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A Framework for Geographically Sensitive and Efficient Recycling Networks

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ABSTRACT *This paper has three primary objectives. First, it seeks to demonstrate that recycling is an important component of sustainable human systems, particularly in the case of electronics, where environmental impacts of disposal are potentially severe. Second, it presents a methodology that could be used to estimate the volumes of electronics or other consumer durable goods that are available for recycling. Third and last, it illustrates, through a case study of Atlanta focused on computers, that metropolitan areas may fruitfully be viewed as opportune centres from which to mine, recycle and reuse cast-off electronic goods. From an environmental and economic development policy perspective, doing so presents an important opportunity to provide new economic opportunities in the most distressed portions of metropolitan areas which have been disproportionately impacted by previous environmentally destructive industrialization practices.*

Introduction

Significant advances have been made in developing the technological processes for remanufacturing and recycling of consumer electronic goods, though much work remains. The environmental impacts of new products have been improved by strategies such as 'design for the environment' for discrete parts manufacture and assembly, and 'green chemistry' for chemical products and processes that generate the material inputs for manufacturing. These efforts have resulted in the development of technologies, as well as technology system assessment and planning tools, that can lower the environmental impact of manufacturing activities. However, the vast majority of all products continue to be made such that they eventually require retirement, either due to their failure or due to their obsolescence. Disposal of electronic goods to landfills is not only costly (in real and sustainable terms) but has also come under increasing fire for its impact on adjacent communities and the limitations closed landfills place upon future development. A sustainable alternative is using cast-off electronic goods as inputs to recycling and remanufacturing.[1] Doing so through an eco-industrial

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system and park sited in distressed areas could prove a promising economic development strategy that promotes urban sustainability, in particular. To this end, the objectives of this paper are, first, to demonstrate that recycling is an important component of sustainable human systems, particularly in the case of electronics, where environmental impacts of disposal are potentially severe. The authors' second objective is to present a methodology that could be used to estimate the volumes of electronics or other consumer durable goods that are available for recycling. The third and final objective is to illustrate, through a case study of Atlanta, that metropolitan areas may fruitfully be viewed as opportune centres from which to mine, recycle and reuse cast-off electronic goods.

The Argument for Recycling

The justifications for recycling are founded upon improvements in environmental and economic performance of industrial systems. While the environmental benefits of recycling were recognized first, there is increasing recognition of the potential to realize economic development benefits. Realizing these economic development benefits arguably presents a greater challenge than that experienced in realizing environmental benefits. The economic benefits are often obscured by current technology and business practices, as well as varying degrees of subsidies of primary production systems. To overcome the power of the incumbent and promote change, legal frameworks that support recycling are being established, particularly in Europe, where 'extended producer responsibility' is a well-developed policy in several countries. Extended producer responsibility includes getting producers to take on the financial responsibility of recycling as well as designing products to facilitate the recycling process. For example, in Europe, Dutch legislation requires manufacturers and importers of electronics to take full responsibility for product take-back systems. Similarly, Sweden has legislation stating that producers of electronics and municipalities have to share the responsibility of recycling and take-back systems (Thorpe & Kruszewska, 1999). It should be noted that take-back systems can result in waste reduction through reuse if the manufacturer is able to supply the intact product to other users.

Environmental benefits accrue primarily in the two areas of waste management and resource preservation. Recycling enhances waste management efforts by reducing the capacity needed for disposal, lowering landfill and incinerator emissions and reducing groundwater pollution from landfill leachate. Americans generate 1.6 million tons (1.45 million metric tonnes) of hazardous household waste (HHW) per year, the leftover contents of consumer products or abandoned consumer products that contain hazardous components. The average home can accumulate as much as 100 pounds (45 kg) of HHW in the basement, garage and storage closets. During the 1980s, many communities started special collection days or permanent collection sites for handling HHW. By 1997, there were more than 3000 HHW permanent programmes and collection events throughout the USA (US Environmental Protection Agency (USEPA), 2001).

Currently, the disposal of consumer electronics accounts for 40% of lead in landfills. Additionally, 22% of the yearly world consumption of mercury is used in electronics (Silicon Valley Toxics Coalition, 1999). More effective recycling would help to eliminate environmental exposure to these hazardous substances.

Recycling also enhances resource preservation through reducing energy use and resultant emissions, reducing extraction and manufacturing process impacts, and furthering the conservation of raw materials.

The initial economic benefits of recycling have been in the cost reduction that industry incurs for waste disposal, and in the direct jobs and firms created to collect and recycle material. However, significant new opportunities for economic development could centre around new manufacturing activities associated with product designs that incorporate higher percentages of recycled materials.

Focusing on initial benefits, an early study in California estimated that recycling could create 20 000 manufacturing jobs and another 25 000 jobs in sorting and processing waste materials, equating to around 1400 recycling jobs per million population (California Integrated Waste Management Board, 1993). A study of actual economic impacts of recycling in the North-east region found firms that undertake recycling or reuse activities employed over 206 000 workers in over 13 000 firms, and had estimated receipts of nearly $44 billion in the region annually (all prices in US dollars) (Northeast Recycling Council, 2001). This translated into a value added per recycling job of over $213 000. Based on these studies, with an estimate of 1400 recycling jobs per one million residents and a US population of 285 million in 1999, the recycling industry could create nearly 400 000 jobs. Further, with a value added per job of nearly $213 000, the monetary contribution to the US economy would equal nearly $850 billion per annum.

