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Abstract. Recycling and remanufacturing activities are gaining in importance, as a growing population and economy use up and wear out modern products, exhaust landfill capacity, threaten the environment, and discard potentially valuable and increasingly scarce resources. As an example, an estimated five billion pounds of carpet were sent to landfills in 2003 (CARE, 2003). Likewise, Americans discard computers, cell phones, LCDs and other electronic devices at an alarming rate. Estimates range from 100 to 250 million such items each year. As discard volumes rise and as resource scarcity becomes more critical, recycling, re-use, and remanufacturing have begun to take hold at ever more substantial scales. To understand the implications of these activities for economic development and sustainability, new methods of tracking their impacts must be developed. While at first blush it might be assumed that these activities could be modeled as could any other new industry, a number of characteristics peculiar to recycling and remanufacturing complicate the process. This paper enumerates a number of such dimensions of recycling, re-use, and remanufacturing, and lays out a scheme for extending the traditional approach.

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Introduction

As global population rises, economies develop, and precious resources become dearer by the year, recycling, reuse, and remanufacturing become necessities not options. Global population now exceeds 6.6 billion[1] and is projected to reach 9 billion by 2042.[2] The population of the United States alone has now topped 300 million, with a 50 million population increase expected within less than 20 years. Growth rates in real gross domestic product are at record levels, with a global rate of growth exceeding 5.2 percent. The economies of sixty two nations are growing faster than the US, and countries like India and China are doubling and tripling the US growth rate.[3] As an example of increasingly scarce resources, the price of metals jumped just over 40% from 2000 to 2005.[4] These trends heighten the awareness of sustainability issues, and underscore the increasingly important role that recycling, reuse, and remanufacturing will have to play in our economic futures.

Accompanying the economic concerns these conditions create are concerns with the environment. As examples, an estimated five billion pounds of carpet were sent to landfills in 2003 (CARE, 2003). Not only is this level of disposal stretching the capacity of our landfills to the limit, but the composition of carpet materials represents an environmental threat to society. Likewise, Americans discard computers, cell phones, LCDs and other electronic devices at an alarming rate. Estimates range from 100 to 250 million such items each year. A number of the chemicals and materials involved in such electronics are known to be toxic, and due to the production processes involved, another set of chemicals and compounds is not even clearly identified. As the volumes of such discards rise, we face critical issues of environmental quality and sustainability. Again, a partial solution must lie in recycling, re-use, and remanufacturing, from paper and plastics through glass and metals.

More fully understanding the economic and environmental consequences of these post-consumption activities requires the development and extension of models of economic systems that can track economic interrelationships and volumes of material flows. This paper identifies a number of issues that must be addressed in formulating useful models of this type. We begin with a brief review of some existing approaches to economic and environmental models, and

[1] http://www.census.gov/
[2] http://www.infoplease.com/, original source: U.S. Census Bureau, International Database.
[3] https://www.cia.gov/library/publications/the-world-factbook/
[4] The Economist's commodity price index http://www.economist.com/media/pdf/monthly.pdf.

then identify a number of complexities in modeling recycling and remanufacturing, and follow this with a formulation that should enable the explicit tracking of material flow within a regional economic system.

Review

Although the linkage economy and environment in input-output (IO) models has a much longer history, the last two decades have seen the rapid development of an extensive literature in industrial ecology involving the application of input-output models to eco-industrial issues. An overview of this voluminous literature lies well beyond the scope of this paper, and in any event would largely duplicate an excellent recent review by Suh and Kagawa (2005) in a special issue of Economic Systems Research on industrial ecology and input-output economics.[5] In brief, input-output analysis has been combined with materials flow analysis (MFA), life cycle assessment (LCA), and ecological network analysis (ENA), and mixed IO and physical units IO models (PIOTs) have been developed and constructed to address environmental impacts. Our work differs from the bulk of this literature in the combination of a) attempting to model recycling, re-use, and remanufacturing consistently within a monetary IO framework, b) in its focus on specific these activities within a systems model, and c) in the emphasis on waste products as outputs of industrial and household activities to be used by industries or final demand rather than as discardable wastes only.

