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Modeling Regional Recycling and Remanufacturing Processes: From Micro to Macro

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Abstract

This paper reports progress in modeling recycling and remanufacturing processes within metropolitan regional economies at the micro and macro levels. The paper presents interim results from a multi-year, inter-institutional research project funded by the National Science Foundation. We identify a number of issues that have arisen from an in-depth industry level analysis of obsolete and waste products generated in the Seattle, WA and Atlanta, GA metro regions from waste electronics (e-waste) and carpet production and consumption. The two metro regions were selected for comparative analysis because Seattle is a recognized leader in e-waste recycling and sustainable development programs, while Atlanta has been slow to embrace recycling but is only 70 miles from the center of US carpet manufacturing (Dalton) and has an industry trade association that has set aggressive targets for carpet recycling and remanufacturing, e-waste forms the focus of this paper. We provide a detailed elaboration of processes at the micro-level, along with an enumeration of problems and solutions in characterizing these new industries, including an integration with environmental Life Cycle Assessment, and embedding the results in a macro-economic modeling framework.

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1. Introduction

The urban landscape and population, and their associated material flows, have been underrepresented in models of sustainable industrial system growth. The research reported on here is part of a larger project to develop a framework for modeling and assessing the impact of redesigning urban materials flows to advance the mutual goals of sustainable industrial and urban systems. The environmental impact and economic benefits of these flows occur at different spatial levels and scales, from the individual urban tract to international trade and the global environment. This creates a strong imperative to develop and use models that can capture, quantify, and qualify materials and flows across these different scales to support a comprehensive assessment of their impacts.

To achieve this, we are engaged in a five-year collaborative research effort between the Georgia Institute of Technology, University of Washington at Seattle, and West Virginia University, involving a research team from the disciplines of Chemical Engineering, Mechanical Engineering, Economic Geography, and City and Regional Planning. Our common focus is on mining specific products and associated materials from metropolitan regions through new recycling and remanufacturing networks and facilities for the Atlanta and Seattle regions, and on modeling the economic development and environmental effects of different material flow scenarios on these regions.

Motivation

Our research highlights the role of metropolitan regions in sustainability because they contain the significant and growing fraction of population and material and energy flows associated with the use and disposal of products. As such, they are one of the most critical factors in the human influence on the environment. Indeed, as a recent Brookings Institution report [BRO07] argues,

> Today, our nation—and our economy—is metropolitan. U.S. metropolitan areas—complex regions of interwoven cities and suburbs—are home to more than eight in ten Americans and jobs. These metros range from global economic centers like New York, Chicago, and San Francisco; to major trade hubs like Louisville, Houston, and Seattle; to smaller, highly productive centers like Bridgeport, Durham, and Des Moines. They concentrate and strengthen the assets that drive our economic productivity, grow the skills and incomes of our workers, and contribute to our environmental sustainability. Our

> major metro areas reflect the face of America in a global economy where, for the first time, more than half the world's population is metropolitan. (2007, p. 4)

Re-engineering the flows of materials – particularly the patterns of their disposal – is critical to achieving sustainable systems within metropolitan areas (as well as other region types). Disposal of consumer and business durable goods to landfills is particularly a growing problem in dense population regions, especially those that have limited landfill space. Disposal is not only costly (in real and sustainable terms) but it is under increasing fire for its impact on adjacent communities and the limitations closed landfills place upon future development [BLU76; HIT01; KAT02]. The European Union (home of many densely populated areas) has acted to reduce waste to landfill through several legislative directives focused on promoting recovery, reuse, and recycling of electronics and automobiles [EU 2000; EU 2003a; EU 2003b; EU 2003c]. Japan has adopted similar measures. In the US, as of November 2008, 17 states had enacted bans on landfilling CRTs. (www.e-takeback.org/docs open/Toolkit_Legislators/state legislation/state_leg_main.htm)

Further, it has been shown that waste diversion from landfills had significantly higher positive impacts on the economy than disposal, leading to more than a doubling of total sales and value-added, and a near doubling of jobs, output and total income impacts [GOL01]. Thus, encouraging new manufacturing activity through waste diversion in distressed areas is a promising economic development strategy that promotes urban sustainability.

To estimate the material flows associated with discarded durables, it is necessary to identify their sources, the rates at which those sources will generate various products, the materials associated with them, and the most favorable processing scenarios and locations in terms of socio-economic and environmental effects. Because of the symbiotic material flow relationship between manufacturing companies and urban regions, engineering and regional planning can make significant contributions to the development of systematic ways to plan and (re)engineer material flow systems for sustaining growth that is efficient in material, energy and land use, as well as in providing components necessary for the development of social capital.