Positive and Negative Impacts of Computer Recycling

In 2000, around 51% of US households owned a computer, up from 42% in 1998 (US Bureau of the Census, 2001). There are distinct differences in computer ownership among socioeconomic groups. Computer usage is greatest among high-income households: among households with $75 000 or more income, 88% had at least one computer. Married-couple households have higher rates of computer ownership than do one-person households. In addition, among households with school-age children, two-thirds own a computer. There are also significant spatial differences in computer ownership. Computer ownership is 58% among households within metro areas (but outside the central city). In central cities, the computer ownership rate falls to 46%, while rural areas have the lowest rate at 42%.

By 2005, one computer will become obsolete for every new one put on the market. It is estimated that between 1997 and 2004, 315 million computers will be obsolete, resulting in the discard of: 1.2 billion pounds (over 544 million kg) of lead, two million pounds (907 200 kg) of cadmium, 400 000 pounds (181 440 kg) of mercury and 1.2 million pounds (544 320 kg) of hexavalent chromium. This will also yield additional waste in the form of 4 billion pounds (over 1.8 billion kg) of plastic and at least 350 million pounds (nearly 159 million kg) of brominated flame-retardants from monitors (Silicon Valley Toxics Coalition, 1999).[2]

Clearly, there is a large and growing supply of computers that could enter the waste or recycle supply stream. However, a balanced discussion of the need for computer recycling requires consideration of possible negative as well as positive impacts. A recent study on electronics recycling issued by the Silicon Valley Toxics Coalition, along with Californians Against Waste and Materials for the

Future, explored the benefits and costs of recycling versus taking no action (Smith, 2001). The study particularly explores the negative impacts that can occur if recycling operations are incorrectly regulated. That is, if hazardous materials are not handled properly, the population can experience greater hazards exposure than if the materials were never recycled because of increased exposure to hazardous vapours and materials to which employees of recycling facilities may be subject. A high level of training is needed to ensure proper disassembly without risk of exposure. For example, when electronics are melted to recover metals, both dioxins and furans are released from the plastics that contain flame-retardants. Previous studies have shown that employees in electronics recycling facilities have abnormally high concentrations of toxins in their blood from breathing in dust that contains toxic flame-retardants (Smith, 2001).

Other materials in electronics that cause hazardous emissions are heavy metals such as lead and cadmium; however, pre-treatment of the hazardous waste can reduce emissions significantly. These substances can also pose problems during the shredding process if the electronics equipment is not properly disassembled and sorted. Presently, 70% of heavy metals found in landfills is attributed to electronic equipment. Allowing this trend to continue, that is, not taking action to divert this material from landfills, can only mean much higher future costs of clean-up (Smith, 2001).

While it was previously believed that only about 60% of a typical personal computer (PC) was recyclable (Mann, 1996), a recent report indicates that 95.5% of a computer is potentially recyclable. Twenty-two per cent is recyclable at a high value and 20% at a moderate value; 58% of a PC is toxic, but recyclable, and only 0.5% is toxic waste, unrecoverable (Californians against Waste, 2001). The improved estimate of recyclability may be due to more recent technologies enabling computer manufacturers to assemble computers with recycle-friendly components.

If the process of recycling is regulated thoroughly to prevent more pollution and health risks from occurring, there are long-term societal benefits. The Silicon Valley Toxics Coalition study estimated that, if no action is taken, the total costs of managing cathode ray tubes (CRTs) generated from 2002 to 2006 in California alone could reach more than $1 billion. The average recycling cost per computer unit during this time period is estimated to be $17.50, while the average hazardous waste disposal cost per unit is $30.00. These expenses are included in the total CRT management costs for 2002–06, but other factors also need to be considered. The rapid expansion of the e-waste stream due to certain technologies becoming obsolete will be a major factor in the future costs of environmental clean-up. Computer obsolescence rates illustrate the problem clearly: lifespans of personal computers have decreased from four or five years to approximately two years (Smith, 2001).

On the negative side, another environmental cost to recycling is that of transporting the materials from a drop-off site or manufacturer to a recycling facility. However, combining as many of the steps of recycling into one central location to minimize transport costs can minimize this cost. This approach would still have to consider environmental and economic costs from individuals and companies transporting materials to such a combined facility.

Legislative Initiatives and Pilot Studies Encouraging Electronics Recycling

In the public sector, there are growing indications that the positive benefits of promoting recycling are viewed to outweigh the disadvantages. Legislative initiatives for the disposal of electronics equipment have been introduced in the states of Massachusetts, Wisconsin, Florida, California and Minnesota.[3] Particular attention has been given to computer monitors and televisions due to the hazardous lead contained in the CRTs, as well as their projected obsolescence rates. The new flat panel screen technology increases the likelihood of even higher obsolescence rates for CRT monitors in the near term. Televisions also face higher rates of obsolescence from replacement with new high-definition models. The broadcast industry has committed to using digital signals by the year 2006, meaning that consumers will be required to either switch to high-definition television or obtain a converter box to pick up the digital signal (Federal Communications Commission, 1999).

At the federal level, the disposal of lead-containing CRTs from a non-residential source in landfills not designated for hazardous waste is a violation of the Resource Conservation and Recovery Act of 1976. Any CRTs with lead concentrations greater than 0.05 mg/l fail the Toxicity Characteristic Leachate Procedure, and thus are considered hazardous wastes (Macauley *et al.*, 2001).[4] Currently, hazardous waste regulations apply only to commercial sources of waste and not households at the state level. Additionally, intact CRTs are exempt from hazardous waste disposal requirements in states such as Massachusetts, in order to aid in the establishment of recycling operations by lowering handling costs.