Early consideration of the recycling and remanufacturing problem context led input output modelers to approach system-wide representation of recycling and manufacturing industries by modeling them as other new industries have been modeled in traditional analyses. To this end, the state of Iowa was among the first government agencies to move proactively when they engaged RW Beck to conduct a study of the economic impacts of recycling in Iowa. The input-output portion of their report, which was first released in 1997 and updated in 2001, essentially treated recycling activities as new industries, substituting new industry output for inputs that would previously have been imported. They adjusted their IMPLAN-based input-output tables to accommodate the introduction of the new industries and the relationships among these new industries and existing industries. Their study was based on an extensive survey process for gathering primary information on the value of recycled materials entering the Iowa economic system (RW Beck 2001b, RW Beck 2001a, RW Beck 1997).

[5] Hence, we provide only a very brief mention of some direct precursors to the project we report on in this paper.

Shortly thereafter, Ferrer and Ayres (2000) developed a formalized method for assessing the impact of remanufacturing in the economy. Their method extended beyond the traditional boundaries of input-output analysis, incorporating implications of price differences between recycled materials and original product, for example. However, their modification of the input-output modeling framework took as its foundation an interindustry framework, ignoring the realities of the accounting frameworks within which modern, monetary-based input-output analysts must work: namely the commodity by industry accounts.

Others in industrial ecology took the approach of combining input-output analysis with lifecycle assessment (Kondo and Nakamura 2005, Kondo and Nakamura 2004, Nakamura and Kondo 2002, Nakamura et al. 2007). Most of the work in this area focused on the end-of-life cycle for a specific product type, but without the present focus on system-wide economic consequences. Notable in contrast to these studies are the economic- environmental modeling efforts of a research team led by Lave, Hendrickson and others at Carnegie Mellon University (Lave et al. 1995, Hendrickson et al. 1998). This team developed a web-based application for assessing environmental impacts for a wide variety of pollutant and emission variables of changes in overall economic activity first at the national level, then later for West Virginia and Pennsylvania regions. While comprehensive in its treatment of environment-economy linkages, the focus of this work differs again from the present focus on system-wide economic consequences of newly introduced recycling and remanufacturing activities and industries.

Issues specific to recycling/remanufacturing (R/R) in IO

An important question that arises early when taking an input-output approach to modeling post-use production activities concerns the ways in which these activities and materials are currently represented in the IO modeling framework. Those familiar with published input-output tables will be aware of the "scrap" industry that appears in the benchmark US input-output tables published by the Bureau of Economic Analysis (1995). Upon first consideration it might seem that this would be a functional working category for materials that are to be recycled, re-used, or remanufactured. However, three problems arise. The first lies in the reporting and accounting problems in the collection of primary data, the second lies in the structure of the accounting framework itself, while the third concerns the activities involved in the process of moving to waste from its point of production through its availability for next use.

In a seldom cited but quite useful and informative report of the U.S. Geological Survey, Swisko (2000) identifies a number of problems related to both reporting and accounting.[6] While the focus of his work was manufacturing generated metal scrap, his experience is relevant to the identification of problems surrounding rigorous material flow analysis of scrap more generally. In launching the discussion, he begins by providing the formal definition and treatment of scrap in the benchmark tables:

> Scrap is usually defined as pieces and fragments from manufacturing or discarded manufactured articles and parts that can be reprocessed or reused. In the 1992 U. S. input-output tables, the most recent benchmark tables produced by the Bureau of Economic Analysis (BEA), U.S. Department of Commerce, scrap is part of broad commodity group I-O 81 …. (Berechman, Ozmen and Ozbay) consists of sales of scrap sold by manufacturers, plus sales of used and secondhand goods and equipment by all segments of the economy, plus the imported values of scrap and used and secondhand goods that are resold in the United States. For the 498-industry input-output tables, the most detailed industry level, I-O 81 is split into two commodity subgroups, Scrap (81.0001) and Used and Secondhand Goods (81.0002). (Swisko 2000, p. 1-2)

He identifies a significant problem with the Census of Manufacturers itself, stating that the reporting of scrap sales in general seems to have deteriorated over time, implying that the quality of the scrap sector estimates in general has declined. Swisko then turns his attention to providing estimates of the missing scrap values. More relevant to the modeling of specific reuse and remanufacturing activities, however, is the composition of the scrap commodity as it appears in the accounting frameworks.