Challenges of Interdisciplinary research

While combining the efforts of engineering and regional planning provides a very useful framework for modeling regional recycling and remanufacturing processes, there are inherent challenges that stem from the different scales at which the two disciplines operate. Engineers perform Life Cycle Assessments (LCAs) to determine the environmental impacts of products, processes or services, through their production, usage, disposal or re-use or remanufacturing. These assessments begin at the micro or unit (product) level, for example estimating energy and materials use and waste for a single industrial process. Regional planners (as well as regional scientists and economic geographers) operate at a larger or macro scale which is also spatial (a city, region, state or nation, for example) to conduct system-wide analyses for a regional economy. Input-output (IO) analysis, for example, shows how the output of one industry becomes an input to other industries, illustrating regional inter- and intra-industry dependences in terms of being customers of output and suppliers of inputs. Both LCA and IO models have their own distinct terminologies and notations, creating challenges and necessitating cross-learning by interdisciplinary research teams. As one simple example, the "technology" matrix in LCA and denoted **A** by convention is equivalent to a Leontief matrix denoted (**I** – **A**) in IO analysis, while a technology matrix in IO analysis is represented simply as **A**. The greater challenge, however, stems from the need to feed information gained from the micro or LCA scale into the macro or regional IO scale. That is, there is a need to scale up the engineering data developed at the unit level to the industry level in order to make use of it in the IO model.

Methods

In developing models and tools to shape the next generation of industrial systems for materials mined from metropolitan regions, the spatial distribution of these material resources must be integrated because successful design of sustainable systems cannot occur in a geographical vacuum; the "where" of a system matters, both in its ecological and human dimension. Thus, we use Geographic Information System (GIS) tools to specifically identify where materials (in our focus here, waste electronics or "e-waste") are located for which the objective is to mine or collect them for re-use and processing, rather than disposal in a landfill. We identify our mining sources as those associated with residences and businesses. Specifically, for our focus on e-waste, we estimate the numbers of obsolete components (e.g., computers, monitors, or cell phones)) that are yielded by households and businesses. In doing so, the yields we estimate are distinguished by household income level, on the one hand, and by industry sector, on the other.

Life Cycle Assessment

For the LCA in this project, the estimate of the metropolitan flows of e-waste is made by numbers of units. Units are characterized by whether they are remanufactured, recycled, disposed into landfills, or removed (or leaked in IO terms) from the region. The materials within each type of e-waste is also characterized, with variation in the amount of materials across equipment types, makers, and equipment size dictating the type and quantities of materials managed in remanufacturing, recycling, and landfilling.

Input-Output Analysis

For the research here, we must construct an extended IO model that explicitly incorporates recycling industry(s) and related commodity(s) accounts to analyze the economic impact of e-waste recycling activity. In addition, our model is intended to account for physical flow of e-waste and the economic value along with subsequent transactions of e-waste within the metropolitan economic system. There is no explicit identification of a recycling industry in published IO data. Instead, recycling activities that do exist are a part of the more aggregate waste management sector. Therefore, the industry and commodity accounts must be re-organized to identify a relevant recycling industry and commodity. Furthermore, traditionally an end-of-life electronic product has been regarded as waste, with no economic value. The flow of these products is observed in physical (non-monetary) units. Increasingly, and aided by e-waste legislation, e-waste collectors, remanufacturers, and recyclers view these e-wastes as a resource. Economic value is created along the transaction of e-waste, between the discarding household or business and the e-waste collectors and processors in a metro area. Thus, the economic values of e-waste in transactions among these economic agents have to be incorporated into the IO table.

In this paper, we report on our progress in modeling recycling and remanufacturing processes within metropolitan regional economies at the micro and macro levels. The paper presents interim results from a multi-year, inter-institutional research project funded by the National Science Foundation. For the larger project, we identify a number of issues that have arisen from an in-depth industry level analysis of obsolete and waste products generated in the Seattle, WA and Atlanta, GA metro regions from electronics (e-waste) and carpet production and consumption. The two metro regions were selected for comparative analysis because Seattle is a recognized leader in e-waste recycling and sustainable development programs, while Atlanta has been slow to embrace recycling, but is only 70 miles from the center of US carpet manufacturing (Dalton) and has an industry trade association that has set aggressive targets for carpet recycling and remanufacturing. E-waste recycling forms the focus of this paper, in which we provide an example elaboration of processes at the micro-level, along with an enumeration of problems and solutions in characterizing these new industries, including an integration with environmental LCA geared toward embedding the results in a macro-economic modeling framework. Our objective here is to develop procedures that generalize to remanufacturing processes and other recyclable materials.

