LIFE-CYCLE ASSESSMENT

Using Input–Output Analysis to Estimate Economy-wide Discharges

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Life-cycle assessment models attempt to quantify the environmental implications of alternative products and processes, tracing pollution discharges and resources use through the chain of producers and consumers. Present life-cycle assessments must draw boundaries that limit consideration to a few producers in the chain from raw materials to a finished product. We show that this limitation considers only a fraction of the environmental discharges associated with a product or process, thereby making current assessments unreliable. We propose an approach that uses economic input–output analysis and pollution discharge data and apply the model to automobiles, refrigerators, and computer purchases, and to a comparison of paper and plastic cups.

Effective environmental decision making requires information about the consequences of alternative designs. For businesses, consumers, and regulators to make informed choices, they must know the environmental consequences of available materials, designs, manufacturing processes, product use pasterns, and disposal. Life-cycle assessment (LCA) is the systematic tool to provide this information (*1–4*). At present, there are no other practical approaches. Life-cycle assessment (LCA) attempts to trace out the major stages and processes involved over the entire life cycle of a product, quantifying the environmental burden at each stage. The Society of Environmental Toxicology and Chemistry (SETAC) has been the most intensive at developing LCA (*3*). LCA is being considered for inclusion in the International Standard Organization's environmental standards (150 14041-44) (*5*). Unfortunately, SETAC's LCA has generated more controversy than agreement; some have criticized it as unable to accomplish what it attempts (*6, 7*). The controversy over the SETAC assessment of environmental implications of paper versus polystyrene foam (plastic) cups illustrates the shortcomings (*8–12*). Equally credible analyses can produce qualitatively different results, so the results of any particular life-cycle analysis cannot be defended scientifically. Thus, current life-cycle analysis is not a reliable scientific tool.

LCA is necessary for sound decision making, but the SETAC LCA method does not provide reliable information. Businesses, consumers, and regulators must either ignore environmental implications or make arbitrary assumptions in using SETAC LCA.

SETAC life-cycle analysis is subject to several major limitations. First, there is a lack of comprehensive data. The model is data intensive, but there are not, and may never be, detailed and accurate data on all the discharges of the various processes and products. The second problem is modeling a new process. A detailed SETAC LCA for a new product or process is inherently difficult to construct. Third is choosing a problem boundary, considering each industry is dependent, directly or indirectly, on all other industries. As an example of this third consideration: Paper cups are made using machinery, which, in turn, is made using other machinery. The machinery is made from steel, which is made with coal, iron ore, and so on. Building the machinery requires the use of automobiles, gasoline, shoes, food, and energy. Because it is impossible to trace directly through all the direct and indirect interactions, the standard recommendation of SETAC LCA is to disregard the environmental implications of machinery and other capital equipment in order to concentrate on the most important process materials (*3*).

