Economic Input/Output Analysis to Aid Life Cycle Assessment of Electronics Products[1]

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Abstract

Economic input/output (EIO) analysis is a well established modelling framework for tracing the flows of inputs and outputs throughout an economy. It can aid life cycle analysis by providing a comprehensive framework for analyzing environmental costs, thereby eliminating the ad hoc boundary assumptions required in conventional life cycle analysis. We illustrate use of the EIO method with applications to electronics manufacture, including Household Refrigerators and Freezers (SIC 3632), Computers and Office Equipment (SIC 357), and Household Audio and Video Equipment (SIC 3651). The EIO provides an estimate of all direct and indirect pollution discharges associated with manufacture of these products. Our EIO model is based upon the Department of Commerce 480x480 commodity sector data and a variety of environmental impact indices, including the toxic release inventory (TRI) and energy use.

1. Introduction

Numerous corporations have adopted policies of "product stewardship" to reduce environmental impacts and health or safety hazards throughout a product's life cycle. Corporate environmental management systems routinely involve working with suppliers and customers to achieve these goals, and these efforts will likely be intensified with the expected adoption of ISO 14000, the draft standard for environmental management systems.

Several approaches to life cycle assessment are available. First, individual companies can keep good records on their own products and supply information to upstream suppliers and downstream customers. However, companies vary in the degree of environmental impact tracking and the numbers of suppliers and customers for an entire product life cycle may be very large. Second, a formal *life cycle assessment* procedure to summarize environmental impacts from the various manufacturing processes for a product may be adopted [6, 3, 10]. Unfortunately, these SETAC-LCA studies suffer from excessive cost, very large information requirements and the difficulty of drawing appropriate analysis boundaries to permit meaningful analysis [9, 1]. This *boundary problem* is particularly acute because of the very large variation in the environmental impacts of different industries. Since toxic emissions per dollar of output vary by several orders of magnitude, a relatively small supplier to a particular industry may have an inordinate share of the overall environmental impact [7].

We illustrate a third approach to life cycle assessment here, based upon models of industrial activity and their interaction. The fundamental economic model consists of a matrix in which each entry represents the supply from one industry to another. Thus, the direct inputs into an industry is represented by a row of input fractions. With this general equilibrium model of the economy, the full range of inputs to a process can be traced, thus avoiding arbitrary analysis boundary decisions. Once all the inputs associated with some industrial output are traced, the environmental impacts of all these different inputs can be assessed. In this paper, we use the Department of Commerce Economic input/output model of the US economy with 480 industrial sectors [2], and we term the method the EIO-LCA approach. Details of the data sources and calculations appear in the paper appendix.

One limitation of the EIO-LCA approach is the difficulty of differentiating product types and processes used within any particular industry. The SETAC-LCA relies on specific models of products and processes, whereas EIO-LCA focuses on industry level outputs. The two can be used in a complementary fashion, with

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the EIO-LCA used to assess industry level impacts for commodity inputs such as electricity or steel. We illustrate such industry level impact assessments in the next section.

2. Environmental Impacts of Electronics Product Manufacture

In this section, we discuss the economic and environmental impacts associated with a $ 10 million increase in the output of six different industrial sectors. Both direct impacts arising in the sector itself and the indirect impacts from all the supplier industries are included. Traced over time, reductions in these environmental impacts can represent genuine product improvements. Faced with the choice of products from different industries, such as selecting aluminum or steel for a computer cabinet, the impacts can represent the relative environmental impacts of the different alternatives. An Appendix to this paper describes the data sources and analysis methods for these impact estimates.

Table 1 represents various economic and environmental impacts associated with a $ 10 million increase in the output for six different industrial sectors:

- *Household refrigerators and freezers* (SIC 3632) including household and farm refrigerators and freezers.
- *Household audio and video equipment* (SIC 3651) including amplifiers, radios, audio electronic systems, television receiving sets, video cassette recorders, and home entertainment equipment.
- *Electronic computers* (SIC 3571) including mainframe, mini, and personal computers. Note that semi-conductor manufacture is a supplier industry to this sector.
- *Computer and peripheral equipment* (SIC 3572, 3575 and 3577) includes storage devices, disk and drum drives, tape drives, terminals, monitors, printers, plotters, scanning devices and other peripheral equipment.
- *Calculation and accounting machines, except electronic computers* (SIC 3578) includes accounting machines, cash registers, calculators, adding machines, banking machines, etc.
- *Office machines* (SIC 3579) includes mailing, letter handling, and addressing machines, typewriters and word processors, paper handling machines and other office machines.