2. Building Complimentary LCAs and IO Regional Models

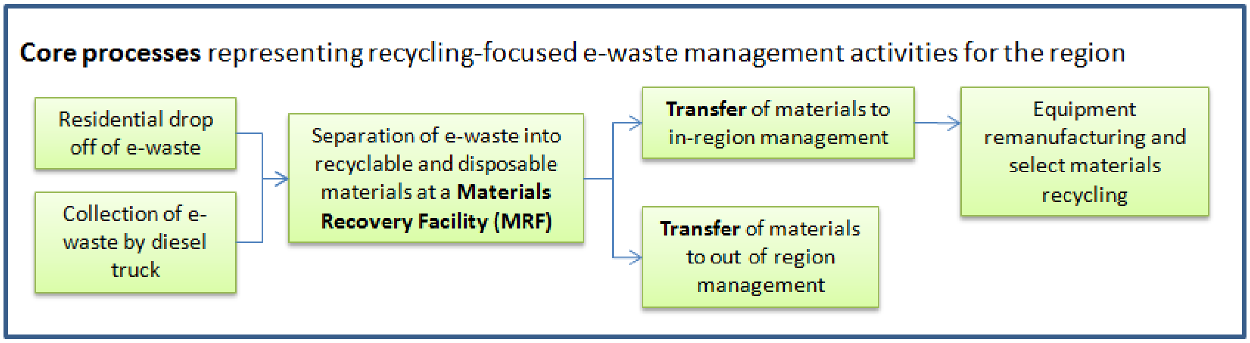
LCA is a protocol standardized by the International Standards Organization [ISO06a, ISO06b] to assess the life cycle impacts of energy and materials use and waste by an industrial system. LCA is most frequently used to quantify environmental impacts (e.g., life cycle energy consumption, contribution to climate change, acidification, toxic impacts, land use, etc.) and includes four interrelated phases of research:

1. **Goal and scope definition:** stating the intended application and scope of the LCA.
2. **Inventory Analysis:** compiling an inventory of materials and energy use and waste as inputs and outputs of the industrial system.
3. **Impact Assessment:** evaluating the potential impacts given the inventory.
4. **Interpretation:** explaining the results (sensitivity, uncertainty) in relation to the objectives of the study.

Thus, in LCA it is the life cycle inventory analysis that describes the interaction of industrial processes, ideally extending from materials and energy acquisition (mining and agriculture) through materials processing, construction/manufacturing, technology use and maintenance, and ultimately to reuse, remanufacturing, recycling, and/or disposal. Construction of a life cycle inventory typically starts with a single technology or set a of processes of interest (i.e., a “core” set of processes), and then moves concentrically “upstream” adding processes needed to produce materials and energy needed in the core and beyond, and “downstream” adding processes using or managing the materials and energy for the core and beyond. The concept of the “core” set of processes is the foundation for the link to regional IO modeling.

Specifically, consider for example our case study on regional management of electronic waste (e-waste) depicted in Figure 1. Here, we are interested in how new and existing recycling-focused e-waste management activities in our study regions might impact regional economic development and the environment. To the extent that some of the activities are already captured but masked by aggregation in IO accounts, the industry representations developed will form the basis for disaggregating existing models. Should entirely new processes be introduced to a region, the industry representations developed will be used to augment the existing accounts.

Figure 1. Case Study Core E-Waste Management System



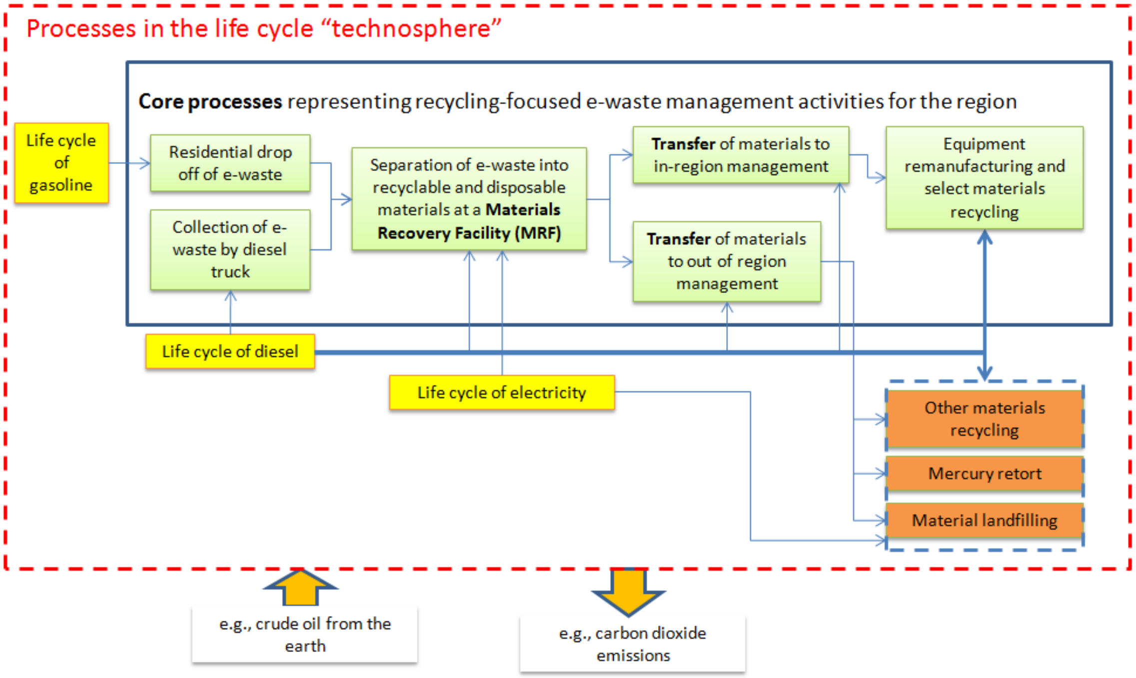
Next, Table 1 presents example and hypothetical process data for our core and assuming the e-waste management system is new to the region. As in a life cycle inventory, processes are represented as columns in a matrix with process inputs as positive numbers and process outputs as negative numbers, forcing the links between processes. For example, the input to the e-waste separation process in our system is e-waste to be disassembled (coming from residential drop offs and collected by truck) and the outputs make links to both logistics (movement of materials from separation to remanufacturing/recycling or landfilling) and to processes representing materials recycling. The units of measure for the process inputs and outputs are typical for a life cycle inventory, based on physical units such as pounds (lbs) or units of e-waste (e.g., a monitor or CPU) or ton-miles for logistics (representing the weight transported times the assumed transport distance).