While scrap appears as a commodity in the Make and Use tables, there is no corresponding scrap industry. This is because industries are identified and named on the basis of their primary products, and there is no industry for which scrap is that primary product. In all cases then, scrap is generated as a byproduct of the production process. Hence, there will be an entry in the most row cells of the scrap column of the Make table, and there will be entries in many columns of the scrap commodity row of the Use table, but no scrap industry appears in either. Further, because of the range of industries that generate scrap as a commodity in the production process there is a large variety and wide array of materials embodied by the scrap

[6] Some of the following discussion of reporting draws liberally on the Swisko (2000) contribution.

estimates in the input-output accounts. The use of any given scrap material is impossible to identify from the benchmark accounts alone.

Benchmark input-output tables provide data for current account expenditures and transactions. For this reason, there are no data published in the make tables for the used and secondhand goods sector "for the obvious reason that such products are made during earlier years, not during the year for which the input-output tables are constructed" (p. 3). This is an issue that clearly will have to be dealt with in any *comprehensive* solution for modeling post use economic activities. This will require a conceptual redefinition of the process of use and secondhand goods production.

Technology Assumptions

Whereas the simple reporting of Make and Use data requires no behavioral assumptions, the transition to the input-output modeling framework does. To generate the kind of solvable structure most commonly used, the modeler must make a two-part assumption about the nature of the production process itself. The first of these is that there will be a fixed and linear relationship between commodity inputs and industry outputs, and is reflected in the process of standardizing the Use matrix. The second part of the assumption also addresses the nature of technology, and is manifested in the selection of either industry-based or commodity-based technology relationships. Specifying industry-based technology implies that industries will produce both primary and secondary commodities with the same fixed input structure. Restated, industries have a fixed input structure, and secondary commodity outputs can be considered to be byproducts. The commodity-based technology instead implies that each commodity is produced with the same unique commodity input structure regardless of which industry produces that commodity.(Swisko 2000, Miller and Blair 1985). Hence, the production of any commodity, whether primary or secondary, requires proportional increases in the inputs required for its production.

Consider the implications for modeling a scrap or waste commodity like used carpet. In this instance, it would be the case that in an average year most industries, and indeed, households as a group, would generate carpet scrap, or “post-use” carpet. The level of carpet scrap produced by each can be considered to be a byproduct of their regular production operations. The amount of this byproduct will be a function of the overall level of each activity, rather than the outcome of a specific decision to produce more scrap according to any particular production function. This production relationship is more consistent with the industry- rather than commodity-based technology assumption.[7]

Dietzenbacher (2005) argues that as by-products, wastes should not be treated as outputs of industrial processes. However, this follows a discussion of the justification for including any entries in input-output accounts based on whether they are to be used downstream by other industries or by final demand. In the case of wastes that are indeed destined for future use, both arguments are countered. Given their future use destiny, materials like carpet scrap no longer fall into the waste discard class but instead become outputs by definition. Nevertheless, Dietzenbacher's position that wastes are essentially by-products also supports the choice of the industry-based technology assumption in recycling, reuse, and remanufacturing modeling (although this in no way implies his general support for the industry-based technology assumption).

Environmental Impacts

If only industries are added, any direct information on commodities collected and processed will be lost. To extend a model to provide more complete information on commodity flow and use by commodity – information useful for understanding the physical side of the system – it is necessary also to establish and track new commodities by value, so that flows of these commodities can be traced explicitly. To accomplish this, we establish two industries and two commodities, using carpet as an example. The two new industries are Collectors and Processors. Collectors harvest "post-use carpet". They bundle and provide very minor sorting services, then sell "collected carpet" to Processors, who convert this to usable commodities (e.g., plastics, carpet backing, etc.). By taking this step, we can add commodity by commodity frameworks to interindustry frameworks for impacts modeling. This step enables an explicit accounting of commodity use in production, and a more direct conversion to physical flows.