A single corporation may have manufacturing activities in only one or in more than one of these industrial sectors. In cases of firms such as IBM with activity in multiple sectors, their plant level activities and associated economic inputs are reported to the appropriate sector.

As shown in Table 1, the overall economic impact of a $ 10 million increment in demand for each sector results in between $ 16.9 and $ 23.3 million dollars in additional economic activity. The extra amount of $ 6.9 to 13.3 million represents additional sales generated from suppliers. For example, an additional output of refrigerators would result in electric utilities buying more coal, trucking companies buying more petroleum and computers for management, etc. Economists refer to this additional economic output as a *multiplier effect* from the direct purchase in each sector.

Table 1 also shows the additional energy use and toxic emissions associated with the industrial outputs. In each case, the impact within the sector and the total impact over the entire economy is shown. For example, production of additional electronic computers requires on average 0.98 kwh of electricity per dollar by the manufacturer and 0.317 kwh for the manufacturer and the supplier industry. If all energy sources are included, such as natural gas for combustion or coal for electricity, the energy use is 5,000 BTU per dollar for manufacture alone and 42,000 BTU overall.

Toxic emissions shown in Table 1 represent the unweighted pounds of toxic materials as reported by the Environmental Protection Agency's Toxic Release Inventory (TRI) of manufacturing plants. Again, for the production of additional electronic computers, the industry itself has toxic air emissions to the environment of 34.3 lb per million dollars and a total of 1069 lb of toxic emissions to the environment or to treatment plants per million dollars of output. However, more toxic materials are generated by suppliers to the industry. Toxic air emissions to the environment are 428 lb per million dollars of output. All emissions directly to the environment (including air, water, underground and land) are 724 lb per million dollars. Including discharges to treatment plants, the total toxic releases are 1,743 lb. per million dollars. As noted earlier, the products from a relatively clean

Table 1. Economic and environmental impacts with $10 million in the output for six different industrial sectors.

	Household refrigerators and freezers (SIC 3632)	Household Audio and Video Equipment (SIC 3651)	Electronic computers (SIC 3571)	Computer and peripheral equipment (SIC 3572, 3575, 3577)	Calculating and accounting machines (SIC 3578)	Office machines (SIC 3579)
Increment in demand (million $)	10	10	10	10	10	10
Increment in total demand (million $)	22	23	20	17	19	19
Electricity Increment (million kWh)						
Sector	1.98	2.57	0.98	1.05	0.88	0.90
Total	5.98	4.58	3.17	3.70	3.19	3.57
Energy Increment (billion BTU)						
Sector	14	18	5	5	4	4
Total	106	67	42	52	46	55
Toxic Air Emmisions (lb)						
Sector	13,909	1,874	343	654	0	3,564
Total	24,124	11,981	4,284	5,308	4,430	9,019
Toxic Water Emissions (lb)						
Sector	4	0	0	0	0	0
Total	912	468	248	302	309	447
Toxic Underground Emissions (lb)						
Sector	0	0	0	0	0	0
Total	5,438	2,201	1,203	1,403	1,681	2,070
Toxic Land Emissions (lb)						
Sector	0	0	0	0	0	0
Total	3,945	2,444	1,508	1,931	1,609	1,752
Subtotal Environmental Emissions (lb)						
Sector	*13,913*	*1,874*	*343*	*654*	*0*	*3,564*
Total	*34,420*	*17,094*	*7,244*	*8,944*	*8,029*	*13,288*
Waste Treatment On-Site (lb)						
Sector	65	45	51	404	0	8
Total	2,097	1,458	802	1,167	915	1,043
Off-site treatment Facility (lb)						
Sector	2,558	2,491	675	941	0	14,293
Total	30,326	20,237	9,388	11,754	10,729	25,543
Subtotal treatment emissions (lb)						
Sector	2,622	2,536	726	1,345	0	14,301
Total	32,424	21,695	10,190	12,921	11,643	26,586
Entire Emissions (lb)						
Sector	*16,535*	*4,411*	*1,069*	*1,999*	*0*	*17,865*
Total	*66,844*	*38,789*	*17,434*	*21,865*	*19,673*	*39,875*

Table 2. Top ten sources of toxic environmental releases associated with the production of 10 million dollars of each industry sector.