At the present time, Georgia, the state that is home to the authors' case study city of Atlanta, does not regulate the disposal of CRTs or any other electronics waste in landfills. The state also does not regulate hazardous waste from households. Facilities generating less than 220 pounds (100 kg) of hazardous waste each month are 'conditionally exempt small quantity generators', while those companies generating more than 220 pounds of hazardous waste are required to pay a fee (depending on the quantity of waste) and dispose of it under hazardous waste regulations. Therefore, computers and televisions from large-quantity generators would fall under regulation and would be banned from landfills due to the heavy metal content (Georgia Environmental Protection Division, 2000).

To create effective recycling and reuse systems for handling the increasing volumes of material now being generated in various states, the authors focus in the next sections on methodologies for estimating the supply of recyclable material.

Relating Demographics to Recycling Behaviour

To develop a methodology for estimating the volumes of electronics and other consumer durable goods that are available for recycling, we need to be able to predict recycling behaviour. As with most market analyses, this requires understanding segmentation in the market and the different responses associated with different markets. In the case of the research here, the authors seek to understand how different demographic groups of electronics users consume and abandon their equipment. The studies published on the relationship between demographics and recycling behaviour to date focus on traditional kerbside collection behaviour of households rather than consumers' use of drop-off sites and recycling events, the types of collection associated with electronics recycling (Berger, 1997; Owens *et al.*, 2000; Ebreo & Vining, 2001). Of particular interest here is Ebreo & Vining's (2001) study, which surveyed a group of Illinois residents to ask what type of recycling activity they had participated in within the past year. The survey asked whether they had participated in any recycling programme, used a drop-off location or engaged in any other recycling activity. Survey results indicated that 58.3% of respondents had used a drop-off location, within the past year. (However, the type of material recycled was not provided.)

Though not focusing on the collection method proposed in this research, previous studies do have certain value in analysing which demographic variables affect recycling habits. For example, education and income were found to be significant factors in whether or not a resident participated in recycling and other environmental actions (Berger, 1997; Owens *et al.*, 2000). The data that have been collected on participation rates at one-time recycling events may result in one collection method working better than another; however, there is not enough information to deduce that certain methods of collection will be cost-effective in any given scenario.

European studies examining the relationship between recycling behaviour and demographics have not found that demographic characteristics significantly influence a person's recycling behaviour. In particular, a Scottish study compared people who made trips specifically for the purpose of recycling with those who recycled while making a journey for another purpose (Tucker & Speirs, 2001). No significant differences in the demographic profile of the two groups were found except for the modes of transport used. Different socioeconomic and age groups preferred certain transportation (i.e. car, bike, walking) over others. Another noteworthy observation from this study was that the special-trip recyclers were more likely to choose a recycling facility based on its nearness and whether it accepted multiple materials (Tucker & Speirs, 2001).

The Argument for Pre-modelling the Stream of Recyclable Goods

The ability of any business to establish itself, and flourish, is predicated on estimates of costs and volumes of raw material supply and final product volumes and values. Recycling activities have been hampered by instabilities in the market for recycled commodities, as well as a significant lack of information on the volume/cost curves for the supply of the raw input to the recycling system. If the primary source of material was considered to be the wastes from personal consumption, then the municipal solid waste (MSW) stream would be the natural starting point to estimate material availability.

Data from 1998 indicated that MSW reached 220 million tons (200 million metric tonnes), an increase of 4 million tons (3.6 million metric tonnes) from 1997. Of the stream in 1998, about 55% was landfilled, 28% recycled or composted and 17% combusted. (USEPA, 1999c). Durable goods accounted for 15.6% of the 1998 MSW stream, which includes household appliances. Major appliances constituted 1.7% of the 1998 MSW stream and small appliances another 0.4%. The percentage of major appliances recovered was 53.2% and only 1.1% for small appliances.

If we are to realize success more quickly in recycling systems, then careful attention must be paid to avoiding supply and/or demand imbalances. Bottlenecks and oversupply in any economic system cause major inefficiencies and contribute to business and industry failures. With recycling systems, the bottlenecks and oversupply problems come from problems with 'harvesting' or recovering the goods—in the present case, computers—from their former users. To establish an efficient recycling system of harvesting, demanufacture and reuse, it is necessary to be able to estimate with a degree of confidence the amount of computer material that can be harvested. The authors' review of the literature, however, yields little insight into harvesting. The analysis of harvesting is far more complex than simply identifying the number of computers sold, and their functional obsolescence or product failure rates, as the authors discuss below.

Considering Product Availability and Return Models for Recycling

Estimation of harvested computer volumes can be stated in the form of the product return estimation problem as: given a product, how can the number of products returned to be recycled be estimated as a function of time and space? For most products there appear to be three major interacting processes: the distribution of sales; the distribution of retirement; and the distribution of return. The key issue for availability and return estimation models is finding ways to connect these processes to existing company and public information sources on products. A second issue is the scope of the modelling effort. Should it stop at the generation of the product for return or include the return process? It is useful to make the model scope distinct because the inclusion of the return process pre-supposes elements of the recycling infrastructure, the collection strategy and investment and the very significant confounding factor of participation by various demographic and business groups. Thus, the authors will distinguish between *product availability* and *product return* models.

There is very little literature on the estimation of specific product availability and return, but it is an area that recently has started to garner interest. This is in contrast to a significant body of literature on MSW volume and composition estimation; for examples see Daskalopoulos *et al.* (1998), Gay *et al.* (1993), Hockett *et al.* (1995) and Sterner & Bartelings (1999). A model for photocopier return is presented in Marx-Gomez & Rautenstrauch (1999) and for mobile telephones in Europe in McLaren *et al.* (1999).[5] A very detailed approach to consumer recycling modelling is presented in a series of papers by Tucker (Tucker, 1997; Tucker *et al.*, 1998a, b).