We focus on this limitation. The interdependent

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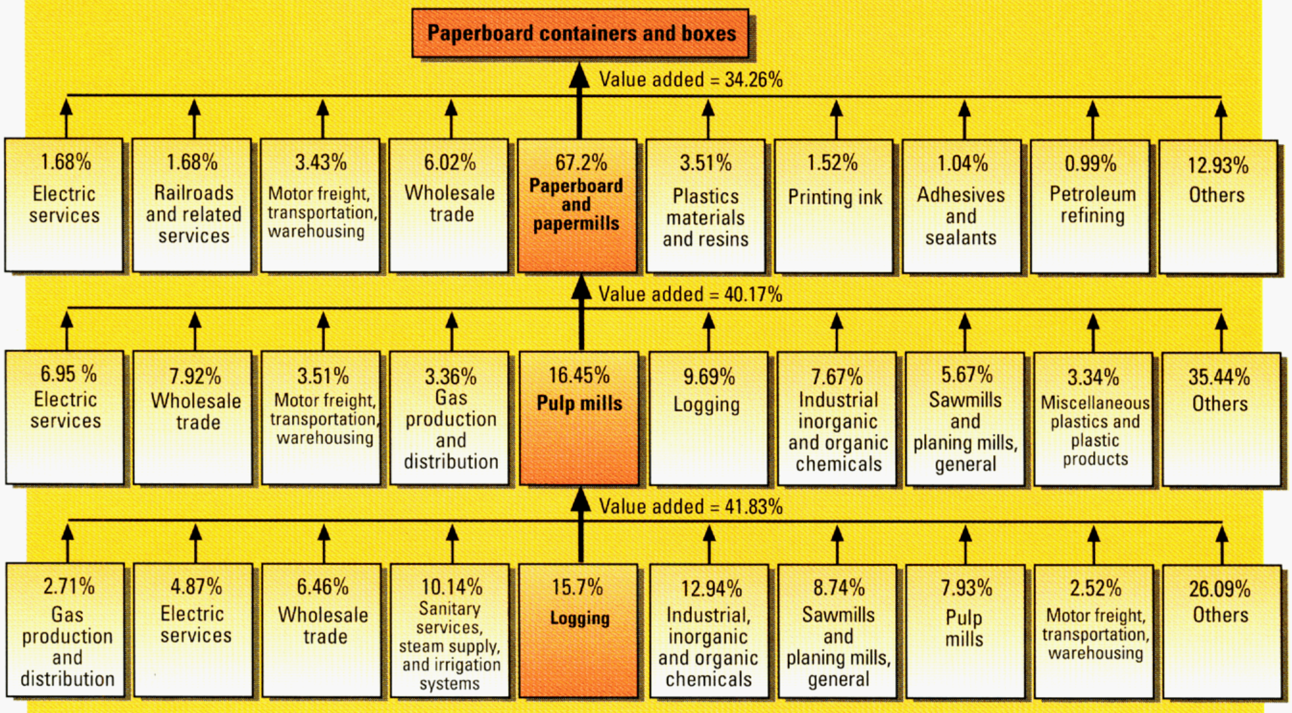
FIGURE 1

Direct suppliers to paper cup manufacturers, paperboard mills, and pulp mills

The SETAC method employed by Hocking (*8*) would consider only one or two of the major direct suppliers at each stage of production (shown in bold), whereas the economic input–output life cycle assessment considers a larger universe of direct suppliers at each stage, as well as indirect contributors.



and interactive nature of the modern economy means that a narrow focus can ignore important effects and lead to qualitatively incorrect conclusions. The indirect effects of increased production of a commodity typically are larger than the direct effects. In our examples, SETAC LCA discharge estimates are less than one-half of the total discharges, considering all interdependencies.

Models of economic interdependence

To examine the economy-wide environmental implications of a design or product, a model must capture economic interdependencies. Two such models currently exist: input–output analysis and computable general equilibrium (*13–16*). The latter allows for general functional forms in characterizing the structure of the economy and has a great deal of flexibility. Unfortunately, the price of this flexibility is that the models are limited to about a dozen sectors because of computational feasibility. This makes them inherently less interesting for this application.

Input–output analysis was developed by Wassily Leontief (for which he received a Nobel Prize in 1973). Leontief assumed that complicated interactions within an economy can be approximated by proportionality relationships. For example, if 90,000 tons of steel are required to make 100,000 cars, 180,000 tons would be required to make 200,000 cars. The model is estimated with data on an entire economy. One might think of an input–output model as a first-order Taylor series approximation to the actual, more complicated relationships. The input-output model results are most accurate when changes in output are relatively small. As changes increase or as new technology is introduced, the model results are likely to be less good approximations of what the economy would deliver.