INDUSTRY_NAME	SIC-GROUP	Household refrigerators and freezers (SIC 3632)	Household audio and video equipment (SIC 3651)	Computer equipment (SIC 3571)	Computer peripheral equipment (SIC 3572, 3575, 3577)	Calculating and accounting machines (SIC 3578)	Office machines (SIC 3579)
Household refrigerators and freezers	3632	1					
Household audio and video equipment	3651		3				
Electronic computers	3571			5			
Computer peripheral equipment	3572, 3575, 3577				5		
Office machines, n.e.c.	3579						1
Industrial inorganic and organic chemical	281, 286	2	1	2	2	1	2
Primary nonferrous metals, n.e.c.	3339	7	2	1	1	2	4
Primary smelting and refining of copper	3331	6	8	3	3	3	6
Miscellaneous plastics products, n.e	308	5	6	4	4	4	3
Plastics materials and resins	2821	4	9	7	7	5	5
Blast furnaces and steel mills	3312	3				6	7
Wood television and radio cabinets	2517		4				
Electron tubes	3671		5				
Other electronic components	3672, 3675-9		7	6	6	8	
Pulp mills	261	9	10	9	9	7	8
Electrometallurgical products, except	3313						9
Synthetic rubber	2822					10	10
Cellulosic manmade fibers	2823	8					
Nitrogenous and phosphatic fertilizer	2873-4	10		8	10	9	
Iron and steel foundries	332				8		
Plating and polishing	3471			10			
Percentage of the total		83%	79%	74%	73%	76%	81%

Figure 1. Toxic releases of the 10 highest direct and indirect industry sectors by media from 10 million dollars of output in the Electronic Computers Sector