The photocopier model considers the prediction of the return volume as a function of time but not space. In other words, the model would have to be combined with a density estimation of the number of photocopiers in a given region and the size of the region in order to predict the total number of photocopiers. The sales model employed was a classical four-stage model, introduction, growth, maturity and decrease. The failure process was divided into several subprocesses, early failure, failure by accident and failure by wear and tear, and assumed to be of a bathtub form for failures per copy.[6] The failure process for the photocopier was mapped to a distribution of failures over time through a distribution of the number of copies per month for the customers. Finally, the return model was assumed to yield a uniform probability of return of a failed product. This model has a general structure as depicted in Figure 1, where product returns are depicted as a function of time, f(t).

An important contribution of this model is the decomposition of the product return process into different subprocesses for which there is a reasonable chance that data exist. It is clear that product sales over time are often available to a company directly and, hence, an explicit sales model may be unnecessary depending on the availability of these data from companies. A manufacturing

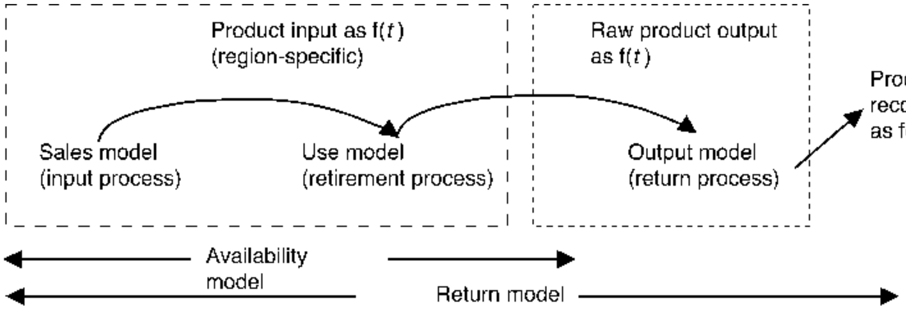

Figure 1. Availability and return models: general structure.

company will often have failure information available due to reliability testing required by law or for quality assurance. Finally, a distribution of use of the product may be available through customer contracts combined with market survey information gathered on it and similar products.

The mobile phone study in McLaren *et al.* (1999) demonstrated the effects of changing patterns of use, and of the materials in a product, on the overall recycling system. The model to generate the outflows for telephones utilized the same framework as the other studies: sales process, use process and disposal. It added a further accumulation in the model, the 'bottom drawer' or 'hibernation stocks', to represent the material that consumers do not throw away after the use phase, but which are stockpiled before disposal at some significantly later time. For mobile telephones, the important transient effects are: the growth in the number sold, from fewer than 1 million in the UK in 1993, to around 6 million in 1999; the decline in the use life; and the decline in phone weight from over 1.5 kg prior to 1992 to 0.13 kg for a current phone.

The above models do not account for the sociodemographic variations and clusterings that may be predictive of both purchase and disposal behaviour. They are concerned with modelling either at a scale that is below that of a metro region in the case of the photocopier study, or above it in the case of mobile phones in Europe and polyvinyl chloride (PVC) in Sweden. Further, they are concerned with predictions in time scales of years.

The models of Tucker (Tucker, 1997; Tucker *et al.*, 1998a, b), on the other hand, are specifically designed to account for spatial and temporal variability in recycling performance of households. Tucker postulates a two-dimensional classification of demographic segments based on housing type and stage of family life-cycle. This classification parameterizes a model of recycling behaviour for each household in a region, where the region can be as small as a street. The model then predicts the participation in recycling schemes and hence the volume of material collected. This is a true return model, because most of the detail of the model is in predicting the participation in recycling rather than in the generation of material that could be recycled. The time scale of the prediction is much shorter than that of the other models, two- to eight-week periods over a horizon of a year. In addition, the model attempts to predict not just averages but also the variation in the levels of participation and, hence, volumes collected. Overall, the model was relatively successful in matching data for paper collection in an urban region of Scotland. The average was close to the real data, and the variability was somewhat underpredicted.

The key difference between this model and the authors' requirements is that the frequency of waste paper generation is relatively high and thus a collection scheme is feasible. For small consumer durables, such an approach is unlikely to work because the infrastructure costs will be very high (USEPA, 1998). This implies that the required models of recycling behaviour at the consumer level will need to be different. The significance of this is that the sociodemographic variables of housing type and stage in family life-cycle are available from census data. This motivates an approach that combines the strengths of the models that utilize explicit descriptions of product lifetimes, and material balance concepts, with sociodemographic models of household behaviour.

Methodological Approach for Product Return Estimation

The authors' overall methodology follows Figure 1. It will focus on the prediction of product availability, and will help provide information to model the product return process. The basis of the approach is the following observation: if we knew the purchase of electronic goods of a given region, and the failure and obsolescence rates of those goods, we could predict the availability of those goods for recycling in the future. The authors hypothesize that the purchase and obsolescence rates for products are determined by the lifestyles of the households within the region, and that the failure rate for products is well known by their manufacturers. Furthermore, the authors assert that the purchase rates for products for different sociodemographic groups are known by marketing companies and available in commercial databases, and that the patterns of those households in a given region are also known.