Table 1. Example Core Process Data for New Regional E-Waste Management Activities

	New Activity in the Region						
	E-waste management	Residential drop off of e-waste at MRF	Collection of e-waste by diesel truck	Separation of materials from e-waste at MRF	Transfer of recyclables by truck	Transfer of materials to landfill by truck	Equipment re-manufacturing and materials recycling
Managed e-waste(units of e-waste)	1	0	0	0	0	0	0
E-waste dropped off at MRF by residents (ton-miles)	-0.039	1	0	0	0	0	0
Collected e-waste (ton-miles)	-0.017	0	1	0	0	0	0
E-waste to be disassembled (units of e-waste)	-1	0	0	1	0	0	0
Recyclable materials to recycling (ton-miles)	0	0	0	-0.041	1	0	0
Materials to landfill (ton-miles)	0	0	0	-0.014	0	1	0
Remanufacturable equipment to remanufactured equipment/ recyclable materials to recycled materials (lb)	0	0	0	-8.3	0	0	1

Here, and in any LCA, inventory inputs and outputs are designated as either "to or from the technosphere" or "to or from the environment." The "technosphere" refers to the set of industrial processes being assessed (i.e., all processes within the system boundary) and in the LCA of our e-waste system includes not only the core processes but also the upstream and downstream processes needed to complete the life cycle, as depicted in Figure 2 (and noting that this is a limited example of what would be included). Inputs and outputs "to or from the technosphere" such as e-waste or recyclable materials, move between industrial processes. Inputs and outputs "to or from the environment" such as crude oil from the earth or carbon dioxide emissions to the air, enter or leave the technosphere, are called environmental flows, and are accounted to form the life cycle inventory results.

Figure 2. Life Cycle Inventory Processes



To solve the life cycle inventory problem as described by Heijungs and Suh [HEI02], the processes in the technosphere are typically formulated into a non-singular matrix (known as the technology matrix and designated as **A**), which is inverted and then subjected to a demand vector f (representing what among the inputs and outputs the entire system should ultimately produce) to solve for a scaling vector s (representing the amount of each process needed to meet the specified demand):

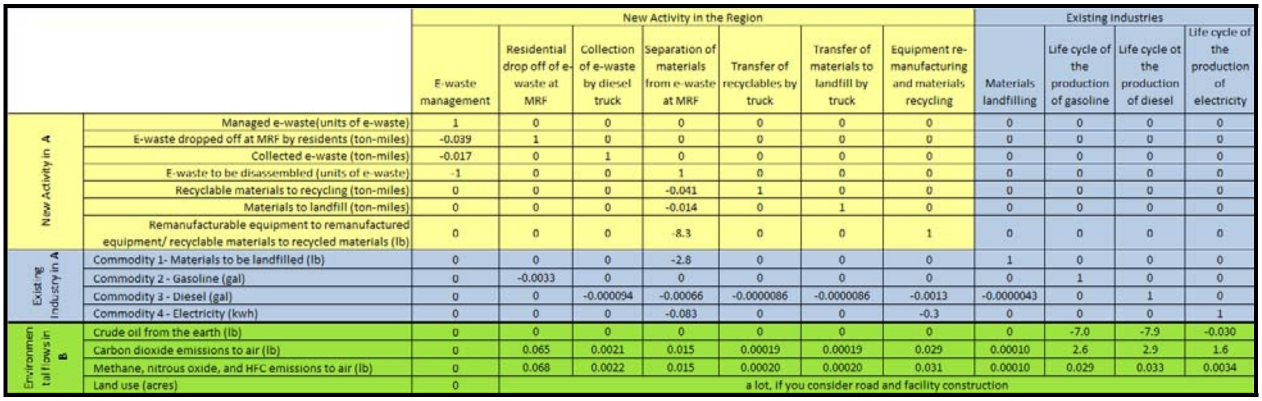
$$\mathbf{A}^{-1} f = s \qquad <1>$$

Next, s is used to scale the environmental flows for each process, which are represented as the matrix **B** with columns corresponding to each process in **A** and rows representing inputs and outputs from the environment (e.g., crude oil and carbon dioxide emissions):