Challenges

Recycling and remanufacturing are in many ways different from most traditional industries. In the first instance, their inputs are not provided by other industries in traditional ways. Most industries purchase their input materials from other industries that can increase or decrease their production according to demand fluctuations. In this sense, the Collector

[7] There is extensive debate in the input-output literature concerning the appropriateness of the industry or the commodity technology assumption. While the resolution of this debate lies beyond the scope of the present paper, it is likely that some form of mixed technology assumption will be the eventual consensus.

industry is more akin to extraction industries than to secondary or tertiary industries. In a very real sense, as Processors recognize economically viable markets, they express demand for more collected waste, which in turn induces Collectors to engage in “resource exploration” types of activities. To the extent that excess post-use waste continues to be discarded, Collectors can increase their output levels by capturing greater proportions of existing discards. For the foreseeable future, it is unlikely that resource constraints on discarded wastes will represent any stronger violation of modeling assumptions than supply constraints on traditional industries. Fortunately, the input-output framework can accommodate the source – collector – processor relationships quite well once collected waste is modeled on current account.

Yet this step is not without its potential pitfalls. To treat collected waste (e.g., carpet) as a current account commodity rigorously requires an analysis of dimensions of the Life Cycle Assessment aspects of the original product. Product inventory estimates (PIEs) must be developed, lifetime distributions of the recycled commodity that effectively capture age of product in use, retirement rates, and other related characteristics are essential to accurately estimate available waste resources. And many issues remain unresolved. Examples include the placement of temporal, physical, and geographical boundaries around the use-reuse system. Several End-of-life (EoL) assumptions also must be made, such as how much potential waste will be stored vs. reused, how many rounds of reuse should be considered, and what will be the effects of various policies on EoL behavior? Addressing these issues becomes part and parcel of the resource exploration process described above.

A final peculiarity of items like carpet waste is that unlike conventional goods that have more or less consistent market values, post-use carpet has potentially three values. If an original user sees the post-use carpet as a nuisance, there will be a payment to the Collector industry for carpet removal. If the user is ambivalent toward the used carpet, or perhaps has access to cheap and easy storage, he or she might agree to let a Collector take the carpet without any monetary transaction. And if the user knows that he or she is sitting on a potentially valuable resource, some Collectors may well pay the user for the opportunity to harvest that resource. Collecting all of these transactions within single sectors can result in a zero, negative, or low positive valued transaction, potentially associated with a very high physical volume of post-use carpet.

The solution here is suggested to lie in the formulation of the Use and Make tables. The crux of the solution is to define a hybrid scrap/services commodity produced by Collectors. Only positive values are then assigned to the post-use/removal services make column for any sources of post-use carpet. The output balance is then maintained by appropriate balancing entries in the Use table.

MAKE						
	Other Comm	Comm X	Comm Y	Comm Z	post-use/removal	collected
Other Ind	+					
Payer Industry X		+			a	
Donater Industry Y			+		b	
Seller Industry Z				+	c	
Collectors					aa+bb+cc	a+b+c
Processors	+	(+)	(+)	(+)		

USE		Payer	Donater	Seller		
	Other Ind	Industry X	Industry Y	Industry Z	Collectors	Processors
Other Comm	+	+	+	+	+	
Comm X	+	+	+	+		
Comm Y	+	+	+	+		
Comm Z	+	+	+	+		
Post-Use/removal		aa			a+b+c+bb+cc	
Collected						a+b+c
Profit		'+a-aa	+b	+c		
Other VA						

Summary and Conclusions

This paper has provided a review of a number of salient issues that arise in the context of modeling recycling and remanufacturing activities in the context of the input-output macro-economic model. We provided a first pass at a solution designed to separate existing recycling and remanufacturing activities from a set of regional accounts, ensuring consistency in the resulting accounts and with the initial accounts. While it establishes consistency in the monetary accounting system, it does not serve fully well the purpose of tracking physical flows. A more desirable solution would provide a formal mechanism linking the micro-process data, often provided in physical units, to the macro-accounting frameworks, most often in monetary units. The development of such a mechanism awaits further research.

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