-back infrastructure, the processing technologies employed during demanufacture, and the markets through which materials are repurposed.

Operational decision-makers within dismantling and material recovery facilities face a daunting task of identifying the preferred processing pathways. For any complex product there exists a range of demanufacturing options (e.g., manual disassembly vs. mechanical segregation), each of which produces materials streams which can be repurposed in a range of end-use markets (e.g., glass recycled into new glass products vs. recycled as smelter flux). The interaction of these choices makes even strictly economically optimized decision-making a challenge; in most cases, firms are not able to evaluate the environmental consequences of their decisions.

To improve their process-related decision-making, recyclers require both a clear actualizable set of metrics by which to assess operational performance and a mechanism to map the impacts of processing decisions onto those metrics. This paper introduces a modeling framework that accomplishes the latter of these goals. The framework is grounded in a process-based cost model that incorporates technical aspects of the recycling process and the incoming material stream composition to determine operational and resource requirements and hence, processing cost. In addition, the model calculates metrics that makes use of value as a measure of operational performance. Value is an attractive metric because it relies on data that is collected by processors and provides insight on environmental impact and retained quality.

This paper begins with background on other electronics recycling modeling efforts, process-based cost models, and value-based recycling metrics. Then, the model scope, methodology, and preliminary results from a demonstration case involving cathode ray tube recycling are presented. Finally, the concluding remarks tie the modeling details back to the ultimate objective of the research, which is to deliver efficient, feasible decision-tools to identify more sustainable processing options within the EoL electronics recycling system.

II. Eco-Efficient Recycling Models

The development of methodologies that combine economic and environmental considerations to determine "eco-efficient" recycling decisions has recently become an active area of research. Economic factors usually include processing, transportation, and disposal costs; environmental aspects are typically based on LCA methods. The difficulty of incorporating so much economic and environmental data for complex products has led many researchers to present their methods as software tools to handle these tasks [1-5]. Most models are geared towards a systems analysis of product demanufacturing, but some focus on disassembly [6-8]. A few

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models incorporate weighting factors to help determine the "best" demanufacturing process using methods such an analytical hierarchy process [5, 9, 10]. The largest differentiators among these tools are the method they use to determine environmental impact and the scope of the system they are analyzing.

Many decisions must be made during recycling operations and much of the aforementioned research may be used to support strategic decisions. However, there are several limitations of the existing body of work that make it difficult for the in-place demanufacturing system to take advantage of the knowledge gained from these studies, especially for recurring operational decisions occurring in a dynamic context.

- Material values are not fixed: Recyclers process more than one type of product and total outgoing value for them value is a function of processing decisions that span several products. Most studies provide recycling decision support for one product, which is a logical first step in exercising a model, but does not enable an understanding of variations in material values across products.
- Sensitivity is rarely considered: Many assumptions must be made when incorporating such a vast amount of data, yet sensitivity to key parameters is rarely considered in studies of demanufacturing systems.
- Processing costs are not fixed: Nearly all recycling studies consider processing costs to be fixed (e.g., $/kg processed); this is obviously not the case. Costs depend on processing location, equipment used, and volume processed, among many other factors.
- Few, if any, methodologies can be used on a regular basis in demanufacturing operations: Detailed analyses are an important component to support strategic decisions, but demanufacturers must constantly modify their operations in order to adjust to changes in markets, demand, and expenses.

There clearly is a need for demanufacturing-support tools that consider the variety of products a recycler processes, are driven by data that a recycler collects, and can respond to rapidly changing conditions. The process-based cost models described in the next section and the value metrics address these issues and are particularly amenable to sensitivity analyses because the models map incoming material stream composition and processing methods to operational costs.

III. PROCESS-BASED COST MODELING

The economic information needed to support technological or regulatory decisions cannot be garnered from accounting records alone. Unfortunately, classical accounting-based tools, being wholly normative and retrospective in their methods, are inappropriate for providing accurate feedback in cases where significant changes are being considered in product (e.g., product redesign for recovery), process (e.g., shifts to alternate or new demanufacturing technologies) and/or process performance (as may arise in response to regulation). Answering economic questions involving change requires a tool capable of capturing the operational effects of change. Process-based cost modeling is such a tool.