Material Stream Estimation Methodology

There are essentially three direct sources of information that are available for estimating material streams for recycling: inputs, outputs and stocks. We can use a general mass balance equation (Felder & Rousseau, 1999) to link this information together for a specific system:

$$\text{INPUT} - \text{OUTPUT} + \text{GENERATION} - \text{CONSUMPTION} = \text{RATE OF ACCUMULATION}$$

We can assume that the materials embodied in electronic goods products are, in general, not transformed by their use and hence simplify the equation to:

$$\text{INPUT} - \text{OUTPUT} = \text{RATE OF ACCUMULATION}$$

Input of material can occur through two different mechanisms. First, there is the sale of products to the existing population. Second, the immigration of population to an area may have material associated with it. Similarly, the output of material can occur through the retirement of products or through the emigration of people. The accumulation term in the above equation could be regarded as the dependent variable from a causal standpoint and hence we do not need to find independent causes for this term. However, it might be useful to regard elements of the output as the dependent variables and seek causes for changes in the rate of accumulation in some circumstances. The overall flow for a given region is pictured in Figure 2.

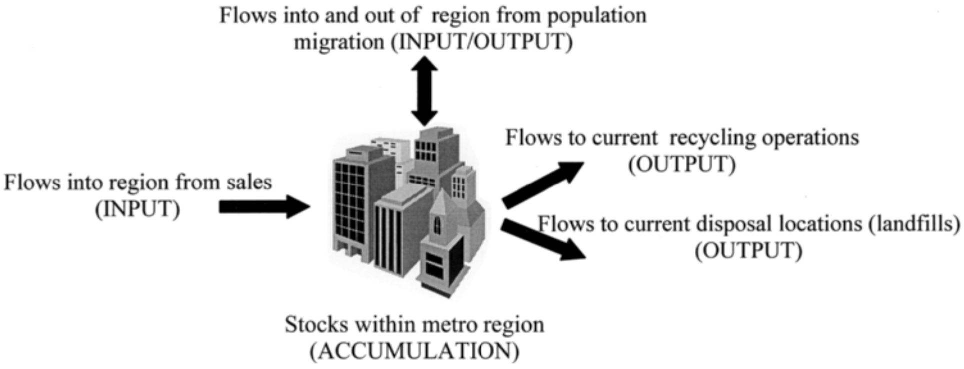

Figure 2. Metro region material balance terms.

The difficulty with finding the terms in this equation is that it is nearly impossible to observe both the input and output flows, or to observe the rate of accumulation and one flow, for every metropolitan area in the USA over long enough time periods to establish the balance directly for a range of different products. Furthermore, if one is seeking a *predictive model* of material output streams, observing current outputs does not help in prediction. Thus, the authors see the value of the material balance equation as its use to validate a predictive model. This leads to trying to establish indirect sources of information that might be correlated with these flows and calibrating the correlations for representative regions through the flow balances. The indirect information can then be obtained for other regions and the flows predicted based on the correlations. This research methodology is described in more detail below and an overall scheme of how the elements in the balance may be related to other quantities is shown in Figure 3.

Input Flow Modelling

In general, the immigration portion of the flow will be small compared to the rest of the input stream, since populations in the USA are relatively stable. Census data should be able to provide estimates of population changes for a given region and then the stock of goods that a particular immigration unit brings with it can be estimated through the same means described below.

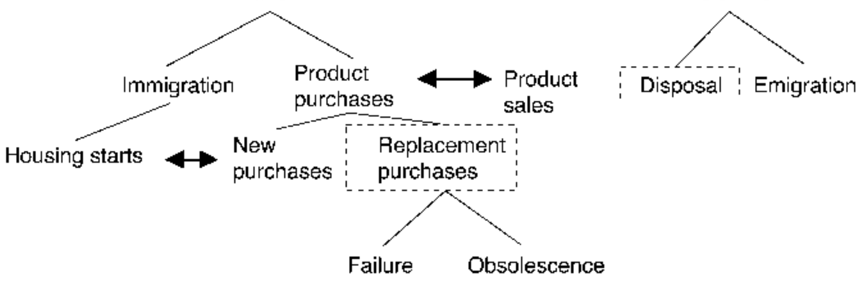

Figure 3. Balance terms and their potential estimation.

The sale of products can be further analysed as two subprocesses. The first is purchase for replacement and the second is new purchases. Purchases for replacement are driven by two mechanisms, failure and obsolescence. Marketing studies and surveys can provide a rich source of information on the purchase decisions of different demographic groups (Weiss, 1988, 2000). This information can be combined with demographic analysis of a region, to estimate the regional purchase decisions over a period of time. If the population is large enough, and the time scale long enough, then the initial state of the product age distribution will follow a normal distribution by the law of large numbers and reasonable estimates obtained.

Output Flow Modelling

The output process is correlated with the input process through the mechanisms of product failure and obsolescence. Product failure is often known by manufacturers and characterized by any one of a number of statistical processes, such as a Weibull or normal distribution. Sometimes the failure data are related to use, such as the number of times the product is switched on and off, or the hours it is left on; these data must be combined with the use pattern of the product to find a distribution of failure with time (Marx-Gomez & Rautenstrauch, 1999). Product disposal through obsolescence is more difficult to analyse. The authors' investigation of data sources indicates that obsolescence rates on electronics products by demographic group are likely only to be attained through private subscription market analysis.

Accumulation Modelling

In accumulation modelling, a steady state assumption is often applied to the balance between input and output. This implies that the rate of accumulation is zero and that input = output. This assumption will hold over long periods, but on the time scales of human development, the transient accumulation of material can be significant (Kleijn *et al.*, 2000) and often reflects an increase in the level of wealth or population of the particular area. If steady state is achieved in terms of the demanded function that the products fulfil, then all inputs are for replacement, and the rate of accumulation is again zero. This might be the case for a mature product such as stereos. There are several caveats to this statement. First, in electronic products, there are and continue to be rapid innovations in the function provided. As an example, in the next five to ten years digital televisions are likely to be introduced on a large scale, leading to a significant 'burst' in the retirement of what otherwise might be regarded as a mature product with a steady state retirement behaviour. This reflects the immediate obsolescence induced by the introduction of a new product function that meets the same consumer need. Second, despite the output being numerically equal to the input in steady state, the composition of the products may change over time. For example, though electronic products currently contain lead solder, it is quite likely that this will be phased out, leading to a changing profile of lead concentration in the output stream over the next decade or so.