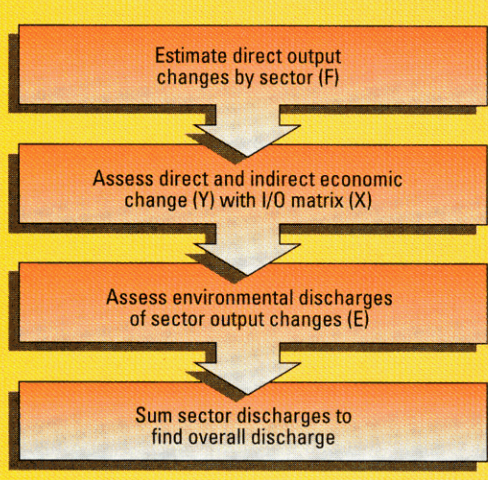
Input–output analysis has been used extensively for planning throughout the world. Many countries, including the United States, collect and publish input–output tables for their economies. The tables are used to calculate the additional resources required for increases in the production of, for example, automobiles or food. The results show the indirect increase in production, for automobiles and for all of the other sectors that supply, directly or indirectly, the automobile industry. In general, each sector contributes directly or indirectly to every other sector. For example, an expansion in automobile production would require steel, electricity, petroleum, plastics, and even the use of other automobiles. The data underlying an input–output table characterize these inputs for every sector.

The use of input–output models for environmental analysis already has been suggested (*17–20*) and applied (*21, 22*). However, we suggest a more ambitious employment of this method for LCA decision making using more detailed data and extensive environmental impact measures. We employ the largest (519 sectors) and most recent (1987) input–output data for the U.S. economy and present examples for the environmental discharge from five products.

The limited nature of the SETAC LCA approach can be illustrated by examining the environmental implications of paper cup production. The first row in Figure 1 lists the largest direct suppliers to the pa-

FIGURE 2

Calculation process for the economic input–output environmental life cycle assessment (EIO-LCA) method



perboard containers and boxes industrial sector as reported by the Department of Commerce's economic input–output model (*23*). The largest supplier, paper and paperboard mills, accounts for 67.2% of the supplies to paperboard container production. But more than 100 of the 519 industrial sectors are direct suppliers to paperboard containers and boxes.

Estimating the environmental discharges associated with making paper cups, Hocking tried to work through a limited chain of suppliers (*8*); he did not examine even the top 10 direct suppliers at each stage. Rather, he followed SETAC-LCA standard practice and limited his analysis to one or two direct suppliers, similar to the boldfaced path in Figure 1. To keep the analysis manageable, Hocking, using the SETAC approach, ignored nearly all but one of the direct suppliers. Instead, he traced a simple path from cutting trees to paper cups. This approach ignores the vast majority of direct suppliers to making paper cups because it cannot handle the numbers. A better method would account for all the suppliers contributing to a product and estimate all their environmental discharges.

Economic input–output life-cycle analysis

Our economic input–output life-cycle analysis (EIO-LCA) method requires several distinct calculations (see Figure 2). The direct economic changes associated with a choice are forecast. For example, switching from steel to aluminum for many automobile components would be represented by an increase in aluminum demand and a decrease in steel demand. An economic input–output model then is used to estimate both direct and indirect changes in output throughout the economy for each sector. Finally, the environmental discharges associated with the changes would be assessed by multiplying the output changes by the average level of toxic discharges and electricity use. Average discharges of conventional pollutants also could be used, but these data are not readily available. The overall environmental impact is characterized by this vector of discharges and electricity use.

The direct changes in output depend upon the choices to be considered. The direct choices are represented by a vector **F**, which contains the monetary changes in each sector's final demand. For example, the vector **F** might have a single entry representing an increased demand for a sector, such as automobiles. Material substitutions might be represented by an increase in one sector (e.g., steel production) and a decrease in other sectors.

Assessing the indirect effects of an incremental economic change is a standard application for input–output models (*13, 24*). The essential tool for the analysis is a matrix indicating sector-to-sector flows of purchases, which is denoted by D. An entry d_{ij} represents the purchases from economic sector i associated with a \$1 output from sector j. Finally, the vector **X** represents overall direct and indirect changes in output by sector.

The input–output system can be written:

$$\mathbf{X} - D\mathbf{X} = \mathbf{F} \tag{1}$$

Premultiplying by $(I - D)^{-1}$ gives:

$$\mathbf{X} = (I - D)^{-1}\,\mathbf{F} \tag{2}$$

which can be expanded to the infinite series of intersector transactions:

$$\mathbf{X} = (I + D + D^2 + D^3 + \ldots)\mathbf{F} \tag{3}$$

Equation 2 says that multiplying the sector of the change in final consumption by $(I - D)^{-1}$ gives the total production required to attain this final output. The direct output ($\boldsymbol{Y}$) associated with final consumption, **F**, can be defined as the first two terms in Equation 3, ($\mathbf{Y} = (I + D)\mathbf{F}$), representing the direct requirements from producers in order to allow the industry to produce this output. Note that all indirect effects (D^2, D^3, etc.) are suppressed.