Process-based cost models (PBCMs) derive operating cost by building up from the engineering realities of a process or activity [11]. Specifically, PBCMs combine engineering process models, operational models, and an economic framework to map from details of product and process to operating costs.

The primary elements in a PBCM are depicted in Figure 1. A description of a product or other process input is the initial input to a process model, which includes technical aspects of the process in question (e.g., calculate the amount of force required to stamp steel sheet, the amount of energy required to heat a casting furnace). The process model calculates the processing requirements (e.g., press size, furnace size), which are used as inputs into an operations model, in addition to other operational inputs (e.g., operating days per year, downtime). This information is used to determine resource requirements (e.g., amount of material, number of presses or furnaces, number of workers), which is used in a financial model in conjunction with factor price inputs (e.g., interest rates, labor wages, overhead rates) to ultimately determine production or processing costs.

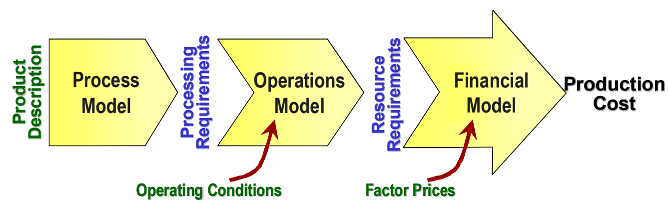

Figure 1. PBCM elements.

Since PBCMs are built around technical details, they allow one to explore how cost evolves as technology or operating conditions change. Through careful selection of modeling parameters, PBCMs can be used not only to estimate the costs of manufacturing products in a wide range of economic and operational circumstances, but can also be used to construct prospective cost estimates of the consequences of design and process changes, as well as "what if" analyses, to establish key economic or technical hurdles to achieving targeted costs.

IV. VALUE AS A RECYCLING METRIC

Ideally, recycling stakeholder decision-making would rely on detailed system-wide analyses. Unfortunately, time and expense preclude this approach beyond the occasional case study. While one-off studies provide valuable insights, they do not fill the operational need for continuous feedback. In order to benchmark performance or evaluate the effect of process changes, a set of low-overhead metrics is needed. Simple weighted indicators may offer the appropriate balance, providing insights without burdensome data requirements. Value has been demonstrated as an insightful metric in a material recovery context with low data inputs.

Value as a metric for recyclability was first proposed by Villalba et al. [12] to examine resource recovery. Kirchain and Atlee then introduced the use of value as an operational sustainability metric for electronics recycling [13]. A complete description of the use of value metrics in recycling operations is given by Atlee in [14], which is summarized here.

At its most basic level, value-weighted mass recovery assessments, when compared against simple mass recovered, provide a better estimate of both environmental impact and retained quality. For materials, value (i.e., price) reflects 1) quality, 2) production cost or use (including energy consumption) and 3) scarcity rents. As such, even with the omission of significant externalities, value does provide significant information about the effectiveness with which resources are reclaimed and returned to productive use.

The "recyclability" index developed by Villalba et al. [12] uses the concept of value as a proxy to examine resource recovery. The basic assumption is that "the recyclability of materials will be reflected by their monetary value" [12]. This leads directly to the Recyclability Index, Vp/Vm, where Vp ($/kg) and Vm ($/kg) represent the market value of secondary and primary material, respectively (shown in Figure 2).

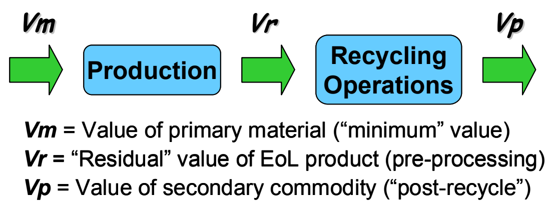

Figure 2. Definition of terms used in value-based metrics.