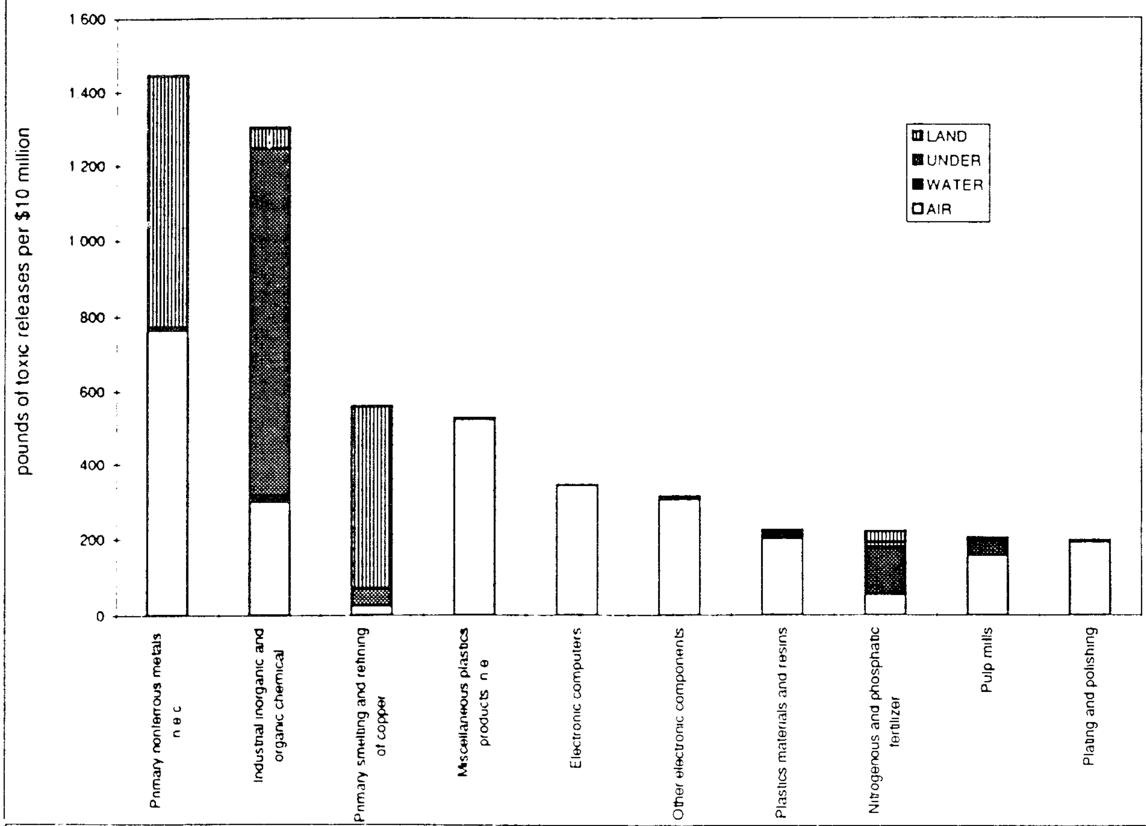
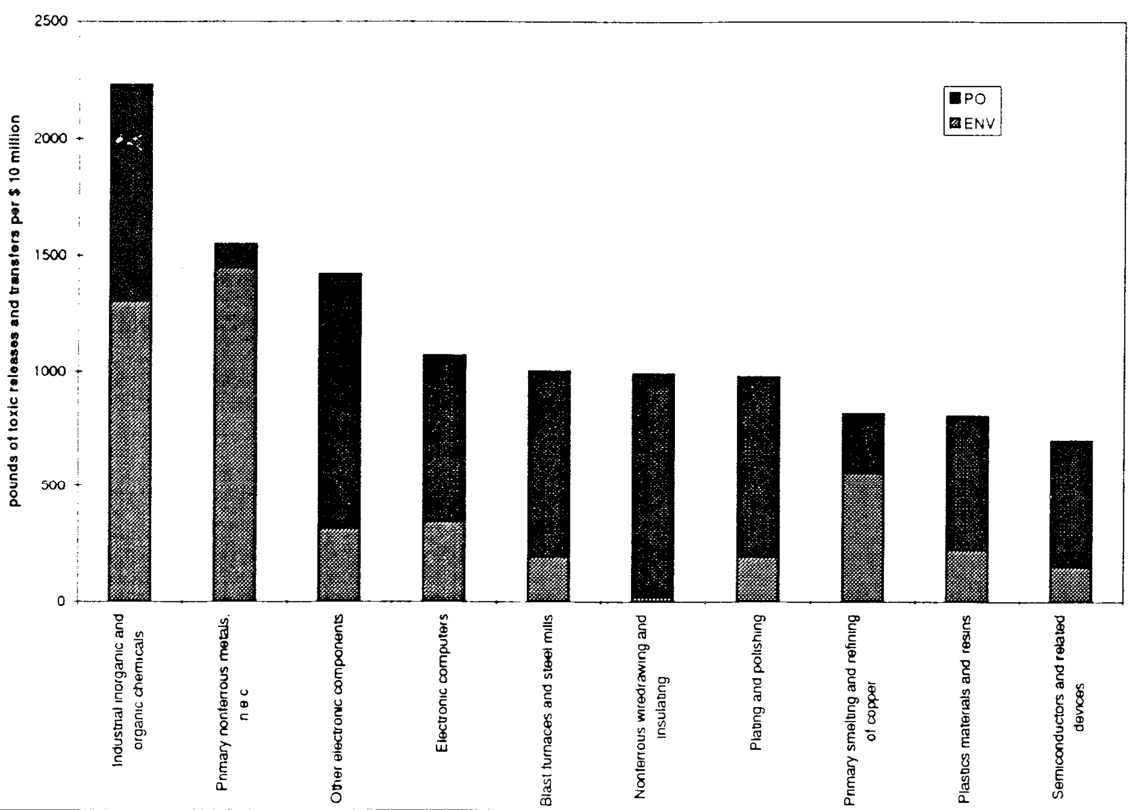


Figure 2. Total environmental releases (ENV) and transfers (PO) of the 10 highest direct and indirect industry sectors from 10 million dollars of output in the Electronic Computers Sector



industry may have more substantial environmental impacts due to the production of needed components and supplies than for the final assembly or manufacture of the product directly.

Some industry comparisons are also possible from the data in Table 1. Production of household refrigerators and freezers requires more energy and results in greater toxic emissions per dollar of output than for any of the other industries shown in Table 1. Electronic computers, peripheral equipment, calculators and other office machine industries are roughly equivalent in their impacts per dollar of output. Production of household audio and video equipment represents an intermediate point in this spectrum, with comparable energy requirements but higher toxic emissions, perhaps due to the manufacture of CRT displays for televisions.