This input–output analysis can be adapted to environmental purposes. An environmental impact would characterize the discharges into air, water, underground, and on land of an additional \$1 of output from each industry. This environmental matrix can be expanded to include energy inputs, occupational safety and health outcomes, and so on. Let R be a matrix of discharges from a dollar of output of each sector and **E** be the vector of environmental effects. If so, the relationship becomes:

$$\mathbf{E}_T = R\mathbf{X} = R(I - D)^{-1}\mathbf{F} \tag{4}$$

for total effect $\mathbf{E}_T$. Similarly, the direct discharges, $\mathbf{E}_D$, are:

$$\mathbf{E}_D = R\mathbf{Y} = R(I + D)\mathbf{F} \tag{5}$$

We stress the importance of the implicit proportionality assumption in the EIO-LCA model: One input cannot be substituted for another and there are no economies of scale. Both the economic input–output matrix D and the environmental matrix R use averages for the entire sector. In principle, nonlinear or incremental change models could be introduced. For example, the incremental changes in discharges resulting from increased (or decreased) demand might be estimated directly. In practice, data availability and estimation problems limit the extent of more detailed analysis. The EIO-LCA framework does account for the important variations from sector to sector in the economy and the various indirect relationships. Sector variations can be extremely important in LCA. Several sectors have high levels of toxic emissions per dollar of output.

The EIO-LCA model requires economic input–output tables and environmental tables. In the United States, national economic input–output tables are compiled by the Interindustry Economics Division of the Department of Commerce for 519 sectors (*23, 25*). With a $4.2 trillion U.S. economy in 1987, each sector represents an average $9.8 billion of economic activity and includes one or more three- or four-digit Standard Industrial Classification (SIC) codes. The Interindustry Economics Division actually prepares several matrices with slightly different definitions for entries. In our EIO-LCA applications, we use the total requirements commodity-by-commodity matrix for 1987.

Comprehensive data are not available on the environmental discharges of each industry. We focus on toxic discharge data as reported to the Toxics Release Inventory (TRI) for 1988 (*26*). Individual plants in specified industries are required to report their air, water, and land discharges of approximately 320 toxic chemicals. Of the 519 sectors in our input–output matrix, 362 are manufacturing, which are required to report TRI emissions. With these data, estimates can be made of discharges associated with particular output changes by destination media and by specific toxic chemicals.

The TRI data have several limitations. Not all plants are required to report. Discharge data for small plants and for some industries are unavailable. The data generally are estimates, rather than measurements of discharges. The quality of the estimates varies; some plants are likely to be accurate to within a few percent on some chemicals whereas other plants may be off by several orders of magnitude. Thus, the estimates must be interpreted cautiously. The amount of emissions changes over time. In many cases, the plants have reduced discharges considerably. The data are only for the chemicals in the TRI inventory. There are no comprehensive data on the most prevalent air pollutants (particles, sulfur dioxide, oxides of nitrogen, carbon monoxide, and volatile organic compounds). Similarly, there are no comprehensive data on the most prevalent water pollution (biochemical oxygen demand, pesticides, etc.). Thus, this analysis gives only a partial characterization of the environmental implications of each industry. The TRI data report pounds of discharges, making no attempt to account for differences in toxicity among the chemicals (*27*).