By extension, this metric can also be used to analyze the recovery effectiveness of a recycling operation or industry. Specifically, this leads to the value-retention and value-added weighted mass recovery indices:

$$\text{Value-Retention Index} = \frac{\sum_j Vp_j m_j}{\sum_i \sum_k Vm_{ki} m_{ki}} \quad (1)$$

$$\text{Value-Added Index} = \frac{\sum_j Vp_j m_j - \sum_i Vr_i m_i}{\sum_i \sum_k Vm_{ki} m_{ki} - \sum_i Vr_i m_i} \quad (2)$$

where subscripts i and j represent values for inflows and outflows respectively and k represents the kth embedded material in a given flow; m_x represents mass of a given flow.

The value retention measure gives insight into recovery effectiveness and provides a quantitative accounting of aggregate downcycling. However, this metric ignores the effect of varying inflow quality and, thus, provides only weak indication of the effectiveness of individual operators. The value-added measure addresses this by integrating the residual value (Vr) of incoming materials. The impact of recycling processes is characterized by the quantity $Vp - Vr$, which is the value added by recycler activities and is normalized against the quantity $Vm - Vr$, the maximum possible value-added.

Kirchain and Atlee applied these metrics to the operations of three American electronics recyclers [13]. The metrics differentiated the practices of the three operators. Although all three operators diverted nearly all of their outgoing material from landfill, not all of the material was repurposed with the same effectiveness; one processor had a value-added index near four times higher than another. The case demonstrated that value-derived metrics have the potential to be economically and environmentally informative while making use of data that processors collect.

V. MODEL DESCRIPTION

There are several different processing steps involved in disposing of or recovering materials from EoL electronics. The major steps are depicted in Figure 3, along with the large number of ways in which these steps may be connected. The graphic does not actually depict the complete set of processing alternatives because the "Material Recovery" box comprehends a variety of processes across the range of EoL electronics materials, each of which may consist of more dismantling, shredding, and material recovery. The lines in the figure generally represent transportation, but some facilities may be collocated, as is often the case for dismantling and shredding.

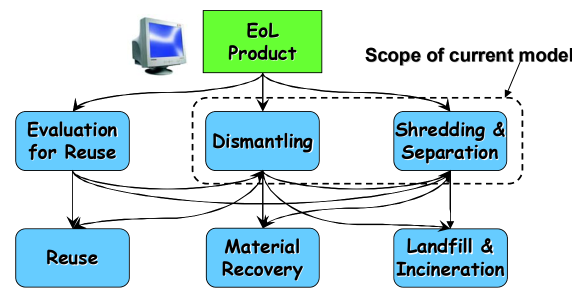

Figure 3. Major processing steps and connections in electronics recycling.

The scope of the current model is depicted in Figure 3 as initial dismantling and shredding, although the modularity of process models makes it easy for future processes to be added. The majority of the input requirements for the processing models are depicted below in Table 1. Since the shredding and dismantling modules are connected, the outgoing information from the dismantling module is automatically transmitted as an input to the shredding module.

TABLE 1. PROCESSING MODELS INPUT REQUIREMENTS.

Incoming Products	Outgoing Streams	Operating Conditions

• Types
• Volumes
• Values
• Composition
  ○ Subassemblies
  ○ Materials
	• Destinations
	  ○ Distance
	  ○ Transport cost
	  ○ Material value
		• Equipment
		  ○ Cost
		  ○ Operating rate
		  ○ Power
		  ○ Space
		• Wages
		• Interest rates
		• Maintenance costs
		• Downtimes

Figure 4 depicts the flow of information within the model from the product description inputs to the outputs of the processing model and the determination of the resource requirements. Several variable and fixed cost elements are calculated, which are summed to determine the net processing cost (total processing cost and material costs or revenues).

The processing models within the dismantling and shredding models include technical details on the processing operations. In the case of dismantling, the model uses algorithms to determine the disassembly time of incoming products and the aggregated material content and volumes of outgoing waste streams based on any specification of disassembly depth for all of the incoming products. The shredding model "receives" one of the outgoing streams from the dismantling model and uses mass fraction composition tables from shredding and separation operations in [15] to determine the composition of the separated output waste streams. The output stream compositions depend on whether the incoming streams contain mostly metals-dominated, glass-dominated, or precious metals-dominated products; multiple incoming streams can be analyzed for a mixture of products.