Table 2 summarizes the sources of toxic environmental emissions associated with production of the six industrial sectors shown in Table 1. In this table, the top ten contributing industries are shown. For example, the largest source of toxic emissions for household refrigerators and freezers is the industry's manufacturing plants themselves. Industrial inorganic and organic chemicals (SIC 281,286) is the second largest source, followed by blast furnaces and steel mills (SIC 3312). The top ten industrial sectors for household refrigerators and freezers represent 83% of the total toxic emissions to the environment.

Toxic emissions sources for production of electronic computers (SIC 3571) offers a strong contrast to refrigerator and freezer production. In rank order, the top five contributing industries are: primary non ferrous metals (lead, etc.), industrial inorganic and organic chemicals, primary smelting and refining of copper, miscellaneous plastic products, and, finally, electronic computer manufacture itself. Thus, direct emissions from the industry itself is only the fifth largest source of toxic environmental emissions. The top ten industries shown in Table 2 contribute 74% of all toxic emissions in this case.

Some more details on toxic releases from the production of electronic computers (SIC 3571) are shown in Figures 1 and 2. Figure 1 shows the toxic environmental emissions from the largest sectors due to $ 10 million in electronic computer production. Production of primary nonferrous metals and of industrial inorganic and organic chemicals both result in over 1,200 lb. of toxic emissions for this production. Remarkably, the fertilizer and pulp industries make this listing of the ten largest sources. Although they contribute only slightly in a economic sense to the production of electronic computers, these industries have a relatively high output of toxic chemicals for each dollar of production.

Figure 2 shows all toxic emissions from the ten highest industrial sectors for the production of $ 10 million in electronic computers. In contrast to figure 1, releases to both the environment and to treatment plants are included in Figure 2. Thus, the weight of releases is larger in Figure 2 by the amount of transfers to treatment plants or landfills. The bar graph in Figure 2 shows releases to treatment plants on the top and releases directly to the environment on the bottom.

3. Conclusions

Several conclusions result from our analysis. First, the EIO method can reveal general information on environmental impacts associated with industrial activity. More specifically, the method can reveal the relative importance of supplier generated impacts versus impacts from the industry itself due to manufacturing. For several industries shown in this paper, the indirect impacts due to suppliers substantially exceeded the direct impacts.

Acknowledgements

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I. Methodology and Data Inputs

The methodology associated with economic input/output models was originally developed by Leontief, for which he received a Nobel Prize in Economics [8].

Input-Output Analysis approximates the interactions of the industry sectors within an economy by proportionality relationships. For example, if 10 tons of steel are required to make 8 cars, 20 tons will be required to produce 16 cars. Input-Output analysis assumes there is a vector B that contains the direct monetary changes in each sector's output, a matrix characterizing the structure of the economy X, and a DY vector of all the direct and indirect changes from B. The matrix equation for impacts is $Y=B[I+X+XX+XXX+....] = B[I- X]^{-1}$.

An Input-Output Economic Matrix for the US is compiled by the US Department of Commerce (Interindustry Economies Division) [2], and the most recent 480x480 table available is for 1987.

The environmental vectors consider the releases and transfers per unit of output of each sector. Therefore for each additional $1 output from an industry sector is it possible to estimate the environmental impacts [7].

Energy and electricity requirements for different industrial sectors are available from the federal Energy Information Administration, although not at the four digit SIC level used in our analysis [4]. Consequently, average uses for more aggregate industry groups are used. For example, the energy and electricity increments of household refrigerators and freezers (SIC 3632) and household audio and video equipment (SIC 3651) are aggregated into two digit levels (SIC 36). The energy and electricity increments of the rest were aggregated into three digit levels (SIC 357).

The toxic release data comes from the EPA's Toxic Releases Inventory (TRI) [5]. TRI is a publicly available database that contains amounts of toxic chemical releases and transfers from manufacturing facilities throughout the United States. This inventory was established under the Emergency Planning and Community Right to Know Act of 1986. It has been reported since 1987 as releases and transfers. The manufacturing facilities that annually process more than 25,000 pounds of chemicals or otherwise use 10,000 pounds of TRI chemicals and have 10 or more full time employees have to report toxic releases. Environmental releases are on-site discharge of toxic chemicals that go into air, water, underground injection wells, and land. Transfers are the off-site transfer of chemicals and wastes from the facility that report TRI to another facility. These transfers are divided into wastewater treatment facilities of the state or local municipality (POTW) and Off-site for recycling, energy recovery, treatment different from POTW, disposal, and other transfers. In this paper, we use the 1991 discharges as the most current data available.