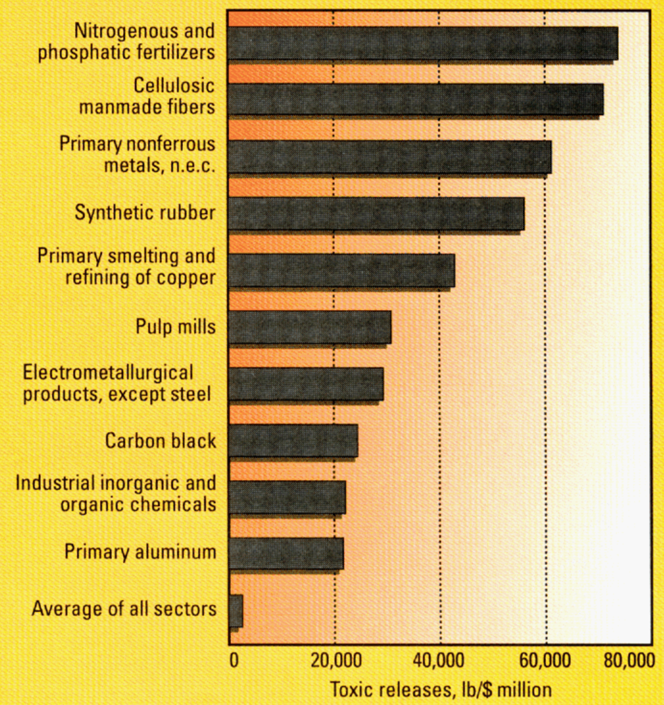
Despite these shortcomings, the TRI data provide indications of discharges of the most important toxic materials. Figure 3 shows the release of toxic materials (measured in pounds) per million dollars of output for all sectors participating in the TRI and for sectors with the highest release ratio. The most intensive release sectors include nitrogenous and phosphatic fertilizers (SIC 2873-2874), cellulose fibers (SIC 2823), nonferrous metals (SIC 3339), synthetic rubber (SIC 2822), and primary smelting and refining of copper (SIC 3331).

Energy and fuel use is another indicator of environmental impact because of the associated use of nonrenewable petroleum sources. The Annual Survey of Manufacturers gives the quantities of electric energy and cost of fuels purchased by four-digit SIC codes (*28*). Unfortunately, comparable data are not available for other industries. Figure 4 shows the 10 most electrically intensive manufacturing sectors as measured by electricity in kilowatt hours (kWh) used per dollar of output.

FIGURE 3

The 10 most intensive industry sectors for toxic emissions, 1988

Data from the Toxic Release Inventory, Environmental Protection Agency.



Direct and indirect effects of increased demand

Table 1 shows the effect of increasing the purchases of automobiles by $10,000. The direct effect of the purchase is $10,000 in cars. The total effect (direct plus indirect) is shown in the next column as $26,700 of total economic activity. Thus, this $10,000 of direct purchase gave rise to indirect purchases of $16,700. The suppliers to the automobile industry that have the greatest TRI discharges also are shown in Table 1, as is the extent to which each supplier contributes to the $26,700 of total spending. The majority of the 519 sectors in the input–output matrix contribute to the automobile industry and so are part of the total spending.

Table 1 also shows the 1988 total toxic releases from each sector as well as electricity usage. Because the indirect purchase of cars resulting from the direct purchase is small (just more than 1%), we can regard the toxic release numbers for cars as indicating direct releases. The discharges are shown as releases into air, water, underground injection, and on land.

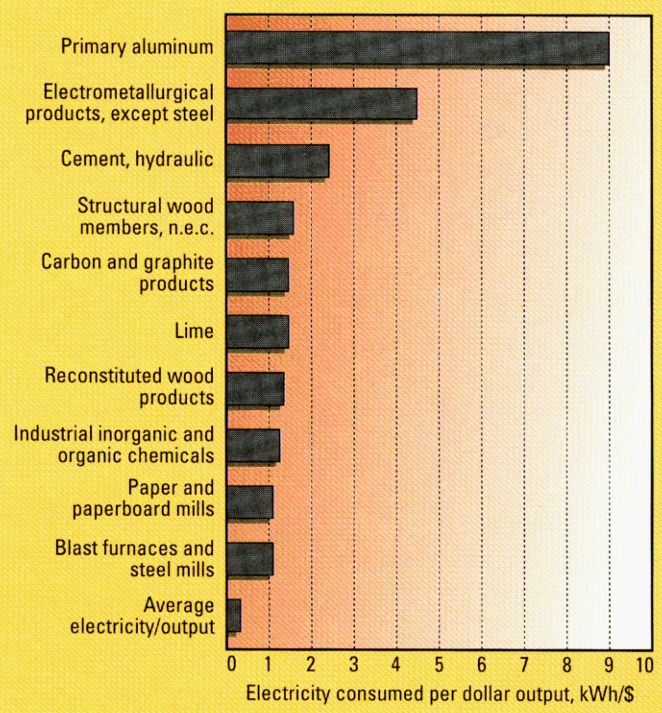
Shown in Table 2 are summary data for increases in the purchases of automobiles, household refrigerators and freezers, and electronic computers. The first column shows the indirect economic activity resulting from a $10,000 order in each industry. Electronic computers has indirect orders only slightly greater than the direct orders. Household refrigerators has indirect orders 20% higher than direct orders. For automobiles, the total (direct plus indirect) orders resulting from a $10,000 order come to $26,700.