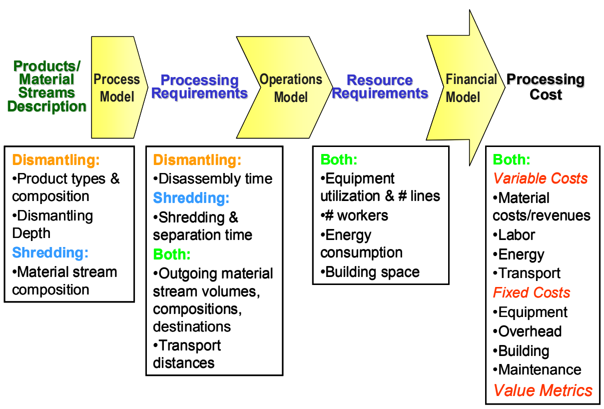

Figure 4. Information flow in dismantling and shredding models.

The total time required to complete disassembly or shredding and separation processes (calculated in the process model) is an important component of the operations model. This time is divided by the available time – which is determined from the number of operating days, number of shifts, hours of downtime, etc. – to yield the utilization of the equipment. If the required time is greater than the available time, multiple processing lines must be used. If not, then the incorporation of the equipment and building costs depends on whether the equipment is dedicated to the incoming products or not. The total cost of dedicated equipment is assigned to the processed material, whereas the cost of non-dedicated equipment is the utilization fraction (required time divided by available time) multiplied by equipment costs; this assumes the equipment is used to process other material during the time not used to process the material in the analysis. This utilization information is an important component of determining the effectiveness of a processing operation.

VI. Model Demonstration

An example involving processing of EoL computer monitors containing cathode ray tubes (CRT) is presented here to demonstrate some of the model's capabilities. The scope of the analysis is limited to the scope depicted in Figure 3: dismantling and shredding and separation. Three scenarios are analyzed, assuming 100,000 monitors processed per year:

1. Dismantling (D)
2. Dismantling and Shredding and Separation (D&S&S)
3. Shredding and Separation (S&S)

The dismantling scenario involves manual disassembly of the monitors with the components (including CRTs) sent to other material recovery facilities. The dismantling and shredding and separation scenario also involves manual disassembly of the monitor, but the CRTs are shredded at the same facility. Finally, the shredding and separation scenario involves shredding the entire monitor.

Space constraints prevent all of the input data from being presented here, but Table 2 lists the primary sources of data. Further details on some of the sources for material value and transport costs are provided in [16].

TABLE 2. SOURCES OF INPUT DATA.

Input Data	Source
Operating conditions (wage, overhead, maintenance, building cost, interest rates, …)	Estimates based on industry experience
Product compositions (subcomponents and materials)	[17]
Disassembly times	[17, 18]
Equipment costs, power, space, etc.	Industry representatives
Shredding & separation fractions	[15]
Material value	Literature & public sources
Landfill & incineration costs	[19]
Transport costs	[20] & discussion w/ author
Transport distances	Generic: 500 km

The cost and value index outputs for the three scenarios are listed in Table 3. No values in the table are zero; some terms (such as energy) require more significant digits to indicate the amount. The majority of the material revenue ($0.68/kg) comes from the $10 charged per monitor for processing; the rest of the revenue comes from sales of the output streams, although fees must be paid to dispose of the CRT glass.

TABLE 3. COST (/KG) AND VALUE INDEX BREAKDOWN FOR THREE SCENARIOS.

Cost Category	D	D&S&S	S&S
Material Cost (Revenue)	($0.77)	($0.77)	($0.72)
Transport	$0.04	$0.06	$0.04
Labor	$0.19	$0.21	$0.02
Energy	$0.00	$0.01	$0.00
Equipment	$0.00	$0.04	$0.04
Other fixed	$0.10	$0.16	$0.05
Total Processing Cost	$0.34	$0.47	$0.15
Net Cost (Revenue)	($0.43)	($0.30)	($0.57)
Value Added Index	21.11%	22.61%	19.75%
Value Retention Index	2.96%	4.80%	1.28%

Note: Values in parenthesis are negative, which indicate revenue.