$$\mathbf{B}s = g \qquad <2>$$

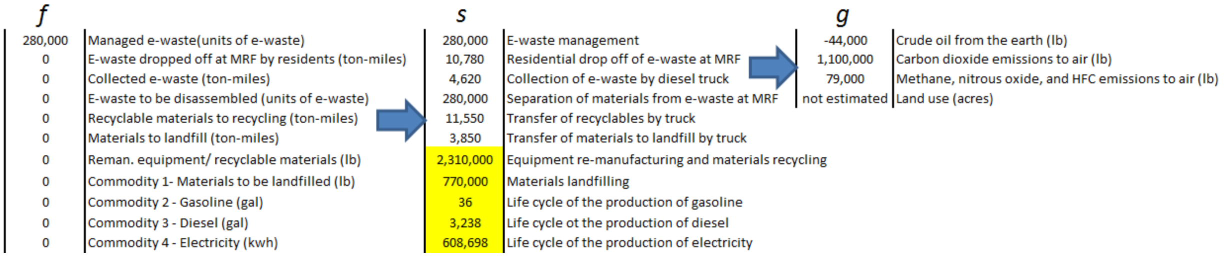
such that the inventory result (vector g) summarizes the life cycle resource use and emissions. Example data, based on the set of core processes described above are presented in Table 2. For the LCA, the core data presented in Table 1 have been repeated, the **A** matrix has been extended to include the life cycle of 4 commodities (landfilling and the production of gasoline, diesel, and electricity), and the **B** matrix has been added to represent example environmental flows (crude oil, select air emissions, and land use). This set up can be used to demand, for example, any number of e-waste units to be managed in the region of interest (using various versions of f), allowing g, or the total life cycle use of crude oil, air emissions, and land use to be estimated for a variety of scenarios.

Table 2. Example LCA Matrices for New E-Waste Management Activities[2]



		New Activity in the Region							Existing Industries			
		E-waste management	Residential drop off of e-waste at MRF	Collection of e-waste by diesel truck	Separation of materials from e-waste at MRF	Transfer of recyclables by truck	Transfer of materials to landfill by truck	Equipment re-manufacturing and materials recycling	Materials landfilling	Life cycle of the production of gasoline	Life cycle ot the production of diesel	Life cycle of the production of electricity
New Activity in A	Managed e-waste(units of e-waste)	1	0	0	0	0	0	0	0	0	0	0
	E-waste dropped off at MRF by residents (ton-miles)	-0.039	1	0	0	0	0	0	0	0	0	0
	Collected e-waste (ton-miles)	-0.017	0	1	0	0	0	0	0	0	0	0
	E-waste to be disassembled (units of e-waste)	-1	0	0	1	0	0	0	0	0	0	0
	Recyclable materials to recycling (ton-miles)	0	0	0	-0.041	1	0	0	0	0	0	0
	Materials to landfill (ton-miles)	0	0	0	-0.014	0	1	0	0	0	0	0
	Remanufacturable equipment to remanufactured equipment/ recyclable materials to recycled materials (lb)	0	0	0	-8.3	0	0	1	0	0	0	0
Existing Industry in A	Commodity 1- Materials to be landfilled (lb)	0	0	0	-2.8	0	0	0	1	0	0	0
	Commodity 2 - Gasoline (gal)	0	-0.0033	0	0	0	0	0	0	1	0	0
	Commodity 3 - Diesel (gal)	0	0	-0.000094	-0.00066	-0.0000086	-0.0000086	-0.0013	-0.0000043	0	1	0
	Commodity 4 - Electricity (kwh)	0	0	0	-0.083	0	0	-0.3	0	0	0	1
Environmental flows in B	Crude oil from the earth (lb)	0	0	0	0	0	0	0	0	-7.0	-7.9	-0.030
	Carbon dioxide emissions to air (lb)	0	0.065	0.0021	0.015	0.00019	0.00019	0.029	0.00010	2.6	2.9	1.6
	Methane, nitrous oxide, and HFC emissions to air (lb)	0	0.068	0.0022	0.015	0.00020	0.00020	0.031	0.00010	0.029	0.033	0.0034
	Land use (acres)	0	a lot, if you consider road and facility construction									