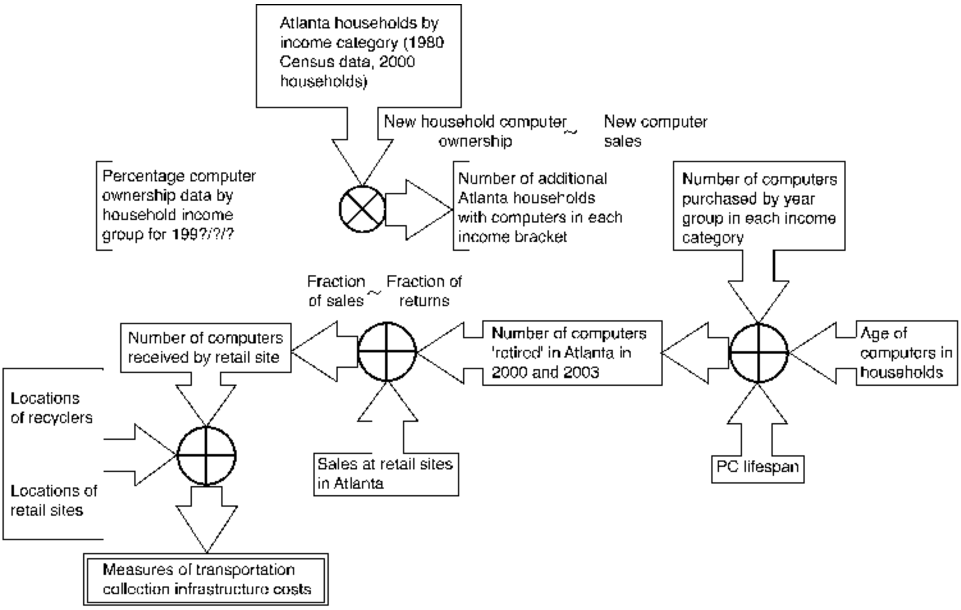

Figure 4. Atlanta computer recycling return model.

Atlanta Model of Household Computer Obsolescence

The authors have developed a model for the Atlanta metropolitan area that estimates the yield of obsolete computers to be recycled and the distances travelled to return the supply of obsolete computers to recycling centres for the years 2000 and 2003. These are two critical steps in developing a robust computer recycling model. The model has three primary areas of estimation: demographic, retail performance and geographical. The demographic component requires estimating household computer ownership. The retail performance component requires estimating the total volume of computer sales and sales per retail outlet. The geographical component of the model focuses on a computer recycling collection system for a specific geographical area, the Atlanta metropolitan region, and distances travelled for recycling collection between actual points—retail outlets and recycling centres—within the metro region (Figure 4).

The first step is to estimate the rate of computer ownership among the Atlanta household population. The authors obtained national computer home ownership rates from special studies of the Census published for ownership prior to 1992 and the years 1993, 1997 and 2000 (US Bureau of the Census, 1993, 1999, 2001). These data provide the percentage of households by income category that owned *a* computer. Essentially, the data indicate over time how the rate of household computer ownership has increased. They do not, however, indicate whether households are multiple computer owners, or whether a computer purchase is a first-time event or made to replace an obsolete computer (Table 1).

From the overall number of households in Atlanta obtained from the 2000 Census, the authors estimated the distribution of households across income categories applying the distribution of households by total money income for metropolitan areas from the March 2000 Current Population Survey (US Bureau of the Census & US Department of Labor, 2000). Assuming one computer per household, the authors applied the national rates of computer ownership by household income level to estimate the number of computers

Table 1. Computer ownership in Atlanta households

Income category	< 1992	Number owning computers 1993	1995	1997	2000
Less than \$15 000	2 000	2 400	6 900	13 100	48 900
\$15 000–\$24 999	2 500	2 800	8 600	14 800	52 400
\$25 000–\$34 999	4 200	4 400	13 500	25 300	79 400
\$35 000–\$49 999	7 100	8 600	25 800	38 400	122 500
\$50 000–\$74 999	10 700	13 800	41 900	64 300	182 900
\$75 000 +	10 100	16 000	54 800	96 800	230 400
Total	36 600	48 000	151 500	252 700	716 500

purchased by each household income level for the Atlanta metro area for five points in time: prior to 1992, 1993, 1995, 1997 and 2000.[7] From the difference in ownership levels between the survey years, and with the above assumption of one computer per household, the authors can calculate the distribution of the age of the stock of computers in the household categories (Table 2). This is simply the difference between ownership levels from one population survey to the next. It is impossible to resolve the age any closer than two years from this approach and the authors assume the survey year to be the year of purchase. Thus, the authors assume that the increase in numbers of computers owned determined for each of the three years in Atlanta represents new computers being added to the overall stock.

The next step is to use the age profile and the lifespan of personal computers to estimate the number of computers that will be retired in the future, or, in the present case, for 2000 and 2003 for comparison purposes. The authors use a personal computer lifespan of three years, regardless of income category, although with more refined consumer data the lifespan could be varied by income group. It can be seen that the exponential growth in home computer ownership over the 1993–2000 period translates into exponential growth in the stock of obsolescent computers that could be recycled between 2000 and 2003.