As expected, the D and D&S&S scenarios have higher labor costs. Even though lower fees are paid on the outgoing glass stream from the D&S&S scenario (mixed glass cullet as opposed to whole CRTs), it is a small price difference which has a negligible effect on the material revenues. However, the additional shredding step adds a great deal of cost, thereby lowering the net revenues.

The S&S scenario uses larger equipment than the D&S&S scenario; this larger equipment is more expensive, but runs at a faster rate. Thus, the S&S scenario has lower required time, which lowers its equipment costs. In fact, the speed of the S&S scenario is what makes its total processing cost the least. Even though it has lower material revenues, this is offset by the lower processing costs, leading to the highest net revenues.

Figure 5 plots the two value indices against the corresponding net revenue for each scenario. It is clear from this plot that there is an inverse relationship between net revenues and both added and retained value. This is consistent with expending greater costs in order to produce higher quality material streams. Interestingly, across the three processing options, the rate of value index growth per decrement of revenue is nearly constant (cf. point-to-point slope). This constant slope implies that while the dismantle-only scenario (D) might be appealing as a compromise solution, it will almost never be the optimal solution.

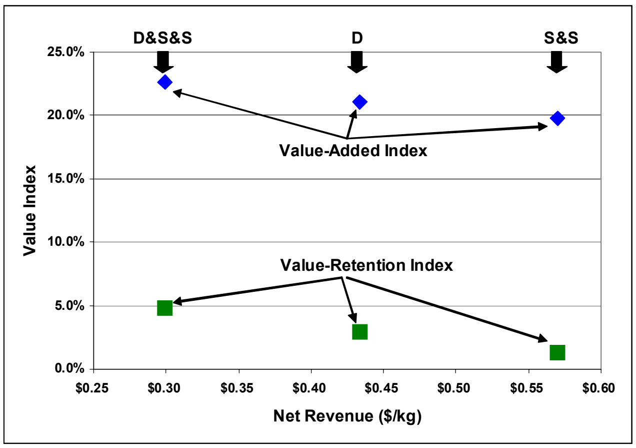

Figure 5. Value-added and value-retention indices vs. net revenue for the three scenarios

A significant advantage of using PBCMs is the ability to explore the sensitivity of important parameters on processing costs. Processing rate is an example of one such parameter and the sensitivity of this rate on the D and S&S scenarios is depicted in Figure 6. In the case of dismantling, the processing rate is total dismantling time for a monitor. For shredding and separation, the processing rate is for the equipment. It is clear from the figure that processing rate can have a significant impact on the total processing cost. The baseline values used in the scenario analyses were chosen to reflect representative processing rates, but other rates are certainly possible, which could bring the processing costs much closer together.

Figure 7 is a map of preferred processing alternatives that is based on the difference between total processing costs for D and S&S scenarios under a range of processing rates (the preferred alternative has lower processing costs). It is clear that the speed of the S&S scenario typically gives it the advantage.

The model also facilitates sensitivity studies of the value metrics as well. Given that nearly half of the weight of a monitor is the CRT, which is primarily glass, the primary and secondary value of the glass has a big impact on the overall value indices. Figure 8 shows that the ratio of the secondary glass value (in the case of shredding) or secondary CRT value (in the case of dismantling) to the primary glass value has a significant impact on the total retained value for the processed products. The ratio of secondary to primary value is negative for the CRT and glass because fees are charged for these material streams. Even though the fees are higher for CRTs, the value of the other waste streams from dismantling are higher than the shredding waste streams (in these scenarios), making the dismantling retained value generally higher than the shredding retained value.

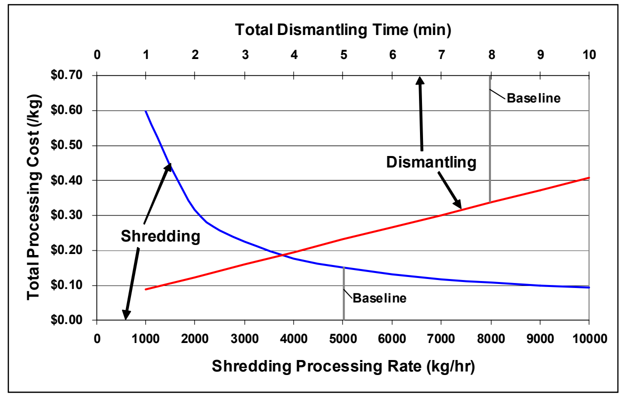

Figure 6. Sensitivity of dismantling and shredding to processing rate.