For example, given *f* demanding management of 280,000 units of e-waste, the life cycle inventory computations can be summarized as:



f		*s*		*g*	
280,000	Managed e-waste(units of e-waste)	280,000	E-waste management	-44,000	Crude oil from the earth (lb)
0	E-waste dropped off at MRF by residents (ton-miles)	10,780	Residential drop off of e-waste at MRF	1,100,000	Carbon dioxide emissions to air (lb)
0	Collected e-waste (ton-miles)	4,620	Collection of e-waste by diesel truck	79,000	Methane, nitrous oxide, and HFC emissions to air (lb)
0	E-waste to be disassembled (units of e-waste)	280,000	Separation of materials from e-waste at MRF	not estimated	Land use (acres)
0	Recyclable materials to recycling (ton-miles)	11,550	Transfer of recyclables by truck		
0	Materials to landfill (ton-miles)	3,850	Transfer of materials to landfill by truck		
0	Reman. equipment/ recyclable materials (lb)	2,310,000	Equipment re-manufacturing and materials recycling		
0	Commodity 1- Materials to be landfilled (lb)	770,000	Materials landfilling		
0	Commodity 2 - Gasoline (gal)	36	Life cycle of the production of gasoline		
0	Commodity 3 - Diesel (gal)	3,238	Life cycle ot the production of diesel		
0	Commodity 4 - Electricity (kwh)	608,698	Life cycle of the production of electricity		

with the life cycle inventory results estimating 44,000lbs of crude is extracted from the earth; 1.1 million lbs of carbon dioxide are emitted to the air; 79,000lbs of methane, and nitrous oxide and HFCs are emitted to the air.

Although the e-waste management activities in reality can be newly introduced or already captured in the IO accounts, we can treat them as though they were new for the purposes of quantifying the data needed to modify the IO model. To form the data for the **make-use** tables in support of our regional IO model, we identified only one modification to the LCA technology matrix **A** presented in Table 2. Specifically, we note that the non-core processes in the technosphere represent existing industries whose interactions with other existing industries in the region are already captured in the regional IO model. Thus and as presented in Table 3, we reformulated the portion of **A** representing the existing industries as an

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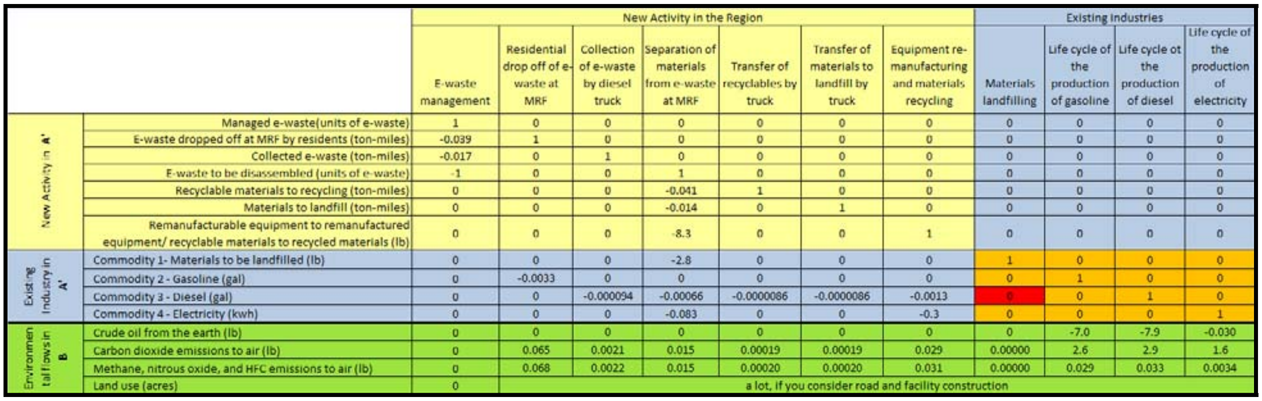
[2] Although all data are presented only for the purpose of developing our example, data for truck emissions and the life cycles of the production of gasoline, diesel, and electricity are based on data in the US Life Cycle Inventory Database, maintained by the US Department of Energy's National Renewable Energy Laboratory and available at http://www.nrel.gov/lci/

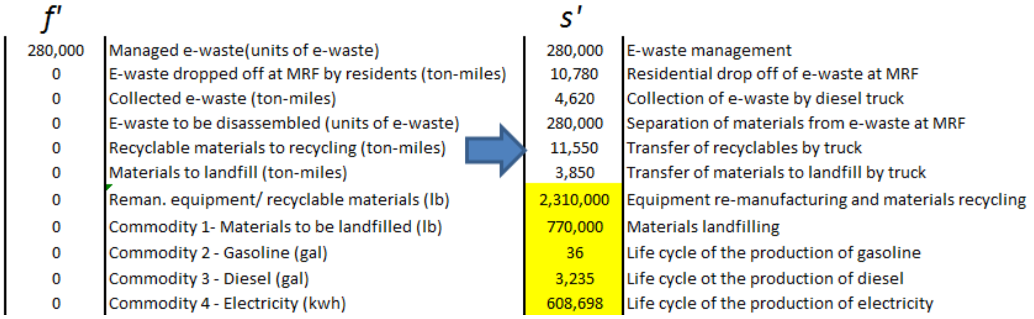
identity matrix (in orange in Table 3) to eliminate double counting of the relationships between existing sectors. We denoted the new matrix as **A'**. This modification can be viewed as a redefinition of the LCA system boundaries, truncating the LCA at the point at which additional activity in existing industries is triggered.