The total direct discharge of TRI pollutants is more than 5 lb for the $10,000 in automobile purchases. The indirect purchases contribute nearly an additional 34 lb of toxic releases, more than six times the direct release. Comparatively, household refrigerators have much larger direct TRI releases, comparable indirect releases, and thus higher total discharges. Indirect discharges are more than twice the level of direct discharges.

FIGURE 4

The 10 most electrically intensive industry sectors, 1988

Data from Input-Output Tables of the U.S. Dept. of Commerce



This input–output analysis can be used to compare the direct and total toxic discharges of choosing paper versus plastic cups. This analysis is not comparable to that of Hocking (*8*) for several reasons. Rather than focus on cups, we assume they are typical of the input–output category, cardboard containers. We also assume that plastic cups are representative of the plastics materials and resins category. A wide range of products are in each of these two sectors. However, it is likely that the inputs and discharges per dollar of paper cup are close to the average inputs and discharges per dollar for the category; the same may be true for foam cups and the plastics category. Our estimate of "direct" effects includes all supplies to the two industries. In Figure 1, direct effects include the discharges of all suppliers in the first row. In contrast, Hocking calculated discharges from the shaded path with boldfaced arrows. Hocking attempted to estimate total environmental discharges associated with each product; we calculate only the toxic discharges shown in the TRI. Electronic computers have tiny direct releases, but the indirect releases are more than 20 times larger.

Table 2 shows that the direct discharges from any process are not a good approximation of the total discharges from the process. Indirect discharges are about 7, 3, and 26 times larger than direct discharges for these three industries. These data relate only to TRI data that cover estimated toxic discharges, excluding small plants and nonmanufacturing industries. If data on all industries were available, the indirect effects would be even larger. If discharges of conventional pollutants are roughly proportional to those of these toxic chemicals, a direct estimate of environmental discharges for an industry still is a not good approximation of the total environmental discharges resulting from increasing production from that industry.

The same is true for comparing paper and plastic cup production. Because the input–output table is measured in dollars, the first step is to estimate the price of a paper cup and the price of a plastic cup. Using prices in the largest supermarket chain in Pittsburgh, we estimate that the paper cups cost about 6 cents; plastic cups about 3 cents. The second step

TABLE 1

Direct and indirect economic effects, toxic releases, and electricity demand for a $10,000 increase in automobile demand

Industry sector (SIC code)	Total economic effect	Toxic releases, lb: Air	Water	Underground	Land	Total	Electricity $\times 10^3$ kWh
Industrial chemicals (281)	200	1.42	0.26	3.68	1.18	6.54	73
Blast furnaces and steel mills (3312)	600	0.84	0.13	0.67	4.64	6.28	8
Motor vehicles (3711)	10,100	5.16	0.00	0.00	0.00	5.16	0
Copper smelting and refining (3331)	100	0.14	0.00	0.00	2.20	2.34	0.1
Synthetic rubber (2822)	—	0.30	0.00	1.97	0.00	2.27	2.2
Motor vehicle parts (3714)	3300	2.07	0.01	0.00	0.09	2.17	0.6
Primary aluminum (3334)	100	0.59	0.01	0.00	1.07	1.67	23.8
Primary nonferrous metals (3339)	—	0.95	0.05	0.00	0.62	1.62	0.24
Fabricated wire products (3495-6)	100	0.59	0.00	0.39	0.02	1.00	0.7
Fabricated rubber products (306)	200	0.87	0.00	0.00	0.00	0.87	1.0
All other industrial sectors	12,000	6.62	0.64	0.37	1.40	9.03	1640
Total	**26,700**	**19.55**	**1.10**	**7.08**	**11.22**	**38.95**	**1750**