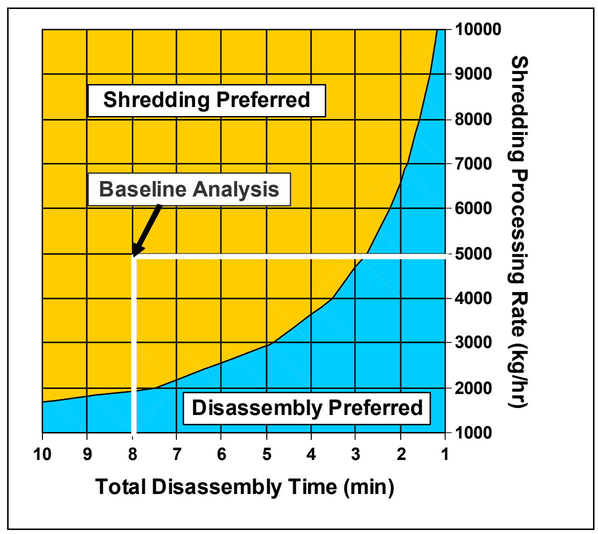

Figure 7. Preferred processing alternative based on the difference between D and S&S total processing cost, dependent on processing rates.

VII. Conclusions

A process-based cost model of end-of-life electronics recycling has been introduced that contains several features that enable eco-efficient processing decisions by recyclers. In particular, the model can be used to study processing of multiple products simultaneously and sensitivity of key parameters on processing costs. Furthermore, the model uses data that processors regularly collect and hence, can be used on a regular basis to guide demanufacturing decisions. The use of value-based performance metrics in the model provides a unique opportunity to evaluate economic performance and provide insight on environmental impact without the extensive data needed in most detailed environmental analyses.

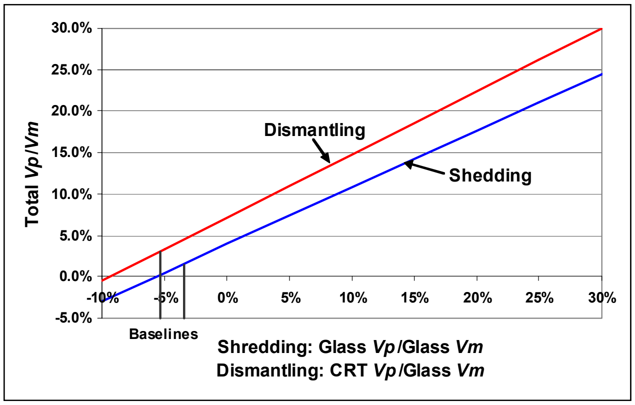

Figure 8. Sensitivity of total value retention index to glass and CRT material values in shredding and dismantling, respectively.

In the presented case, the model reveals that for a broad set of operating conditions the shredding and separation (S&S) of monitors is the economically preferred processing option. However, the model results show that S&S processing results in 10% less value added and only 1/3 of the value retained in the D&S&S scenario. These results provide a necessary element required to enable data-driven decision-making regarding the preferred processing pathway for these products.

Future work involving the model will include: expansion to include other processing models, utilization of data from actual recycling facilities, and incorporation of other environmental metrics for information and validation purposes.