The authors' basic return model assumes that home computer owners will return their obsolete machines to computer retail outlets. The authors assign the purchase of estimated total computer sales for the metro Atlanta household population to 64 retail outlets that the authors identified through Dun and Bradstreet and Atlanta Business directory data.[8] They then distribute the total volume of computer sales to households across the 64 retail outlets based on

Table 2. Estimated age of Atlanta computers owned by household income levels

Income category	Seven	Computer age (years) Five	Three	New (2000)
Less than \$15 000	400	4 500	6 200	35 800
\$15 000–\$24 999	300	5 800	6 200	37 600
\$25 000–\$34 999	200	9 100	11 800	54 100
\$35 000–\$49 999	1 500	17 200	12 600	84 100
\$50 000–\$74 999	3 100	28 100	22 400	118 600
\$75 000 +	5 900	38 800	42 000	133 600
Total	11 400	103 500	101 200	463 800

their history of retail sales.[9] That is, the authors calculate the fraction of total sales that each store has and then assume this will be the fraction of obsolete computers returned to the store in a collection scheme. Thus, the fraction of sales were multiplied by projected retirement rates for the years 2000 and 2003, assuming a 100% participation rate by owners of obsolete computers. This yielded the number of retired computers that will be returned to each retail outlet.

To compute the distances that must be travelled by the recycler to collect the obsolete computers, the authors used geographic information systems to calculate the distances between the 64 store locations and six recycling centres for computers located in the metro region. The authors assume the obsolete computers will be returned to the nearest recycling facility. The number of trips per month the recycler must make to collect the computers is determined from the authors' estimates of each store's volume of computers. A standard 48 foot (14.63 m) trailer has a volume of 3456 cubic feet (97.86 m^3) and can hold approximately 40 000 pounds (18 144 kg) of computer equipment. From this the authors could determine that the smallest retail outlets are projected to have less than a half-trailer of computers to be collected while the largest outlets would have filled 22 trailers in the year 2000. By the year 2003, the smallest stores will fill two trailers and the largest will fill 101 trailers. Clearly, this indicates that the choice of collection method should vary between stores. It is unrealistic to assume that the smaller stores will stockpile computers for a year or more before a pick-up of a trailer is made. More realistic would be the use of smaller containers for these stores or a pick-up that involves hand loading the computers from a storage point. Thus the authors assume that, regardless of the number of computers brought back to a retail site, one trip per month to the site is required.

The sensitivity of the model's results is determined by three variables. The first is the assumption of the participation rate of the households in returning their obsolete computers to their place of purchase. The authors assume 100% participation in the example described above. If the rate were 50% or 10%, then the volume of computers to be collected would be much lower and would affect the frequency and cost of collection. However, the effect is not linear with the participation rate—or with any change in the volume of computers. There is significant 'sunk cost' in making a trip to a given location, and the discrete nature of the capacity of the pick-up means that volumes could increase significantly without incurring extra trips. A decline in numbers would not change the overall cost, but would dramatically affect unit cost. This is why, although the volume of computers to recycle nearly triples from 2000 to 2003, the number of trips increases by only a factor of a half.

The second variable to which the results are sensitive is the estimate of the number of obsolete computers per household. This will be affected if the retirement life of the computer is less than or greater than the authors' assumed three years, and if households own more than one computer. The decreasing relative cost of computers will almost certainly cause the rate of obsolescence to increase among certain demographic groups. Whether or not this increased rate immediately leads to higher rates of retirement will depend on factors such as the number of persons in the household, but eventually this will feed through to higher numbers of computers to recycle in a given period.

The final variable is the number and location of stores. On the one hand, the current study could be underestimating the number of stores that receive computers because it did not cover all retail sites, and hence there is likely to be even wider dispersal of the computers over retail sites. On the other hand, as it is unlikely there will be a 100% participation by stores that sell computers, the authors' estimates could be reasonable.

Policy Implications and Future Work

The authors have presented the first two critical steps—estimating the yield of obsolete computers to be recycled and the distances travelled to return the supply of obsolete computers to recycling centres—that are required to develop a robust computer recycling model for a specific geographical area. The authors have shown in their partial model how three primary areas of estimation can be satisfied for the Atlanta metropolitan area using secondary public and inexpensive private data sources.[10] The authors believe their data demonstrate the validity of undertaking this exercise to further the state of geographically sensitive product return models. Obsolete computers that are not recycled or reused will ultimately be discarded: the authors' estimate for Atlanta indicates that there will be exponential growth in discarded computers from an amount that would fill 146 trailers in 2000 to 671 trailers in 2003.

Creating a robust household computer return and recycling model requires many more steps. These include improving the estimation of the supply of obsolete computers to take into account multiple computer ownership by demographic characteristics, and distinctions in obsolescence or retirement patterns for single computer owners versus multiple computer owners. The authors' model has assumed 100% recycling rates among home computer users to translate product availability to recycled quantities. The authors acknowledge the dependence of the results on this assumption. A more robust approach would model the effectiveness of different kinds of incentives provided to the households to recycle. These can be characterized under carrot (payment for the obsolete computer) or stick (banning from landfills) approaches. In a computer recycling pilot in Somerville, Massachusetts, computer owners were required to pay a fee to recycle in the first year (USEPA, 1998). Dropping this fee in the second year raised the rate of recycling significantly, although it still was quite low. From a sustainability perspective, the authors' assumption of a virtual 100% recycling rate would be the objective. Evaluation of the cost and benefits of different approaches to attain this goal would need to consider legislative approaches, market approaches and the role and responsibility of computer consumers versus manufacturers and sellers.