Table 3. Modified LCA A Matrix for Use in Preparing Regional IO Models



		New Activity in the Region							Existing Industries			
		E-waste management	Residential drop off of e-waste at MRF	Collection of e-waste by diesel truck	Separation of materials from e-waste at MRF	Transfer of recyclables by truck	Transfer of materials to landfill by truck	Equipment re-manufacturing and materials recycling	Materials landfilling	Life cycle of the production of gasoline	Life cycle ot the production of diesel	Life cycle of the production of electricity
New Activity in **A'**	Managed e-waste(units of e-waste)	1	0	0	0	0	0	0	0	0	0	0
	E-waste dropped off at MRF by residents (ton-miles)	-0.039	1	0	0	0	0	0	0	0	0	0
	Collected e-waste (ton-miles)	-0.017	0	1	0	0	0	0	0	0	0	0
	E-waste to be disassembled (units of e-waste)	-1	0	0	1	0	0	0	0	0	0	0
	Recyclable materials to recycling (ton-miles)	0	0	0	-0.041	1	0	0	0	0	0	0
	Materials to landfill (ton-miles)	0	0	0	-0.014	0	1	0	0	0	0	0
	Remanufacturable equipment to remanufactured equipment/ recyclable materials to recycled materials (lb)	0	0	0	-8.3	0	0	1	0	0	0	0
Existing Industry in **A'**	Commodity 1- Materials to be landfilled (lb)	0	0	0	-2.8	0	0	0	1	0	0	0
	Commodity 2 - Gasoline (gal)	0	-0.0033	0	0	0	0	0	0	1	0	0
	Commodity 3 - Diesel (gal)	0	0	-0.000094	-0.00066	-0.0000086	-0.0000086	-0.0013	0	0	1	0
	Commodity 4 - Electricity (kwh)	0	0	0	-0.083	0	0	-0.3	0	0	0	1
Environmental flows in **B**	Crude oil from the earth (lb)	0	0	0	0	0	0	0	0	-7.0	-7.9	-0.030
	Carbon dioxide emissions to air (lb)	0	0.065	0.0021	0.015	0.00019	0.00019	0.029	0.00000	2.6	2.9	1.6
	Methane, nitrous oxide, and HFC emissions to air (lb)	0	0.068	0.0022	0.015	0.00020	0.00020	0.031	0.00000	0.029	0.033	0.0034
	Land use (acres)	0	a lot, if you consider road and facility construction									

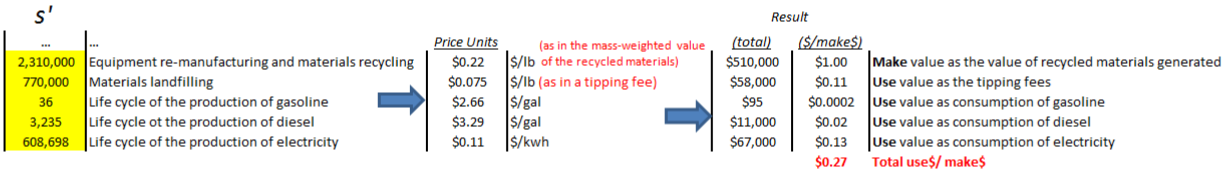
Given this, the scaling vector s' for a *f'* demanding the management of 280,000 units of e-waste is:



f'		*s'*	
280,000	Managed e-waste(units of e-waste)	280,000	E-waste management
0	E-waste dropped off at MRF by residents (ton-miles)	10,780	Residential drop off of e-waste at MRF
0	Collected e-waste (ton-miles)	4,620	Collection of e-waste by diesel truck
0	E-waste to be disassembled (units of e-waste)	280,000	Separation of materials from e-waste at MRF
0	Recyclable materials to recycling (ton-miles)	11,550	Transfer of recyclables by truck
0	Materials to landfill (ton-miles)	3,850	Transfer of materials to landfill by truck
0	Reman. equipment/ recyclable materials (lb)	2,310,000	Equipment re-manufacturing and materials recycling
0	Commodity 1- Materials to be landfilled (lb)	770,000	Materials landfilling
0	Commodity 2 - Gasoline (gal)	36	Life cycle of the production of gasoline
0	Commodity 3 - Diesel (gal)	3,235	Life cycle ot the production of diesel
0	Commodity 4 - Electricity (kwh)	608,698	Life cycle of the production of electricity

with only a very small change in the diesel scaling factor from *s* to *s'* due to the small change from **A** to **A'** in our example (only one cell of the matrix was changed, as highlighted in red).