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References

1. Huisman, J., Stevels, A.L.N., and Stobbe, I. (2004). Eco-efficiency considerations on the end-of-life of consumer electronic products, *IEEE Transactions on Electronics Packaging Manufacturing*. **27**(1): p. 9-25.
2. Nissen, N.F., Griese, H., Muller, J., Middendorf, A., Stobbe, I., Reichl, H., and Funk, T. (2000). Environmental Assessment Using the IZM/EE Toolbox, in *Electronics Goes Green 2000+*. Berlin, Germany.
3. Masanet, E.R. and Horvath, A. (2004). A decision-support tool for the take-back of plastics from end-of-life electronics, in *Proceedings of the 2004 IEEE International Symposium on Electronics and the Environment, 10-13 May 2004*. Scottsdale, AZ, USA: IEEE.
4. Lamvik, T., Myklebust, O., and Miljeteig, G. (2002). The AEOLOS methodology, in *2002 IEEE International Symposium on Electronics and the Environment, 6-9 May 2002*. San Francisco, CA, USA: IEEE.
5. Ardente, F., Beccali, G., and Cellura, M. (2003). Eco-sustainable energy and environmental strategies in design for recycling: the software "ENDLESS", *Ecological Modelling*. **163**(1-2): p. 101-118.
6. Hula, A., Jalali, K., Hamza, K., Skerlos, S.J., and Saitou, K. (2003). Multi-criteria decision-making for optimization of product disassembly under multiple situations, *Environmental Science & Technology*. **37**(23): p. 5303-5313.
7. Meng, P., Duan, G., Xiang, D., Liu, X., Wu, Y., Li, F., and Li, Y. (2003). An information system management of assessment of disassembly and recycle, in *2003 IEEE International Symposium on Electronics and the Environment, May 19-22 2003*. Boston, MA, US.
8. Shrivastava, P., Zhang, H.C., Li, J., and Whitely, A. (2005). Evaluating obsolete electronic products for disassembly, material recovery and environmental impact through a decision support system, in *2005 IEEE International Symposium on Electronics and the Environment, May 16-19 2005*. New Orleans, LA, US: IEEE.
9. Kim, J., Hwang, Y., Matthews, H.S., and Park, K. (2004). Methodology for recycling potential evaluation criterion of waste home appliances considering environmental and economic factor, in *2004 IEEE International Symposium on Electronics and the Environment, 10-13 May 2004*. Scottsdale, AZ, USA: IEEE.
10. Lou, S., Leu, J., and Jorjani, S. (1996). Comparing different disassembly strategies, in *1996 IEEE International Symposium on Electronics and the Environment, ISEE, May 6-8 1996*. Dallas, TX, USA: IEEE.
11. Kirchain, R.E. and Field, F.R. (2001). Process-Based Cost Modeling: Understanding the Economics of Technical Decisions, in *Encyclopedia of Materials Science & Engineering*. p. 1718–1727.
12. Villalba, G., Segarra, M., Fernandez, A.I., Chimenos, J.M., and Espiell, F. (2002). A proposal for quantifying the recyclability of materials, *Resources, Conservation and Recycling*. **37**(1): p. 39-53.
13. Kirchain, R. and Atlee, J. (2004). Operational sustainability metrics - assessing performance of electronics recycling systems, in *2004 IEEE International Symposium on Electronics and the Environment, 10-13 May 2004*. Scottsdale, AZ, USA: IEEE.
14. Atlee, J. (2005). Operational Sustainability Metrics: A Case of Electronics Recycling. Thesis, Massachusetts Institute of Technology.
15. Huisman, J. (2003). The QWERTY/EE Concept: Quantifying Recyclability and Eco-Efficiency for End-of-Life Treatment of Consumer Electronic Products. Thesis, Delft University of Technology.
16. Gregory, J.R. and Kirchain, R.E. (2006). Eco-efficient recycling alternatives for end-of-life cathode ray tubes, in *Proceedings of 2006 TMS Annual Meeting & Exhibition, Recycling General Sessions, San Antonio, TX, March 12-16, 2006.*
17. Huisman, J. (2004). QWERTY and Eco-Efficiency analysis on treatment of CRT containing appliances at Metallo – Chimique NV. Huisman Recycling Research.
18. Boks, C.B., Kroll, E., Brouwers, W.C.J., and Stevels, A.L.N. (1996). Disassembly modeling: two applications to a Philips 21 double prime television set, in *1996 IEEE International Symposium on Electronics and the Environment, ISEE, May 6-8 1996*. Dallas, TX, USA: IEEE.
19. Repa, E.W. (2005). NSWMA's 2005 Tip Fee Survey. National Solid Wastes Management Association.
20. US Department of Transportation Federal Highway Administration Expenses per Mile for the Motor Carrier Industry: 1990 through 2000 and Forecasts through 2005.