is to increase demand in the paperboard containers and plastic materials input–output sectors by $10,000 and $5000, respectively (166,667 cups). The direct purchase of $10,000 and $5000 of paper and plastic cups give rise to indirect purchases of $13,860 and $5850, respectively. The 10 most polluting suppliers (direct and indirect) to each sector are shown in Tables 3 and 4. Producing 166,667 paper cups leads to 54.96 lb of toxic discharges and uses 8600 kWh of electricity. Producing 166,667 plastic cups leads to 35.75 lb of toxic discharges and uses 4400 kilowatt hours of electricity.

Several conclusions arise from this comparison. The indirect economic effects of an initial order are large, generally more than twice that of the direct effect; they cannot be neglected in the analysis. The toxic discharges from the direct suppliers of the paperboard and plastics sectors are substantial. Thus, focusing on only one or two of these suppliers would distort the results. Indirect suppliers have substantially greater toxic discharges than direct suppliers. They cannot be neglected without seriously underestimating the total toxic discharges. Per dollar, or pound, of output, plastic generates greater toxic discharges than does paperboard. However, on a per cup basis, paperboard generates more.

TABLE 2

Direct and indirect toxic discharges for three industries

Commodity	Indirect economic activity, dollars	Direct discharge, lb	Indirect discharge, lb	Total discharge, lb
Automobiles	16,700	5	34	39
Household refrigerators	12,310	16	42	58
Electronic computers	10,040	0.5	13	14

Note: Changes are calculated for a $10,000 purchase in each case.

TABLE 3

Direct and indirect toxic releases and electricity demand for a $10,000 increase in paper cup demand

Industry sector (SIC code)	Toxic releases, lb Air	Water	Underground	Land	Total	Electricity $\times 10^3$ kWh
Pulp mills (3312)	9.85	3.89	0.00	0.50	14.24	0.3
Industrial chemicals (281)	2.89	0.53	7.50	2.41	13.33	0.7
Paper and paperboard mills (262-3)	10.30	0.54	0.00	0.84	11.68	4.7
Fertilizers (2873-4)	1.61	1.45	0.54	0.56	4.16	0.0
Paperboard (265)	2.69	0.03	0.00	0.00	2.72	1.8
Synthetic rubber (2822)	0.30	0.00	1.97	0.00	2.27	0.0
Plastics materials (2821)	1.29	0.18	0.03	0.06	1.56	0.2
Blast furnaces and steel mills (3312)	0.11	0.02	0.09	0.63	0.85	0.1
Primary aluminum (3334)	0.20	0.00	0.00	0.36	0.56	0.2
Fabricated wire products (3495-6)	0.31	0.00	0.20	0.01	0.52	0.0
All other industrial sectors	2.20	0.07	0.18	0.62	3.07	0.6
Total	**31.75**	**6.71**	**10.51**	**5.98**	**54.96**	**8.6**

Comparing conventional LCA and EIO-LCA

In principle, the conventional LCA could be used to compare various forms of PET resin or disposable (paper versus plastic) cups against ceramic hot drink cups. However, the conventional LCA will not give equally confident answers in all comparisons. In comparing diverse materials, products, or processes, the full range of direct and indirect material use and impacts are important. For example, the differences among the indirect impacts of different PET resins are probably small. If so, drawing a narrow boundary around the comparison is appropriate. In contrast, comparing disposable plastic with ceramic cups could not be done with confidence using a narrow boundary. They use very different production processes and raw materials and, whereas the plastic cup is disposed of after a single use, the ceramic cup is washed (with eventual disposal). Our EIO-LCA method focuses on quantifying the full range of direct and indirect effects and their environmental consequences. It is best at comparing aggregate, disparate products or processes. The current EIO-LCA method cannot distinguish between the different forms of PET resin.