With regard to cost recovery, the computer recycling system must be paid for one way or another. Here again, a cost–benefit analysis of a purely market approach versus a publicly subsidized approach versus a private–public combination approach is required. If the policy objective is to create a computer recycling system at a specific geographical scale to meet other policy objectives such as inner city redevelopment, understanding the sensitivity of transport costs is especially necessary. For example, to maximize the collection system's efficiency, a more centralized collection system (e.g. focusing on a subset of larger stores) may need to be encouraged over a more decentralized system involving all stores, large and small. To facilitate such an objective, it may be necessary to levy a fee on the sale of computers from all stores, and revenue from stores not participating in the collection system would help cover the costs of the participating stores.

The framework presented in this paper represents the first steps towards a planning tool for geographically sensitive and efficient recycling networks. By identifying a specific spatial focus, the authors seek to illuminate the necessity and opportunity that engineering and other industry efforts have to promote sustainability for those social groups and geographical areas most negatively impacted by past unsustainable industry practices. During the prolonged growth period of the national economy and unprecedented low unemployment rate of the previous decade, prosperity was not distributed evenly and there were, in fact, widening disparities between inner cities and the rest of the nation (US Department of Housing and Urban Development, 1999). The authors also seek to encourage environmental planners and policy makers to consider the possibilities of promoting economic development activity through recycling and reuse projects that can help to meet the needs of communities of colour in inner cities previously adversely impacted by industry waste disposal practices.

These distressed communities are in need of stronger and more diversified economic bases, new firm development, new sources of employment and strategies to reuse existing industrial infrastructure, as well as remediation of, and new uses for, brownfields. They have historically experienced the greatest negative externalities from landfill sitings due to the fact that they have, or are near, the inexpensive land upon which such landfills were placed.[11] However, inner cities are located within the major centres of population and business that will be the primary providers of the inputs, such as computers, to the durable goods recycling industry. They, therefore, now present the opportunity to replace previous unsustainable economic development practices of promoting landfills in these areas with sustainable practices of durable goods recycling. At the same time, the resources of inner cities can provide a competitive advantage to companies engaged in recycling, demanufacturing and reuse. Slovinski (1998) identifies these resources as those of extensive transportation infrastructure systems, large supply of underutilitized skilled and low-skilled labour and strong research capabilities in urban universities that can assist with needed technology innovations.

Finally, this paper has sought to justify and describe a multidisciplinary approach to modelling product recovery flows. It is through this multidisciplinary approach that a sustainable solution can be most effectively realized. While the authors provide only a partial model, they have presented a broad discussion of the complex and extensive range of factors that must be considered in order to develop a robust model for recycling, demanufacturing and reuse at a specific geographical scale. In further research, the authors hope to extend the modelling effort, successfully demonstrating the efficacy of a structural economics approach (e.g. specifying distinctions in household consumption patterns (Duchin, 1998)) to estimating consumer durables recycling streams for computers at a geographically sensitive level. By situating the development of a robust modelling effort within a specific geographical area, the authors hope to contribute to economic development planning tools that can be employed to the benefit of those geographical areas, such as inner cities, most in need of attention.

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Notes

1. Resolving the national problem of waste management is a complex problem requiring a multifaceted solution. Within the national hierarchy of waste management procedures, reduction of waste at the source is most preferred. However, recycling and reuse are preferred waste management procedures over landfill disposal. Reuse has a smaller environmental consequence than recycling or remanufacturing, as the object is simply reused in its present form—thereby extending its usefulness beyond that of the original owner. Eventually, most products (especially electronics) do become obsolete for any user. At this point, recycle and remanufacturing activity prevents the product from being landfilled.
2. These are underestimates because they do not take into account computer towers or printed wiring boards (PWBs).
3. See for Massachusetts, Macauley *et al.* (2001), Northeast Recycling Council (2001); for California, California Department of Toxics Substances Control (2001); for Minnesota, Minnesota Pollution Control Agency (1999), Hainault *et al.* (2001); for Florida, National Recycling Coalition (2001), Clarke (1999), Online Sunshine (2001).
4. This test, "intended to simulate a 20-year decomposition process in a landfill", involves crushing the monitor and testing for leachabililty of materials. Colour monitors typically fail the test and have to be treated as hazardous waste, while monochrome CRTs do not (Macauley *et al.*, 2001).
5. Keijn (2000) presents a model for PVC availability which the authors do not discuss here.
6. Bathtub form refers to the shape of the probability of failure at a given point in the product life—high and declining at the start followed by a stable low probability with then a rapid rise towards the end of the life.
7. Because the authors do not take into account replacement computer purchases or multiple computer purchases by household, they are probably underestimating the total number of computers owned by Atlanta households.
8. The authors are unable to verify that this is the total universe of retail outlets selling computers in the Atlanta metro region because, in the case of Dun and Bradstreet data, outlets with substantial computer sales may have self-identified with a sales category other than computers as their primary commodity.
9. The authors determined sales per store of the 64 outlets that are part of national chains from TWICE: This Week in Consumer Electronics (2000). For stores in Atlanta that were not part of the top 100 the returns were estimated based on their similarity in size and type to those included in the top 100.
10. An avenue for future research would be to seek the co-operation of computer manufacturers and retailers for obtaining direct production, distribution and market data.
11. For example, during the Olympic building boom in downtown Atlanta in the early 1990s, it was discovered that the Atlanta housing project, Herndon Homes, had been built on landfill containing slag and other toxic chemicals. (Gordon Sprewell, Atlanta Housing Authority, personal interview with Nancey Green Leigh, 21 August 2002). Another Atlanta Housing Authority property, Perry Homes, was built next to a municipal-owned landfill.

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