Finally, we use only a portion of *s'* to make our transition to our regional IO model. Specifically, the *s'* vector estimate corresponding to “materials recycling” represents the weight of recyclable materials “made” in our system, the estimate corresponding to “materials landfilling” represents additional use of regional landfills (as the weight received by the landfill from the new activities), and the estimates corresponding to the life cycles of gasoline, diesel, and electricity correspond to additional energy use in the region. To make the transition to data for use in the regional make-use tables, each of these *s'* vector estimates is multiplied by their commensurate prices, for example as:



s'		Price	Units		Result (total)	($/make$)	
…	…			(as in the mass-weighted value			
2,310,000	Equipment re-manufacturing and materials recycling	$0.22	$/lb	of the recycled materials)	$510,000	$1.00	**Make** value as the value of recycled materials generated
770,000	Materials landfilling	$0.075	$/lb	(as in a tipping fee)	$58,000	$0.11	**Use** value as the tipping fees
36	Life cycle of the production of gasoline	$2.66	$/gal		$95	$0.0002	**Use** value as consumption of gasoline
3,235	Life cycle ot the production of diesel	$3.29	$/gal		$11,000	$0.02	**Use** value as consumption of diesel
608,698	Life cycle of the production of electricity	$0.11	$/kwh		$67,000	$0.13	**Use** value as consumption of electricity
						$0.27	**Total use$/ make$**

Thus, our new industry represents a new column in our regional use table, including $58,000 for landfill operations, $95 for gasoline consumption, $11,000 for diesel consumption, and $67,000 for electricity consumption. The corresponding table in the regional make table would include the production of recycled materials at $510,000. We do note however that our hypothetical data is based only on material and energy prices and landfill tipping fees, and therefore is pending estimates of other business costs.

To provide a comprehensive framework for regional analysis, activities can be further disaggregated. For example, e-waste to be disassembled (in units of e-waste), recyclable materials to recycling (in ton-miles), materials to landfill (in ton-miles), recyclable materials to recycled materials (in lb) can all be split into two activities each, adding suffixes “in-region” and “out-of-region”. Further, local industry supply percentages for materials used in the new activities can be either set to known values, or estimated by regional supply percentage. Finally, outputs of recycled materials generated can be disaggregated by material type.

3. Scenario Construction and Implementation

Once the new use and make table values have been computed, the regional tables can be directly edited. In the event that the estimated values are deemed to represent additions to the economy, a new industry column augments the use table, and a new industry row augments the make table. The values in the use column correspond to commodities used by the new recycling or remanufacturing industry, while the values in the new make row correspond to the regional production of commodities. In the event that the newly parameterized industry values are deemed to have been embedded in the IO accounts within an aggregate industry such as waste management, the new rows and columns still augment the make and use tables, but their values are subtracted from the original, aggregate industry.

Given the IO accounts in absolute value, product inventory estimates, and product life estimates, the forecasts of the numbers of units to be processed as e-waste can be generated. These translate into new values for intermediate demands and supplies of inputs and outputs. A number of alternatives exist for impact model drivers. The first and most straightforward is simply to allow all new output to enter the production system as replacement for imports. This method reflects the consideration of avoided life cycles in LCA (e.g., a remanufactured computer monitor temporarily avoids the need to construct a new computer monitor. Post-adjustment output, employment and income levels can be compared to pre-adjustment levels to determine impacts. However, should total demand for new activity output be less than total new output, a final demand entry corresponding to exports will be required to balance the accounts, a concept that would be reflected in a well-developed, consequential LCA (as in [EKV06]). Likewise, other well-founded final demand forecasts can be used.

4. Discussion

Although the method presented here is highly generalizable, certain differences among remanufacturing and recycling behaviors will require careful attention and potentially some modification to the LCA and IO models. As an example, distinct differences between carpet and e-waste collection behaviors became apparent early on. Whereas e-waste can be delivered by consumers to transfer points (such as retail outlets, waste transfer stations, or community collection events) or can be picked up at businesses, schools, etc., consumers do not tend to deliver waste carpet to any central collection points or recycling facilities. These kinds of differences, not to mention differences in the types of materials and remanufacturing/ recycling processes, must be addressed explicitly when moving from one to another kind of recyclable product.

In our case study, although we have included several of the important aspects of e-waste recycling, we have omitted others. For example, in the interest of brevity we have not included consideration of e-waste reuse and the re-entry of reused and remanufactured equipment and recycled materials into the system. In short, these additions would add to **A** not only columns for a host of upstream and downstream processes to complete the life cycle, but also processes representing the life cycle of new electronics, as reuse and remanufacturing avoids the need for new electronics to be manufactured. Within this same context, the production recycled materials theoretically avoids the need to produce similar materials from virgin feedstocks, which have also been omitted from our example life cycle inventory. Although the implications of these omissions in **A** are also expected to have implications in **A’**, we leave their investigation to future work.

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