There are other limitations to our EIO-LCA. Conventional economic input–output matrices do not include activities associated with final consumers, such as energy for product use or wastes of product disposal. Nor are the economic transactions and environmental impacts of exports and imports of goods included in the model. The input–output matrix employed, in principle could be estimated for any geographic region, but the data gathering and estimation cost might be prohibitive.

Heterogeneity of products within industrial categories also is a problem for EIO-LCA. Most of the 519 industrial sectors represented in the input–output table include many products. Even SIC codes are fairly broad. For example, SIC category 3221, glass containers, includes glass ampules; glass bottles for packing, bottling, and canning; glass carboys; glass vials; and glass fruit jars. Environmental effects of the entire product mix are considered in the EIO-LCA, thereby leading to potential errors from aggregation.

The environmental impact data also are limited in that human exposure, health effects, and other impacts are not measured. Again, this is a problem largely of data availability.

These qualifications are significant, limiting our current EIO-LCA to diverse or aggregate comparisons. But EIO-LCA has the advantages of tracing out the full direct and indirect implications of a material, process, or product. The low cost of the analysis is another major advantage. An EIO-LCA analysis can be accomplished in a few hours without additional data, once the matrix has been filled out.

Life-cycle assessment is a necessary tool for pollution prevention decisions. However, as currently practiced, it is seriously incomplete and likely to lead to both quantitative and qualitative errors. Prod-

TABLE 4

Direct and indirect toxic releases and electricity demand for a $5,000 increase in plastic cup demand

Industry sector (SIC code)	Toxic releases, lb Air	Water	Underground	Land	Total	Electricity $\times 10^3$ kWh
Industrial chemicals (281)	3.67	0.68	9.54	3.07	16.96	0.9
Misc. plastics products (308)	6.09	0.04	0.00	0.02	6.15	2.1
Plastic materials and resins (2821)	4.48	0.62	0.09	0.21	5.40	0.6
Synthetic rubber (2822)	0.34	0.00	2.23	0.00	2.57	0.0
Fertilizers (2973-4)	0.30	0.27	0.10	0.10	0.77	0.0
Pulp mills (261)	0.38	0.15	0.00	0.02	0.55	0.0
Blast furnaces and steel mills (3312)	0.05	0.01	0.04	0.28	0.38	0.0
Cellulosic fibers (2823)	0.35	0.00	0.00	0.02	0.37	0.0
Copper smelting and refining (3331)	0.02	0.00	0.00	0.32	0.34	0.0
Paper (262-3)	0.30	0.02	0.00	0.02	0.34	0.1
All other industrial sectors	1.18	0.05	0.27	0.42	1.92	0.7
Total	**17.16**	**1.84**	**12.27**	**4.48**	**35.75**	**4.4**

ucts and processes require the outputs of nearly all sectors of the economy, directly or indirectly. Ignoring virtually all of these inputs ignores the vast majority of environmental discharges. Electronic computers' direct discharges are very small, for example, but the indirect discharges are 26 times larger.

If the analysis were undertaken to determine which form of PET resin is better environmentally, our EIO-LCA would not be useful. The conventional LCA could address this detailed comparison, but would not account for indirect effects. For this case, the indirect effects of different PET resins are likely to be quite similar. Thus, the conventional LCA likely will be able to identify the best resin, although it could not indicate whether PET is better than high-density polyethylene (HDPE) or aluminum.

The inability of EIO-LCA to address detailed comparisons is not an inherent limitation of the approach. With more extensive data, such as that from a conventional LCA, and a two-step process that integrates these data into the input–output matrix, we believe the two approaches can be integrated. Assuming this is true, the integrated approach would range from a standard SETAC LCA for comparing different forms of PET to a combination of SETAC LCA and EIO-LCA for comparing PET to aluminum in a particular product to a straight EIO-LCA for more aggregate comparisons.

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